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Lottery scheduler for the Linux kernel

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Abstract
This paper describes the design and implementation of Lottery Scheduling, a proportional-share resource management algorithm, on the Linux kernel. A new lottery scheduling class was added to the kernel and was placed between the real-time and the fair scheduling class in the hierarchy of scheduler modules. This work evaluates the scheduler proposed on compute-intensive, I/O-intensive and mixed workloads. The results indicate that the process scheduler is probabilistically fair and prevents starvation. Another conclusion is that the overhead of the implementation is roughly linear in the number of runnable processes.

Keywords: Lottery scheduling, Schedulers, Linux kernel, operating system.

Planificador lotería para el núcleo de Linux

Resumen
Este artículo describe el diseño e implementación del planificador Lotería en el núcleo de Linux, este planificador es un algoritmo de administración de proporción igual de recursos, Una nueva clase, el planificador Lotería (Lottery scheduler), fue adicionado al núcleo y ubicado entre la clase de tiempo-real y la clase de planificador completamente equitativo (Complete Fair scheduler-CFS) en la jerarquía de los módulos planificadores. Este trabajo evalúa el planificador propuesto en computación intensiva, entrada-salida intensiva y cargas de trabajo mixtas. Los resultados indican que el planificador de procesos es probabilísticamente equitativo y previene la inanición de procesos. Otra conclusión es que la sobrecarga de la implementación es aproximadamente lineal en el número de procesos que corren.

Palabras clave: Planificador Lotería, Planificador de procesos, núcleo Linux, sistemas operativos.

1. Introduction

Process management is one of the major responsibilities of any operating system. It involves allocating various resources to processes. The CPU is the most important resource that must be shared efficiently among many competing processes in a given system. The scheduler manages the running processes in the system and runs a scheduling algorithm to service running those processes. Different scheduling algorithms are better for particular application types: real time, batch, and user-interactive.

There are many algorithms in the literature that provide efficient and fair scheduling for a CPU. Some of these algorithms are First-In-First-Out (FIFO), Round Robin, and Fixed-Priority Preemptive Scheduling. There are basically five criteria by which a scheduling algorithm can be evaluated: fairness that makes sure each process gets its fair share of the CPU, efficiency that keeps the CPU busy 100% of the time, response time that minimizes response time for interactive users, turnaround that minimizes the time batch users must wait for output and, finally, throughput that maximizes the number of jobs processed in a given timeframe [1].

In 1994, Waldspurger et al. [2] proposed the Lottery Scheduler, a randomized resource allocation algorithm that efficiently implements proportional-share resource management. This scheduling algorithm solves the problems of starvation (perpetual denial of CPU time-slice) and priority inversion, and is probabilistically fair, unlike other process scheduling algorithms which do not ensure fairness.

For this work, the lottery scheduling algorithm was implemented on the Linux 2.6.24 kernel. Although, the actual stable Linux kernel version is 3.14.1, the scheduler algorithm has not been modified mainly since the 2.6.23 version where the Completely Fair Scheduler (CFS) was introduced [3,4]. The rest of this report has been organized as follows. Section presents related work. Section provides an overview of the lottery scheduling algorithm. Section discusses the implementation of the lottery scheduling algorithm in detail. It includes the implementation of the lottery scheduling class, the integration of the scheduler with the Linux kernel, and the experience with User-Mode Linux which gives a virtual machine ideal for kernel development that supports the Linux 2.6.24 without risking the main Linux installation [14]. Section presents an overview of test cases and test scenarios, followed by a detailed discussion of the results obtained. Lastly, the conclusion and future work sections are presented.

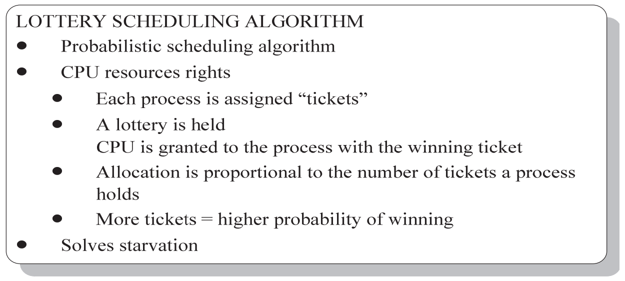

LOTTERY SCHEDULING ALGORITHM
- Probabilistic scheduling algorithm
- CPU resources rights
  - Each process is assigned "tickets"
  - A lottery is held
    CPU is granted to the process with the winning ticket
  - Allocation is proportional to the number of tickets a process holds
  - More tickets = higher probability of winning
- Solves starvation

Figure 1. Main ideas of the Lottery Scheduling Algorithm.
Source: Owner

2. Related work

Computer resource allocation has been a research target in computer science with several works with different approaches to this topic. Miller and Drexler [5] proposed the escalating-bid auction mechanism in "Incentive Engineering for Computational Resource Management" as an alternative to be used for CPU allocation. The main goal of the Share scheduler presented by Kay and Lauder [6] in "A Fair Share Scheduler" is to grant fairness between users encouraging load spreading and avoiding starvation. This work describes an algorithm that grants users shares on a system in a comparable way to the resource rights granted to a user by lottery tickets. The Share scheduler seeks to guarantee fair-share allocation of CPU resources, being similar to lottery scheduling related to users' resource rights preservation. Waldspurger et al [7] implement a distributed computational economy with CPU resource as the commodity of the economy (SPAWN), proposing that computer resource allocation can be performed according to resource allocation in a marketplace. This approach can solve the issue of fairness, but complexity and overhead are big issues on the corresponding implementation. In contrast, a lottery scheduler can also fairly manage resources with the advantage of minimal overhead.

