Hashed and Hierarchical Timing Wheels: Data Structures for the Efficient Implementation of a Timer Facility

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Abstract

Conventional algorithms to implement an Operating System timer module take $O(n)$ time to start or maintain a timer, where n is the number of outstanding timers: this is expensive for large n. This paper begins by exploring the relationship between timer algorithms, time flow mechanisms used in discrete event simulations, and sorting techniques. Next a timer algorithm for small timer intervals is presented that is similar to the timing wheel technique used in logic simulators. By using a circular buffer or timing wheel, it takes $O(1)$ time to start, stop, and maintain timers within the range of the wheel.

Two extensions for larger values of the interval are described. In the first, the timer interval is hashed into a slot on the timing wheel. In the second, a hierarchy of timing wheels with different granularities is used to span a greater range of intervals. The performance of these two schemes and various implementation tradeoffs are discussed.

1 Introduction

In a centralized or distributed operating system, we need timers for:

- Failure Recovery: Several kinds of failures cannot be detected asynchronously. Some can be detected by periodic checking (e.g. memory corruption) and such timers always expire. Other failures can be only be inferred by the lack of some positive action (e.g. message acknowledgment) within a specified period. If failures are infrequent these timers rarely expire.

- Algorithms in which the notion of time or relative time is integral: Examples include algorithms that control the rate of production of some entity (process control, rate-based flow control in communications), scheduling algorithms, and algorithms to control packet lifetimes in computer networks. These timers almost always expire.

The performance of algorithms to implement a timer module becomes an issue when any of the following are true:

- The algorithm is implemented by a processor that is interrupted each time a hardware clock ticks, and the interrupt overhead is substantial.

- Fine granularity timers are required.

- The average number of outstanding timers is large.

As an example, consider communications between members of a distributed system. Since messages can be lost in the underlying network, timers are needed at some level to trigger retransmissions. A host in a distributed system can have several timers outstanding. Consider for example a server with 200 connections and 3 timers per connection. Further, as networks scale to higher speeds (> 100 Mbit/sec), both the required resolution and the rate at which timers are started and stopped will increase.

If the hardware clock interrupts the host every tick, and the interval between ticks is in the order of microseconds, then the interrupt overhead is substantial. Most host operating systems offer timers of coarse (milliseconds or seconds) granularity. Alternately, in some systems finer granularity timers reside in special purpose hardware. In either case, the performance of the timer algorithms will be an issue as they determine the latency incurred in starting or stopping a timer and the number of timers that can be simultaneously outstanding.

2 Model and Performance Measures

Our model of a timer module has four component routines:

START_TIMER(Interval, Request_ID, Expiry_Action): The client calls this routine to start a timer that will expire after "Interval" units of time. The client supplies a Request_ID which is used to distinguish this timer from other timers that the client has outstanding. Finally, the client can specify what action must be taken on expiry: for instance, calling a client-specified routine, or setting an event flag.

STOP_TIMER(Request_ID): This routine uses its knowledge of the client and Request_ID to locate the timer and stop it.

PER_TICK_BOOKKEEPING: Let the granularity of the timer be T units. Then every T units this routine checks whether any outstanding timers have expired; if so, it calls STOP_TIMER, which in turn calls the next routine.

EXPIRY_PROCESSING: This routine does the Expiry_Action specified in the START_TIMER call.

The first two routines are activated on client calls while the last two are invoked on timer ticks. The timer is often an external hardware clock.

The following two performance measures can be used to choose between the various algorithms described in the rest of this paper. Both of them are parameterized by n, the average (or worst-case) number of outstanding timers.

1. SPACE: The memory required for the data structures used by the timer module.
2. LATENCY: The time between the invoking of a routine in the timer module and its completion, assuming that the caller of the routine blocks until the routine completes. Both the average and worst case latency are of interest.

For example, a client application that implements a transport protocol may find that space is cheap and the critical parameters for each routine in the timer module are as shown in Figure 1.

The performance measures important for the client applications should be used to choose among timer algorithms.

3 Currently Used Timer Schemes

There are two schemes we know of:

3.1 Scheme 1 — Straightforward

Here [3] START_TIMER finds a memory location and sets that location to the specified timer interval. Every T units, PER_TICK_BOOKKEEPING will decrement each outstanding timer; if any timer becomes zero, EXPIRY_PROCESSING is called.

This scheme is extremely fast for all but PER_TICK_BOOKKEEPING. It also uses one record per outstanding timer, the minimum space possible. Its performance is summarized in Figure 4. It is appropriate if:

- there are only a few outstanding timers.
- most timers are stopped within a few ticks of the clock.
- PER_TICK_PROCESSING is done with suitable performance by special-purpose hardware.

Note that instead of doing a DECREMENT, we can store the absolute time at which timers expire and do a COMPARE. This option is valid for all timer schemes we describe; the choice between them will depend on the size of the time-of-day field, the cost of each instruction, and the hardware on the machine implementing these algorithms. In this paper we will use the DECREMENT option, except when describing Scheme 2.

3.2 Scheme 2 — ORDERED LIST/TIMER QUEUES

Here [3] PER_TICK_BOOKKEEPING latency is reduced at the expense of START_TIMER. Timers are stored in an ordered list. Unlike Scheme 1, we will store the absolute time at which the timer expires, and not the interval before expiry.

The timer that is due to expire at the earliest time is stored at the head of the list. Subsequent timers are stored in increasing order as shown in Figure 2.

In Fig. 2 the lowest timer is due to expire at absolute time 10 hours, 23 minutes, and 12 seconds.

Because the list is sorted, PER_TICK_PROCESSING need only increment the current time of day, and compare it with the head of the list. If they are equal, or the time of day is greater, it deletes that list element and calls EXPIRY_PROCESSING. It continues to delete elements at the head of the list until the expiry time of the head of the list is strictly less than the time of day.

START_TIMER searches the list to find the position to insert the new timer. In the example, START_TIMER will insert a new timer due to expire at 10:24:01 between the second and third elements.

