Lottery scheduling on xv6 with basic statistical analysis

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Abstract. *This paper describes an implementation of the lottery scheduler in the xv6 operating system. Lottery scheduling is a process scheduling mechanism that randomly chooses a process to run based on its tickets (just like a lottery). The more tickets one process have, the higher the probability of it being chosen by the scheduler. In the code presented here, the Binary Indexed Tree (BIT, or Fenwick Tree) is used to efficiently count every process' amount of tickets. Then we analyze the scheduler behavior by looking at what order a group of processes with the same task, but different amounts of tickets, finish their job.*

1. Introduction

The xv6 operating system is a simple Unix-like teaching operating system developed by MIT and widely used in Operating Systems classes all over the world. Originally, every time the scheduler was to choose a process to run, it would linearly search through the array of processes looking for the first one that is `RUNNABLE` [Cox et al. 2014]. In our class, we were assigned to implement the lottery scheduler on xv6.

As seen in [Waldspurger and Weihl 1994], the lottery scheduler is a probabilistic scheduler algorithm that works similarly to a real world lottery. Every process is given a certain amount of tickets and the scheduler randomly picks one of the available tickets among all processes. The process holding the chosen ticket is then picked to be run by the processor in the next quantum. This way, a process that has a high quantity of tickets has a high probability of being chosen by the scheduler and it will thus be run more frequently than a process that has less tickets.

2. The lottery scheduler

In order to implement the lottery scheduler, a few changes were needed in some data structures used by xv6 and a new library was created, `lottery.h`:

```
#include "param.h"

#define MAXTICKS     NPROC * NPROC // maximum number of tickets a process is allowed to have
#define MINTICKS     1 // mininum number of tickets a process is allowed to have
#define SYSTICKS     MAXTICKS / 2 // number of tickets for all system processes
#define DEFTICKS     MAXTICKS / 2 // default number of tickets

#define min(a, b) ((a) < (b) ? (a) : (b))
#define max(a, b) ((a) > (b) ? (a) : (b))

unsigned long rand(void);
```

The constants defined here are used to control the maximum and minimum amount of tickets any process can hold. Additionally, the `SYSTICKS` is the constant amount of tickets that every system process receives and DEFTICKS is for the user if it does not know how many tickets a process should have. The rand function was already defined in the usertests.c file, but wasn't being used, so it was moved to this library so it can be used when it is time to choose the next process to run.

Then, in the proc.h file, the tickets attribute was added to the structure proc, which describes a process, to hold the quantity of tickets a process has:

```
// Per-process state
struct proc {
  uint sz;                     // Size of process memory (bytes)
  pde_t* pgdir;                // Page table
  char *kstack;                // Bottom of kernel stack for this process
  enum procstate state;        // Process state
  int pid;                     // Process ID
  struct proc *parent;         // Parent process
  struct trapframe *tf;        // Trap frame for current syscall
  struct context *context;     // swtch() here to run process
  void *chan;                  // If non-zero, sleeping on chan
  int killed;                  // If non-zero, have been killed
  struct file *ofile[NOFILE];  // Open files
  struct inode *cwd;           // Current directory
  char name[16];               // Process name (debugging)
  int tickets;                 // Quantity of tickets assigned to this process
};
```

Some other modifications made in the code relate to the ptable structure, found in the proc.c file: the deadstack array (a stack), its top and the tickets array:

```
struct {
  int deadstack[NPROC], top;
  int tickets[NPROC + 1];
  struct spinlock lock;
  struct proc proc[NPROC];
} ptable;
```

The deadstack array is a stack of the currently available pids. When xv6 starts and the function pinit is called, deadstack will be initialized with all pids from NPROC to 1 (so the pid 1 will be at the top, and the value of top will end up being equal to NPROC). Then, whenever a new process is created, it will be identified by the pid found on top of deadstack. Similarly, when a process dies and its position in the proc array is once again set to UNUSED, the pid that was being used by that process is given back to the top of deadstack so it can be used again later.

