CS 335: Runtime Environments

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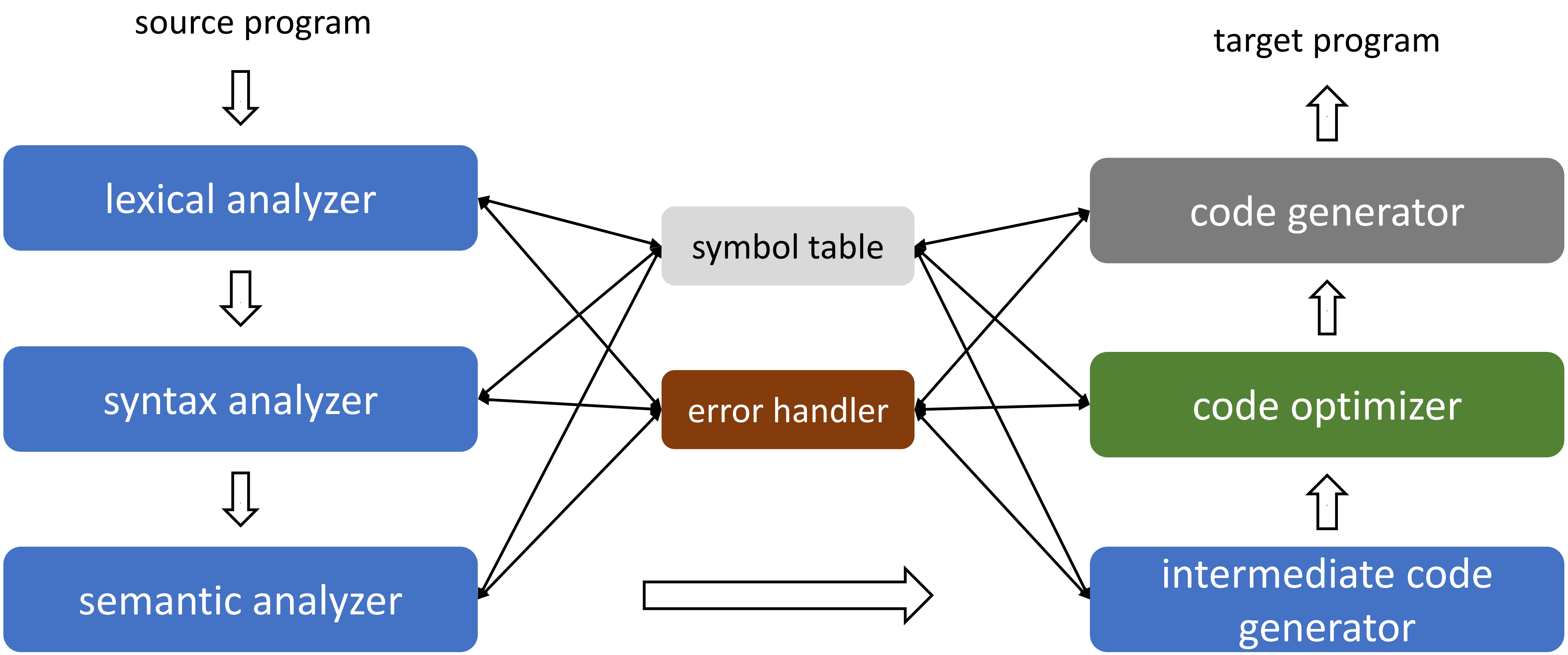
Content influenced by many excellent references, see References slide for acknowledgements.

An Overview of Compilation



Abstraction Spectrum

- Translating source code requires dealing with all programming language abstractions
  - For example, names, procedures, objects, control flow, and exceptions
- Physical computer operates in terms of several primitive operations
  - Arithmetic, data movement, and control jumps
- It is not enough to just translate intermediate code to machine code, need to manage memory when a program is executing

Runtime Environment

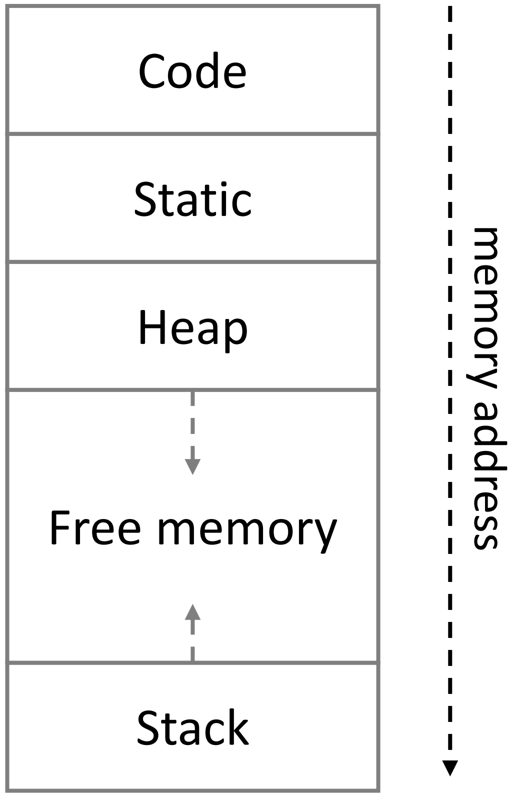
- A runtime environment is a **set of data structures** maintained at run time to implement high-level program structures
  - Examples of data structures are stack, heap, and virtual function tables
  - Program structures depend on the features of the source and the target language, examples are procedures and inheritance
- Compilers create and manage the runtime environment in which the target programs execute
- Runtime deals with the layout, allocation, and deallocation of storage locations, linkages between procedures, and passing parameters among other concerns

Issues Dealt with Runtime Environments

- How to pass parameters when a procedure is called?
- What happens to locals when procedures return from an activation?
- How to support recursive procedures?
- Can a procedure refer to nonlocal names? If yes, then how?
- …

Storage Organization

- Target program runs in its own logical address space
- Size of generated code is usually fixed at compile time, unless code is loaded or produced dynamically
- Compiler can place the executable at fixed addresses
- Runtime storage can be subdivided into
  - Target code
  - Static data objects such as global constants
  - Stack to keep track of procedure activations and local data
  - Heap to keep all other information like dynamic data



Virtual Address Space

```
#include <cstdlib>
#include <iostream>
using std::cout;
int main() {
  int x = 3;
  cout << "Start of code segment: "
       // Note the typecast
       << (void*)&main
       << "\nStart of heap segment: "
       << new int
       << "\nStart of stack segment: "
       << &x << "\n";
  return EXIT_SUCCESS;
}
```

```
❯ g++ virtual-address-space.cpp -o
virtual-address-space

❯ ./virtual-address-space
Start of code segment: 0x55da0d8df1e9
Start of heap segment: 0x55da0f8722c0
Start of stack segment: 0x7ffd7d557b44
```

[The Abstraction: Address Spaces]

Program Segments

```
int gv = 2; // Initialized global in .data
float gb; // Uninitialized global in .bss
const int MAX = 10000; // .rodata
const int MIN = 100;   // .rodata

int main() {
  // Uninitialized static in .bss
  static double s_bss;
  // Initialized static in .data
  static int st = 77;
  static char s_str[] = "CS335!\n";
  const float pi = 3.14; // local, .rodata
  int l_value = 42; // local to main
  return 0;
}
```

```
❯ g++ -std=c++17 --save-temps -o data-segments cpp
❯ size data-segments.o
   text    data     bss     dec     hex filename
    135      16      16     167      a7 data-segments.o
❯ objdump -CS -s -j .data data-segments
...
0000000000004010 <g_value>:
    4010:       02 00 00 00                                     ....
0000000000004014 <main::st>:
    4014:       4d 00 00 00                                     M...
0000000000004018 <main::s_str>:
    4018:       43 53 33 33 35 21 0a 00
```

[C++ Internals :: Memory Layout]()

Strategies for Storage Allocation

- Static allocation – Lay out storage at compile time only by studying the program text
  - Memory allocated at compile time will be in the static area
- Dynamic allocation – Storage allocation decisions are made when the program is running
  - Stack allocation – Manage run-time allocation with a stack storage
    - Local data are allocated on the stack
  - Heap allocation – Memory allocation and deallocation can be done at any time
    - Requires memory reclamation support

Static Allocation

- Names are bound to storage locations at compilation time
  - Bindings do not change, so no run time support is required
  - Names are bound to the same location on every invocation
  - Values are retained across activations of a procedure
- Limitations
  - Size of all data objects must be known at compile time
  - Data structures cannot be created dynamically
  - Recursive procedures are not allowed

Allocating Arrays Statically

```
#define NUM_ELEMS (1 << 30)

int main() {
  int large_array[NUM_ELEMS];
  cout << "Allocation successful!";
  for (int i = 0; i < NUM_ELEMS; i++) {
    large_array[i] = 0;
    cout << "Array[i]: " <<
            large_array[i] << "\n";
  }
  return EXIT_SUCCESS;
}
```

```
❯ g++ static-large-array.cpp -o static-large-array

❯ ./static-large-array
fish: Job 1, './static-large-array' terminated by signal SIGSEGV (Address boundary error)
```

[Why does a large static array give a seg-fault but dynamic doesn't? (C++)]()

Stack vs Heap Allocation

Stack	Heap
• Allocation/deallocation is automatic	• Allocation/deallocation is explicit
• Faster, just move the stack pointer	• More expensive
• Space for allocation is limited	• Challenge is fragmentation

Comparing the Cost of Stack and Heap Allocations

```
#define NUM_ITERS (1e9)
using HR =
std::chrono::high_resolution_clock;
using HRTimer = HR::time_point;
using std::chrono::duration_cast;
using std::chrono::microseconds;
void on_stack() { int i; }
void on_heap() { int* i = new int; }

int main() {
  HRTimer start = HR::now();
  for (int i = 0; i < NUM_ITERS; ++i) {
    on_stack();
  }
  HRTimer end = HR::now();
  auto duration =
duration_cast<microseconds>(end -
start).count();
  cout << "Time for per on_stack alloc:
" << (float)duration / NUM_ITERS << "
us\n";
```

```
  start = HR::now();
  for (int i = 0; i < NUM_ITERS; ++i) {
    on_heap();
  }
  end = HR::now();
  duration =
duration_cast<microseconds>(end -
start).count();
  cout << "Time for per heap alloc: "
<< ((float)duration / NUM_ITERS) / 2 <<
" us\n";
```

```
❯ g++ stack-heap-allocation.cpp -o
stack-heap-allocation
❯ ./stack-heap-allocation
Time for per stack alloc: 0.0017 us
Time for per heap alloc: 0.0069 us
```

Which is faster: Stack allocation or Heap allocation

Static vs Dynamic Allocation

Static	Dynamic

• Variable access is fast
  • Addresses are known at compile time
• Cannot support recursion
	• Variable access is slow
	  • Accesses need redirection through stack/heap pointer
	• Supports recursion

Procedure Abstraction

Activations, calling conventions, accessing local and non-local data

Procedure Calls

- Procedure definition is a declaration that associates an identifier with a statement (procedure body)
  - Formal parameters appear in declaration while actual parameters appear when a procedure is called
- Important abstraction in programming
  - Provides control abstraction and name space
  - Defines critical interfaces among large parts of a software
- Creates a controlled execution environment
  - Each procedure has its own private named storage or name space
  - Executing a call instantiates the callee's name space

