OPERATING SYSTEMS

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PART 3 Memory

CHAPTER 7

MEMORY MANAGEMENT

appears at the end of the memory space, is quickly broken up into small fragments. Thus, compaction may be required more frequently with next-fit. On the other hand, the first-fit algorithm may litter the front end with small free partitions that need to be searched over on each subsequent first-fit pass. The best-fit algorithm, despite its name, is usually the worst performer. Because this algorithm looks for the smallest block that will satisfy the requirement, it guarantees that the fragment left behind is as small as possible. Although each memory request always wastes the smallest amount of memory, the result is that main memory is quickly littered by blocks too small to satisfy memory allocation requests. Thus, memory compaction must be done more frequently than with the other algorithms.

Replacement Algorithm In a multiprogramming system using dynamic partitioning, there will come a time when all of the processes in main memory are in a blocked state and there is insufficient memory, even after compaction, for an additional process. To avoid wasting processor time waiting for an active process to become unblocked, the OS will swap one of the processes out of main memory to make room for a new process or for a process in a Ready-Suspend state. Therefore, the operating system must choose which process to replace. Because the topic of replacement algorithms will be covered in some detail with respect to various virtual memory schemes, we defer a discussion of replacement algorithms until then.

Buddy System

Both fixed and dynamic partitioning schemes have drawbacks. A fixed partitioning scheme limits the number of active processes and may use space inefficiently if there is a poor match between available partition sizes and process sizes. A dynamic partitioning scheme is more complex to maintain and includes the overhead of compaction. An interesting compromise is the buddy system ([KNUT97], [PETE77]).

In a buddy system, memory blocks are available of size 2^K words, $L \leq K \leq U$, where

2^L = smallest size block that is allocated

2^U = largest size block that is allocated; generally 2^U is the size of the entire memory available for allocation

To begin, the entire space available for allocation is treated as a single block of size 2^U. If a request of size s such that $2^{U-1} < s \leq 2^U$ is made, then the entire block is allocated. Otherwise, the block is split into two equal buddies of size 2^{U-1}. If $2^{U-2} < s \leq 2^{U-1}$, then the request is allocated to one of the two buddies. Otherwise, one of the buddies is split in half again. This process continues until the smallest block greater than or equal to s is generated and allocated to the request. At any time, the buddy system maintains a list of holes (unallocated blocks) of each size 2^i. A hole may be removed from the $(i + 1)$ list by splitting it in half to create two buddies of size 2^i in the i list. Whenever a pair of buddies on the i list both become unallocated, they are removed from that list and coalesced into a single block on the $(i + 1)$

list. Presented with a request for an allocation of size k such that $2^{i-1} < k \leqslant 2^i$, the following recursive algorithm is used to find a hole of size 2^i:

```
void get_hole(int i)
{
  if (i == (U + 1)) <failure>;
  if (<i_list empty>) {
     get_hole(i + 1);
     <split hole into buddies>;
     <put buddies on i_list>;
  }
  <take first hole on i_list>;
}
```

Figure 7.6 gives an example using a 1-Mbyte initial block. The first request, A, is for 100 Kbytes, for which a 128K block is needed. The initial block is divided into two 512K buddies. The first of these is divided into two 256K buddies, and the first of these is divided into two 128K buddies, one of which is allocated to A. The next request, B, requires a 256K block. Such a block is already available and is allocated. The process continues with splitting and coalescing occurring as needed. Note that when E is released, two 128K buddies are coalesced into a 256K block, which is immediately coalesced with its buddy.

Figure 7.7 shows a binary tree representation of the buddy allocation immediately after the Release B request. The leaf nodes represent the current partitioning of the memory. If two buddies are leaf nodes, then at least one must be allocated; otherwise they would be coalesced into a larger block.