To keep track of every process' tickets, the tickets array was created to be used as a Binary Indexed Tree (BIT, also known as Fenwick Tree) to efficiently count how many tickets there are up until a given process (among all existing processes). This way, we can binary search our tree until we find the leftmost position in the array that sums greater than or equal to the ticket that was picked this time around. This position in the BIT is the chosen process pid and, because of the deadstack way of handling pids, it is also its position in the proc array (but -1, because proc is indexed from 0 to $\texttt{NPROC} - 1$).

To manipulate the BIT, the functions uptick and ticount are used. The former updates the BIT whenever a process is created, executed or exits and the latter returns the sum of tickets up until a given position. Just as deadstack, tickets is initialized in the pinit function, where all positions are set to 0.

This data structure was chosen because all operations (either getting the sum or updating it) cost $O(\log n)$ each [Halim and Halim 2013]. As an also $O(\log n)$ binary search is used to find the chosen process, rather than an $O(n)$ linear search, the total resulting complexity ends up being:

$$O(\log n \times \log n) = O(\log^2 n)$$

2.1. Managing pids

The attribution of pids is done in the allocproc function, when creating a new process. As the top variable is always one position above the last valid index of the stack, we get it with --ptable.top. Likewise, we give a process' pid back to the stack in the wait function, but this time with ptable.top++.

2.2. Updating the BIT

As said before, uptick is used to update the BIT whenever a process is created, executed or exits. It is critical that we don't call it any time more or less than needed, as the BIT will end up accumulating a wrong amount of tickets or one process will be considered to have more tickets than it actually does. Also note that passing a positive argument to this function increments the BIT and passing a negative argument decrements it. Incrementing is the act of giving tickets to a process and decrementing is taking them away from it (either permanently or temporarily, to avoid it being picked when it's not RUNNABLE).

The BIT is updated in the functions that initialize a process: incrementing on userinit and fork; when a process is chosen to be executed: decrementing on scheduler; when a process gives up the processor because its time is over: incrementing on yield; when a process is woken up: incrementing on wakeup1, called by wakeup; and when a process is killed and we have to wake up the parent, if it is sleeping, so it can wait for that process to exit: incrementing, for that parent, on kill (wakeup is not used here).