The worst case latency to start a timer is $O(n)$. The average latency depends on the distribution of timer intervals (from time started to time stopped), and the distribution of the arrival process according to which calls to START_TIMER are made.

Interestingly, this can be modeled (Figure 3) as a single queue with infinite servers; this is valid because every timer in the queue is essentially decremented (or served) every timer tick. It is shown in [4] that we can use Little's result to obtain the average number in the queue; also the distribution of the remaining time of elements in the timer queue seen by a new request is the residual life density of the timer interval distribution.

If the arrival distribution is Poisson, the list is searched from the head, and reads and writes both cost one unit, then the average cost of insertion for negative exponential and uniform timer interval distributions is shown in [4] to be:

$2 + 2/3n$ — negative exponential

$2 + 1/2n$ — uniform

Results for other timer interval distributions can be computed using a result in [4]. For a negative exponential distribution we can reduce the average cost to $2 + n/3$ by searching the list from the rear. In fact, if timers are always inserted at the rear of the list, this search strategy yields an $O(1)$ START_TIMER latency. This happens, for instance, if all timers intervals have the same value. However, for a general distribution of the timer interval, we assume the average latency of insertion is $O(n)$.

STOP_TIMER need not search the list if the list is doubly linked. When START_TIMER inserts a timer into the ordered list it can store a pointer to the element. STOP_TIMER can then use this pointer to delete the element in $O(1)$ time from the doubly linked list. This can be used by any timer scheme.

If Scheme 2 is implemented by a host processor, the interrupt overhead on every tick can be avoided if there is hardware support to maintain a single timer. The hardware timer is set to expire at the time at which the the timer at the head of the list is due to expire. The hardware intercepts all clock ticks and interrupts the host only when a timer actually expires. Unfortunately, some processor architectures do not offer this capability.

Algorithms similar to Scheme 2 are used by both VMS and UNIX in implementing their timer modules. The performance of the two schemes is summarized in Figure 4.

As for Space, Scheme 1 needs the minimum space possible; Scheme 2 needs $O(n)$ extra space for the forward and back pointers between queue elements.

4 Timer Algorithms, Sorting Techniques, and Time-Flow Mechanisms in Discrete Event Simulations

4.1 Sorting Algorithms and Priority Queues

Scheme 2 reduced PER_TICK_BOOKKEEPING latency at the expense of START_TIMER by keeping the timer list sorted. Consider the relationship between timer and sorting algorithms depicted in Figure 5.

However:

- In a typical sort all elements are input to the module when the sort begins; the sort ends by outputting all elements in sorted order. A timer module performs a more dynamic sort because elements arrive at different times and are output at different times.

- In a timer module, the elements to be "sorted" change their value over time if we store the interval. This is not true if we store the absolute time of expiry.

A data structure that allows "dynamic" sorting is a priority queue [5]. A priority queue allows elements to be inserted and deleted; it also allows the smallest element in the set to be found. A timer module can use a priority queue, and do PER_TICK_BOOKKEEPING only on the smallest timer element.

4.1.1 Scheme 3: Tree-based Algorithms

A linked list (Scheme 2) is one way of implementing a priority queue. For large n, tree-based data structures are better. These include unbalanced binary trees, heaps, post-order and end-order trees, and leftist-trees [4,6]. They attempt to reduce the latency in Scheme 2 for START_TIMER from $O(n)$ to $O(log(n))$. In [7] it is reported that this difference is significant for large n, and that unbalanced binary trees are less expensive than balanced binary trees. Unfortunately, unbalanced binary trees easily degenerate into a linear list; this can happen, for instance, if a set of equal timer intervals are inserted.

We will lump these algorithms together as Scheme 3: Tree-based algorithms. The performance of Scheme 3 is summarized in Figure 6.

4.2 Discrete Event Simulation

In discrete event simulations [8], all state changes in the system take place at discrete points in time. An important part of such simulations are the event-handling routines or time-flow mechanisms. When an event occurs in a simulation, it may schedule future events. These events are inserted into some list of outstanding events. The simulation proceeds by processing the earliest event, which in turn may schedule further events. The simulation continues until the event list is empty or some condition (e.g. clock > MAX-SIMULATION-TIME) holds.

There are two ways to find the earliest event and update the clock:

1. The earliest event is immediately retrieved from some data structure (e.g. a priority queue [5]) and the clock jumps to the time of this event. This is embodied in simulation languages like GPSS [9] and SIMULA [10].

2. In the simulation of digital circuits, it is often sufficient to consider event scheduling at time instants that are multiples of the clock interval, say c. Then, after the program processes an event, it increments the clock variable by c until it finds any outstanding events at the current time. It then executes the event(s). This is embodied in languages for digital simulation like TEGAS [11] and DECSIM [12].

We have already seen that algorithms used to implement the first method are applicable for timer algorithms: these include linked lists and tree-based structures. What is more interesting is that algorithms for the second method are also applicable. Translated in terms of timers, the second method for PER_TICK_BOOKKEEPING is: "Increment the clock by the clock tick. If any timer has expired, call EXPIRY_PROCESSING."

An efficient and widely used method to implement the second method is the so-called timing-wheel [11,13] technique. In this method, the data structure into which timers are inserted is an array of lists, with a single overflow list for timers beyond the range of the array.

In Figure 7, time is divided into cycles; each cycle is N units of time. Let the current number of cycles be S. If the current time pointer points to element i, the current time is $S * N + i$. The event notice corresponding to an event scheduled to arrive within the current cycle (e.g. at time $S * N + j$, for integer j between 0 and n) is inserted into the list pointed to by the jth element of the array. Any event occurring beyond the current cycle is inserted into the overflow list. Within a cycle, the simulation increments the current time until it finds a non-empty list; it then removes and processes all events in the list. If these schedule future events within the current cycle, such events are inserted into the array of lists; if not, the new events are inserted into the overflow list.