In "Lottery Scheduling: Flexible Proportional-Share Resource Management", Waldspurger and Weihl [8] introduced the idea of lottery scheduling, giving each process a set of numbered lottery tickets and picking a random number that gives the winning process access to a required resource. A process' odds of receiving the CPU are directly related to the number of lottery tickets that have been allocated to the process. Also, Waldspurger and Weihl [9] on "Stride Scheduling: Deterministic Proportional-Share Resource Management" introduced another scheduler designed to retain a high degree of control over proportional resource allocation like the lottery scheduler, attempting to improve the variability in process latency.

Fong & Squillante [10] presented TFS (Time-Function Scheduling), which is similar to lottery scheduling, trying to maintain a high degree of control over resource allocation. With this approach, processes are grouped together in classes that are defined by a time-function, putting on the same class processes with similar scheduling objectives and similar characteristics. Petrou, Milford and Gibson [11] found some poor response time for I/O bound process on the implementation of the lottery scheduling algorithm in "Implementing Lottery Scheduling: Matching the Specializations in Traditional Schedulers". This work was focused on the required changes to address the found shortcomings and performance of one hybrid lottery scheduler. Jennifer Spath [12] explores lottery scheduling in the Linux Kernel. This work focuses on the implementation of lottery scheduling in the Linux kernel. There is a comparison between system performances with the standard Linux scheduler. Compensations tickets are also implemented to ensure equal CPU time for interactive process.

Zepp [13] explores how the Linux OS performs using the lottery method scheduling as compared to priority based scheduler, and "fair-share" scheduling in managing the CPU resource. All the tests are performed on vanilla 2.4 kernel, using the Linux user account as the trust boundary form modular resource management. This work focuses on the scheduler's capacity to manage CPU bound and I/O bound processes.

3. Background – Lottery Scheduling

Lottery scheduling is a probabilistic process scheduling algorithm. Each process is assigned a few lottery tickets, and the scheduler holds a lottery to draw a random ticket. The CPU is granted to the process with the winning ticket. The ticket distribution could be non-uniform. If a process has more tickets than other processes, it has a higher probability of winning and being selected for execution. Since a process with at least one ticket will eventually win a lottery, the problem of starvation is solved and probabilistic fairness is ensured. See Fig.1.The throughput of the system as well as the responsiveness depends on the distribution and allocation algorithm used [2]. The lottery scheduling approach can be used for any other kind of resource as well, not just the CPU [19,18]. In such situations, we refer to the competing entities as clients.

Some techniques for implementing resource management policies with lottery tickets are:

3.1. Ticket transfers

This technique is used in situations where a client is blocked holding a resource due to some dependencies, and another client is waiting for the first client to release the shared resource. One solution is to transfer the tickets to the blocked client, so that it has a higher probability of executing and can finish the task faster and release the resource sooner from which both clients will benefit. A client must have the ability to transfer its tickets to one or more clients that it depends on.

3.2. Ticket inflation

This is considered an alternative to explicit ticket transfers where a client can create more tickets for itself. On one hand, this approach can present problems in the sense that a client can monopolize a resource by creating a large number of lottery tickets. On the other hand, inflation/deflation can be used to adjust resource allocations without any explicit communications between clients, leading to a better throughput.

3.3. Compensation tickets

If a client uses only a fraction f of its allocated resource unit (for example, CPU cycles/time), it can be assigned compensation that inflates its number of tickets by a factor of 1/f. This ensures fairness and better responsiveness in case of process scheduling. Interactive processes show this behavior frequently because they enter the wait state while reading data from the disk/memory. Compensation helps these processes get their fair share of the CPU.

Fig.2 shows an example of how this algorithm works. For selecting the winning process, the algorithm generates a random number between one and the total number of tickets in the system. It then traverses the run-queue by accumulating the number of tickets it has seen so far. For each process in the queue, it checks whether the accumulated number of tickets is greater than the random number. If it is, then this would be the winning process which holds the randomly drawn lottery ticket. Observe that the total number of tickets in the system is 40 and the random number is 35. For each process, we check whether the number of tickets accumulated so far is greater than 35. We continue until we reach the fourth process, which is declared to be the winner and is granted the CPU.

4. Implementation

We present an overview of User-mode Linux and the existing Linux 2.6 scheduler followed by a detailed description of our implementation on the Linux 2.6.24 kernel.

4.1. User-mode Linux

User-Mode Linux (UML) [14] is a virtual machine environment that lets us run Linux guest systems in user-

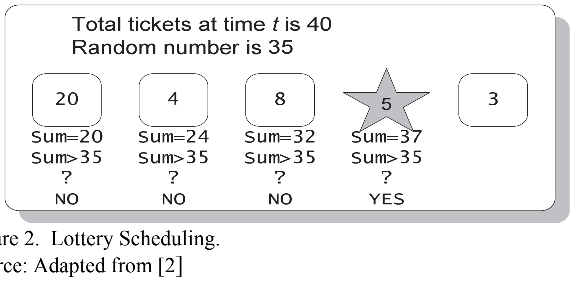


Figure 2. Lottery Scheduling.
Source: Adapted from [2]

space. It is used for multiple purposes, such as kernel development, testing new distributions and patches, hosting of virtual servers, and running network services independently of a real system.