Control Abstraction

- Each language has rules to
  - Invoke a procedure (pass control by manipulating the PC)
  - Map a set of arguments from the caller’s name space to the callee’s name space (pass data)
  - Allocate space for local variables when a procedure executes
  - Return control to the caller, and continue execution after the call

- Linkage convention standardizes the actions taken by the compiler and the OS to make a procedure call

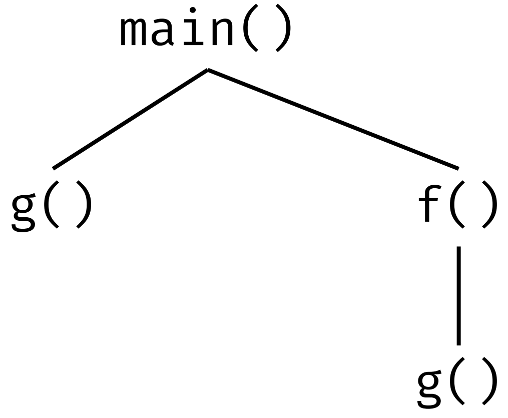
Procedure Calls

- Each execution of a procedure P is an **activation** of the procedure P
- A procedure is recursive if an activation can begin before an earlier activation of the same procedure has ended
  - If procedure is recursive, several activations may be alive at the same time
- The **lifetime** of an activation of P is all the steps to execute P including all the steps in procedures that P calls
  - Given activations of two procedures, their lifetimes are either non-overlapping or nested

Activation Tree

- Depicts the way control enters and leaves activations
  - Root represents the activation of `main()`
  - Each node represents activation of a procedure
    - Node a is the parent of b if control flows from a to b
    - Node a is to the left of b if lifetime of a occurs before b
- Flow of control in a program corresponds to depth-first traversal of activation tree

```
int g() { return 42; }
int f() { return g(); }
int main() {
  g();
  f():
}
```

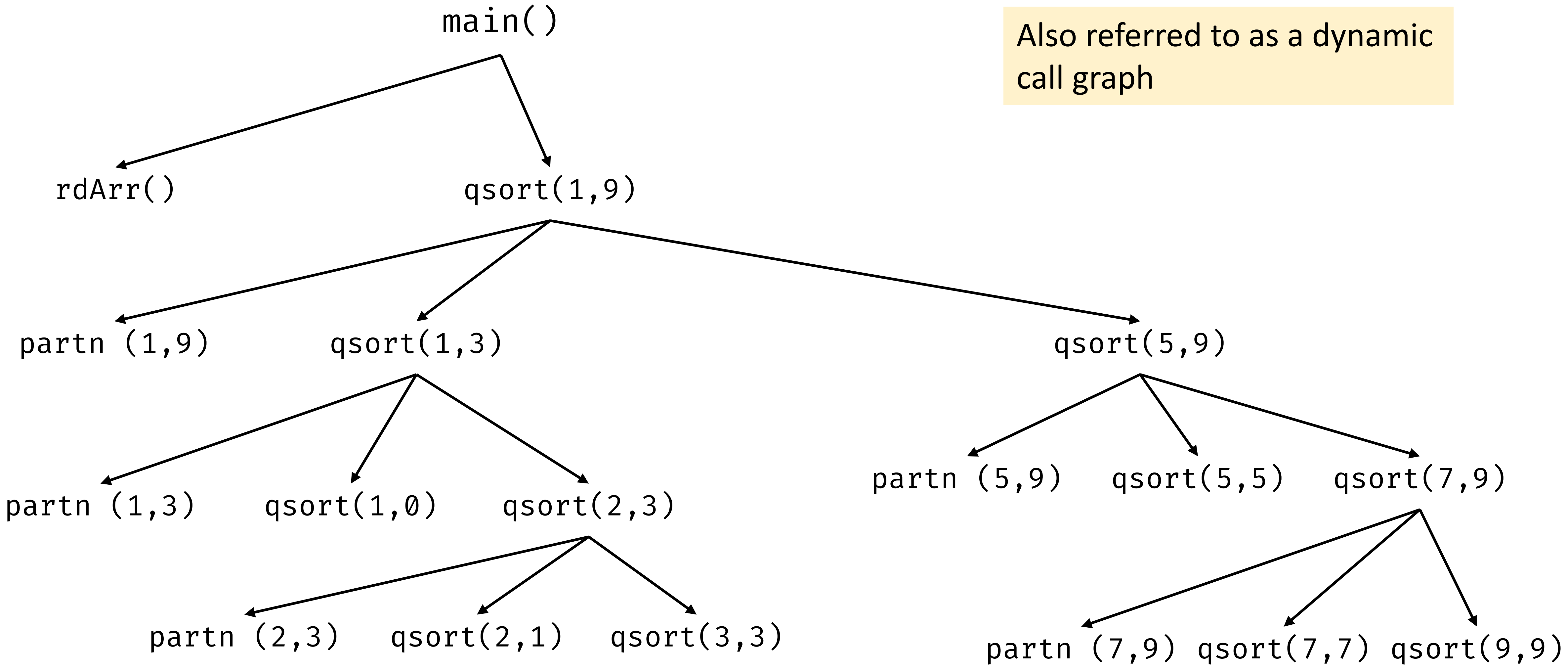


Quicksort Code

```
int a[11];
void readArray() {
  int i;
  …
}

int main() {
  readArray();
  a[0] = -99999;
  a[10] = 99999;
  quicksort(1, 9);
}
```

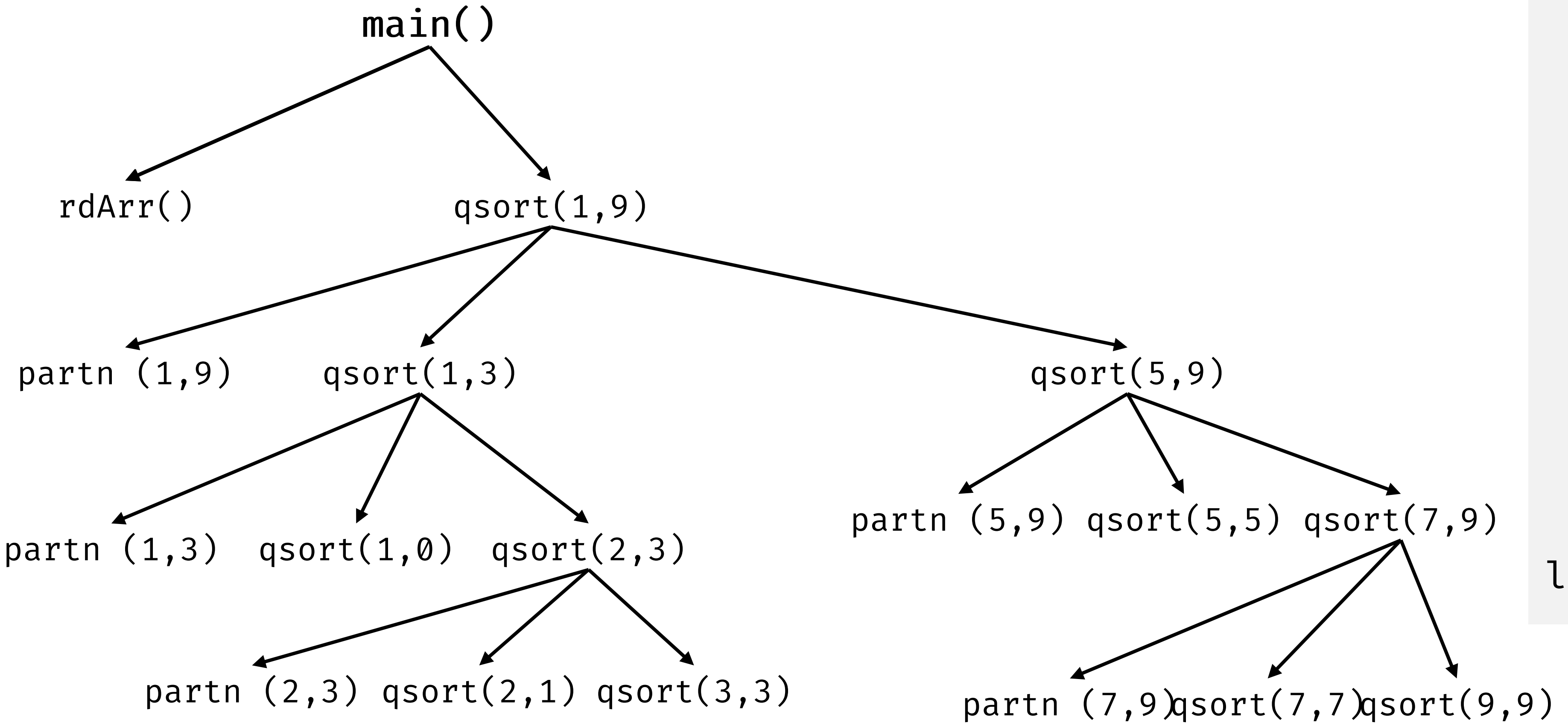
```
void quicksort(int m, int n) {
  int i;
  if (n > m) {
    i = partition(m, n);
    quicksort(m, i-1);
    quicksort(i+1, n);
  }
}

int partition(int m, int n) {
  …
}
```

One Possible Activation Tree



Also referred to as a dynamic call graph

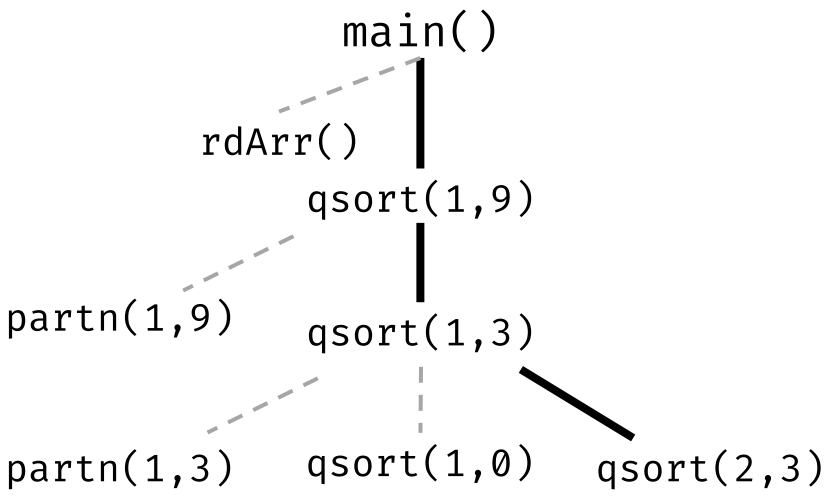
Example of Procedure Activations

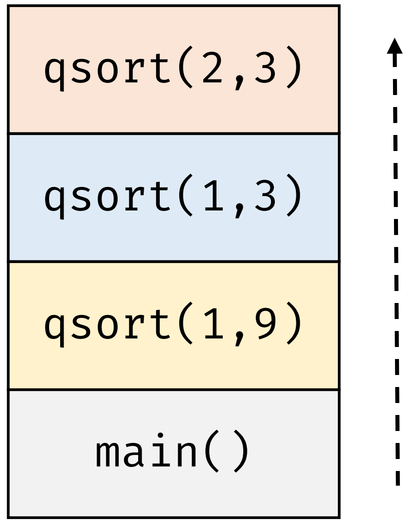



```
enter main()
  enter readArray()
  leave readArray()
  enter quicksort(1,9)
    enter partition(1,9)
    leave partition(1,9)
    enter quicksort(1,3)
    ...
    leave quicksort(1,3)
    enter quicksort(5,9)
    ...
    leave quicksort(5,9)
  leave quicksort(1,9)
leave main()
```

Control Stack

- Procedure calls and returns are usually managed by a run-time stack called the **control stack**
- Each live activation has an activation record on the control stack (also called a **frame**)
  - Stores control information and data storage needed to manage the activation
- Frame is pushed when activation begins and popped when activation ends
- Suppose node n is at the top of the stack, then the stack contains the nodes along the path from n to the root





Is a Stack Sufficient?