The current time pointer is incremented modulo N. When it wraps to 0, the number of cycles is incremented, and the overflow list is checked; any elements due to occur in the current cycle are removed from the overflow list and inserted into the array of lists. This is implemented in TEGAS-2 [11].

The array can be conceptually thought of as a timing wheel; every time we step through N locations, we rotate the wheel by incrementing the number of cycles. A problem with this implementation is that as time increases within a cycle and we travel down the array it becomes more likely that event records will be inserted in the overflow list. Other implementations [12] reduce (but do not completely avoid) this effect by rotating the wheel half-way through the array.

In summary, we note that time flow algorithms used for digital simulation can be used to implement timer algorithms; conversely, timer algorithms can be used to implement time flow mechanisms in simulations.

However, there are differences to note:

- In Digital Simulations, most events happen within a short interval beyond the current time. Since timing wheel implementations rarely place event notices in the overflow list, they do not optimize this case. This is not true for a general purpose timer facility.
- Most simulations ensure that if 2 events are scheduled to occur at the same time, they are removed in FIFO order. Timer modules need not meet this restriction.
- Stepping through empty buckets on the wheel represents overhead for a Digital Simulation. In a timer module we have to increment the clock anyway on every tick. Consequently, stepping through empty buckets on a clock tick does not represent significant extra overhead *if* it is done by the same entity that maintains the current time.
- Simulation Languages assume that canceling event notices is very rare. If this is so, it is sufficient to mark the notice as "Canceled" and wait until the event is scheduled; at that point the scheduler discards the event. In a timer module, STOP_TIMER may be called frequently; such an approach can cause the memory needs to grow unboundedly beyond the number of timers outstanding at any time.

We will use the timing-wheel method below as a point of departure to describe further timer algorithms.

5 Scheme 4 — Basic Scheme for Timer Intervals within a Specified Range

We describe a simple modification of the timing wheel algorithm. If we can guarantee that all timers are set for periods less than *MaxInterval*, this modified algorithm takes O(1) latency for START_TIMER, STOP_TIMER, and PER_TICK_BOOKKEEPING. Let the granularity of the timer be 1 unit. The current time is represented in Figure 8 by a pointer to an element in a circular buffer with dimensions $[0, MaxInterval - 1]$.

To set a timer at j units past current time, we index (Figure 8) into Element $i+j$ mod $MaxInterval$), and put the timer at the head of a list of timers that will expire at a time $= CurrentTime + j$ units. Each tick we increment the current timer pointer (mod$MaxInterval$) and check the array element being pointed to. If the element is 0 (no list of timers waiting to expire), no more work is done on that timer tick. But if it is non-zero, we do EXPIRY_PROCESSING on all timers that are stored in that list. Thus the latency for START_TIMER is $O(1)$; PER_TICK_BOOKKEEPING is $O(1)$ except when timers expire, but we can't do better than that. If the timer lists are doubly linked, and, as before, we store a pointer to each timer record, then the latency of STOP_TIMER is also $O(1)$.

This is basically a timing wheel scheme where the wheel turns one array element every timer unit, as opposed to rotating every *MaxInterval* or *MaxInterval*/2 units [11]. This guarantees that all timers within *MaxInterval* of the current time will be inserted in the array of lists; this is not guaranteed by conventional timing wheel algorithms [11,13].

In sorting terms, this is a bucket sort [5,14] that trades off memory for processing. However, since the timers change value every time instant, intervals are entered as offsets from the current time pointer. It is sufficient if the current time pointer increases every time instant.

A bucket sort sorts N elements in $O(M)$ time using M buckets, since all buckets have to be examined. This is inefficient for large $M > N$. In timer algorithms, however, the crucial observation is that some entity needs to do $O(1)$ work per tick to update the current time; it costs only a few more instructions for the same entity to step through an empty bucket. What matters, unlike the sort, is not the total amount of work to sort N elements, but the average (and worst-case) part of the work that needs to be done per timer tick.

Still memory is finite: it is difficult to justify 2^{32} words of memory to implement 32 bit timers. One solution is to implement timers within some range using this scheme and the allowed memory. Timers greater than this value are implemented using, say, Scheme 2. Alternately, this scheme can be extended in two ways to allow larger values of the timer interval with modest amounts of memory.

6 Extensions

6.1 Extension 1: Hashing

The previous scheme has an obvious analogy to inserting an element in an array using the element value as an index. If there is insufficient memory, we can hash the element value to yield an index.

For example, if the table size is a power of 2, an arbitrary size timer can easily be divided by the table size; the remainder (low order bits) is added to the current time pointer to yield the index within the array. The result of the division (high order bits) is stored in a list pointed to by the index.

In Figure 9, let the table size be 256 and the timer be a 32 bit timer. The remainder on division is the last 8 bits. Let the value of the last 8 bits be 20. Then the timer index is 10 (Current Time Pointer) + 20 (remainder) = 30. The 24 high order bits are then inserted into a list that is pointed to by the 30th element.

Other methods of hashing are possible. For example, any function that maps a timer value to an array index could be used. We will defend our choice at the end of Section 6.1.

Next, there are two ways to maintain each list.

6.1.1 Scheme 5: Hash Table with Sorted Lists in each Bucket

Here each list is maintained as a ordered list exactly as in Scheme 2. START_TIMER can be slow because the 24 bit quantity must be inserted into the correct place in the list. Although the worst case latency for START_TIMER is still $O(n)$, the average latency can be $O(1)$. This is true if $n < TableSize$, and if the hash function (Timer Value mod $TableSize$) distributes timer values uniformly across the table. If so, the average size of the list that the ith element is inserted into is $i - 1/TableSize$ [14]. Since $i \leq n < TableSize$, the average latency of START TIMER is O(1). How well this hash actually distributes depends on the arrival distribution of timers to this module, and the distribution of timer intervals.

PER_TICK_BOOKKEEPING increments the current time pointer. If the value stored in the array element being pointed to is zero, there is no more work. Otherwise, as in Scheme 2, the top of the list is decremented. If it expires, EXPIRY_PROCESSING is called and the top list element is deleted. Once again, PER_TICK_BOOKKEEPING takes O(1) average and worst-case latency except when multiple timers are due to expire at the same instant, which is the best we can do.

