Programming Assignment 4: Virtual Memory Paging Strategies

CSCI 3753 - Operating Systems
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1   Assignment Introduction

All modern operating systems use virtual memory and paging in order to effectively utilize the computer's memory hierarchy. Paging is an effective means of providing memory space protection to processes, of enabling the system to utilize secondary storage systems for additional memory space, and of avoiding the need to allocate memory sequentially for each process.

We have studied how virtual memory systems are structured and how the MMU converts virtual memory address to physical memory addresses by means of a page table and a translation lookaside buffer (TLB). When a page has a valid mapping from VM address to physical address, we say the page is "swapped in". When no valid mapping is available, the page is either invalid (a segmentation fault), or more likely, "swapped out". When the MMU determines that a memory request requires access to a page that is currently swapped out, it calls the operating system's page-fault handler. This handler must swap-in the necessary page, possibly evicting another page to secondary memory in the process. It then retries the offending memory access and hands control back to the MMU.

As you might imagine, how the OS chooses which page to evict when it has reached the limit of available physical memory can have a major effect on the performance of the processes running under the OS. In this assignment, we will look at various strategies for managing the system page table and controlling when pages are paged in and when they are paged out.

2   Your Task

The goal of this assignment is to implement a paging strategy that maximizes the performance of program memory access across a set of predefined processes. You will accomplish

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this task by using a paging simulator that has already been created for you. Your job is to write the paging strategy that the simulator utilizes (roughly equivalent to the role the page fault handler plays in a real OS). You will be graded on the throughput of your paging strategy (the ratio of time spent doing useful work vs time spent waiting on the necessary paging to occur).

2.1   The Simulator Environment

The simulator has been provided for you. You have access to the source code if you wish to review it (`simulator.c` and `simulator.h`), but you should not need to modify this code for the sake of this assignment. You will be graded using the stock simulator, so any enhancements to the simulator program made with the intention of improving your performance will be for naught.

The simulator runs a random collection of processes utilizing a limited number of shared physical pages. Each process has a fixed number of virtual pages composing the processes virtual memory space that it might try to access. For the purpose of this simulation, all memory access is due to the need to load program code. Thus, the simulated program counter (PC) for each process dictates which memory location that process currently requires access to, and thus which virtual page must be swapped-in for the process to successfully continue.

The values of the constants mentioned above are available in the `simulator.h` file. For the purposes of grading your assignment, the default values will be used:

- 20 virtual pages per process (`MAXPROCPAGES`)
- 100 physical pages (frames) total (`PHYSICALPAGES`)
- 20 simultaneous processes competing for pages (`MAXPROCESSES`)
- 128 memory unit page size (`PAGESIZE`)
- 100 tick delay to swap a page in our out (`PAGEWAIT`)

As you can see, you are working in a very resource constrained environment. You will have to deal with attempts to access up to 400 virtual pages (20 processes times 20 virtual pages per process), but may only have, at most, 100 physical pages swapped in at any given time.

In addition, swapping a page in or out is an expensive operation, requiring 100 ticks to complete. A tick is the minimum time measurement unit in the simulator. Each instruction or step in the simulated programs requires 1 tick to complete. Thus, in the worst case where every instruction is a page miss (requiring a swap-in), you will spend 100 ticks of paging overhead for every 1 tick of useful work. If all physical pages are in use, this turns into 200 ticks per page miss since you must also spend 100 ticks swapping a page out in order to make room for the required page to be swapped in. This leads to a overhead to useful work ratio of 200 to 1: very, very, poor performance.

2.2   The Simulator Interface

The simulator exports three functions through which you will interact with it. The first function is called `pageit`. This is the core paging function. It is roughly equivalent to the

page-fault handler in your operating system. The simulator calls `pageit` anytime something interesting happens (memory access, page fault, process completion, etc). It passes the function a page map for each process, as well as the current value of the program counter for each process. See `simulator.h` for details. You will implement your paging strategy in the body of this function.

The `pageit` function is passed an array of `pentry` structs, one per process. This struct contains a copy of all of the necessary memory information that the simulator maintains for each process. You will need the information contained in this struct to make intelligent paging decisions. It is the simulator's job to maintain this information. You should just read it as necessary. The struct contains:

long `active`
> A flag indicating whether or not the process has completed. `1` if running, `0` if exited.

long `pc`
> The value of the program counter for the process. The current page can be calculates as $page = pc/PAGESIZE$.

long `npages`
> The number of pages in the processes memory space. If the process is active (running), this will be equal to MAXPROCPAGES. If the process has exited, this will be 0.

long `pages[MAXPROCPAGES]`
> A bitmap array representing the page map for a given process. If `pages[page #]` is `0`, page is swapped out. If `pages[page #]` is `1`, page is currently swapped in.

