Run-Time Environments

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Introduction

- A compiler must accurately implement the *abstractions* embodied in the source language definition.
- Abstractions include: the concepts such as names, scopes, bindings, data types, operators, procedures, parameters, and flow-of-control constructs.
- The compiler must cooperate with the operating system and other systems software to support these abstractions on the target machine.
- To do so, the compiler creates and manages a '***run-time environment'*** in which it assumes its target programs are being executed.

Run-time Environment Issues

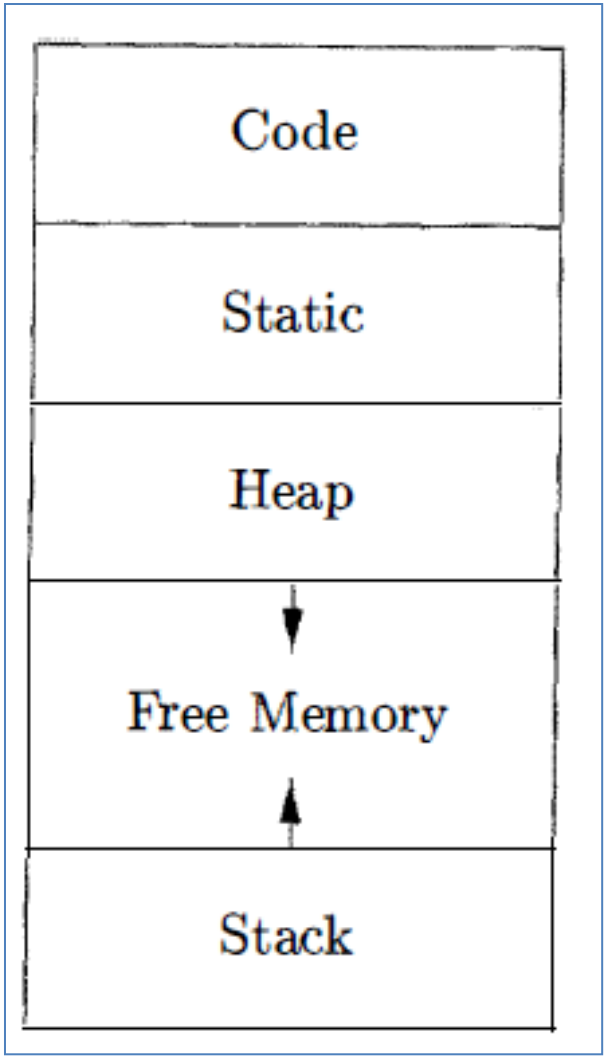
- the *layout & allocation* of storage locations for the objects named in the source program
- the mechanisms used by the target program to access variables
- the linkages between procedures
- the mechanisms for passing parameters
- the interfaces to the operating system
- the interfaces to the input/output devices
- the interfaces to the other programs

Storage Organization

- From the perspective of the compiler writer, the executing target program runs in its own logical address space in which each program value has a location.
- The management & organization of this logical address space is shared between the compiler, operating system, and target machine.
- The operating system maps the logical addresses into physical addresses, which are usually spread throughout memory.

Typical subdivision of run-time memory into code and data areas

- The run-time representation of an object program in the logical address space consists of *data and program areas*
- A compiler for a language like C + + on an operating system like Linux might subdivide memory in this way.



- run-time storage comes in blocks of contiguous bytes, where a byte is the smallest unit of addressable memory.
- A byte is eight bits and four bytes form a machine word.
- Multibyte objects are stored in consecutive bytes and given the address of the first byte.

❑ The amount of storage needed for a name is determined from its type.

❑ An elementary data type, such as a character, integer, or float, can be stored in an integral number of bytes.

❑ Storage for an aggregate type, such as an array or structure, must be large enough to hold all its components.

- The storage layout for data objects is strongly influenced by the addressing constraints of the target machine.
- On many machines, instructions to add integers may expect integers to be ***aligned***, that is, placed at an address ***divisible by 4***.
- Although an array of ten characters needs only enough bytes to hold ten characters, a compiler may allocate 12 bytes to get the proper alignment , leaving 2 bytes unused.
- Space left unused due to alignment considerations is referred to as **padding**.
- When space is at a premium, a compiler may pack data so that no padding is left; additional instructions may then need to be executed at run time to position packed data so that it can be operated on as if it were properly aligned.