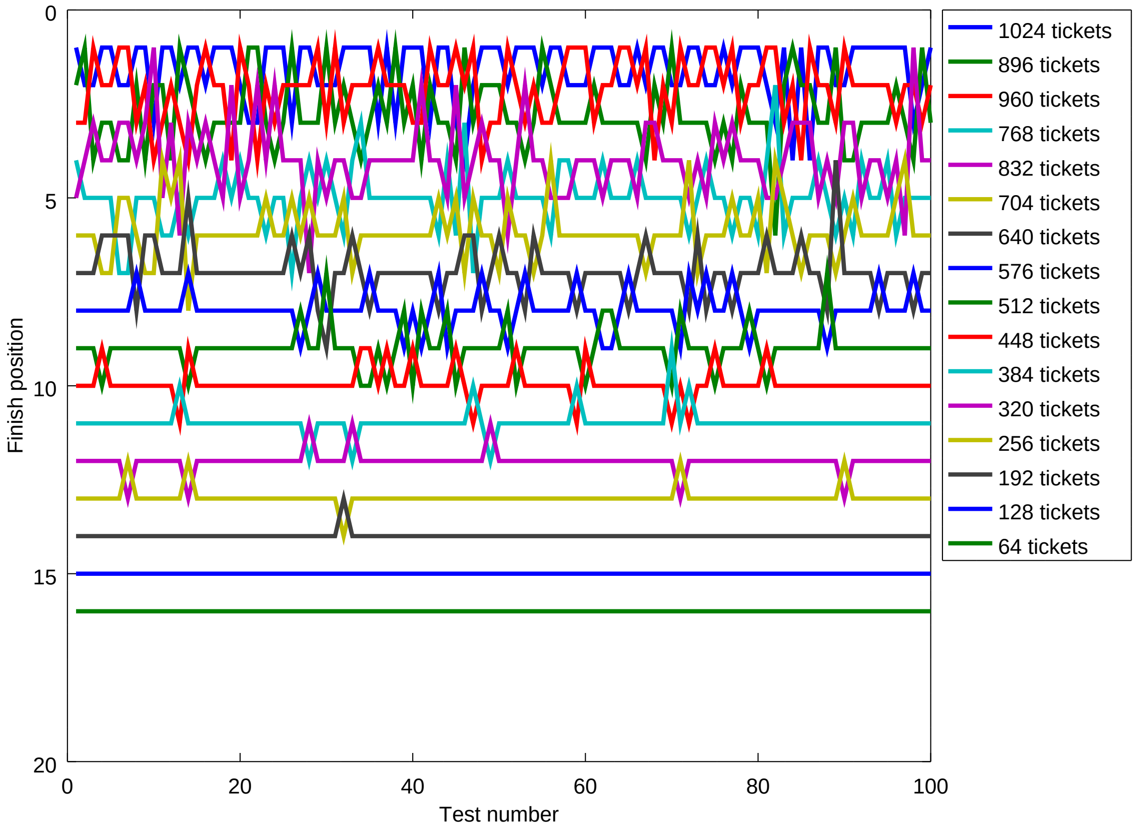
2.3. Tickets

As every process now needs tickets to be chosen to run and every process should have an amount of tickets proportional to its importance or priority, the user must be able to tell xv6 how many tickets its process will need. To accomplish this, the fork system call was changed so that it receives that amount of tickets as its sole argument.

Of course, the user might want to cheat and give the highest possible amount of tickets to all of its processes so they run more frequently than everyone else. Unfortunately, we can't do anything but trust in the amount that we receive. The purpose of the lottery is simply run the available processes proportionally to their amount of tickets. There is no way to know how important a user process is. The only treatment done here is to prevent a quantity less than the minimum or more than the maximum (using the min and max macros). There is also the DEFTICKS constant that the user can use, which is also automatically set if we receive 0 as argument.

3. Statistical analysis and conclusion

After all the modifications presented here, it is time to see if the scheduler is working as intended. To test it, the lotterytests.c file was created and configured as an xv6 executable just like usertests.c. It works like the following: 16 processes are created with the job of counting from 0 up to $\approx 10^8$. The i^{th} process received $i \times NPROC$ tickets. This test was executed 100 times. A `cprintf` was purposely added to the `exit` function, in the `proc.c` file, to print the amount of tickets a process that just terminated had. This was later processed in the host operating system by an ordinary C program that produced output conforming to the GNU Octave syntax to generate the following graphic showing the order in which those processes terminated:



Please note that the *x-axis* represent the test number and the *y-axis* is the position between 1 and 16 that a process with a number of tickets (represented by the color) terminated. Also take into account that the processes were created sequentially from the one holding the least amount of tickets to the one holding the highest amount of tickets.

As a random algorithm, there is no guarantee in the order of execution of the processes. The only sure thing is that the higher the amount of tickets, the higher the probability of being chosen to run and the larger the amount of tests, the more this order will converge to the pattern established by that probability. Additionally, there is no way to trigger the processes all at once and this is also part of the reason that a process sometimes terminates before another one that has more tickets: it started running before. If the processes were created in the inverse order, from the one holding the highest amount of tickets to the least amount of tickets, this behavior would not happen so frequently.

Despite that, it is clear that the processes with the highest amount of tickets terminated first (again, with some variation among those with a similar quantity of tickets), and the ones with the lowest amount of tickets terminated last, as we expected.

References

Cox, R., Kaashoek, F., and Morris, R. (2014). *xv6 - a simple, Unix-like teaching operating system.*

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