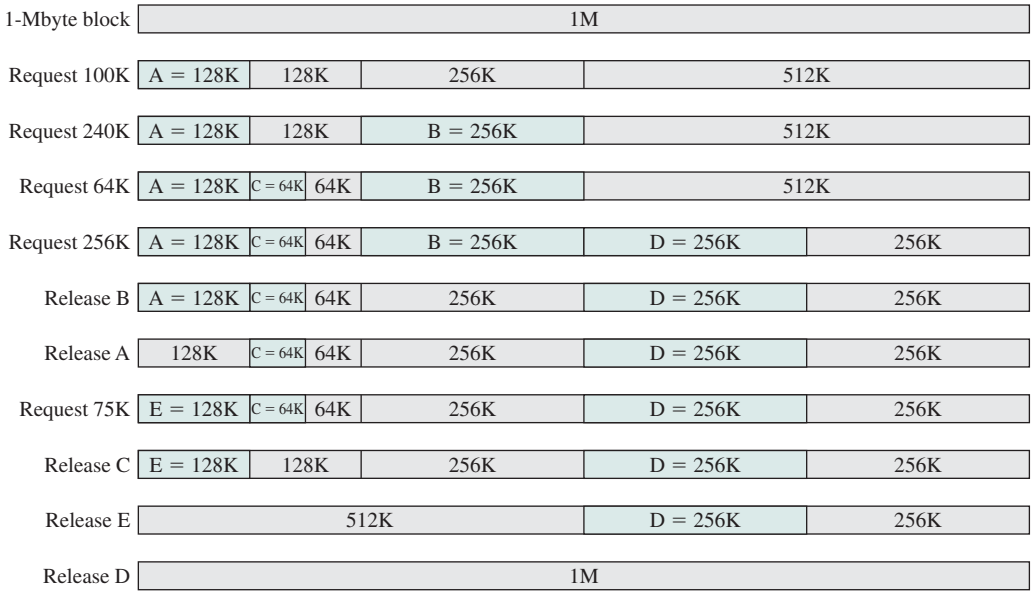

Figure 7.6 Example of Buddy System

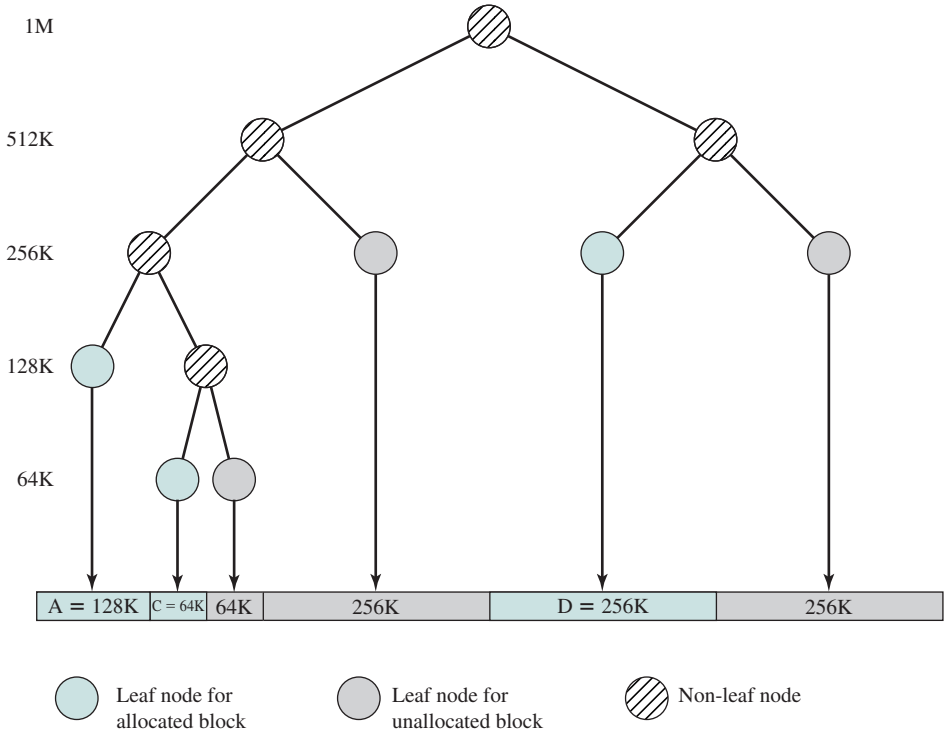

Figure 7.7 **Tree Representation of Buddy System**

The buddy system is a reasonable compromise to overcome the disadvantages of both the fixed and variable partitioning schemes, but in contemporary operating systems, virtual memory based on paging and segmentation is superior. However, the buddy system has found application in parallel systems as an efficient means of allocation and release for parallel programs (e.g., see [JOHN92]). A modified form of the buddy system is used for UNIX kernel memory allocation (described in Chapter 8).

Relocation

Before we consider ways of dealing with the shortcomings of partitioning, we must clear up one loose end, which relates to the placement of processes in memory. When the fixed partition scheme of Figure 7.3a is used, we can expect that a process will always be assigned to the same partition. That is, whichever partition is selected when a new process is loaded will always be used to swap that process back into memory after it has been swapped out. In that case, a simple relocating loader, such as is described in Appendix 7A, can be used: When the process is first loaded, all relative memory references in the code are replaced by absolute main memory addresses, determined by the base address of the loaded process.

In the case of equal-size partitions (Figure 7.2), and in the case of a single process queue for unequal-size partitions (Figure 7.3b), a process may occupy different partitions during the course of its life. When a process image is first created, it is

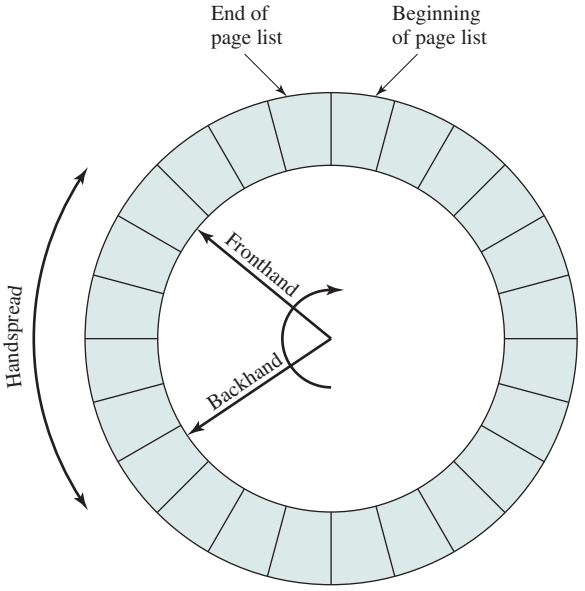

Figure 8.23 **Two-Handed Clock Page Replacement Algorithm**

