EECS 6891 - Homework (10% of grade)

The homework will be a single BPF program/userspace loader you need to write. The goal here is to get you set up with an environment where you can try out eBPF, write a simple program, and fight with the verifier a bit. It's a good learning experience, especially the first time :)

eBPF Tutorial Examples

Please review the eBPF tutorial slides and examples:
https://github.com/tengjiang/eBPF-Tutorial

ChatGPT Policy

We recommend using ChatGPT (or similar tech) for:

- Better understanding of the kernel structure.
- Userspace boilerplate (e.g., terminal printing)
- Questions about understanding and not about solving.
- Debugging compiler/verifier errors.

You SHOULD NOT use ChatGPT for:

- Solving your homework without having to think about it.

Other ways to look at kernel data structures is to a Linux browser:
https://elixir.bootlin.com/linux/v6.11/source

Submission

Upload your solution to GitHub and paste the repo URL here:
Invite Teng (GitHub ID: tengjiang) and Hubertus Franke (Github ID: frankeh) to your **PRIVATE** github repo. **Do not make it a public repo**!

Problem - Off-CPU/Blocked time analysis

Homework inspired by https://www.brendangregg.com/offcpuanalysis.html.

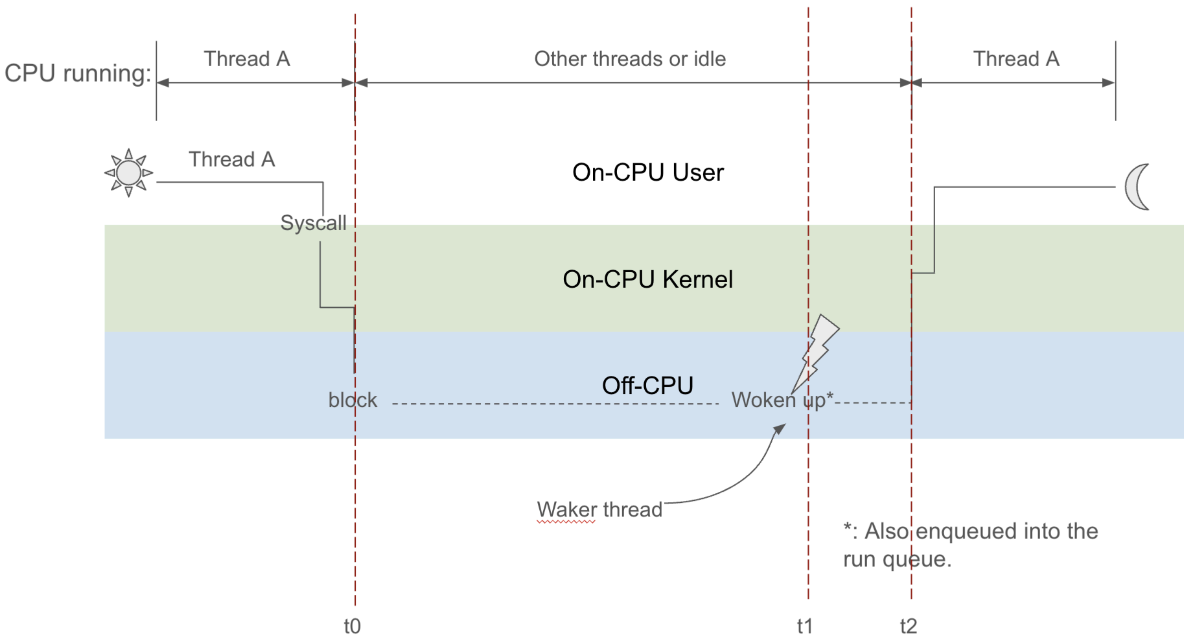


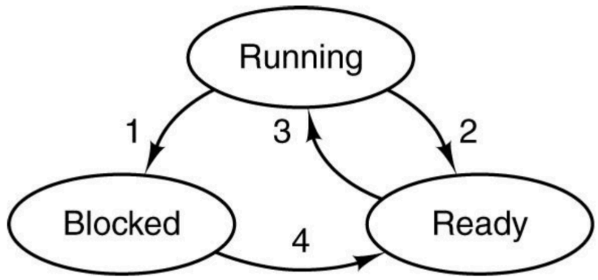
Figure 1. Illustration of blocked and off-CPU time.

In this exercise, you are going to shed some light on the internal scheduling of Linux and understand the intrinsic differences between different workloads (I/O heavy or computation-heavy, multi-threaded setting vs single-threaded setting…). **You will be developing using libbpf, as covered in the tutorial class.**

The interface of your program should be defined like this:

- A mandatory time interval, which determines how often you print out the histogram (in seconds)
- An optional PID, which determines the process ID of the process you want to trace. If not supplied, then trace all the possible processes. (A better way is to implement per-cgroup tracing, but for simplicity, we don't have to do it here.)

```
Unset
make
sudo ./executable_name --time_interval <value> [--pid <value>]
```



1. Process blocks for input
2. Scheduler picks another process
3. Scheduler picks this process
4. Input becomes available

Figure 2. State Transition Diagram of Processes

The output of the program should be 2 histograms:

- Off-CPU Time Histogram: This histogram shows the time a thread spends not running on any CPU. It represents the duration between when the thread stops running (t0 in Figure 1) and when it starts running again (t2 in Figure 1). In other words, it captures the time from one **transition out of the running state** to the next **transition back into the running state** (as shown in Figure 2).
- Blocked Time Histogram: This histogram shows the time it takes for a blocked thread to be woken up and placed back into the run queue. It represents the duration between when the thread is blocked (t0 in Figure 1) and when it is re-enqueued into the run queue (t1 in Figure 1). Essentially, it measures the time the thread spends in the **blocked state** (depicted in Figure 2).