- The size of the generated code is fixed at compile time, so the compiler can place the executable target code in a statically determined area **Code**, usually in the low end of memory.
- Similarly, the size of some program data objects, such as global constants, and data generated by the compiler, such as information to support garbage collection, may be known at compile time, and these data objects can be placed in another statically determined area called **Static**.

- One reason for statically allocating as many data objects as possible is that the addresses of these objects can be compiled into the target code.
- In early versions of Fortran, all data objects could be allocated statically.

- ❑ To maximize the utilization of space at run time, the other two areas, **Stack** and **Heap**, are at the opposite ends of the remainder of the address space.
- ❑ These areas are dynamic; their size can change as the program executes.
- ❑ These areas grow towards each other as needed.
- ❑ The stack is used to store data structures called **activation records** that get generated during procedure calls.

- In practice, the stack grows towards lower addresses, the heap towards higher.
- an activation record is used to store information about the status of the machine, such as the value of the program counter and machine registers, when a procedure call occurs .
- When control returns from the call, the activation of the calling procedure can be restarted after restoring the values of relevant registers and setting the program counter to the point immediately after the call.
- Data objects whose lifetimes are contained in that of an activation can be allocated on the stack along with other information associated with the activation .

Static Versus Dynamic Storage Allocation

- A storage-allocation decision is **static**, if it can be made by the compiler *looking only at the text of the program*, not at what the program does when it executes.

- A decision is dynamic if it can be decided only *while the program is running*.

Strategies for dynamic storage allocation

- 1. **Stack storage**. Names local to a procedure are allocated space on a stack. The stack supports the normal call/return policy for procedures.
- 2. **Heap storage**. Data that may outlive the call to the procedure that created it is usually allocated on a "heap" of reusable storage.

- The heap is an area of virtual memory that allows objects or other data elements to obtain storage when they are created & to return that storage when they are invalidated.

Stack Allocation of Space

- Almost all compilers for languages that use procedures, functions, or methods as units of user-defined actions *manage at least part of their run-time memory as a stack*.
- Each time a procedure is called, space for its local variables is **pushed** onto a stack, and when the procedure terminates, that space is **popped off** the stack.

Activation Trees

- Stack allocation would not be feasible if procedure calls, or activations of procedures, did not nest in time.

Nesting of procedure calls

Example7.1: Figure 7.2 contains a sketch of a program that reads nine integers into an array a & sorts them using the recursive quicksort algo.

```
int a[11];
void readArray() { /* Reads 9 integers into a[1], ..., a[9]. */
    int i;
    ...
}
int partition(int m, int n) {
    /* Picks a separator value v, and partitions a[m..n] so that
       a[m..p-1] are less than v, a[p] = v, and a[p+1..n] are
       equal to or greater than v. Returns p. */
    ...
}
void quicksort(int m, int n) {
    int i;
    if (n > m) {
        i = partition(m, n);
        quicksort(m, i-1);
        quicksort(i+1, n);
    }
}
main() {
    readArray();
    a[0] = -9999;
    a[10] = 9999;
    quicksort(1,9);
}
```

- The main function has three tasks:
- It calls *readArray*, *sets the sentinels*, & then calls *quicksort* on the entire data array.

Fig. suggests a sequence of calls that might result from an execution of the program.

```
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()
```

```
int a[11];
void readArray() { /* Reads 9 integers into a[1], ..., a[9]. */
    int i;
    ...
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void quicksort(int m, int n) {
    int i;
    if (n > m) {
        i = partition(m, n);
        quicksort(m, i-1);
        quicksort(i+1, n);
    }
}
main() {
    readArray();
    a[0] = -9999;
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enter main()
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    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()
```

- In this execution, the call to ***partition(1, 9)*** returns **v= 4**, so **a[1]** through **a[3]** hold elements less than its chosen separator value **v**, while the larger elements are in **a[5]** through **a[9]** .

Activation of Procedures

- Procedure activations are nested in time.
- If an activation of procedure **p** calls procedure **q**, then that activation of **q** must **end** before the activation of **p** can end. **There are three common cases:**

1. The activation of **q** terminates normally. Then in essentially any language, control resumes just after the point of **p** at which the call to **q** was made.
2. The activation of **q**, or some procedure **q** called, either directly or indirectly, aborts; i.e., it becomes impossible for execution to continue. In that case, *p ends simultaneously with q*.