Finally, if each list is doubly linked and START_TIMER stores a pointer to each timer element, STOP_TIMER takes $O(1)$ time.

A pleasing observation is that the scheme reduces to Scheme 2 if the array size is 1. In terms of sorting, Scheme 5 is similar to doing a bucket sort on the low order bits, followed by an insertion sort [5] on the lists pointed to by each bucket.

6.1.2 Scheme 6: Hash Table with Unsorted Lists in each Bucket

If a worst case START_TIMER latency of $O(n)$ is unacceptable, we can maintain each time list as an unordered list instead of an ordered list. Thus START_TIMER has a worst case and average latency of $O(1)$. But PER_TICK_BOOKKEEPING now takes longer. Every timer tick we increment the pointer (mod $TableSize$); if there is a list there, we must decrement the high order bits for every element in the array, exactly as in Scheme 1. However, if the hash table has the property described above, then the average size of the list will be $O(1)$.

We can make a stronger statement about the average behavior regardless of how the hash distributes. Notice that every $TableSize$ ticks we decrement once all timers that are still living. Thus for n timers we do $n/TableSize$ work on average per tick. If $n < TableSize$ then we do $O(1)$ work on average per tick. If all n timers hash into the same bucket, then every $TableSize$ ticks we do $O(n)$ work, but for intermediate ticks we do $O(1)$ work.

Thus the hash distribution in Scheme 6 only controls the "burstiness" (variance) of the latency of PER_TICK_BOOKKEEPING, and not the average latency. Since the worst-case latency of PER_TICK_BOOKKEEPING is always $O(n)$ (all timers expire at the same time), we believe that that the choice of hash function for Scheme 6 is insignificant. Obtaining the remainder after dividing by a power of 2 is cheap (AND instruction), and consequently recommended. Further, using an arbitrary hash function to map a timer value into an array index would require PER_TICK_BOOKKEEPING to compute the hash on each timer tick, which would make it more expensive.

We discuss implementation strategies for Scheme 6 in Appendix A.

6.2 Extension 2: Exploiting Hierarchy, Scheme 7

The last extension of the basic scheme exploits the concept of hierarchy. To represent the number 1000000 we need only 7 digits instead of 1000000 because we represent numbers hierarchically in units of 1's, 10's, 100's etc. Similarly, to represent all possible timer values within a 32 bit range, we do not need a 2^{32} element array. Instead we can use a number of arrays, each of different granularity. For instance, we can use 4 arrays as follows:

- A 100 element array in which each element represents a day
- A 24 element array in which each element represents an hour
- A 60 element array in which each element represents a minute
- A 60 element array in which each element represents a second

Thus instead of 100 * 24 * 60 * 60 = 8.64 million locations to store timers up to 100 days, we need only 100 + 24 + 60 + 60 = 244 locations.

As an example, consider Figure 10. Let the current time be 11 days 10 hours, 24 minutes, 30 seconds. Then to set a timer of 50 minutes and 45 seconds, we first calculate the absolute time at which the timer will expire. This is 11 days, 11 hours, 15 minutes, 15 seconds. Then we insert the timer into a list beginning 1 (11 - 10 hours) element ahead of the current hour pointer in the hour array. We also store the remainder (15 minutes and 15 seconds) in this location. We show this in Figure 10, ignoring the day array which does not change during the example.

The seconds array works as usual: every time the hardware clock ticks we increment the second pointer. If the list pointed to by the element is non-empty, we do EXPIRY_PROCESSING for elements in that list. However, the other 3 arrays work slightly differently.

Even if there are no timers requested by the user of the service, there will always be a 60 second timer that is used to update the minute array, a 60 minute timer to update the hour array, and a 24 hour timer to update the day array. For instance, every time the 60 second timer expires, we will increment the current minute timer, do any required EXPIRY_PROCESSING for the minute timers, and re-insert another 60 second timer.

Returning to the example, if the timer is not stopped, eventually the hour timer will reach 11. When the hour timer reaches 11, the list is examined; EXPIRY_PROCESSING will insert the remainder of the seconds (15) in the minute array, 15 elements after the current minute pointer(0). Of course, if the minutes remaining were zero, we could go directly to the second array. At this point, the table will look like Figure 11.

Eventually, the minute array will reach the 15th element; as part of EXPIRY_PROCESSING we will move the timer into the SECOND array 15 seconds after the current value. 15 seconds later the timer will actually expire, and we do the user-specified EXPIRY_PROCESSING.

What are the performance parameters of this scheme?

START_TIMER: Depending on the algorithm, we may need $0(m)$ time, where m is the number of arrays in the hierarchy, to find the right table to insert the timer and to find the remaining time. A small number of levels should be sufficient to cover the timer range with an allowable amount of memory; thus m should be small ($2 \leq m \leq 5$ say.)

STOP_TIMER: Once again this can be done in $O(1)$ time if all lists are doubly linked.

PER_TICK_BOOKKEEPING: It is useful to compare this to the corresponding value in Scheme 6.

Both have the same average latency of $O(1)$ for sufficiently large array sizes but the constants of complexity are different. More precisely:

let T be the average timer interval (from start to stop or expiry).

Let M be the total amount of array elements available.

Let m be the total number of levels in the hierarchy.

The total work done in Scheme 6 for such an average sized timer is:

c(6)* T/M

where $c(6)$ is a constant denoting the cost of decrementing the high order bits, indexing etc. in Scheme 6. If a timer lives for T units of time, it will be decremented T/M times.

And in Scheme 7 it is bounded from above by:

c(7) * m

where $c(7)$ represents the cost of finding the next list to migrate to, and the cost of migration, in Scheme 7; m is the maximum number of lists to migrate between.