When will a control stack work?

- Once a function returns, its activation record cannot be referenced again
- We do not need to store old nodes in the activation tree
- Every activation record has either finished executing or is an ancestor of the current activation record

When will a control stack not work?

- A function's activation record can be referenced after the function returns
- Function closures – procedure and run-time context to define free variables

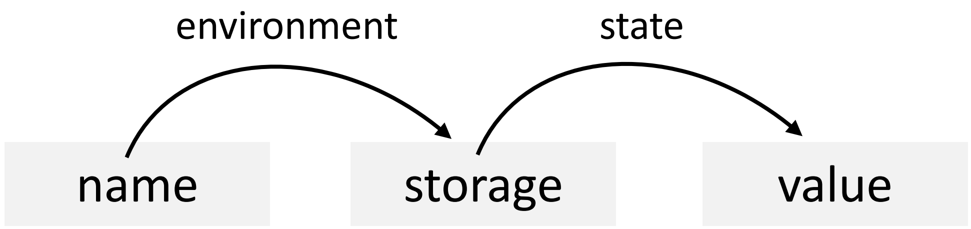
Function Closure

- Function closure stores a function together with the **environment**
- Popularly used in languages where functions are first-class objects
  - Functions can be returned as results from higher-order functions, or passed as arguments to other function calls

```
def f(x): # returns a closure
  def g(y):
    return x+y
  return g
def h(x): # returns a closure
  return lambda y: x+y
# assign closure to variable
a = f(1)
b = h(1)
# use the closure stored in variables
assert a(5) == 6
assert b(5) == 6
# use closures without binding to variables
assert f(1)(5) == 6
assert g(1)(5) == 6
```

[Wikipedia: Closure]

Environment and State



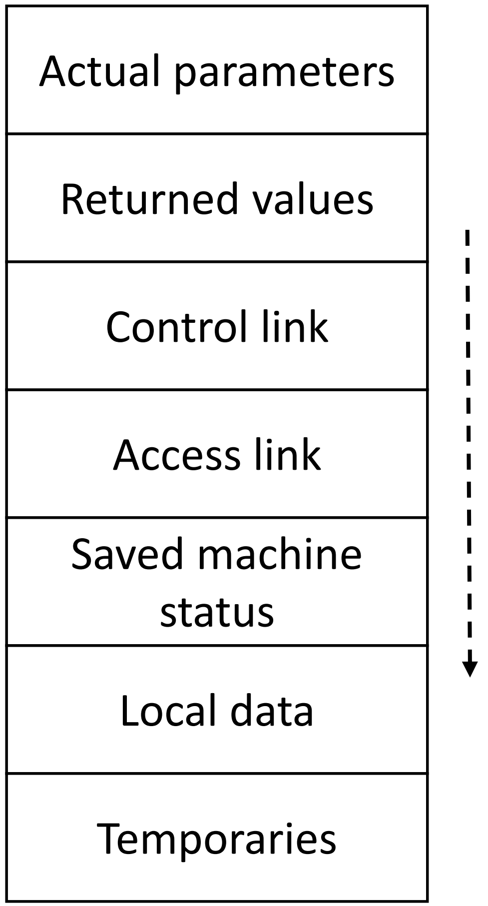
Environment	State
• Refers to a function that maps a name to a storage location • Maps a name to a l-value	• Refers to a function that maps a storage location to the stored value • Maps the l-value to a r-value

An assignment changes state, not the environment

An expression evaluated to a location is a l-value.
An expression evaluated to a value is a r-value.

Activation Record

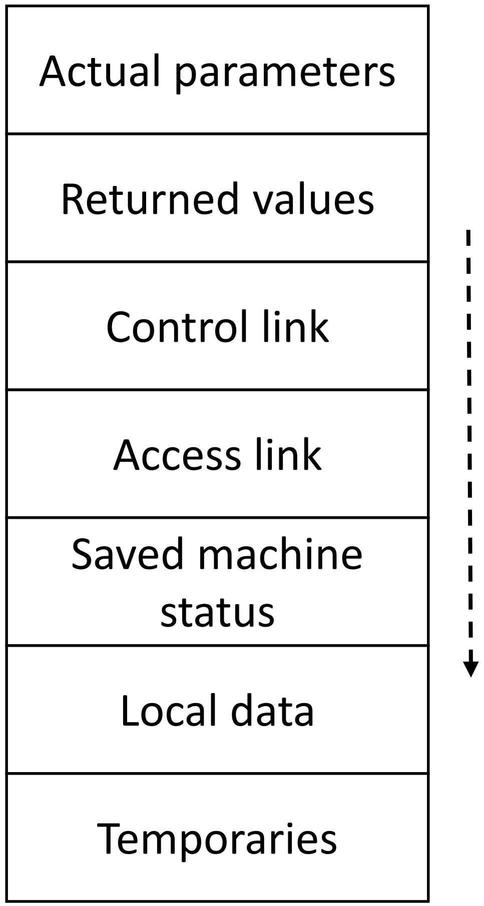
- A pointer to the current activation record is maintained in a register
- Fields in an activation record
  i. Temporaries – evaluation of expressions
  ii. Local data – field for local data
  iii. Saved machine status – information about the machine state before the procedure call
     - Return address (value of program counter)
     - Register contents
  iv. Access link – access non-local data



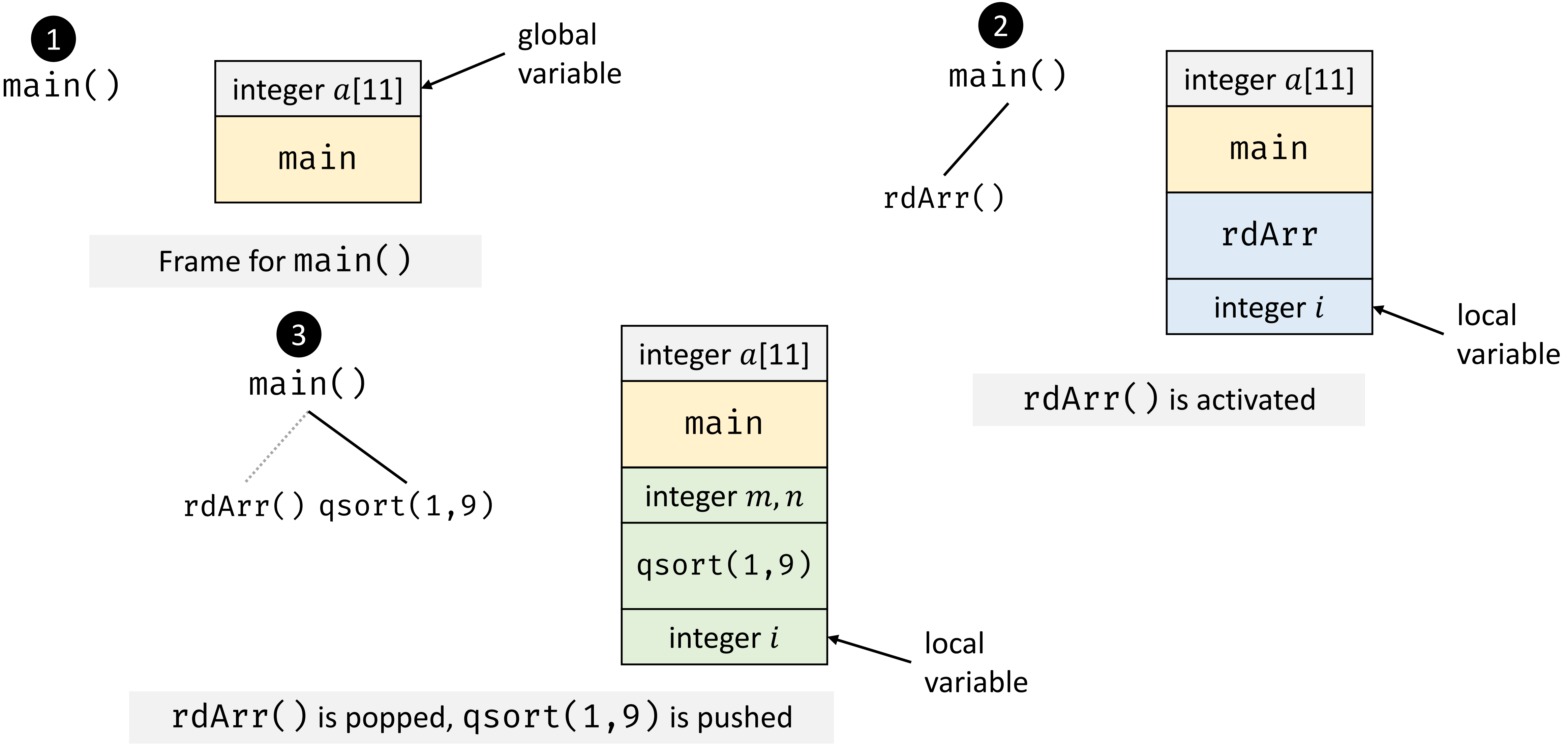
Activation Record

- Fields in an activation record
    v. Control link – Points to the activation record of the caller
    vi. Returned values – Space for the value to be returned
    vii. Actual parameters – Space for actual parameters