Instead of interacting directly with the hardware, the UML kernel interacts with a Linux kernel like a user-space program. In addition, given that it is a virtual machine, it allows the user to run programs on top of it as if they were running under a normal kernel. Even if UML crashes, the host kernel is still working and is unaffected by the error. This makes UML an ideal platform for kernel development. It is possible to modify and program an instance of a kernel without suffering any damage in the host Linux. UML can also be debugged like any other normal process using standard debuggers like gdb. In other words, it is possible to carry out new development and testing at the kernel level in a safe way.

Despite its advantages, UML is limited and does not offer all the functionality that a host Linux system would offer. For instance, it does not support multiple virtual consoles or terminals that are important when testing the kernel, and it is very difficult to set up networking. Another limitation is that testing for multiple users is not feasible. Because of these shortcomings, we could not test our implementation in a multiuser setup as UML did not return to the shell promptly after setting a user, rendering it impossible to set another user. We also had to run our processes in the background, as we had access to only one terminal screen and we could not launch multiple processes in the foreground and test them.

UML can be downloaded and built from source by using the ARCH=um option while configuring and building the source. UML has a detailed installation guide [14,15].

4.2. Overview of the Linux 2.6 Scheduler

The Linux 2.6 kernel introduced an O(1) process scheduling algorithm that was independent of the number of runnable tasks in the system. The previous scheduler was an O(n) scheduler which was slow and lacked scalability. The pre-2.6 scheduler also used a single run-queue for all the processors and used a single run-queue lock, which further degraded performance [1,16].

One of the main differences in the earliest Linux 2.6 scheduler is that each processor has its own run-queue, which helps in reducing lock contention. Additionally, the concept of a priority array is introduced which uses the active array and the expired array to keep track of tasks in the system. The O(1) running time is obtained with the help of these new data structures. The scheduler puts all processes that used their time-slice in the current scheduling run into the expired array. When there are no active processes left in active array, it swaps active array with expired array. The scheduler always schedules the task with the highest priority first, and if multiple tasks exist at the same priority level, they are scheduled in a round robin fashion. The scheduler also achieves load balancing by migrating tasks from busy processors to idle processes. The earliest 2.6 kernel supports SCHED_FIFO and SCHED_RR for real-time scheduling, and the SCHED_NORMAL uses the O (1) policy. In kernel 2.6.23, the Completely Fair Scheduler (CFS) was introduced.

This scheduler, instead of relying on run queues, uses a red-black tree implementation for task management.

Linux 2.6 kernel also introduced the notion of scheduling classes, and a hierarchy of scheduler modules. Each scheduling class encapsulates a scheduling policy. These classes are maintained as a linked list, and provide an extensible framework. The current implementation includes the CFS class, and the RT (Real Time) class which comprises of the SCHED_FIFO and SCHED_RR policies. When the policy of a task is set to SCHED_NORMAL or SCHED_IDLE, the CFS scheduling policy is used. This concept of scheduling classes led to a significant refactoring of the process scheduling code.

We now provide a brief overview of the important data structures and the schedule() function from the Linux 2.6 scheduler. We discuss the fields that are most relevant to our implementation. The next subsection then illustrates how our code integrates with the data structures discussed here.

4.2.1. Struct task_struct

This is the Process Control Block. Every process in the system is represented by a task_struct. This is a very large data structure that holds together all information related to a process. When a process or a thread is created, the kernel allocates a new task_struct for it. The kernel then stores this in a circular linked list called task_list. The most important fields from this structure from the point of view of implementing a scheduling algorithm are:

- state: describes the current state of a process, which could correspond to TASK_RUNNING, TASK_INTERRUPTIBLE, TASK_UNINTERRUPTIBLE, TASK_ZOMBIE or TASK_STOPPED.
- policy: holds a value of scheduling policies.
- sched_class: a pointer to schedule class.

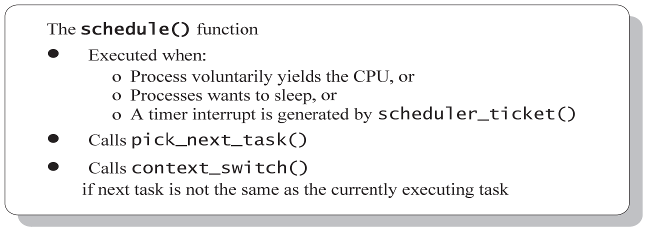
4.2.2. Struct rq

- The kernel creates a run-queue of type struct rq for each available processor at boot time. This structure further contains a run-queue for each scheduling policy and holds the following information:
- nr_running: number of runnable tasks on the run-queue
- nr_switches: number of context switches
- cfs: run-queue for the CFS scheduling policy
- rt: run-queue for the real-time scheduling policy
- curr: pointer to the currently executing task
- lock: spin lock for the run-queue
- active: the active priority array, contains tasks that have not used up their time-slices
- expired: the expired priority array, contains tasks that have used up their time-slices

4.2.3. Struct sched_class

This structure provides the framework to implement a new scheduling class. It uses the following callback functions. To implement a new scheduling policy, we need to define a new scheduling class. A run-queue has to be created, and queue operations such as enqueue, dequeue, requeue need to be implemented. These are discussed below.