The output histogram should look something like this: (only the format, the distribution will largely depend on what is your workload.)

```
Off-cpu time histogram
     usecs               : count    distribution
         0 -> 1          : 0        |                                        |
         2 -> 3          : 0        |                                        |
         4 -> 7          : 47       |************************************    |
         8 -> 15         : 48       |************************************    |
        16 -> 31         : 41       |*******************************         |
        32 -> 63         : 32       |************************                |
        64 -> 127        : 52       |****************************************|
       128 -> 255        : 22       |****************                        |
       256 -> 511        : 16       |************                            |
       512 -> 1023       : 7        |*****                                   |
      1024 -> 2047       : 30       |***********************                 |
      2048 -> 4095       : 27       |********************                    |
      4096 -> 8191       : 25       |*******************                     |
      8192 -> 16383      : 4        |***                                     |
```

```
        16384 -> 32767      : 9        |******                                  |
        32768 -> 65535      : 19       |**************                          |
        65536 -> 131071     : 5        |***                                     |
       131072 -> 262143     : 25       |*******************                     |
       262144 -> 524287     : 21       |****************                        |
       524288 -> 1048575    : 15       |***********                             |
      1048576 -> 2097151    : 7        |*****                                   |
      2097152 -> 4194303    : 50       |**************************************  |

   Blocked time histogram
        usecs               : count    distribution
            0 -> 1          : 0        |                                        |
            2 -> 3          : 0        |                                        |
            4 -> 7          : 10       |*********                               |
            8 -> 15         : 15       |*************                           |
           16 -> 31         : 19       |*****************                       |
           32 -> 63         : 4        |***                                     |
           64 -> 127        : 2        |*                                       |
          128 -> 255        : 8        |*******                                 |
          256 -> 511        : 4        |***                                     |
          512 -> 1023       : 0        |                                        |
         1024 -> 2047       : 24       |*********************                   |
         2048 -> 4095       : 17       |***************                         |
         4096 -> 8191       : 24       |*********************                   |
         8192 -> 16383      : 5        |****                                    |
        16384 -> 32767      : 9        |********                                |
        32768 -> 65535      : 16       |**************                          |
        65536 -> 131071     : 6        |*****                                   |
       131072 -> 262143     : 25       |**********************                  |
       262144 -> 524287     : 20       |******************                      |
       524288 -> 1048575    : 17       |***************                         |
      1048576 -> 2097151    : 7        |******                                  |
      2097152 -> 4194303    : 44       |****************************************|
```

Let's break it down:

- Each row is a latency bucket. For example, the first row is for requests with latencies 0-1 us, the second for latencies 2-3us, and so on… (The bucket size is for your own choosing, but a log2 scale is preferred)
- The first column is the bucket range. The second column is the bucket count, how many requests have latencies in that range. The third column is a visualization of the distribution. The proportion is the count for that bucket over the total number of counts in all buckets.

The output should be printed regularly (every x seconds) and only include entries that are completed during that time.

Run different workloads and compare the results of the histogram. Also, create a **README.md** file describing one interesting workload you've tested with the eBPF program. For example, some comparisons could be:

- Running a CPU-heavy workload and an I/O-heavy workload, compare their differences in the 2 histograms.
- Running the same workload with different numbers of threads
- Concurrently running different workloads (some performing IO, some performing computation…), and comparing different proportions of the workload (20% computation+80%IO v.s. 20%IO+80%computation, for example)

Environment

Please use Debian 12 to develop your homework. The recommended way is to run a VM on your laptop. The recommended way is to use VMWare Fusion (there's a free student license).

WARNING: Running a Debian container is not enough! The kernel is the same as the underlying machine.

Deliverables

- eBPF program
- Userspace loader that prints the distribution every x seconds
- README file describing an interesting use case

I should be able to run your program like so:

```
Unset
make
sudo ./executable_name --time_interval <value> [--pid <value>]
```

If you have a better idea for the interface design, you can make changes, but make sure to specify them in the readme file. The minimum requirement is to be able to do per-process tracing.

Hints

- Start by thinking about what kind of map you want. How many kinds of maps do you need? For each of them do you want a per-CPU map or a global map?
- Remember you need bpf-helpers to interact with map (**bpf_map_lookup_elem**, for example) or kernel data structures (**bpf_core_read**, for example)
- You need to look into trace points related to scheduling. See the list of scheduling tracepoints in Linux: https://elixir.bootlin.com/linux/v6.11/source/include/trace/events/sched.h. Also, if you want to understand what arguments are passed into the eBPF program attached to the tracepoint, pay attention to the fields defined with macro **TO_PROTO** and **TP_ARGS**
- You can generate IO requests with fio. You can generate CPU-heavy requests and IO with sysbench.
- The pid in the userspace corresponds to tgid (thread group ID) in the kernel task_struct. The tid in the userspace corresponds to the pid in the kernel task_struct. The --pid flag option is meant to be the pid in the user space, So we're actually tracing a whole thread group here. For example, if you run sysbench cpu with 256 threads, all of them will have the same pid but different tid, and we want to trace all of them if we input their pid to the ebpf program.
- A very similar but different example is https://github.com/iovisor/bcc/blob/master/libbpf-tools/runqlat.bpf.c. You can refer to it with map designs, histogram designs, and so on.