The average cost per unit time for an average of n timers then becomes:

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n * c(6) / M        ---   Scheme 6
n * c(7) * m / T    ---   Scheme 7
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The choice between Scheme 6 and Scheme 7 will depend on the parameters above. Since $c(6)$ and $c(7)$ will not be drastically different, for small values of T and large values of M, Scheme 6 can be better than Scheme 7 for both START_TIMER and PER_TICK_BOOKKEEPING. However, for large values of T and small values of M, Scheme 7 will have a better average cost (latency) for PER_TICK_BOOKKEEPING but a greater cost for START_TIMER.

Wick Nichols has pointed out that if the timer precision is allowed to decrease with increasing levels in the hierarchy, then we need not migrate timers between levels. For instance, in the example above we would round off to the nearest hour and only set the timer in hours. When the hour timer goes off, we do the user specified EXPIRY_PROCESSING without migrating to the minute array. Essentially, we now have different timer modes, one for hour timers, one for minute timers, etc. This reduces PER_TICK_BOOKKEEPING overhead further at the cost of a loss in precision of up to 50% (e.g. a 1 minute and 30 second timer that is rounded to 1 minute). Alternately, we can improve the precision by allowing just one migration between adjacent lists.

Scheme 7 has an obvious analogy to a radix sort [5,14]. We discuss implementation strategies for Scheme 7 in Appendix A.

7 Summary and Conclusions

In this paper, we have examined the relationship between sorting algorithms, time flow mechanisms in discrete event simulations, and timer algorithms. We have extended the timing wheel mechanism used in logic simulation to yield 3 timer algorithms (Schemes 5-7) that have constant complexity for setting, stopping, and maintaining a timer. The extensions include rotating the timing wheel every clock tick, having separate overflow lists per bucket, and using a hierarchical set of timing wheels (Scheme 7): the extensions are necessary because the requirements of a scheduler in a logic simulation and those of a general timer module are different.

In choosing between schemes, we believe that Scheme 1 is appropriate in some cases because of its simplicity, limited use of memory, and speed in starting and stopping timers. Scheme 2 is useful in a host that has hardware to maintain the clock and a single timer. Although it takes $O(n)$ time to start a timer, the host is not interrupted every clock tick.

In a host (e.g. a VAX) without hardware support for timers, we believe Schemes 2 and 3 are inappropriate because of the cost of START_TIMER when there are a large number of outstanding timers. Clearly, this is not uncommon in hosts that have a significant amount of real-time activity or have several open communication links.

Scheme 4 is useful when most timers are within a small range of the current time. For example, it could be used by a networking module that is maintaining its own timers. Scheme 5 depends too much on the hash distribution (for a fast START_TIMER) to be generally useful.

For a general timer module, similar to the operating system facilities found in UNIX or VMS, that is expected to work well in a variety of environments, we recommend Scheme 6 or 7.

We have implemented Scheme 6 on a VAX using

MACRO-11. We used cheap VAX instructions, where the average cost of a "cheap" instruction can be taken to be that of a CLRL (longword clear). We *did not* use VAX Queue instructions. The numbers given below for the implementation do not include the cost of synchronization (e.g. by lowering and raising interrupt priority levels) in the START_TIMER and STOP_TIMER routines; they are needed for any timer algorithm and their costs are machine specific.

The implementation took 13 cheap VAX instructions to insert a timer and 7 to delete a timer. The cost per tick was 4 instructions to skip an empty array location, and 6 instructions to decrement a timer and move to the next queue element. A further 9 instructions were needed to delete an expired timer and call the EXPIRY_PROCESSING routine. Thus even if we assume that every outstanding timer expires during one scan of the table, the average cost per tick is $4 + 15 * n/TableSize$ instructions. (Once again this is because during every scan of the table all n —the average number of outstanding timers — timers will be decremented and possibly expire.) If the size of the array is much larger than n, the average cost per tick can be close to 4 instructions.

If the amount of memory required for an efficient implementation of Scheme 6 is a problem, Scheme 7 can be pressed into service. Scheme 7, however, will need a few more instructions in START_TIMER to find the correct table to insert the timer.

Both Schemes 6 and 7 can be completely or partially (see Appendix A) implemented in hardware using some auxiliary memory to store the data structures. If a host had such hardware support, the host software would need $O(1)$ time to start and stop a timer and would not need to be interrupted every clock tick.

Finally we note that designers and implementors have assumed that protocols that use a large number of timers are expensive and perform poorly. This is an artifact of existing implementations and operating system facilities. Given that a large number of timers can be implemented efficiently (e.g. 4 to 13 VAX Instructions to start, stop, and, on the average, to maintain timers), we hope this will no longer be an issue in the design of protocols for distributed systems.

8 Acknowledgments

Barry Spinney suggested extending Scheme 4 to Scheme 5. Hugh Wilkinson independently thought of exploiting hierarchy in maintaining timer lists. John Forecast helped us implement Scheme 6. Andrew Black commented on an earlier version and helped improve the presentation. Andrew Black, Barry Spinney, Hugh Wilkinson, Steve Glaser, Wick Nichols, Paul Koning, Alan Kirby, Mark Kempf, and Charlie Kaufman (all at DEC) were a pleasure to discuss these schemes with. We would like to thank Ellen Gilliam for her help in assembling the references, and the program committee for helpful comments.

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A Implementation Considerations

A.1 Hardware Assist

Since the cost of handling clock interrupts becomes more significant for fine granularity (e.g. microseconds) timers, it may be necessary to employ special purpose hardware assist. In the extreme, we can use a timer chip which maintains all the data structures (say in Scheme 6) and interrupts host software only when a timer expires.

Another possibility is a chip (actually just a counter) that steps through the timer arrays, and interrupts the host only if there is work to be done. When the host inserts a timer into an empty queue pointed to by array element X it tells the chip about this new queue. The chip then marks X as "busy". As before, the chip scans through the timer arrays every clock tick. During its scan, when the chip encounters a "busy" location, it interrupts the host and gives the host the address of the queue that needs to be worked on. Similarly when the host deletes a timer entry from some queue and leaves behind an empty queue it needs to inform the chip that the corresponding array location is no longer "busy".

