CPEN 411: Assignment 2
High-Performance Cache Policies for the Last Level Cache (LLC)

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October 11, 2024

Contents

Chapter 1

Introduction and Setup [0 Points]

This assignment aims to implement high-performance cache policies for the shared Last Level Cache (LLC). It uses ChampSim, an industry and academic simulator. This document enables you to execute your code on the ECE server. For the ECE server, please ensure that you have at least **300 MB of free space** on the server's home directory. Please read this document very carefully and in detail.

You may choose to run this on your personal machine. We do not provide any support for that, *but it is allowed and valid.* However, be warned that some machines may get 'cooked' off as they can't handle these simulations. We are not responsible for such events.

1.1. Preparatory Steps: Setup

1. Copy the **assignment2.tar.gz** to the **<username>@ssh.ece.ubc.ca** server.

```
prashantnair@Prashants-Mac-mini Downloads % rsync -avzh --progress --stats assignment2.tar.gz prashantnair@ssh.ece.ubc.ca:~/.
prashantnair@ssh.ece.ubc.ca's password:
building file list ...
1 file to consider
assignment2.tar.gz
      107.51M 100%  417.22kB/s    0:04:11 (xfer#1, to-check=0/1)

Number of files: 1
Number of files transferred: 1
Total file size: 107.51M bytes
Total transferred file size: 107.51M bytes
Literal data: 107.51M bytes
Matched data: 0 bytes
File list size: 80
File list generation time: 0.004 seconds
File list transfer time: 0.000 seconds
Total bytes sent: 107.54M
Total bytes received: 42

sent 107.54M bytes  received 42 bytes  403.54K bytes/sec
total size is 107.51M  speedup is 1.00
```

If you do not have rsync installed. You could try installing it or use the scp command. For instance, Mac users can install these tools using Homebrew [1]. Windows and Mac users can use GUI tools like VSCode [2], CyberDuck [3], and MobaXterm [4] (**Windows Only**) to transfer files to remote servers. Linux users can use their *package manager* and install *rsync*, *scp*, or *sftp*.

2. Switch to a bash script by typing the command bash. Then untar **assignment2.tar.gz** in the ECE server and change the directory into the **ChampSim** folder.

```
ssh-linux4:~> bash
prashantnair@ssh-linux4:~$ tar -xzf assignment2.tar.gz
prashantnair@ssh-linux4:~$ cd ChampSim
prashantnair@ssh-linux4:~/ChampSim$
```

3. ChampSim uses vcpkg to manage its dependencies. In this repository, vcpkg is included as a submodule. You should bootstrap it with the following command (required only once).

```
prashantnair@ssh-linux4:~/ChampSim$ vcpkg/bootstrap-vcpkg.sh
Downloading vcpkg-glibc...
vcpkg package management program version 2023-08-09-9990a4c9026811a312cb2af78bf77f3d9d288416

See LICENSE.txt for license information.
Telemetry
---------
vcpkg collects usage data in order to help us improve your experience.
The data collected by Microsoft is anonymous.
You can opt-out of telemetry by re-running the bootstrap-vcpkg script with -disableMetrics,
passing --disable-metrics to vcpkg on the command line,
or by setting the VCPKG_DISABLE_METRICS environment variable.

Read more about vcpkg telemetry at docs/about/privacy.md
```

4. Install vcpkg with the following command (required only once).

```
prashantnair@ssh-linux4:~/ChampSim$ vcpkg/vcpkg install
A suitable version of cmake was not found (required v3.27.1) Downloading portable cmake 3.27.1...
Downloading cmake...
https://github.com/Kitware/CMake/releases/download/v3.27.1/cmake-3.27.1-linux-x86_64.tar.gz->/ubc/ece/home/pnj/faculty/prashantnair/ChampS
im/vcpkg/downloads/cmake-3.27.1-linux-x86_64.tar.gz
Extracting cmake...
Detecting compiler hash for triplet x64-linux...
The following packages will be built and installed:
    bzip2[core,tool]:x64-linux -> 1.0.8#5
    catch2:x64-linux -> 3.4.0
    cli11:x64-linux -> 2.3.2
    fmt:x64-linux -> 10.1.0
    liblzma:x64-linux -> 5.4.3#1
    nlohmann-json:x64-linux -> 3.11.2
```

5. Create softlinks for your workloads using the following command (required only once).

```
prashantnair@ssh-linux4:~/ChampSim$ ./softlinks.sh
```