- Contents and position of fields may vary with language and implementations



Sequence of Activation Record Manipulation

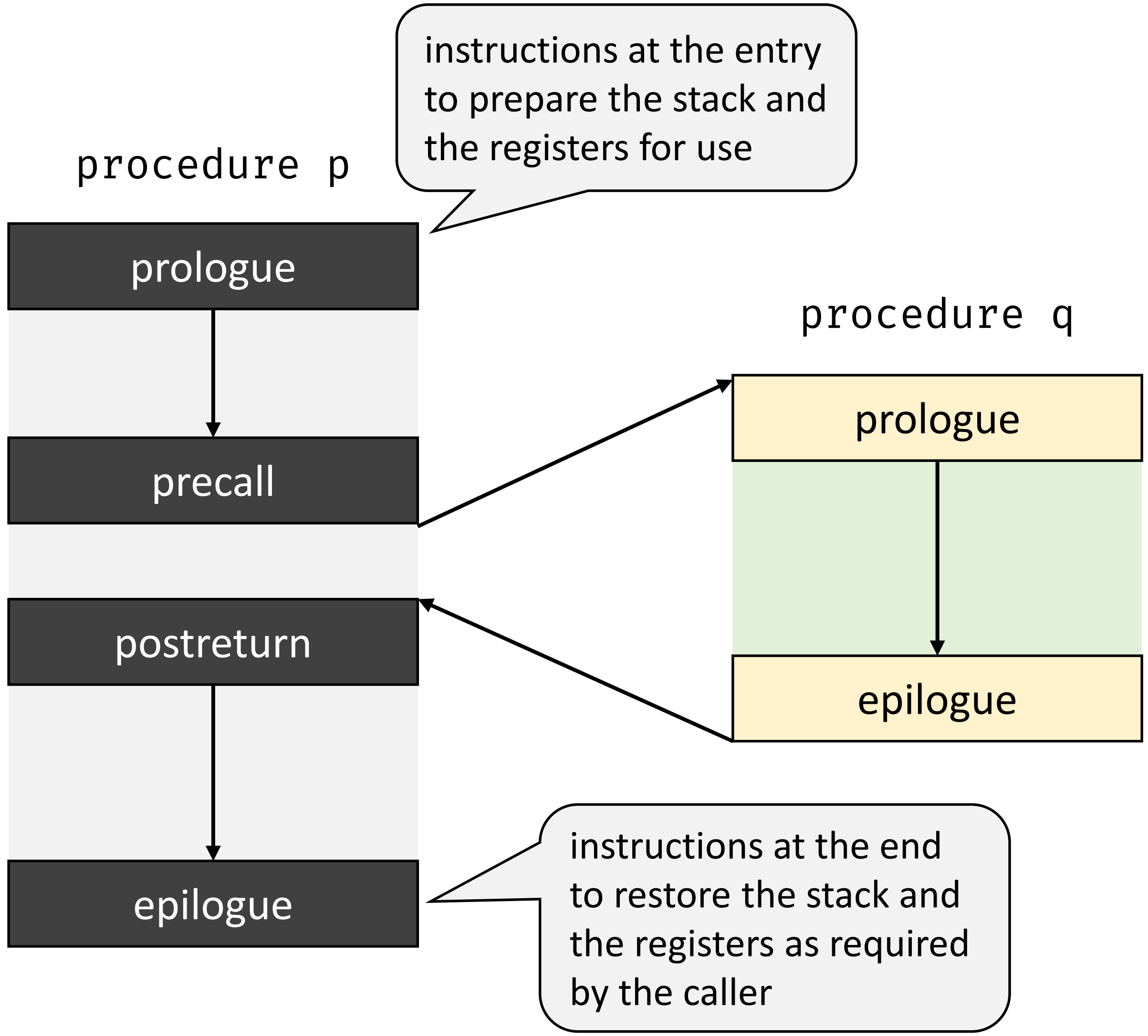


What is in G( )'s Activation Record when F( ) calls G( )?

- If a procedure F calls G, then G's activation record contains information about both F and G
- F is suspended until G completes, at which point F resumes
  - G's activation record contains information needed to resume execution of F
- G's activation record contains
  - G's return value (needed by F)
  - Actual parameters to G (supplied by F)
  - Space for G's local variables

A Standard Procedure Linkage

- Procedure linkage is a contract between the compiler, the OS, and the target machine
- Divides responsibility for naming, allocation of resources, addressability, and protection



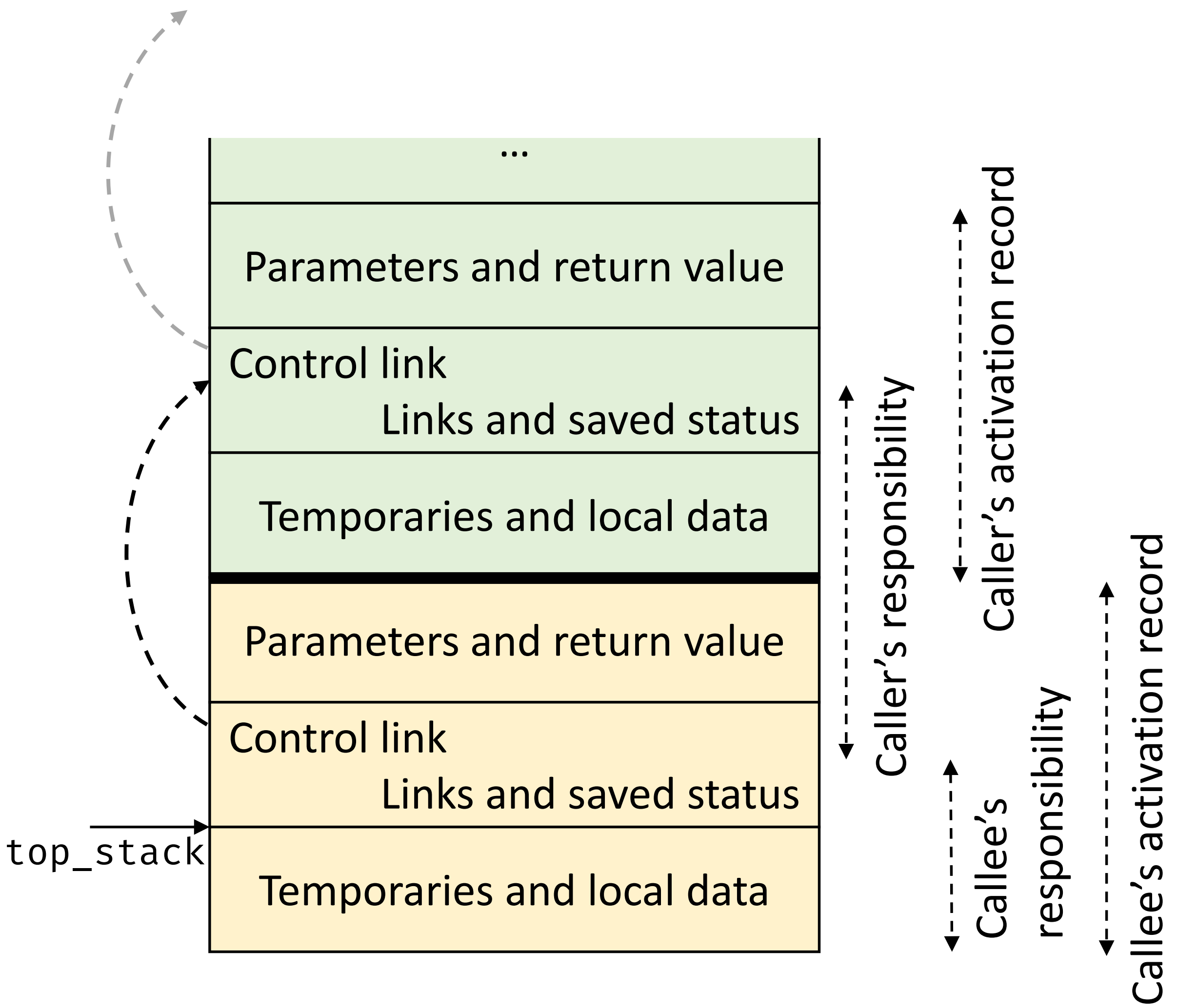
Calling and Return Sequence

- **Calling sequence** allocates an activation record on the stack and enters information into its fields
  - Responsibility is shared between the caller and the callee
- **Return sequence** is code to restore the state of the machine so the calling procedure can continue its execution after the call

Calling Sequence

- Policies and implementation strategies can differ
  - Place values communicated between caller and callee at the beginning of the callee’s activation record, close to the caller's activation record
  - Fixed-length items are placed in the middle
  - Data items whose size are not known during intermediate code generation are placed at the end of the activation record
  - Top-of-stack points to the end of the fixed-length fields
    - Fixed-length data items are accessed by fixed offsets from top-of-stack pointer
    - Variable-length fields records are actually "above" the top-of-stack

Division of Tasks Between Caller and Callee



Division of Tasks Between Caller and Callee

Call sequence

a. Caller evaluates the actual parameters

b. Caller stores a return address and the old value of `top_stack` into the callee's activation record

c. Caller then increments `top_stack` past the caller's local data and temporaries and the callee's parameters and status fields

i. Callee saves the register values and other status information

ii. Callee initializes its local data and begins execution

Calling Conventions

- Specifies how functions calls are set up and executed
  - E.g., passing arguments and return values

```
MyFunc(a,b)
```

```
push a
push b
call MyFunc
```

or

```
push b
push a
call MyFunc
```

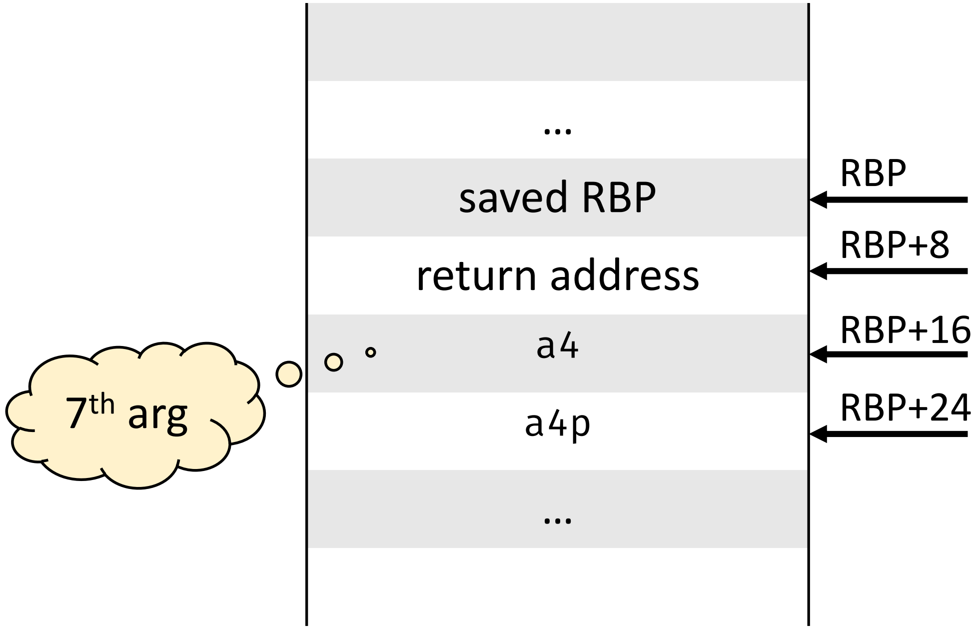
- x86-64 calling convention
  - First six integral (including pointers) function arguments are passed in registers `%rdi`, `%rsi`, `%rdx`, `%rcx`, `%r8`, and `%r9`
  - Subsequent arguments are passed on the stack in the reverse order (arg 7 is at the top)
  - The return value is passed in register `%rax`
  - Floating point parameters are passed in `xmm0-xmm7`
  - If the function takes a variable number of arguments (like `printf`), then `%rax` must be set to the number of floating point arguments
  - The stack pointer register `%rsp` must be aligned to 16-byte boundary before the call
  - Complete set of rules (System V ABI) are complex

[CS61: Assembly]
[System V Application Binary Interface]

Example Procedure Call

```
void proc(long a1, long *a1p,
          int a2, int *a2p,
          short a3, short *a3p,
          char a4, char *a4p) {
  *a1p += a1;
  *a2p += a2;
  *a3p += a3;
  *a4p += a4;
}
```

```
❯ gcc -S -m64 -fno-asynchronous-unwind-tables -fno-exceptions proc-call.c

  …
```