Note that the synchronization overhead is minimal because the host can keep the actual timer queues in its memory which the chip need not access, and the chip can keep the timing arrays in its memory, which the host need not access. The only communication between the host and chip is through interrupts.

In Scheme 6, the host is interrupted an average of T/M times per timer interval, where T is the average timer interval and M is the number of array elements. In Scheme 7, the host is interrupted at most m times, where m is the number of levels in the hierarchy. If T and m are small and M is large, the interrupt overhead for such an implementation can be made negligible.

Finally, we note that conventional hardware timer chips use Scheme 1 to maintain a small number of timers. However, if Schemes 6 and 7 are implemented as a single chip that operates on a separate memory (that contains the data structures) then there is no a priori limit on the number of timers that can be handled by the chip. Clearly the array sizes need to be parameters that must be supplied to the chip on initialization.

A.2 Symmetric Multiprocessing

If the host consists of a set of processors, each of which can process calls to the timer module (symmetric multiprocessing), Steve Glaser has pointed out that algorithms that tie up a common data structure for a large period of time will reduce efficiency. For instance in Scheme 2, when Processor A inserts a timer into the ordered list other processors cannot process timer module routines until Processor A finishes and releases its semaphore. Scheme 5, 6, and 7 seem suited for implementation in symmetric multiprocessors.

ROUTINE	CRITICAL PARAMETER
START_TIMER	LATENCY
STOP_TIMER	LATENCY
PER_TICK_BOOKKEEPING	LATENCY
EXPIRY_PROCESSING	NONE

FIGURE 1 - AN EXAMPLE OF THE PARAMETERS OF THE TIMER MODULE THAT A NETWORKING APPLICATION MIGHT CONSIDER IMPORTANT

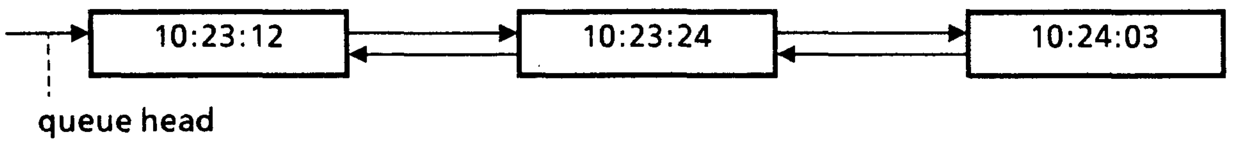
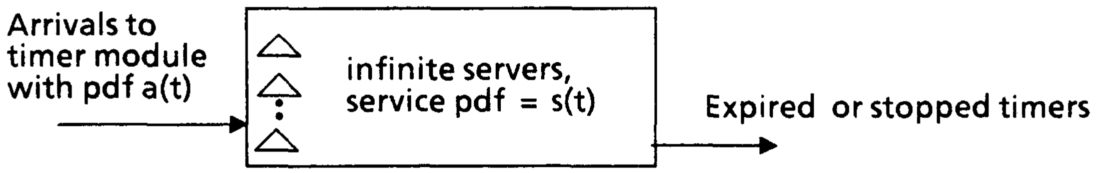


FIGURE 2 - TIMER QUEUE EXAMPLE USED TO ILLUSTRATE SCHEME 2


Arrivals to timer module with pdf a(t)
infinite servers, service pdf = s(t)
Expired or stopped timers

Note: s(t) is density function of interval between starting and stopping (or expiration) of a timer

FIGURE 3 - A G/G/INF/INF QUEUEING MODEL OF A TIMER MODULE

	START_TIMER LATENCY	STOP_TIMER LATENCY	PER_TICK_BOOKKEEPING LATENCY
Scheme 1	O(1)	O(1)	O(n)
Scheme 2	O(n)	O(1)	O(1)

FIGURE 4 - COMPARING AVERAGE AND WORST-CASE LATENCIES OF SCHEMES 1 AND 2

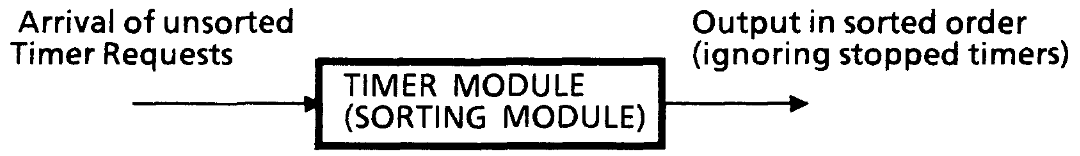

Arrival of unsorted Timer Requests
TIMER MODULE (SORTING MODULE)
Output in sorted order (ignoring stopped timers)

FIGURE 5 - ANALOGY BETWEEN A TIMER AND A SORTING MODULE

START_TIMER LATENCY	STOP_TIMER LATENCY	PER_TICK_BOOKKEEPING LATENCY
O(log(n))	O(1) or O(log(n))	O(1)

NOTE: STOP_TIMER is O(1) for unbalanced trees and O(log(n)) --- because of the need to rebalance the tree after a deletion --- for balanced trees