- enqueue_task: called when a task enters a runnable state; increments nr_running
- dequeue_task: called when a task needs to go to the wait state; decrements nr_running
- requeue_task: called when the time-slice of a task expires and it needs to be requeued
- check_preempt_curr: checks if a task that entered the runnable state should preempt the currently executing task
- pick_next_task: chooses the task that should run next from the run-queue
- next: This is a pointer to the next scheduling class in the hierarchy


The `schedule()` function

- Executed when:
  - o Process voluntarily yields the CPU, or
  - o Processes wants to sleep, or
  - o A timer interrupt is generated by `scheduler_ticket()`
- Calls `pick_next_task()`
- Calls `context_switch()`
  if next task is not the same as the currently executing task

Figure 3. The Schedule() function in brief.
Source: Owner

4.2.4. The Schedule() function

The schedule() function is the most important function in the sched.c file. It is in-charge of selecting the next process based on the scheduling classes and for performing a context switch between the currently executing process and the process that has been selected to be executed. This function is called when a timer-interrupt occurs (scheduler_tick), when a process wants to sleep or when a process voluntarily yields the CPU (sys_sched_yield). Fig.3 and the call graph in Fig.4 provides an overview of this process.

The first general instruction of the schedule() is to disable preemption. It then retrieves the run-queue based on current processor by calling smp_processor_id() followed by cpu_rq(). Then, it releases the kernel lock on the current task and obtains the lock on the current run-queue. The next step is to invoke the pre_schedule() method. At this point, it is time to determine which task should be executed next, and this is done by calling pick_next _task(). The scheduler invokes the function based on the scheduling policy, and looks for the appropriate implementation in the corresponding scheduling class. Once the next task has been chosen, the schedule function checks not only whether the current task is the same as the next task but also whether a context switch is really required. If the two tasks are the same, it simply releases the lock of running queue and executes post_schedule(). Otherwise, it performs a context switch and then executes post_schedule().

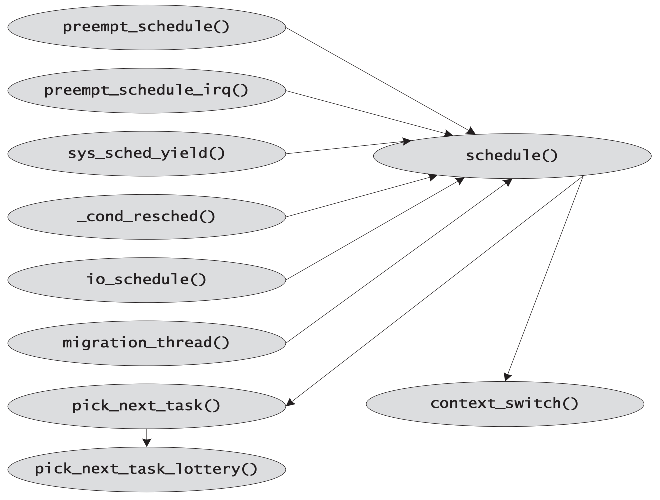


Figure 4. Call graph for schedule() function.
Source: Owner

4.3. *Implementing the Lottery Scheduler*

This subsection describes the detailed implementation of the lottery scheduling policy. We begin by stating our assumptions and the data structures that we introduced in the kernel. We then discuss the scheduling class that we added. Further, Section 4.4 explains our debugging and logging mechanisms [11,17].

4.3.1. Assumptions

For the scope of this implementation, we make the following 3 assumptions: 1) Every new process will be initialized to three tickets. 2) At any point in time, a process can possess a maximum of five tickets, and a minimum of one ticket. And 3) Compensation would favor interactive processes and punish processes that have been luckier than others. If less than 10ms have elapsed since the last time the process was on the CPU, the process loses one ticket. If more than 100ms have elapsed since the last time the process was on the CPU, the process gains one ticket [11]. See Fig.5 for the complete process undertaken every time the scheduler has to pick the next task for being processed in the CPU , taking into account the assumptions for Lottery scheduling.

4.3.2. Initialization and Data Structures

To begin with, a new policy with the name SCHED_LOTTERY was added to include/linux/sched.h and a configuration option was set up for the lottery scheduler in arch/um/KConfig. The copy_process() function in fork.c was modified to initialize three tickets to each task that was being created in the system. We then modified the process control block structure, task_struct and added two fields to this structure that let us account for the number of tickets that the process held at the time, and the previous jiffies value, which is compared to the current jiffies value to check for compensation. A new run-queue that would hold tasks

RULES
- Every new process gets INT_TICKETS (i.e. 3)
- At any time a process can hold MAX_TICKETS (i.e. 5)
- Compensation tickets:
  - o i.e., if less than 10 ms elapsed since the last time the process was on the CPU, the process losses 1 ticket
  - o i.e. if more than 100 ms have elapsed since the last time the process was on the CPU, the process gains 1 ticket
- Select the winner
  - o $1 \leq$ random_ticket $\leq$ total_tickets (i.e. 35)

Figure 5. Assumptions for the Lottery scheduling implemented in this work.
Source: Owner

that have their scheduling policy set to SCHED_LOTTERY was declared in kernel/sched.c. An instance of the lottery run-queue was created in struct rq. The following code snippets illustrate these changes.