The simulator also exports a function called `pagein` and a function called `pageout`. These functions request that a specific page for a specific process be swapped-in or swapped-out, respectively. You will use these function to control the allocation of virtual and physical pages when writing your paging strategy. Each of these functions return `1` if they succeed in *starting* a paging operation, or if a paging operation is *already in progress*. 100 ticks after starting a paging operation, the operation will complete. Upon completion, the page maps passed to `pageit` will reflect the new state of the simulator. These functions return `0` if the paging request can not be processed (due to exceeding the limit of physical pages or because another paging operation is currently in process on the requested page) or if the request is invalid (paging operation requests non-existent page, etc). You can use these function to test whether or not a page is available to be paged in or out. If `1` is returned, the page is available and paging has begun. If `0` is returned, the page is not available.

2.3 The Simulated Programs

The simulator populates its 20 processes by randomly selecting processes from a collection of 5 simulated "programs". Pseudo code for each of the possible 5 programs is provided in Listings 1 through 5.

```
1  # loop with inner branch
2    for 10 30
3        run 500
4        if .4
```

```
5        run 900
6     else
7        run 131
8     endif
9   end
10  exit
11 endprog
```

Listing 1: Test Program 1 - A loop with an inner branch

```
1 # one loop
2   for 20 50
3       run 1129
4   end
5   exit
6 endprog
```

Listing 2: Test Program 2 - Single loop

```
1 # doubly-nested loop
2   for 10 20
3       run 1166
4       for 10 20
5           run 516
6        end
7   end
8   exit
9 endprog
```

Listing 3: Test Program 3 - Double Nested Loop

```
1 # entirely linear
2   run 1911
3   exit
4 endprog
```

Listing 4: Test Program 4 - Linear

```
1 # probabilistic backward branch
2   for 10 20
3 label:
4       run 500
5       if .5
6           goto label
7       endif
8   end
9   exit
10 endprog
```

Listing 5: Test Program 5 - Probabilistic backward branch

This simple pseudo code notation shows you what will happen in each process:

- **for X Y**: A "for" loop with between X and Y iterations (chosen randomly)

- **run Z**: Run Z (unspecified) instructions in sequence
- **if P**: Run next clause with probability P, run else clause (if any) with probability (1-P).
- **goto label**: Jump to "label"

You may wish to use this knowledge about the possible programs to:

- Predict what pages a process will need next with rather high accuracy.
- Profile processes and know which kind of process each is.
- Accurately predict what pages are needed next by a process.

3   Some Implementation Ideas

A basic "one-process-at-a-time" implementation is provided for you. This implementation never actually ends up having to swap out any pages. Since only one process is allocated pages at a time, no more than 20 pages are ever in use. When each process completed, it release all of its pages and the next process is allowed to allocate pages and run. This is a very simple solution, and as you might expect, does not provide very good performance. Still, it provides a simple starting point that demonstrates the simulator API. See `pager.c` for more information.

To start, create some form of "Least Recently Used" (LRU) paging algorithm. An LRU algorithms select a page that has not been accessed for some time when they must swap a page out to make room for a new page to be swapped in. An LRU algorithm can either operate globally, or with respect to a given process. In the latter case, you may wish to pre-reserve a number of physical pages for each process and only allow each process to compete for pages from this subset. Your LRU algorithm should perform much better than the trivial solution discussed above, but will still suffer from performance issues. We can do better.

To really do well on this assignment, you must create some form of predictive paging algorithm. Predictive algorithms attempt to predict what pages each process will require in the future and then swaps these pages in before they are needed. When these pages are needed, they are thus already swapped in and ready to go. The process need not block to wait for the required pages to be swapped in.

There are effectively two approaches to predictive algorithms. The first approach is to leverage your knowledge of the possible program types (see previous section). In this approach, one generally attempts to heuristically determine which program each process is an instance of by tracking the movement of the processes' program counter. Once each process is classified, you can use further heuristics to determine where in it;s execution the process is, and then implement a paging strategy that attempts to swap-in pages required by upcoming program actions before they occur. Since the programs all have probabilistic elements, this approach will never be perfect, but it can do very well if successful.