FIGURE 6 - AVERAGE LATENCY FOR TREE-BASED SCHEMES

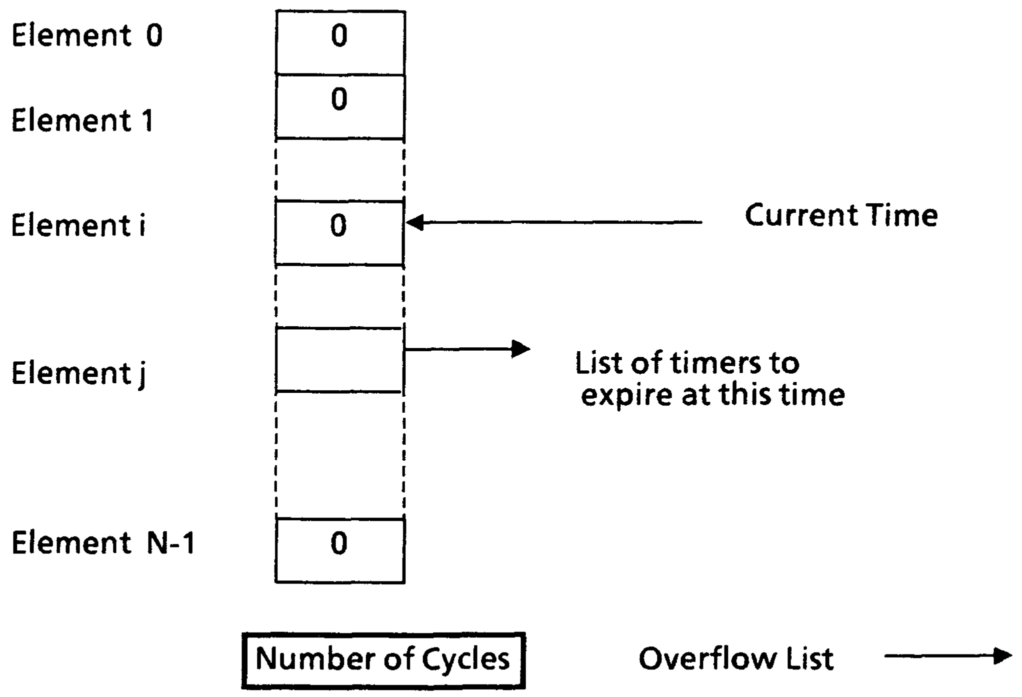


FIGURE 7 - TIMING WHEEL MECHANISM USED IN LOGIC SIMULATION [11]