3. The activation of **q** terminates because of an *exception* that **q** *cannot handle*.

- Procedure **p** may handle the exception, in which case the activation of **q** has *terminated* while the activation of **p** *continues*, although not necessarily from the point at which the call to q was made.
- If *p cannot handle the exception*, then this activation of **p** terminates at the **same time** as the activation of **q**, and presumably the exception will be handled by some other open activation of a procedure.

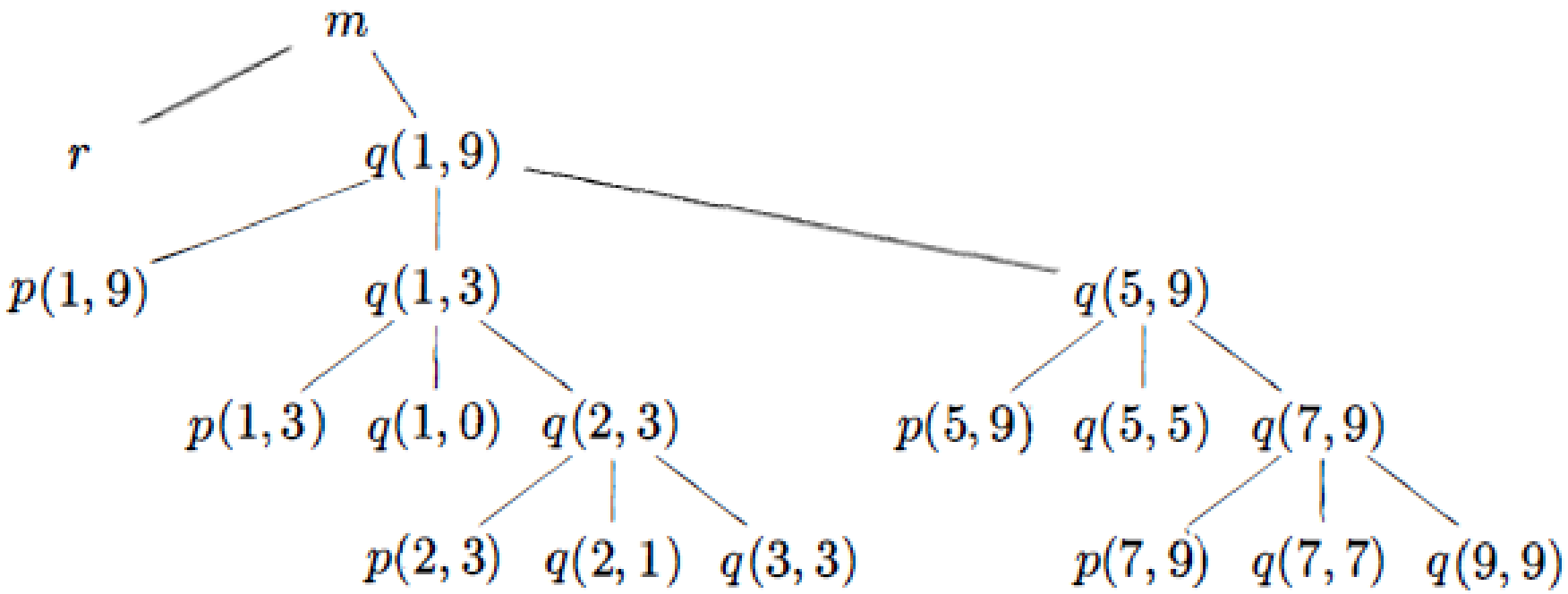
Activation Trees

- We therefore can represent the activations of procedures during the running of an entire program by a tree, called an **activation tree**.