Example Procedure Call

```c
void proc(long a1, long *a1p,
          int a2, int *a2p,
          short a3, short *a3p,
          char a4, char *a4p) {
  *a1p += a1;
  *a2p += a2;
  *a3p += a3;
  *a4p += a4;
}
```

```
❯ gcc -O2 -S -m64 -fno-asynchronous-unwind-tables -fno-exceptions proc-call.c
  …
  ; Fetch a4p, move 8 bytes
  movq    16(%rsp), %rax
  addq    %rdi, (%rsi) ; *a1p += a1
  addl    %edx, (%rcx) ; *a2p += a2
  ; Fetch a4 to %dl
  movl    8(%rsp), %edx
  addw    %r8w, (%r9) ; *a3p += a3
  addb    %dl, (%rax) ; *a4p += a4
  ret
  …
```

Register Saving Conventions

```
proc1:
    …
    movq $0x100, %rdx
    call proc2
    addq %rdx, %rax
    …
    ret
```

```
proc2:
    …
    subq $0x200, %rdx
    …
    ret
```

- **Caller saved**
  - Caller saves temporary values in its frame (on the stack) before the call
  - Callee is then free to modify their values
- **Callee saved**
  - Callee saves temporary values in its frame before using
  - Callee restores them before returning to callee

- %rbx, %rbp, and %r12–%r15 are callee-saved registers
- All other registers, excepting %rsp, are caller-saved
- %rax holds the return value, so implicitly caller saved
- %rsp is the stack pointer, so implicitly callee saved

Use of Callee-Saved Registers

```c
long proc2(long);

long proc1(long x, long y) {
  long u = proc2(y);
  long v = proc2(x);
  return u+v;
}
```

```
❯ gcc -S -m64 -fno-asynchronous-
unwind-tables -fno-exceptions
callee-saved-regs.c
```

```
proc1: ; x is in %rdi, y is in %rsi
   pushq   %rbp
   movq    %rsp, %rbp
   subq    $32, %rsp
   movq    %rdi, -24(%rbp)
   movq    %rsi, -32(%rbp)
   movq    -32(%rbp), %rax
   movq    %rax, %rdi
   call    proc2@PLT
   movq    %rax, -16(%rbp)
   movq    -24(%rbp), %rax
   movq    %rax, %rdi
   call    proc2@PLT
   movq    %rax, -8(%rbp)
   movq    -16(%rbp), %rdx
   movq    -8(%rbp), %rax
   addq    %rdx, %rax
   leave
   ret
```

Division of Tasks Between Caller and Callee

Return Sequence

- Callee places the return value next to the parameters
- Callee restores `top_stack` and other registers
- Callee branches to the return address that the caller placed in the status field
- Caller copies return value into its activation record

Data Communication between Procedures

- **Parameter binding** maps the actual parameters at a call site to the callee's formal parameters
- Types of mapping conventions: call by value, call by reference, call by name

Call by Value and Call by Reference

Call by Value	Call by Reference
• Convention where the caller evaluates the actual parameters and passes their r-values to the callee • Formal parameter in the callee is treated like a local name • Any modification of a value parameter in the callee is not visible in the caller	• Convention where the compiler passes an address for the formal parameter to the callee • Any redefinition of a reference formal parameter is reflected in the corresponding actual • A formal parameter requires an extra indirection

Call by Name

- Reference to a formal parameter behaves as if the actual parameter had been textually substituted in its place
  - Renaming is used in case of clashes
  - Can update the given parameters
- Actual parameters are evaluated inside the called function
- Example: Algol-60

```
procedure double(x);
  real x;
begin
  x := x*2
end;
double(c[j]) → c[j] := c[j]*2
```

```
int f(int j) {
  int k = j; // k = 0
  i = 2; // modify global i
  // a[i] is reevaluated, giving 2
  k = j;
}
char array[3] = { 0, 1, 2 };
int i = 0;
f(a[i]);
```

[Pass-By-Name Parameter Passing]

[What is "Call By Name"?]

Challenges with Call by Name

```
procedure swap(a, b)
integer a, b, temp;
begin
    temp := a
    a :=  b
    b := temp
end;
```

What will happen when you call `swap(i, x[i])`?

```
temp := i
i := x[i]
x[i] := temp
```

Before call	i=2	x[2]=5	
After call	i=5	x[2]=5	x[5]=2

Pass-By-Name Parameter Passing

Name Spaces, and Lexical and Dynamic Scoping

- **Scope** is the part of a program to which a name declaration applies
  - Scope rules provide control over access to data and names
  - A variable that a procedure refers to and that is declared outside the procedure's own scope is called a **free** variable
- **Lexical scope** – a name refers to the definition that is lexically closest to the use
  - With lexical (a.k.a., static) scoping, a free variable is bound to the declaration for its name that is lexically closest to the use
- With **dynamic scoping**, a free variable is bound to the **variable most recently created** at run time (e.g., Common Lisp)
- Lexical scoping is more popular, dynamic scoping is relatively challenging to implement
  - Both are identical as far as local variables are concerned

Nested Lexical Scopes in Pascal

```
program Main_0(inp, op);
  var x_1, y_1, z_1: integer;
  procedure Fee_1;
    var x_2: integer;
    begin { Fee_1 }
      x_2 := 1;
      y_1 := x_2*2+1
    end;
  procedure Fie_1;
    var y_2: real;
    procedure Foe_2;
      var z_3: real;
      procedure Fum_3;
        var y_4: real;
        ...
```

- Compilers can use a static coordinate for a name for lexically-scoped languages
- Consider a name x declared in a scope s
- Static coordinate is a pair $<l, o>$ where l is the lexical nesting level of s and o is the offset where x is stored in the scope's data area

Scope	x	y	z
Main	<1,0>	<1,4>	<1,8>
Fee	<2,0>	<1,4>	<1,8>
Fie	<1,0>	<2,0>	<2,8>
Foe	<1,0>	<2,0>	<3,0>
Fum	<1,0>	<4,0>	<3,0>

Lexical and Dynamic Scope

```
int x = 1, y = 0;
int g(int z) {
  return x + z;
}
int f(int y) {
  int x;
  x = y + 1;
  return g(x * y);
}
int main() {
  print(f(3));
}
```

free variable

- What is printed?
  - With lexical scoping: 13
  - With dynamic scoping: 16

[Static (Lexical) Scoping vs Dynamic Scoping (Pseudocode)]

Lexical and Dynamic Scoping in Perl

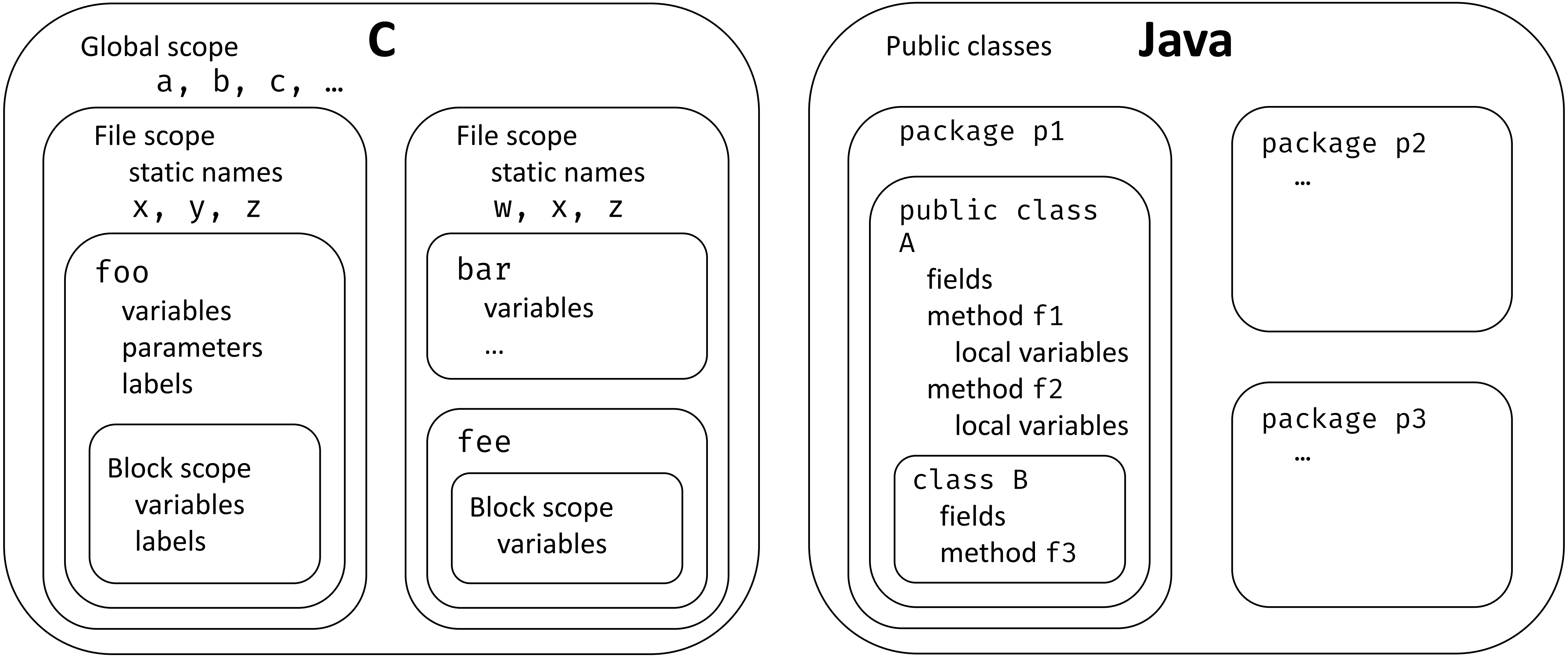
```
$x = 10;
sub f
{
   return $x;
}
sub g
{
  # If local is used, x uses dynamic scoping
  # If my is used, x uses lexical scoping
  local $x = 20;
  # my $x = 20;
  return f();
}
print g()."\n";
```

```
Dynamic scope

$ perl scope.pl
20
```

```
Lexical scope

$ perl scope.pl
10
```

[Static (Lexical) Scoping vs Dynamic Scoping (Pseudocode)]