The second approach to predictive algorithms is to ignore the knowledge you have been given regarding the various program types. Instead, you might track each processes program counter to try to detect various common patterns (loops, jumps to specific locations, etc). If you detect a pattern, you assume that it will continue to repeat and attempt to swap in the necessary pages that the pattern touches before it needs them.

Note that in any predictive operation, you ideally wish to stay 100-200 ticks ahead of the execution of each process. This is the necessary predictive lead time in which you must make paging decisions in order to insure that the necessary pages are available when the process reaches them and that no blocking time is required.

There are a number of additional predictive notions that might prove useful involving state-space analysis and similar techniques. We will leave such solutions to the student to investigate if she wishes. Please see the references section for additional information and ideas.

4   What's Included

We provide some code to help get you started. Feel free to use it as a jumping off point (appropriately cited).

1. **Makefile** A GNU Make makefile to build all the code listed here.
2. **README** As the title so eloquently instructs: read it.
3. **simulator.c** The core simulator course code. For reference only.
4. **simulator.h** The simulator header file including simulator API.
5. **programs.c** Struct representing simulated programs for use by simulator. For reference and use by simulator code only.
6. **pager-basic.c** A basic paging implementation that only runs one process at a time.
7. **pager-lru.c** A stub for your LRU paging implementation.
8. **pager-predict.c** A stub for your predictive paging implementation.
9. **test-*** Executable test programs. Runs the simulator using your pager-*.c strategy. Built using `Makefile`. The simulator provides a lot of tools to help you analyze your program. Run `./test -help` for information on available options. It also responds to various signals by printing the current page table and process execution state to the screen (try `ctrl-c` while simulator is executing).
10. **see.R** An R script for displaying a visualization of the process run/block activity in a simulation. You must first run `./test -csv` to generate the necessary trace files. To run visualization, lunch R in windowed graphics mode (in Linux: `R -g Tk &` at the command prompt) from the directory containing the trace files (or use `setwd` to set working directory to directory containing trace files). Then run `source(''see.r'')` at the R command prompt to lunch the visualization.

5   What You Must Provide

When you submit your assignment, you must provide the following as a single archive file:

1. A copy of your LRU paging implementation
2. A copy of your best predictive paging implementation
3. A makefile that builds any necessary code
4. A README explaining how to build and run your code

6   Grading

40% of you grade will be based on the performance of the best pager implementation that you provide.

To received full credit your submission must:

- Meet all requirements elicited in this document

- Code must build with "-Wall" and "-Wextra" enabled, producing no errors or warnings.

- Code must adhere to good coding practices.

The other 60% of your grade will be determined via your grading interview where you will be expected to explain your results and answer questions regarding them and any concepts related to this assignment.

7   Extra Credit

8   Obtaining Code

The starting code for this assignment is available on the Moodle and on github. If you would like practice using a version control system, consider forking the code from github. Using the github code is not a requirement, but it will help to insure that you stay up to date with any updates or changes to the supplied codebase. It is also good practice for the kind of development one might expect to do in a professional environment. And since your github code can be easily shared, it can be a good way to show off your coding skills to potential employers and other programmers.

Github code may be forked from the project page here:
`https://github.com/asayler/CU-CS3753-2012-PA4`.

9   Resources

Refer to your textbook and class notes on the Moodle for an overview of OS paging policies and implementations.

If you require a good C language reference, consult K&R[2].

The Internet[3] is also a good resource for finding information related to solving this assignment.

The most recent version of the assignment from which this assignment was adopted is available at [1].

You may wish to consult the man pages for the following items, as they will be useful and/or required to complete this assignment. Note that the first argument to the "man" command is the chapter, insuring that you access the appropriate version of each man page. See `man man` for more information.

- `man 1 make`

References

[1] Couch, Alva. *Comp111 - A5*. Tufts University: Fall 2011. `http://www.cs.tufts.edu/comp/111/assignments/a5.html`.

[2] Kernighan, Brian and Dennis, Ritchie. *The C Programming Language*. Second Edition: 2009. Prentice Hall: New Jersey.

[3] Stevens, Ted. *Speech on Net Neutrality Bill*. 2006. `http://youtu.be/f99PcP0aFNE`.