4.3.3. Implementation of the lottery_sched_class

As discussed in Section 4.2, to implement a new scheduling policy, we need to introduce a new scheduling class in the kernel. This involves creating a new run-queue for the scheduling policy, implementing the queue operations and the callback functions in the scheduling class, and making the design decision of where to place this scheduling class in the existing hierarchy of schedulers.

```
File:include/linux/sched.h

#ifdef CONFIG_SCHED_LOTTERY
#define SCHED_LOTTERY        11
#define INIT_TICKETS         3
#define MAX_TICKETS          5
#define MIN_TICKETS          1
#endif

struct task_struct {
….

#ifdef CONFIG_SCHED_LOTTERY
     unsigned int numberOfTickets;
     unsigned long prevjiffies;
#endif

};
```

```
File:kernel/sched.c

#ifdef CONFIG_SCHED_LOTTERY
struct lottery_rq
{
     struct list_head lottery_list_head;
     unsigned long nr_running;
};
#endif

struct rq {
…

#ifdef CONFIG_SCHED_LOTTERY
     struct lottery_rq lrq;
#endif

};
```

The lottery scheduling algorithm is not real-time, so we decided to place it between the real-time scheduling class and the fair scheduling class. This would mean that any process that is not real-time and has its policy set to SCHED_LOTTERY would be given preference over the regular SCHED_NORMAL policy, which is the CFS algorithm. This is illustrated in Fig.6.

The following code snippet shows the definition of the lottery scheduling class.

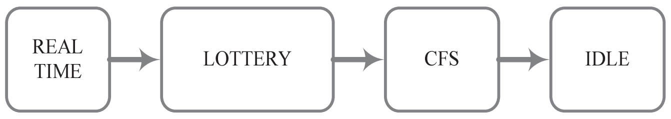


Figure 6. Hierarchy of scheduler modules including the Lottery scheduler.
Source: Owner

```
const  struct_sched_class lottery_sched_class = {

    .next                    = &fair_sched_class,
    .enqueue_task            = enqueue_task_lottery,
    .dequeue_task            = dequeue_task_lottery,
    .yield_task              = yield_task_lottery,

    .check_preempt_curr  = check_preempt_curr_lottery,
    .pick_next_task         = pick_next_task_lottery,
    .put_prev_task         = put_prev_task_lottery,
    .set_curr_task                  = set_curr_task_lottery,
    .task_tick               = task_tick_lottery,
};
```

As discussed earlier, the main algorithm for a scheduling policy is contained in pick_next_task. For the lottery scheduler, this function uses the following algorithm:

Step 1: Check for compensation

This is done by subtracting the value of p->prevJiffies from jiffies. The number that we obtain gives us the time elapsed since the last time the process p was on the CPU. If this is less than 10ms, the process loses one ticket. If this is greater than 100ms, the process gains one ticket. While using jiffies is fine-grained enough for compensation, we realized that using a high-resolution timer like RDTSC could produce more accurate values. We modified our initial implementation to use exact CPU cycles and the processor clock frequency to obtain the elapsed time. A detailed discussion on timers can be found in Section 4.5.

Step 2: Count the total number of tickets in the system

We traverse the run-queue and add the total tickets present in the system at this time. Note that this depends on the number of runnable processes available, and is a linear scan.

Step 3: Draw a lucky ticket randomly

The get_random_bytes function is used to draw a random ticket in the range of 1 to total number of tickets in the system (as calculated in Step 2).

Step 4: Search for the winning process

As discussed in Section 3, we now scan the queue and search for the process with the lucky ticket. This is done by accumulating the tickets of the processes we have seen so far in the queue, and then checking whether the current process has the lucky ticket. This check is performed by comparing the accumulated value with the random value obtained in Step 3. This algorithm scans the entire queue in the worst case, and is hence linear in the number of runnable processes.

Step 5: Set next to the winning process, update the prevJiffies (or TSC value) and return.

This step returns back the control to the schedule function that had invoked pick_next_task. The schedule function then does a context switch and allocates the CPU to the winning process. A code snippet of pick_next_task has been attached in Appendix A.

Table 1 lists all files that were modified or added in order to implement the lottery scheduling algorithm on Linux 2.6.24 kernel.

Table 1.
List of files modified or added to Linux 2.6.24 and the main changes.

Linux 2.6.24 kernel - File	Main changes
include/linux/sched.h	task_struct (process control block), declaration of sch_event and sch_event_log, register_sch_event().
kernel/fork.c	copy_process() initialize tickets.
kernel/sched.c	runqueue structures, sched_init(), schedule(), sched_fork(), _set_scheduler().
kernel/sched_lottery.c	Scheduling class for our policy, pick_next_task(),queue operations.
fs/proc/proc_misc.c	sch_operations (sch_open, sch_read, sch_release).

Source: Owner

4.4. *Debugging and logging information from the kernel*

One of the most challenging issues when writing kernel code is debugging. Kernel code cannot be easily traced or attached to a debugger. The most common debugging technique for application programming is to use printf statements. The same can be accomplished in kernel code with the help of the printk statement. Priorities, or log-levels, can be associated with printk statements. These log-levels are defined as macros. Some examples of log-levels include KERN_INFO, KERN_ALERT, KERN_ERR, KERN_CRIT and KERN_DEBUG. Depending on the log-level, the message could be printed to the console or terminal. If the klogd and syslogd daemons are running on the system, these messages are appended to /var/log/messages. If klogd is not running, the message would have to be retrieved by reading the /proc/kmesg file. The printk function writes messages out to a circular buffer. The klogd process retrieves these and dispatches them to syslogd, which in turn decides whether or not to print the message to the console based on its priority.