Scoping Rules for C and Java Languages

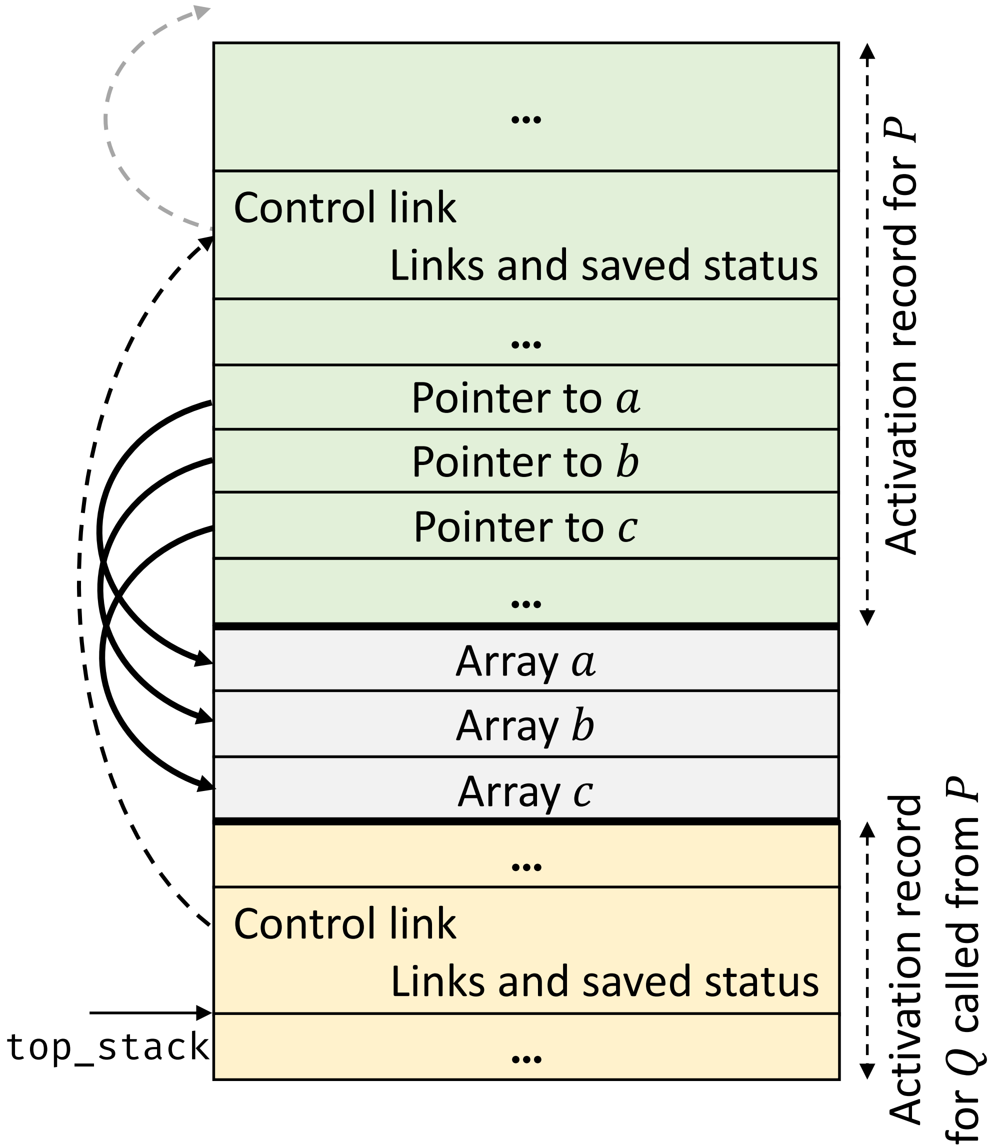


Allocating Activation Records

- Stack allocation
  - Activation records follow LIFO ordering (e.g., Pascal, C, and Java)
- Heap allocation
  - Needed when a procedure can outlive its caller (e.g., Implementations of Scheme and ML)
  - Garbage collection support eases complexity
- Static allocation
  - Procedure P cannot have multiple active invocations if it does not call other procedures
  - A **leaf procedure** makes no calls to other procedures

Variable Length Data on the Stack

- Data may be local to a procedure but the size may not be known at compile time
  - For example, a local array whose size depends upon a parameter
- Data may be allocated in the heap but would require garbage collection
- Possible to allocate variable-sized local data on the stack



Data Access without Nested Procedures

- Consider the C-family of languages
- Any name local to a procedure is non-local to other procedures

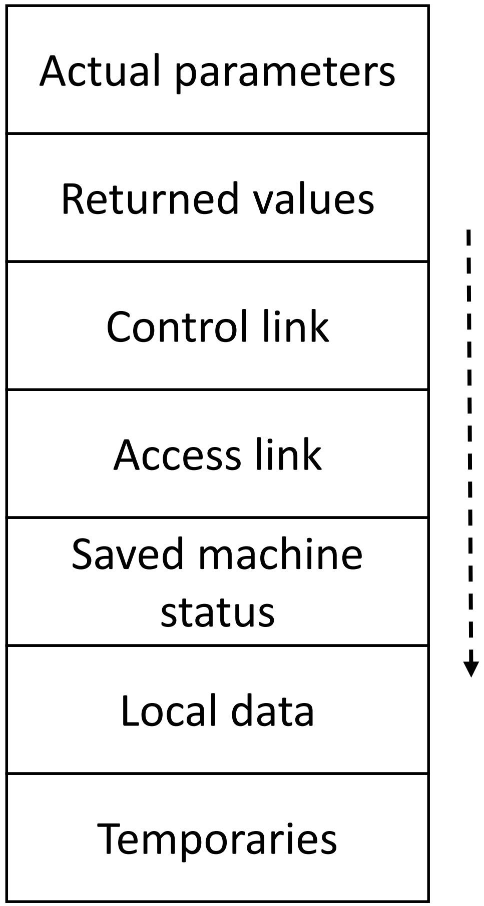
- Access rules
  i. Global variables are in static storage
     - Addresses are fixed and known at compile time, use the addresses in the code
  ii. Any other name must be local to the activation at the top of the stack

Access to Non-local Data in Nested Procedures

- Suppose procedure p at lexical level m is nested in procedure q at level n, and x is declared in q
  - Our aim is to resolve a non-local name x in p
  - Finding the declaration for non-local x in p is a static decision
- Compiler models the reference by a static distance coordinate $<m - n, o>$ where o is x's offset in the activation record for q
  - Compiler needs to translate $<m - n, o>$ into a runtime address
- Finding the relevant activation of q from an activation of p is a dynamic decision
  - We cannot use compile-time decisions since there could be many activation records of p and q on the stack
- Two common strategies: **access links** and **displays**

Access Links

- Suppose procedure p is **nested** immediately within procedure q
- Access link in any activation of p points to the most recent activation of q
- Access links form a chain up the nesting hierarchy
  - All activations whose data and procedures are accessible to the currently executing procedure



Nesting Depth

- Procedures not nested within other procedures have nesting depth 1
  - For example, all functions in C have depth 1
- If p is defined immediately within a procedure at depth i, then p is at depth $i + 1$

Quicksort in ML using Nested Procedures

```
1) fun sort (inputFile, outputFile) =
     let
2)     val a = array(11,O);
3)     fun readArray(inputFi1e) = ... ;
4)       ...a... ; // use
5)     fun exchange(i, j) =
6)       ...a... ; // use
```

```
7)     fun quicksort(m,n) =
         let
8)         val v= ... ; // pivot
9)         fun partition(y,z) =
10)          ...a...v...exchange... // use
         in
11)        ...a...v...partition...quicksort
         end
     in
12)    ...a...readArray...quicksort...
     end;
```

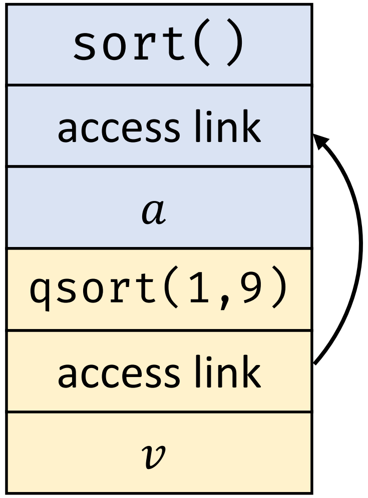
Procedure	Nesting Depth
sort	1
readArray	2
exchange	2
quicksort	2
partition	3

How to find non-local x?

- Suppose procedure p is at the top of the stack and has depth n_p, and q is a procedure that surrounds p and has depth n_q
  - Usually $n_q < n_p$; $n_q == n_p$ only if p and q are the same

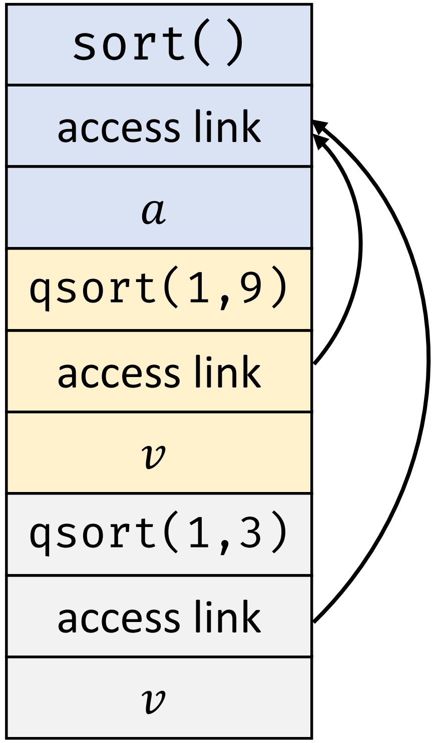
- Follow the access link $(n_p - n_q)$ times to reach an activation record for q
  - That activation record for q will contain a definition for local x

Example of Access Links

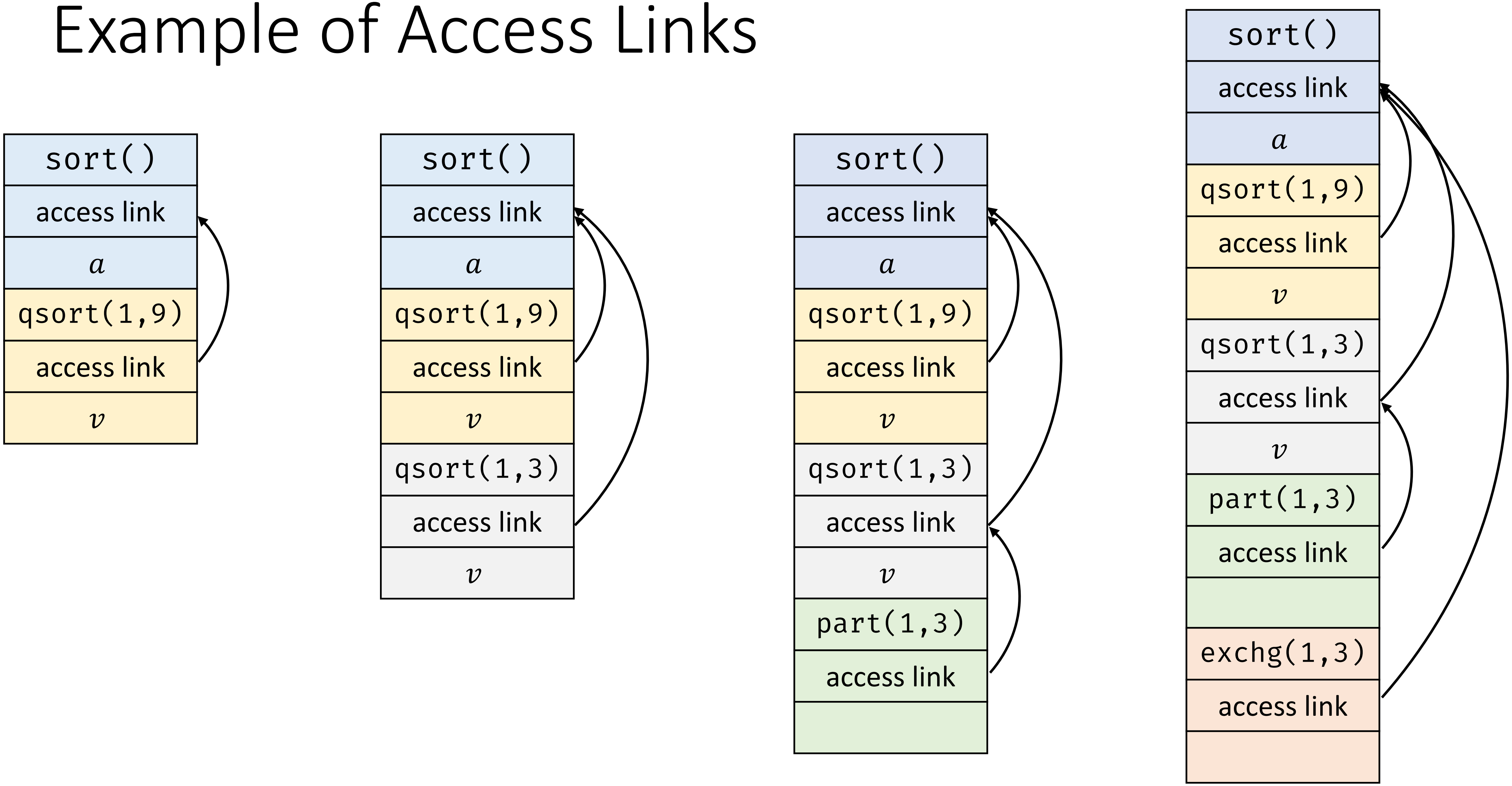


Because `sort()` called `quicksort()`?