❑ **Properties**

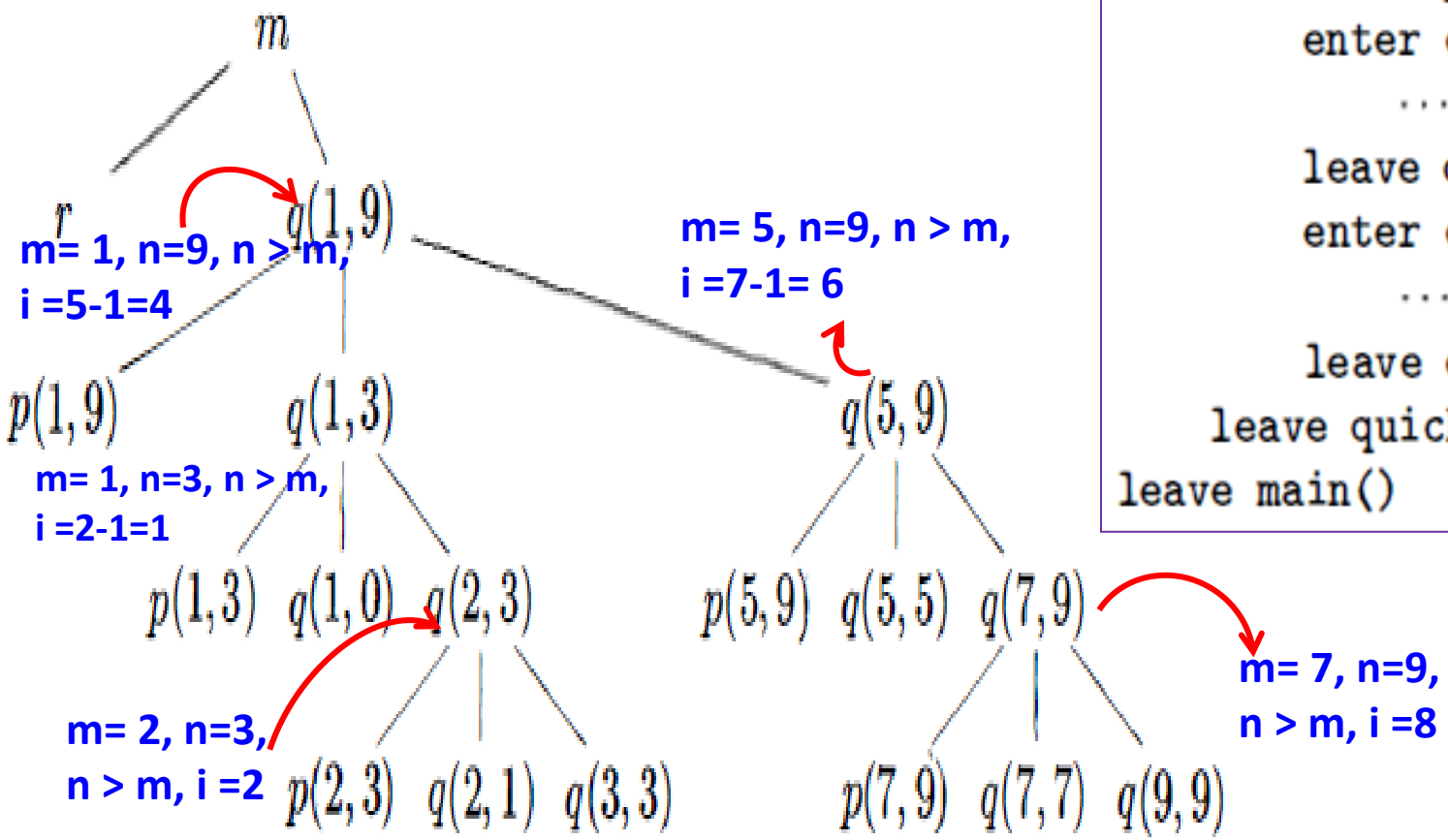
- **Each node** corresponds to **one activation**,
- **root** is the activation of the "**main**" procedure that initiates execution of the program.
- At a node for an activation of procedure p, *the children correspond to activations of the procedures called by this activation of p*.
- Show these activations in the order that they are called, from left to right
- Notice that *one child must finish before the activation to its right can begin*.

Example 7.2: One possible activation tree that completes the sequence of calls and returns suggested in Fig. 7.3 is shown in Fig. 7.4. Functions are represented by the first letters of their names. Remember that this tree is only one possibility, since the arguments of subsequent calls, and also the number of calls along any branch is influenced by the values returned by *partition*. □



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

```
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()
```



The use of a run-time stack is enabled by several useful relationships between the activation tree & the behavior of the program:

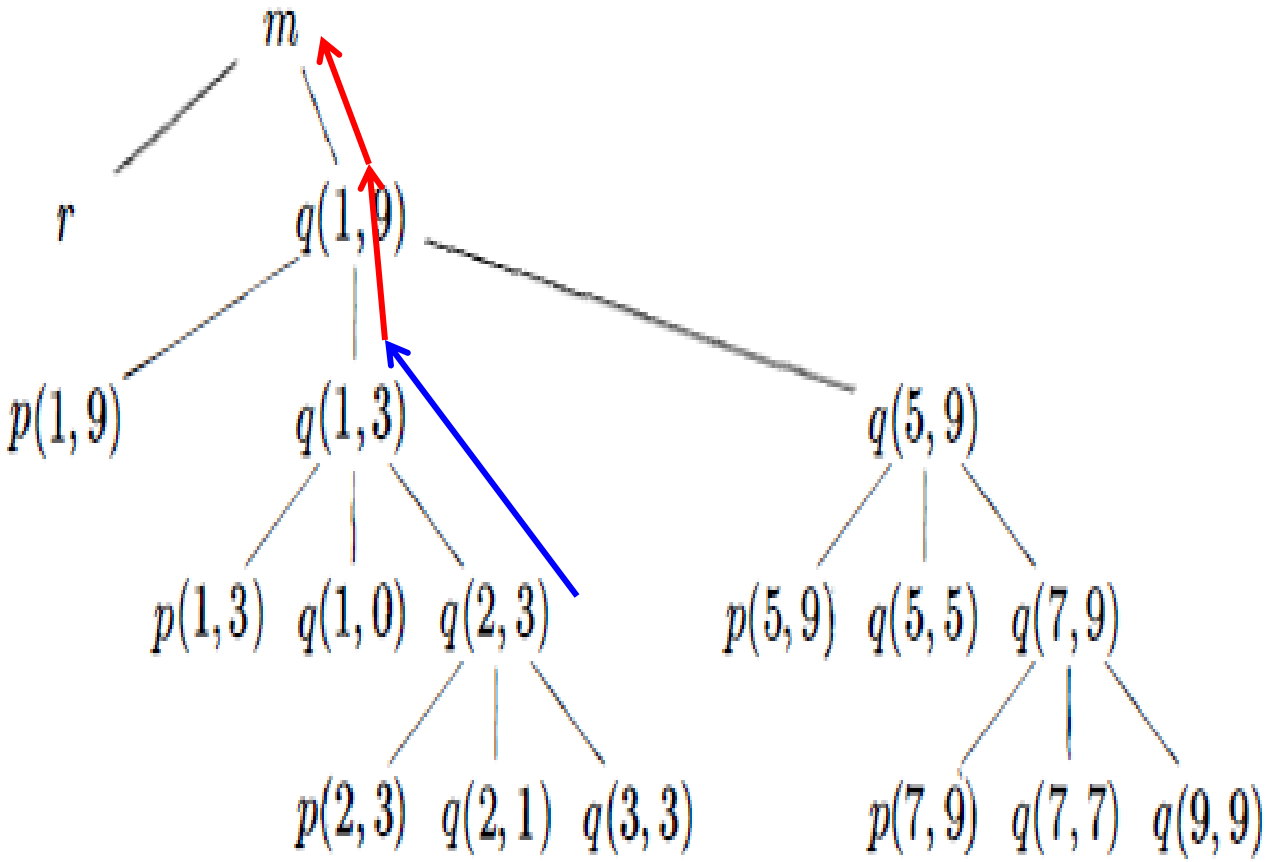
1. The sequence of *procedure calls corresponds to a preorder traversal* of the activation tree.
2. The sequence of *returns corresponds to a postorder traversal* of the activation tree .
3. Suppose that control lies within a particular activation of some procedure, corresponding to a node N of the activation tree.

- Then the activations that are currently open (**live**) are those that correspond to node N & its ancestors.
- The order in which these activations were called is the order in which they appear along the path to N, starting at the root , and they will return in the reverse of that order.

Activation Records

- Procedure *calls & returns* are usually managed by a run-time stack called the **control stack**.
- Each live activation has an activation record (frame) on the control stack, with the root of the activation tree at the bottom, & the entire sequence of activation records on the stack corresponding to the path in the activation tree to the activation where control currently resides.
- The latter activation has its record at the top of the stack.