conditions. The parameter varies linearly between the values slowscan and fastscan (set at configuration time) as the amount of free memory varies between the values *lotsfree* and *minfree*. In other words, as the amount of free memory shrinks, the clock hands move more rapidly to free up more pages. The handspread parameter determines the gap between the fronthand and the backhand and therefore, together with scanrate, determines the window of opportunity to use a page before it is swapped out due to lack of use.

Kernel Memory Allocator

The kernel generates and destroys small tables and buffers frequently during the course of execution, each of which requires dynamic memory allocation. [VAHA96] lists the following examples:

- The pathname translation routing may allocate a buffer to copy a pathname from user space.
- The `allocb()` routine allocates STREAMS buffers of arbitrary size.
- Many UNIX implementations allocate zombie structures to retain exit status and resource usage information about deceased processes.
- In SVR4 and Solaris, the kernel allocates many objects (such as proc structures, vnodes, and file descriptor blocks) dynamically when needed.

Most of these blocks are significantly smaller than the typical machine page size, and therefore the paging mechanism would be inefficient for dynamic kernel memory allocation. For SVR4, a modification of the buddy system, described in Section 7.2, is used.

In buddy systems, the cost to allocate and free a block of memory is low compared to that of best-fit or first-fit policies [KNUT97]. However, in the case of kernel memory management, the allocation and free operations must be made as fast as possible. The drawback of the buddy system is the time required to fragment and coalesce blocks.