Although printk can be successfully used for debugging, it can slow down the system substantially. This is because syslogd needs to synchronize all the output file views, which means that every printk would incur a disk I/O penalty. syslogd tries to write everything out to the disk as soon as possible because the system might encounter a fatal state or could crash after printing out information from the kernel. Because of this limitation, debugging by printing is not considered to be the best practice when writing kernel code. The better approach is to query the system for relevant information when needed, instead of continuously producing data that might not necessarily be read. Thus, it is more appropriate to add a new file to the /proc/ file system and use the strategy of debugging by querying. We provide a brief overview of how the /proc/ file system works and discuss our event-logging mechanism in the next subsection.

4.4.1. Adding a Log to the /proc/File System

The /proc/ file system is widely used in Linux to obtain statistical and configuration information. It is a pseudo file system that is used by the kernel to export its internal information and state to the user space. Files in the /proc/ file system do not map to physical files on disks and hence do not take up any space. The contents of the files are generated dynamically when a user attempts to read the file and are stored in memory as opposed to the disk. The /proc/

file system registers itself with the Virtual File System (VFS), however, when VFS requests it for i-node or directory information, it creates these files/directories on the fly from information within the kernel. It thus provides a view into the running kernel.

The linux/proc_fs.h header file provides the API that can be used to create /proc/ entries. /proc/ entries are created based on the proc_dir_entry structure, that links the created entry to the callback functions that would be used when it is read/written to. The following code segment depicts this.

```
File: fs/proc/proc_misc.c
//File Operations
static int sch_open(struct inode *inode, struct file *file) {…}
static int sch_read(char *filp, char *buf, size_t count, loff_t *f_pos){..}
static int sch_release(struct inode *inode, struct file *file) {…}

//Callback functions
Static const struct file_operations proc_sch_operations = {
                .open           = sch_open,
                .read           = sch_read,
                .release        = sch_release,
};

struct proc_dir_entry *sch_entry;
sch_entry = create_proc_entry("scheduler_log",0666,&proc_root);
if (sch_entry) {
                sch_entry->proc_fops =&proc_sch_operations;
                sch_entry->data = NULL;
                  }
```

The next code segment explains how we implemented the logging mechanism in our kernel. Here, sch_event is defined as the basic unit of logging in the /linux/sched.h file. This structure comprised of an action (like enqueue, dequeue, context switch or debug) that identified a significant event, a time-stamp to record when the event occurred, and a message that could contain some extra information about the event. A structure for holding the log that would record a series of events that occurred is also created. We further defined functions that would help initialize and obtain the log and register an event. The register_sch_event() is the key function that gets called whenever an event needs to be logged. Fig.7 shows a call graph that explains how this works.

4.5. Accurate time-stamping

Another important aspect of this implementation was the resolution of the timers that we used for compensation and time-stamping. The kernel keeps track of time using timer interrupts. These interrupts are generated by the timing hardware, and an architecture-dependent value for this is defined in the Hz variable in linux/param.h. This value specifies the number of interrupts that would occur per second, and is usually set to 100, or 1000. Every time a timer interrupt occurs, a counter maintained by the kernel called jiffies is incremented. This counter must be treated as read-only when writing kernel code. If the Hz value is set to 1000, a timer interrupt would occur every millisecond (1000 times in a second), and jiffies would be incremented every millisecond. A lower value of the Hz variable would mean lesser interrupt handler overhead and slower wrap around; however, this would lead to a low resolution and sampling rate of the kernel time-line.

```
File: include/linux/sched.h
#define  MSG_SZ                    200
#define  MAX_EVT_LINES   1000

#define LOTTERY_CONTEXT_SWITCH    3

struct sch_event
{
      int action;                  /*Any of the above #defines */
      unsigned long long ts;   /*TimeStamp*/
      char msg[MSG_SZ];
};

struct sch_event_log
{
      struct sch_event schEvent[MAX_EVT_LINES];
      unsigned  long lines;
      unsigned long cursor;
};

void init_sch_event_log(void);
struct sch_event_log* get_sch_event_log(void);
Void register_sch_event (unsigned long long t, char *m, int a);
```

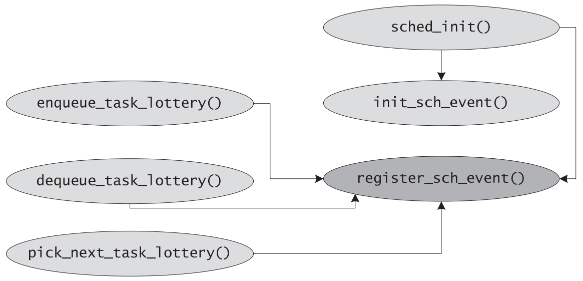


Figure 7. Call graph for register_sch_event().
Source: Owner

Lottery scheduling uses compensation tickets, which means that a process that has not been "lucky" enough to win and has not been scheduled recently needs to be favored by granting it additional tickets. This requires accurate information about the time associated with the process. Also, when measuring scheduling overhead, we want to measure the time taken by the pick_next_task() to scan the queue and select the next task to be run. Both these operations, namely, checking for compensation and measurement of overhead need higher resolution timers than jiffies. The main reason for higher resolution is that modern processors have a clock cycle of the order of GHz, and this means that they perform tasks faster and need to be sampled at a resolution in the range of 0.5 to 1 nanoseconds.

To address this issue, the RDTSC time stamp counter, which is a 64-bit machine specific register available on Pentium machine was used. This counts the number of processor cycles, and is incremented once per clock cycle making it highly accurate. RDTSC can be accessed from user space as well as kernel space with the help of the API present in asm/msr.h. This header file provides three functions to read the RDTSC value. These are rdtsc (low, high), rdtscl(low) and rdtscll(long_val). The first function reads the lower and higher order bits of the register in the low and high variables. The second function reads the lower order bits into low, and the third function reads the entire 64-bit value in an unsigned long long variable long_val.