Example 7.3: If control is currently in the activation $q(2,3)$ of the tree of Fig. 7.4, then the activation record for $q(2,3)$ is at the top of the control stack. Just below is the activation record for $q(1,3)$, the parent of $q(2,3)$ in the tree. Below that is the activation record $q(1,9)$, and at the bottom is the activation record for m, the main function and root of the activation tree. □

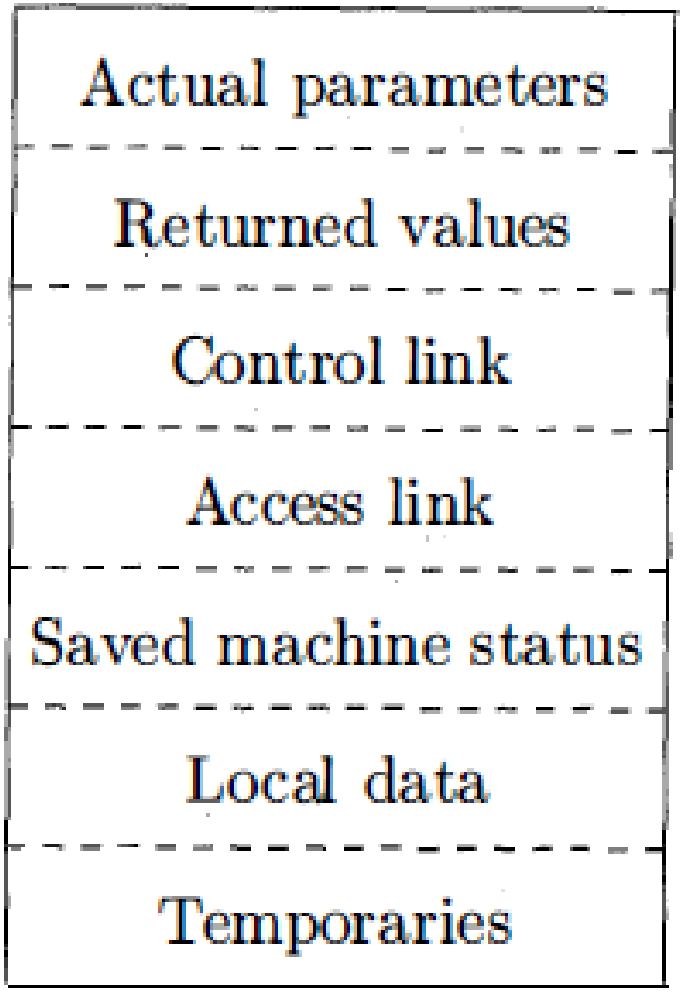


General Activation Record

1 . **Temporary values**, such as those arising from the evaluation of expressions, in cases where those temporaries cannot be held in registers.

2. **Local data** belonging to the procedure whose activation record this is.

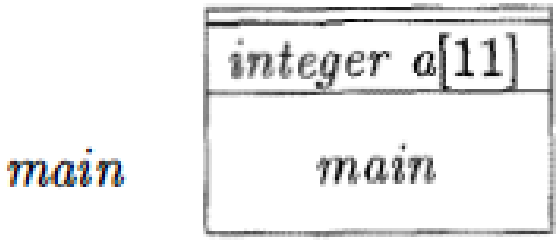
3. A **saved machine status**, with information about the state of the machine just before the call to the procedure. This information typically includes the return address (value of the program counter, to which the called procedure must return) and the contents of registers that were used by the calling procedure and that must be restored when the return occurs.



4. An "**access link**" may be needed to locate data needed by the called procedure but found elsewhere, e.g., in another activation record.
5. A **control link**, pointing to the activation record of the caller.
6. Space for the **return value** of the called function, if any. Again, not all called procedures return a value, and if one does, we may prefer to place that value in a register for efficiency.
7. The **actual parameters** used by the calling procedure. Commonly, these values are not placed in the activation record but rather in registers, when possible, for greater efficiency. However, we show a space for them to be completely general.

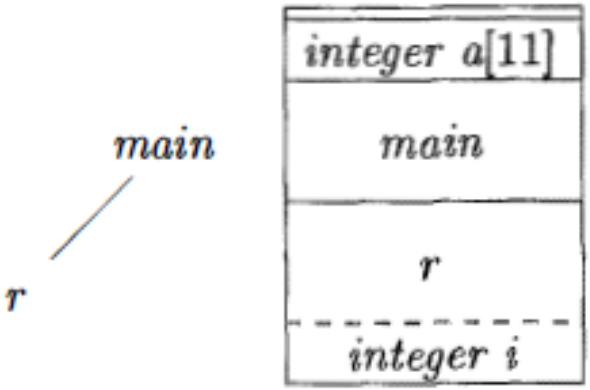
Example 7.4: Figure 7.6 shows snapshots of the run-time stack as control flows through the activation tree of Fig. 7.4. Dashed lines in the partial trees go to activations that have ended. Since array *a* is global, space is allocated for it before execution begins with an activation of procedure *main*, as shown in Fig. 7.6(a).