No, because `sort` is the most closely **nested** function surrounding `quicksort`

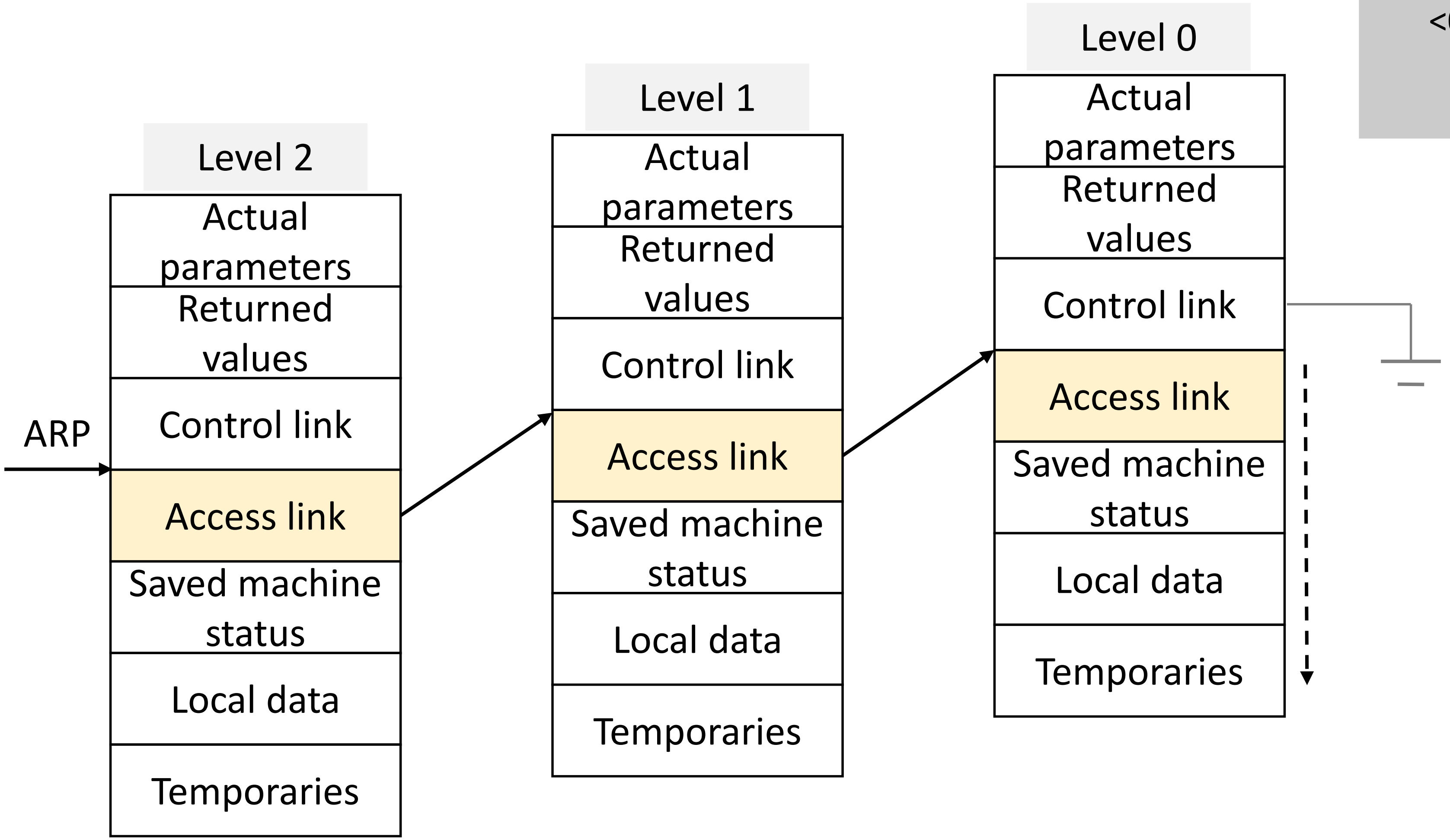


Example of Access Links



Manipulating Access Links

Coordinate	Code
<2, 24>	`loadAI` r_{arp}, 24 $\Rightarrow$ r_2
<1, 12>	`loadAI` r_{arp}, -4 $\Rightarrow$ r_1 `loadAI` r_1, 12 $\Rightarrow$ r_2
<0, 16>	`loadAI` r_{arp}, -4 $\Rightarrow$ r_1 `loadAI` r_1, -4 $\Rightarrow$ r_1 `loadAI` r_1, 16 $\Rightarrow$ r_2



Manipulating Access Links

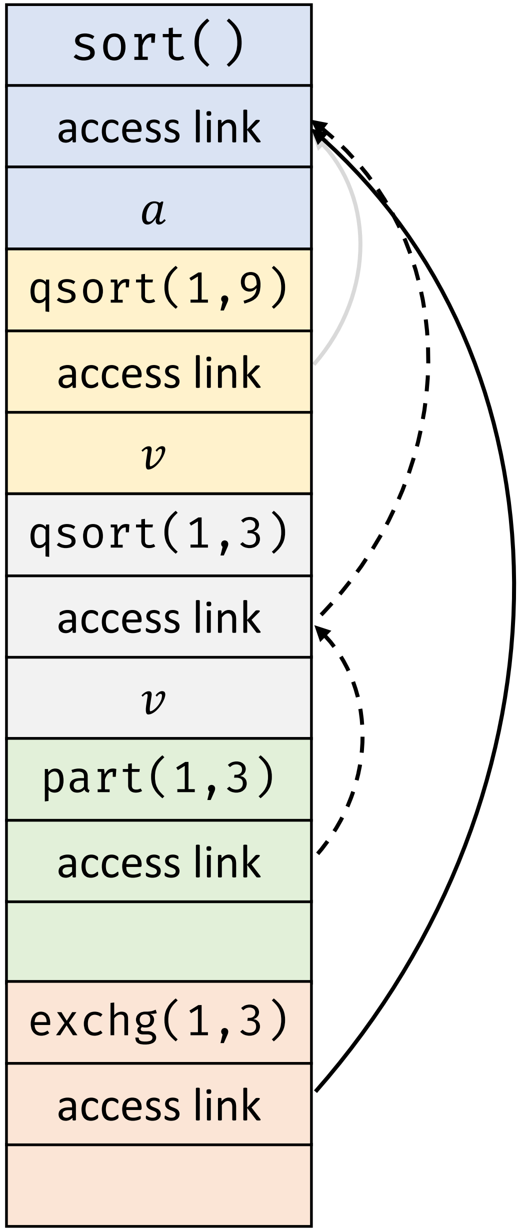
- Code to setup access links is part of the calling sequence
- Suppose procedure q at depth n_q calls procedure p at depth n_p
- The code for setting up access links depends upon whether or not the called procedure is nested within the caller

Manipulating Access Links

- Case 1: $n_q < n_p$
  - Called procedure p is nested more deeply than q
  - Therefore, p must be declared in q, or the call by q will not be within the scope of p
  - Access link in p should point to the access link of the activation record of the caller q
  - E.g., `sort()` calls `quicksort()`, `quicksort()` calls `partition()`
- Case 2: $n_p == n_q$
  - Procedures are at the same nesting level (recursive call)
  - Access link of called procedure p is the same as q
  - E.g., `quicksort(1,9)` calls `quicksort(1,3)`

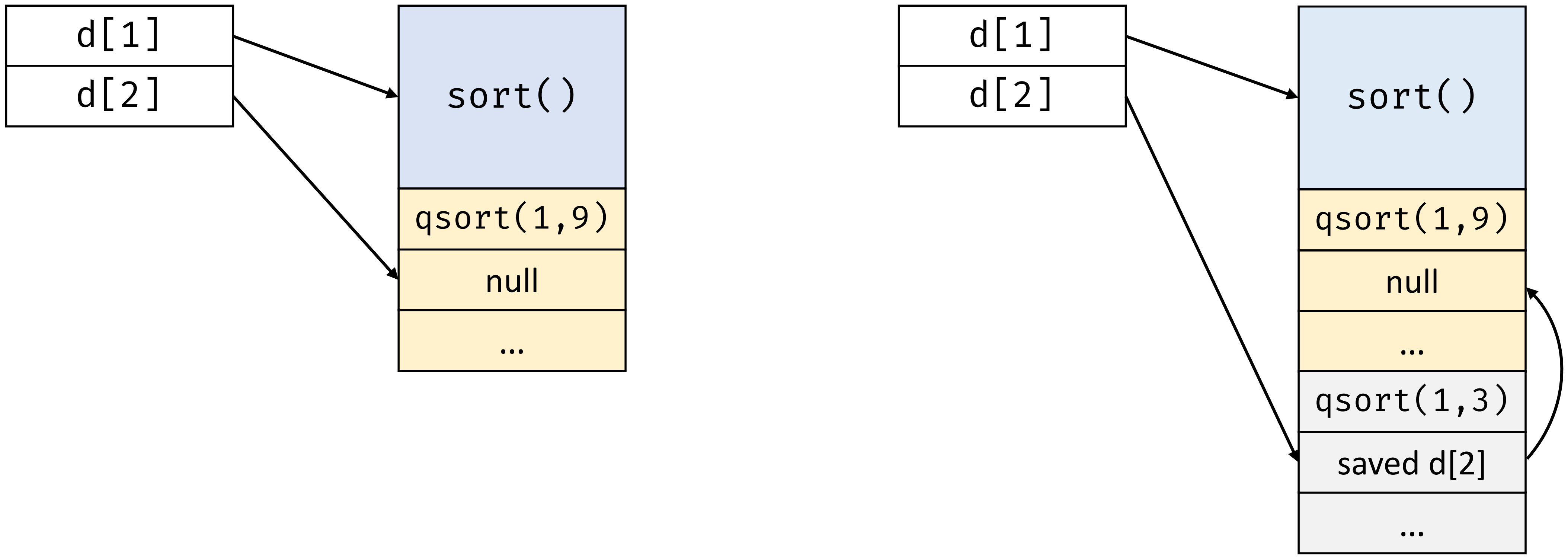
Manipulating Access Links

- Case 3: $n_q > n_p$
  - For the call within q to be in the scope of p, q must be nested within some procedure r, while p is defined immediately within r
  - Top activation record for r can be found by following chain of access links for $n_q - (n_p - 1)$ hops, starting in the activation record for q
  - Access link for q will go to the activation for r
- Example:
  - Nesting depth of calling function `partition` is 3
  - Nesting depth of called function `exchange` is 2