The following code snippet shows the usage of the rdtscl() function to gather the lower-order 32-bits of the RDTSC counter. We used this to measure scheduling overhead and also to calculate compensation accurately by measuring processor cycles.

```
#include <asm/msr.h>

unsigned long  rdtsc_start, rdtsc_end,rdtsc_cycles;

rdtscl(rdtsc_start);
//code to be measured
rdtscl(rdtsc_end);

rdtsc_cycles = rdtsc_end - rdtsc_start;
```

5. Evaluation

As discussed in Section 1, the goals of a scheduler are to ensure fairness, prevent starvation, provide a good response time for interactive processes and have a high system throughput. In a multi-user system, it is also important to ensure load insulation. Another important aspect to be considered when evaluating a scheduling policy is the overhead incurred by the algorithm. We address these aspects in this section and present our results.

All our experiments were run with root permissions, in a single-user, User-mode Linux setup with SMP disabled. UML was launched with 512MB of memory.

5.1. Test cases

We used two test-cases to evaluate the performance of our scheduler. The first test-case was compute-bound. This test spawns four processes, and each process runs a long computational loop. To preclude the compiler from optimizing the loops, it is necessary to generate values that cannot be determined by the compiler in advance. Also, the loop termination condition needs to be unpredictable. This ensures that poor cache performance for the loop and that the computations cannot be incrementally calculated. This is important when evaluating fairness, because processes spawned later could take advantage of relevant data being present in the cache, and this would bias the results greatly.

The second test-case is I/O-intensive. A structure that comprises of integer, floating-point and string data that is a little bigger than the memory page size is declared. We then write out thousands of such records to the disk, and read these in both random and sequential manner. After each operation, a cache flush is performed to ensure that we have a fair comparison between processes.

5.2. Test scenarios

Equipped with the test-cases described previously, we evaluated how fair our scheduling policy is. The following test scenarios were considered:

- Compute-intensive workload
- I/O-intensive workload
- Mixed workload, which comprises of both compute-intensive and I/O-intensive processes.

For the compute-intensive workload, we executed up to five instances of our compute-bound test-case. Similarly, for the I/O-intensive workload, we ran up to five instances of our I/O-bound test-case. For the mixed workload, we ran one instance of the compute-bound and two instances of our I/O bound test-case.

Since the lottery scheduler is expected to be linear in the number of processes in the run-queue, it was necessary to evaluate the overhead of our scheduling policy. As discussed in section 4.5, an important aspect of measuring this overhead was the accuracy and resolution of our time-stamping mechanism. We used the RDTSC time stamp counter to measure the exact number of CPU cycles taken for the pick_next_task() function to count the total tickets in the system, draw a random ticket and scan the queue to find the process holding the winning ticket. All the results are presented in the next sub-section.

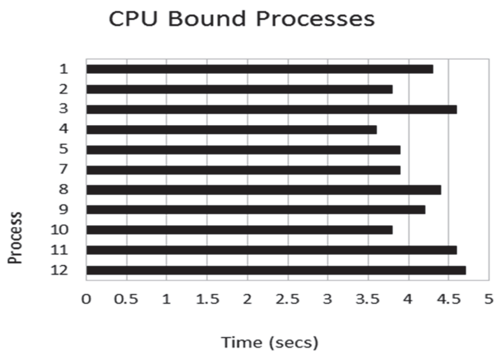
5.3. Results

Figs. 8 and 9 illustrate the fairness results. The first set of graphs shows compute-intensive workload, and the second set of graphs illustrates the I/O-intensive and mixed workloads. When ran individually, the CPU-bound process (just one of the forked processes) takes about 3.5 seconds to execute. When 12 such processes were launched, it was observed that about half of these finished in less than 4 seconds. Two of the processes took as long as 4.6 seconds to execute. Similarly, when twenty such processes were launched, we observed that three of these took more than 4.5 seconds to execute, while most of the processes finished in less than four seconds. We can conclude from these results that the lottery scheduler is probabilistically fair, and does not starve compute-bound processes. Also, as there is some randomness involved, even with compensation, there may be a few processes (about 10 – 15 % of the processes launched) that may be slowed down significantly.

We ran a similar test for I/O-bound processes, and observed the same phenomenon. When executed in isolation, the I/O bound process takes a little over 0.55 seconds to finish. When five such processes were launched, we observed that two of these finished a little earlier than expected (in about 0.53 seconds), and two other processes with the same workload took about 0.7 seconds.

For the mixed workload, we observed an important trend-- the performance of the I/O-intensive tasks was not influenced by the compute-intensive tasks. This depicts the effectiveness of using compensation tickets. In sum, we observed that the implementation of the lottery scheduler was probabilistically fair, had good performance with I/O-intensive workload, and prevented starvation.

Fig. 10 presents the overhead of our scheduling policy. Theoretically, we expect the scheduler to take linear time in the number of runnable processes, as we scan the run-queue to determine the process with the winning ticket when we pick the next task. We noted a few anomalies in our actual results though, and we would attribute these to the error in RDTSC measurements because of wrapping around of the counter values. Also, we conducted the experiment on UML and not on a real machine. Another thing to note here is that the overhead includes the scheduling overhead for background processes and daemons that were running in the system, such as the kthreadd, ksoftirq, and keventd. We observed that the overhead is still roughly linear, especially after a queue length of six, beyond which most processes are the user-space processes.