Since array a is global, space is allocated for it before execution begins with an activation of procedure *main*



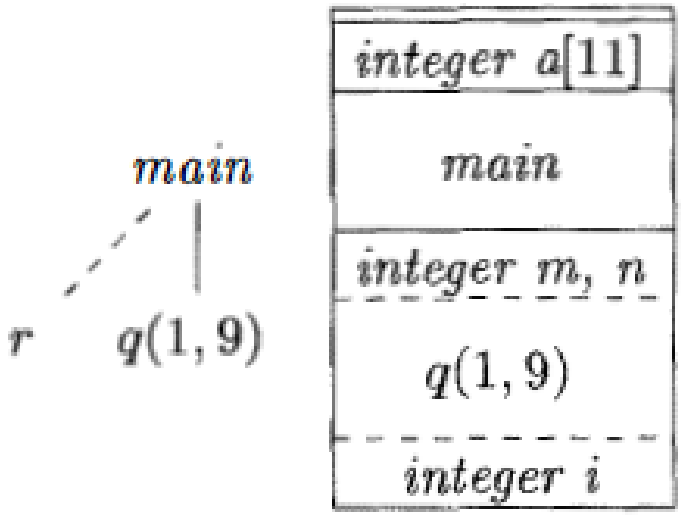
(a) Frame for main

- When control reaches the first call in the body of *main*, procedure **r** is activated, and its activation record is **pushed** onto the stack .
- The activation record for **r** contains space for local variable **i**
- Recall that the top of stack is at the bottom of diagrams. When control returns from this activation, its record is **popped**, leaving just the record for main on the stack.



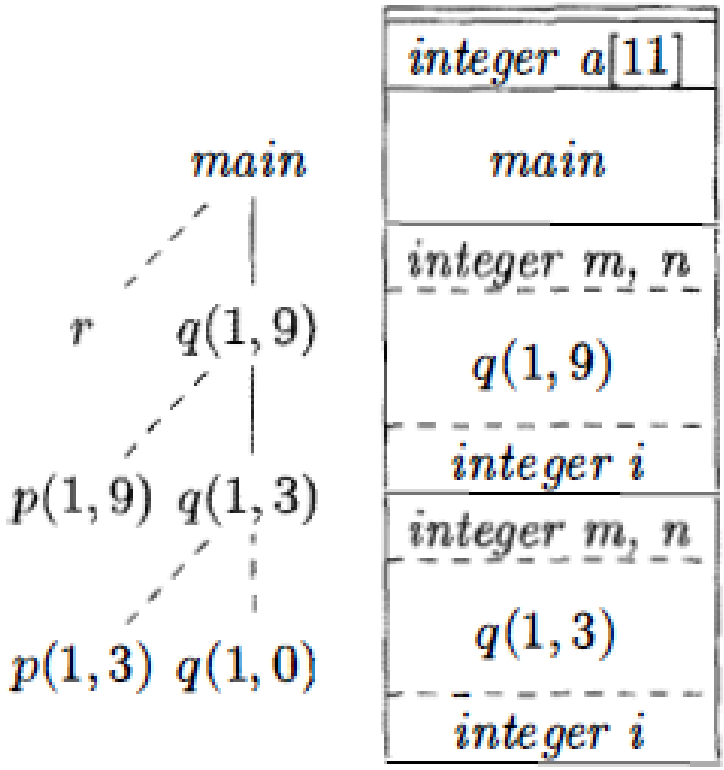
(b) r is activated

- Control then reaches the call to **q** (quicksort) with actual parameters 1 & 9, and an activation record for this call is placed on the top of the stack.
- The activation record for **q** contains space for the parameters **m** & **n** and the local variable **i**
- Notice that space once used by the call of **r** is reused on the stack.
- No trace of data local to **r** will be available to **q(1, 9)**.
- When **q (1, 9)** returns, the stack again has only the activation record for main.



(c) r has been popped & q(1,9) pushed

- Several activations occur between the last two snapshots.
- A recursive call to **q (1,3)** was made.
- Activations **p(1,3)** and **q (1, 0)** have begun & ended during the lifetime of **q (1, 3),** leaving the activation record for **q(1, 3)** on top
- Notice that when a procedure is recursive, it is normal to have several of its activation records on the stack at the same time.



(d) Control returns to q (1, 3)

Heap Management

- **Page 452-454: Read Yourself**