Displays

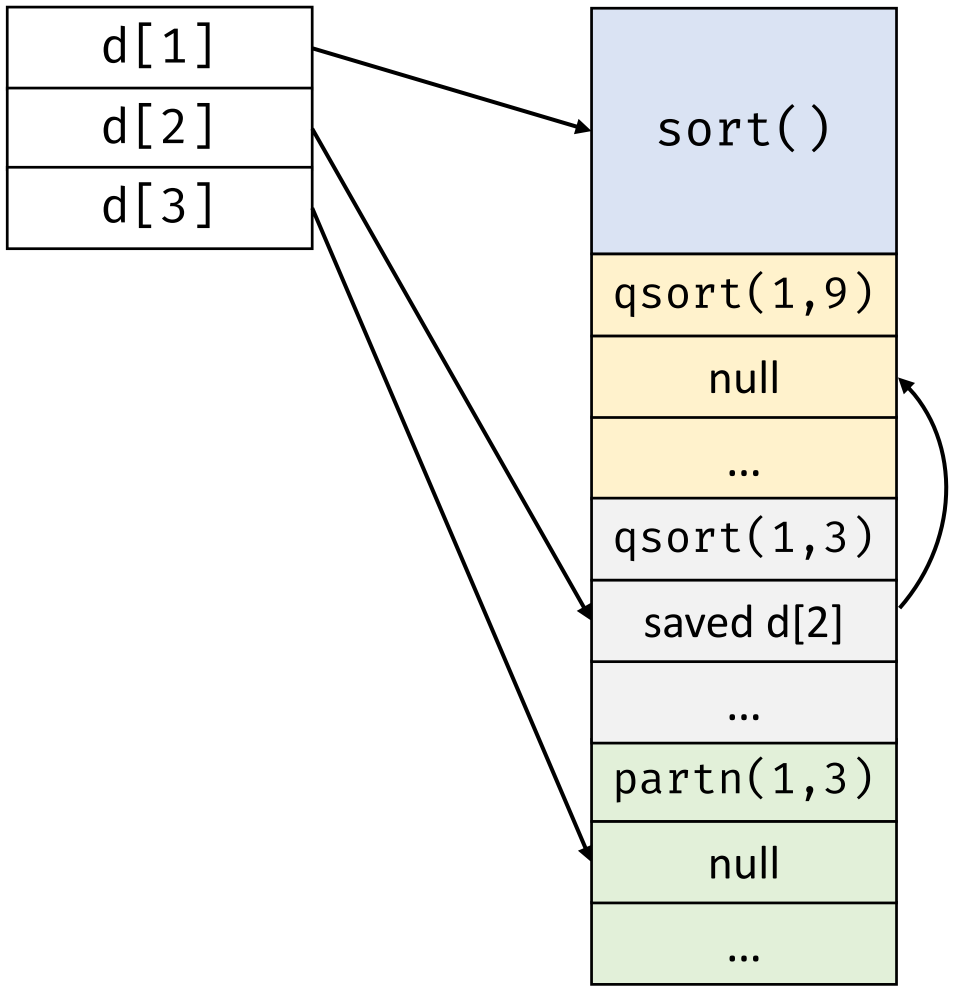
- Display is a global array to hold the activation record pointers for the most recent activations of procedures at each lexical level



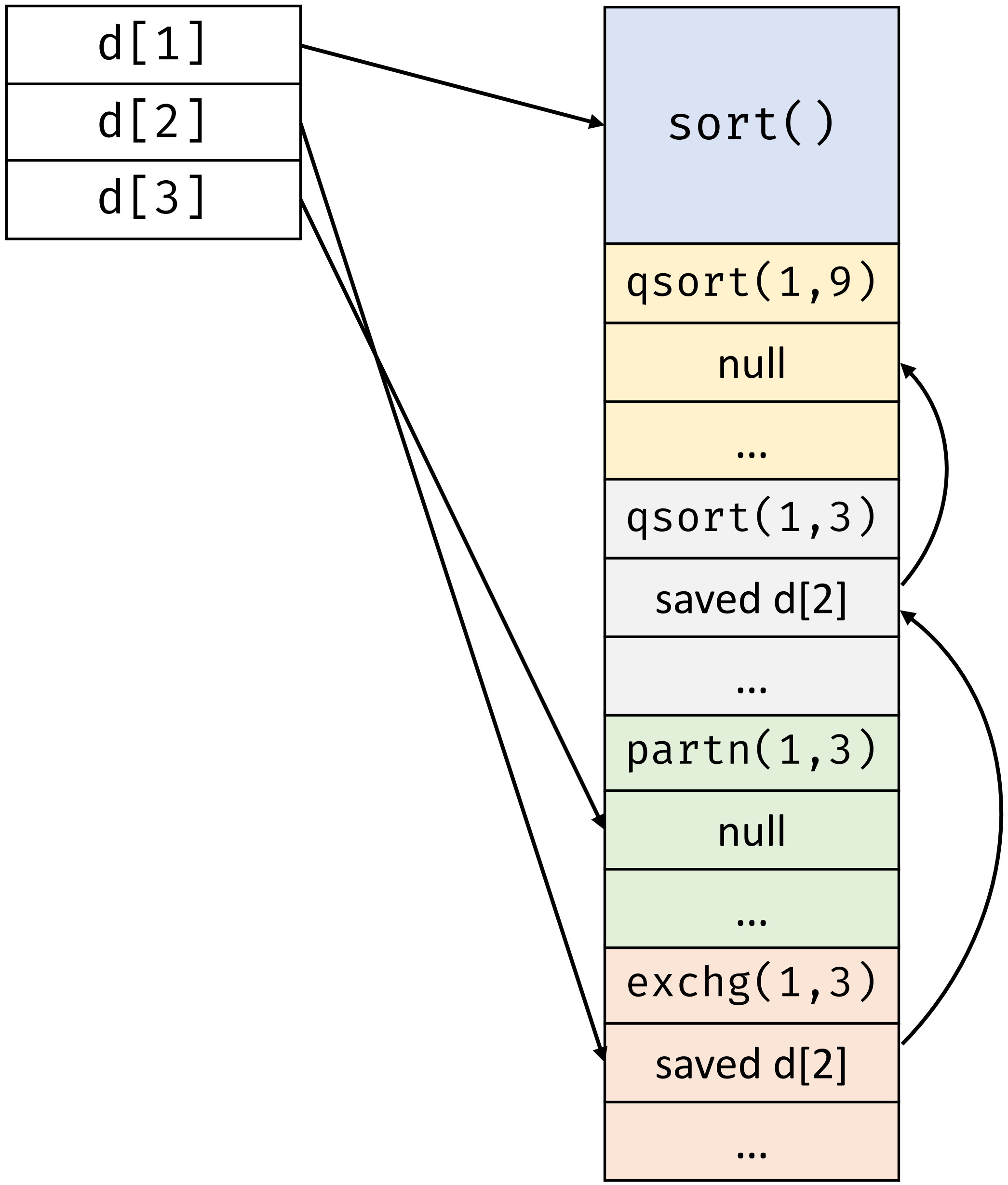
Insight in Using Displays

- Suppose a procedure p is executing and needs to access element x belonging to procedure q
- The runtime only needs to search in activations from $d[i]$, where i is the nesting depth of q
  - Follow the pointer $d[i]$ to the activation record for q, wherein x should be defined at a known offset

Displays



d[1]
d[2]
d[3]
sort()
qsort(1,9)
null
...
qsort(1,3)
saved d[2]
...
partn(1,3)
null
...



d[1]
d[2]
d[3]
sort()
qsort(1,9)
null
...
qsort(1,3)
saved d[2]
...
partn(1,3)
null
...
exchg(1,3)
saved d[2]
...

Access Links vs Displays

Access Links	Displays
• Cost of lookup varies • Common case is cheap, but long chains can be costly • Cost of maintenance also is variable	• Cost of lookup is constant • Cost of maintenance is constant

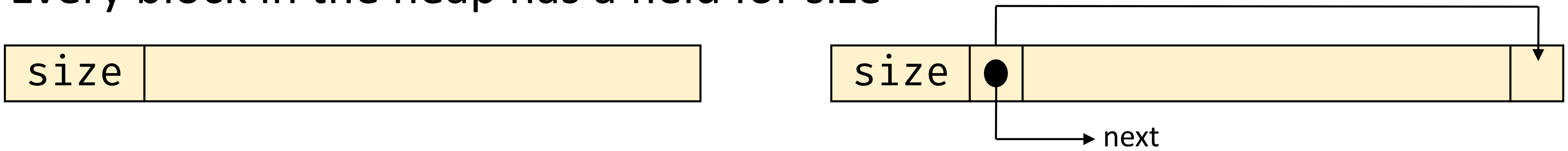
Heap Management

Heap Management

- Heap is used for allocating space for objects created at run time that can outlive the parent procedure
- Manage (either manual or automatic strategies) heap memory by implementing mechanisms for allocation and deallocation
  - Interface to the heap: `allocate(size)` and `free(addr)`
  - Commonly-used interfaces: `malloc()/free()` in C or `new/delete` in C++
  - Allocation and deallocation may be completely manual (C/C++), semi-automatic (Java), or fully automatic (Lisp)
- Goals
  - Space efficiency – minimize fragmentation
  - Program efficiency – take advantage of locality of objects in memory and make the program run faster
  - Low overhead – allocation and deallocation must be efficient

First-fit Allocation

- Emphasizes speed over memory utilization
- Every block in the heap has a field for size



Allocated block

Free block

- `allocate(k)`
  - Traverse the free list to find a block b_i with size greater than k+1
  - If found, remove b_i from the free list and return pointer to the next word of b_i
    - If b_i is larger than k, then split the extra space and add to the free list
  - If not found, then request for more virtual memory, report error if request fails
- `free(addr)`
  - Add b_j to the head of the free list, efficient but leads to fragmentation

Reducing Fragmentation

- Merge free blocks if adjacent blocks are free
  - Check the preceding end-of-block pointer when processing b_j and merge if both blocks are free
  - Can also merge with successor block
- Other variants – best-fit and next-fit allocation strategy
  - Best-fit strategy searches and picks the smallest (best) possible chunk that satisfies the allocation request
  - Next-fit strategy tries to allocate the object in the chunk that has been split recently

Problems with Manual Deallocation

- Common problems
  - Fail to delete data that is not required, called memory leak
    - Critical for performance of long-running or server programs
  - Reference deleted data, i.e., dangling pointer reference
  - These problems are hard to debug

- Possible solution is support for implicit deallocation of objects that reside on the runtime heap (a.k.a. garbage collection)

References

- A. Aho et al. Compilers: Principles, Techniques, and Tools, 1st edition, Chapter 7.
- A. Aho et al. Compilers: Principles, Techniques, and Tools, 2nd edition, Chapter 7.1-7.4.
- K. Cooper and L. Torczon. Engineering a Compiler, 2nd edition, Chapter 6, 7.1-7.2.