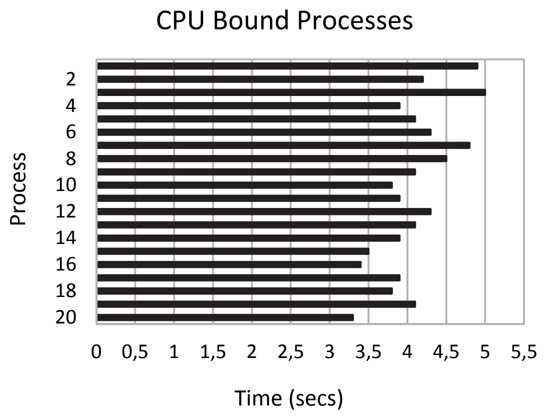
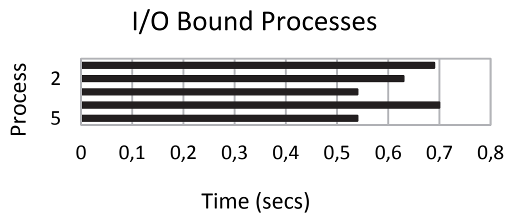


Figure 8. Fairness of CPU-intensive workload.
Source: Owner



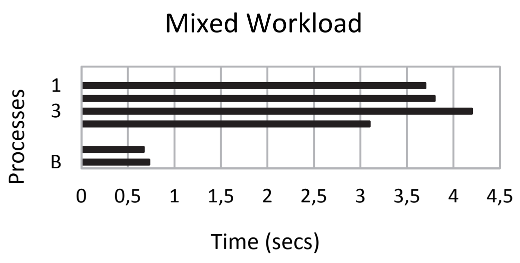


Figure 9. Fairness for I/O-intensive and mixed workload.
Source: Owner

Table 2.
Existing solutions vs. Lottery scheduling.

Priority Based Schedulers	Fair Share Scheduling	Lottery Scheduling
Tasks are given absolute priority. Issues: Starvation and difficult to compose or abstract inter- module priority relations	CPU usage is equally distributed among clients. Issues: Complexity and overhead.	Probabilistic resource allocation. Solves starvation and it is fairness. Efficient and responsive over relative execution rates of computation.

Source: Owner

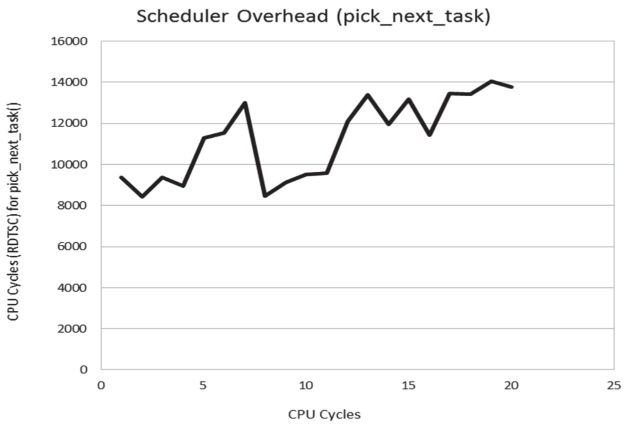


Figure 10. Overhead of the Lottery Scheduler.
Source: Owner

6. Conclusions

We presented the design and implementation of the lottery based process scheduling algorithm for the Linux 2.6 kernel. The results indicate that the scheduling policy is fair, and that compensation tickets help in boosting the performance of I/O-bound processes. Also, the scheduler prevents starvation and priority inversion. We also measured the scheduling overhead and observed that the algorithm is roughly linear in the number of runnable processes, as expected.

Some suggested enhancements would include implementing a O(log n) algorithm for picking the next task. This would reduce the overhead of the scheduler significantly. Also, as discussed in [2,4] the performance can be further improved by using kernel priorities and abbreviated quanta.

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APPENDIX A

Code snippet for the pick_next_task function. The algorithm was explained in Section 4.3.

```
File: kernel/sched_lottery.c

static struct task_struct *pick_next_task_lottery(struct rq *rq)
{
//      Declare variables, time stamp counters etc.

//      Check for compensation tickets
        temp = queue;
        list_for_each(temp, queue)  {
                p = list_entry(temp, struct task_struct, run_list);

                if(((jiffies - p->prevJiffies) < 1 ) &&
                  (p->numberOfTickets > MIN_TICKETS))
                        p->numberOfTickets--;

                 if (((jiffies - p->prevJiffies) > 10) &&
                 (p->numberOfTickets < MAX_TICKETS))
                        p->numberOfTickets++;
        }

//      Count Total Number of Tickets
        temp = queue;
        list_for_each(temp, queue) {
                p = list_entry(temp, struct task_struct, run_list);
                totalTickets += p->numberOfTickets;    }

//      Draw a lucky ticket randomly
        do{
                get_random_bytes(&luckyTicket, sizeof(unsigned long));
                if(totalTickets == 0){  return NULL;}
                luckyTicket = (luckyTicket % totalTickets) + 1;
        }while(luckyTicket < 0);

//      Search for the process with the lucky ticket
        temp = queue;
        list_for_each(temp,queue){
                p = list_entry(temp, struct task_struct, run_list);
                totalSoFar += p->numberOfTickets;
                if (totalSoFar >= luckyTicket )    break;   }

//Set the next process to the process that has the lucky ticket
        next = p;
 return next;
}
```