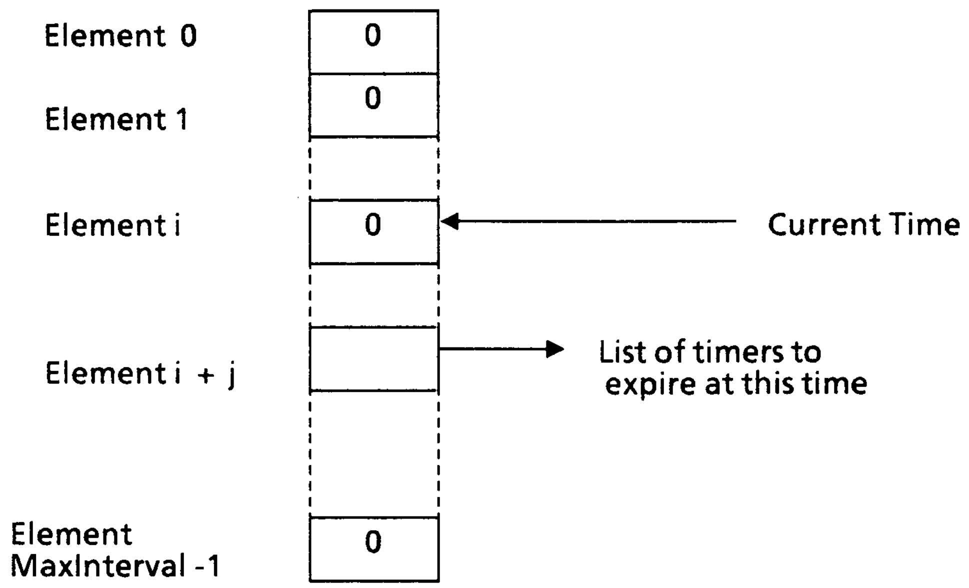


FIGURE 8 - ARRAY OF LISTS USED BY SCHEME 4 FOR TIMER INTERVALS UP TO A MAXIMUM INTERVAL

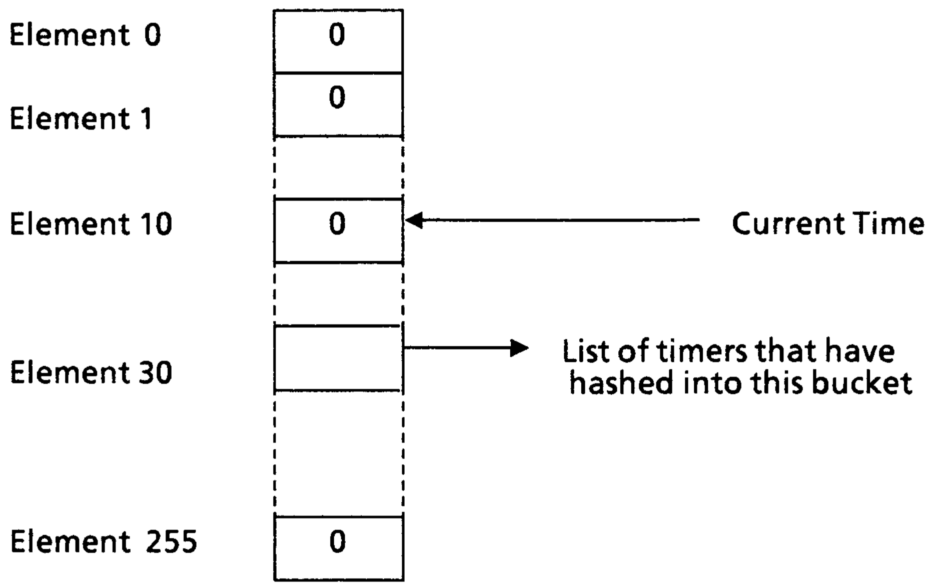


FIGURE 9 - ARRAY OF LISTS USED BY SCHEMES 5 AND 6 FOR ARBITRARY SIZED TIMERS: BASICALLY A HASH TABLE

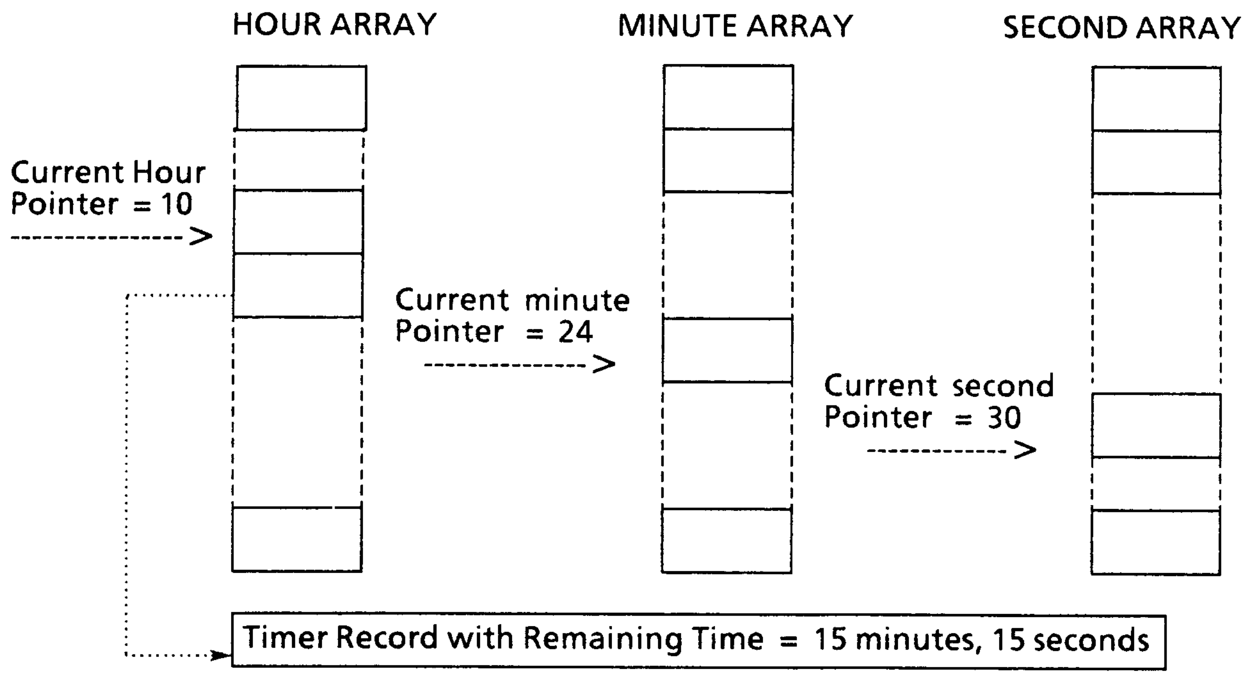

HOUR ARRAY
MINUTE ARRAY
SECOND ARRAY
Current Hour Pointer = 10
Current minute Pointer = 24
Current second Pointer = 30
Timer Record with Remaining Time = 15 minutes, 15 seconds

FIGURE 10 - HIERARCHICAL SET OF ARRAYS USED BY SCHEME 7 TO "MAP" TIME MORE EFFICIENTLY

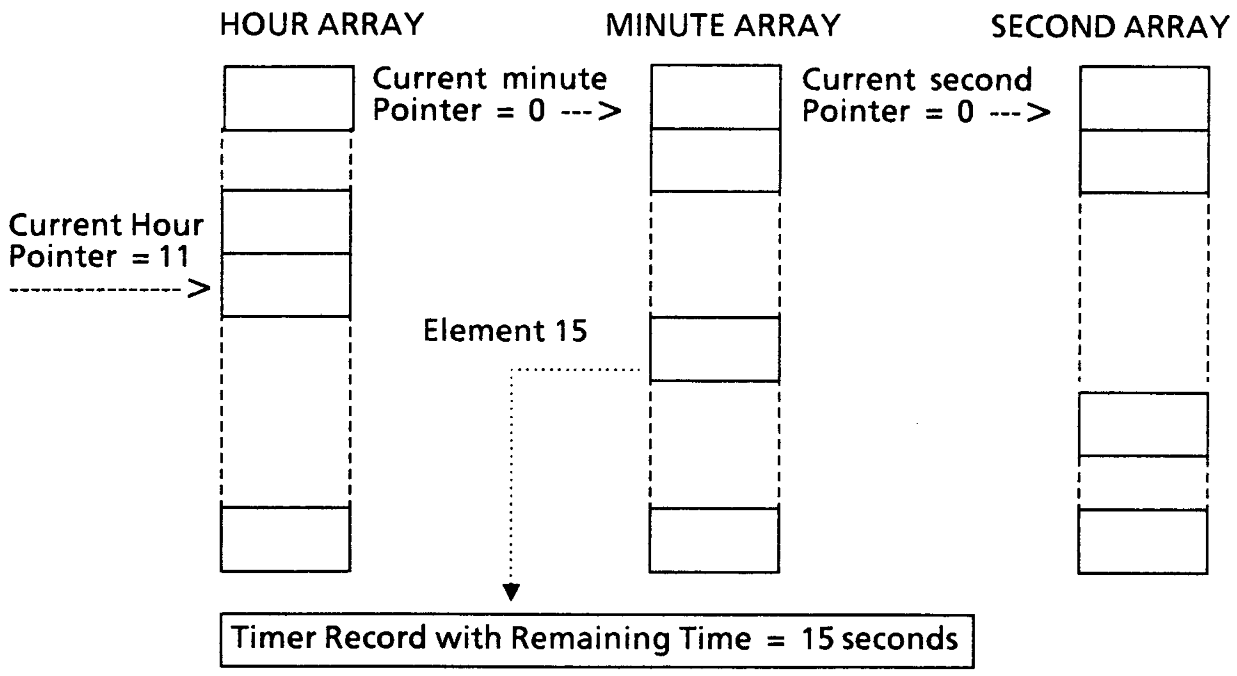

HOUR ARRAY
MINUTE ARRAY
SECOND ARRAY
Current minute Pointer = 0 --->
Current second Pointer = 0 --->
Current Hour Pointer = 11
Element 15
Timer Record with Remaining Time = 15 seconds

FIGURE 11 - FIGURE 10 AFTER THE HOUR COMPONENT EXPIRES