Barkley and Lee at AT&T proposed a variation known as a lazy buddy system [BARK89], and this is the technique adopted for SVR4. The authors observed that UNIX often exhibits steady-state behavior in kernel memory demand; that is, the amount of demand for blocks of a particular size varies slowly in time. Therefore, if a block of size 2^i is released and is immediately coalesced with its buddy into a block of size 2^{i+1}, the kernel may next request a block of size 2^i, which may necessitate splitting the larger block again. To avoid this unnecessary coalescing and splitting, the lazy buddy system defers coalescing until it seems likely that it is needed, and then coalesces as many blocks as possible.

The lazy buddy system uses the following parameters:

N_i = current number of blocks of size 2^i.

A_i = current number of blocks of size 2^i that are allocated (occupied).

G_i = current number of blocks of size 2^i that are globally free; these are blocks that are eligible for coalescing; if the buddy of such a block becomes globally free, then the two blocks will be coalesced into a globally free block of size 2^{i+1}. All free blocks (holes) in the standard buddy system could be considered globally free.

L_i = current number of blocks of size 2^i that are locally free; these are blocks that are not eligible for coalescing. Even if the buddy of such a block becomes free, the two blocks are not coalesced. Rather, the locally free blocks are retained in anticipation of future demand for a block of that size.

The following relationship holds:

$$N_i = A_i + G_i + L_i$$

In general, the lazy buddy system tries to maintain a pool of locally free blocks and only invokes coalescing if the number of locally free blocks exceeds a threshold. If there are too many locally free blocks, then there is a chance that there will be a lack of free blocks at the next level to satisfy demand. Most of the time, when a block is freed, coalescing does not occur, so there is minimal bookkeeping and operational costs. When a block is to be allocated, no distinction is made between locally and globally free blocks; again, this minimizes bookkeeping.

The criterion used for coalescing is that the number of locally free blocks of a given size should not exceed the number of allocated blocks of that size (i.e., we must have $L_i \leq A_i$). This is a reasonable guideline for restricting the growth of locally free blocks, and experiments in [BARK89] confirm that this scheme results in noticeable savings.

To implement the scheme, the authors define a delay variable as follows:

$$D_i = A_i - L_i = N_i - 2L_i - G_i$$

Figure 8.24 shows the algorithm.

Initial value of D_i is 0
After an operation, the value of D_i is updated as follows

(I) if the next operation is a block allocate request:
    if there is any free block, select one to allocate
        if the selected block is locally free
            then $D_i := D_i + 2$
            else $D_i := D_i + 1$
    otherwise
        first get two blocks by splitting a larger one into two (recursive operation)
        allocate one and mark the other locally free
        D_i remains unchanged (but D may change for other block sizes because
                of the recursive call)

(II) if the next operation is a block free request
    Case $D_i \geqslant 2$
        mark it locally free and free it locally
        $D_i = 2$
    Case $D_i = 1$
        mark it globally free and free it globally; coalesce if possible
        $D_i = 0$
    Case $D_i = 0$
        mark it globally free and free it globally; coalesce if possible
        select one locally free block of size 2^i and free it globally; coalesce if possible
        $D_i := 0$

Figure 8.24 **Lazy Buddy System Algorithm**

8.4 LINUX MEMORY MANAGEMENT

Linux shares many of the characteristics of the memory management schemes of other UNIX implementations but has its own unique features. Overall, the Linux memory management scheme is quite complex [DUBE98]. In this section, we give a brief overview of the two main aspects of Linux memory management: process virtual memory and kernel memory allocation.

Linux Virtual Memory

VIRTUAL MEMORY ADDRESSING Linux makes use of a three-level page table structure, consisting of the following types of tables (each individual table is the size of one page):

- **Page directory:** An active process has a single page directory that is the size of one page. Each entry in the page directory points to one page of the page middle directory. The page directory must be in main memory for an active process.