1.2. Preparatory Steps: `tmux`

1. Start a **tmux** session. This is needed to keep your simulations running even if you get disconnected. **Note that you MUST NOT generate more than one session**.

```
prashantnair@ssh-linux4:~/ChampSim$ tmux new -s champsim-session
```

2. Once inside the session, please type the bash command.

```
ssh-linux4:~/ChampSim> bash
prashantnair@ssh-linux4:~/ChampSim$
```

3. You must now detach this **tmux** session by pressing: **Ctrl+b, then d**. We will use **tmux** to execute our simulations at a later stage.

```
prashantnair@ssh-linux4:~/ChampSim$ tmux new -s champsim-session
[detached (from session champsim-session)]
prashantnair@ssh-linux4:~/ChampSim$
```

1.3. Preparatory Steps: Compilation

1. You can compile your code with the **compile_champsim.sh** command. For instance, if you have to compile for the lru policy, you should type

```
prashantnair@ssh-linux4:~/ChampSim$ ./compile_champsim.sh lru
```

2. The following policies are valid policy names that can be supplied to the compilation script: lru, srrip, drrip, ship, plru, bip, dip, random, lfu. The policies in red would not compile without you first implementing these policies.

3. These policies must be implemented at **replacement/<policyname>/<policyfile>.cc**

4. You can ONLY edit the files for the policies in red. For these, you can edit ONLY **replacement/<policyname>/<policyfile>.cc**. **You MUST NOT edit any other folders or files in ChampSim. You will directly get ZERO points if you do**.

5. If your compilation is successful. You will see a statement at the end of the compilation. For LRU policy, this would look as follows.

```
Configuration build complete for lru. The binary is now named champsim-lru.
```

1.4. Preparatory Steps: Execution

1. Before you execute your code. You should switch to the **tmux** session that you created. You may do so using the following command.

```
prashantnair@ssh-linux4:~/ChampSim$ tmux attach -t champsim-session
```

2. You will be taken to the same **tmux** session screen where you left off before detaching from **tmux**.

```
ssh-linux4:~/ChampSim> bash
prashantnair@ssh-linux4:~/ChampSim$
```

3. You can execute your LRU policy code with the **run_champsim.sh** command. For instance, if you have to compile for the LRU policy, you should type

```
prashantnair@ssh-linux4:~/ChampSim$ ./run_champsim.sh lru
```

4. You may detach from the **tmux** screen once the simulations start. Your assignment has nine workloads. The simulation time, per workload, will vary. You may take nearly *one hour per simulation* to run across workloads. DO NOT EDIT any of the simulation scripts.

5. Make sure you kill your simulations before you start new simulations. You can kill a simulation by attaching your **tmux** session and typing **Ctrl+C**.

6. You can monitor the progress of your simulation run by typing the **htop** command.

7. You may iterate Preparatory Steps 1.2, 1.3, and 1.4 for srrip, drrip, and ship policies – these policies are already implemented in ChampSim.

8. You can see the outputs of your runs in the **outputs/<policyname>** folder. The outputs are log files with the names of the SPEC2006 benchmarks.

9. For each benchmark, you will primarily be interested in LLC statistics like hit rate and CORE IPC values (you find other statistics interesting as well). For instance, for the astar benchmark, we see the following statistics for LRU policy.

```
ChampSim completed all CPUs

=== Simulation ===
CPU 0 runs ../workloads/astar.trace.xz
Region of Interest Statistics

CPU 0 cumulative IPC: 0.5523 instructions: 100000000 cycles: 181054815
CPU 0 Branch Prediction Accuracy: 73.61% MPKI: 50.35 Average ROB Occupancy at Mispredict: 5.081
Branch type MPKI
BRANCH_DIRECT_JUMP: 0.00034
BRANCH_INDIRECT: 0
BRANCH_CONDITIONAL: 50.4
BRANCH_DIRECT_CALL: 0.00016
BRANCH_INDIRECT_CALL: 0
BRANCH_RETURN: 0.00022

LLC TOTAL        ACCESS:    1541990 HIT:    1303272 MISS:     238718 HITRATE: 0.845188
```

10. **Note that: For this assignment, your baseline system policy is LRU. You would need to compare the metrics of your implemented policies, such as IPC and hit rate, to LRU. Thus, you must run LRU policy for all benchmarks first.**

11. ChampSim also provides **drrip**, **srrip**, and **ship** policies. You may run them too (especially if you are implementing **gimmik**) if you like.

Chapter 2

Evaluation: Cache Policies [5 + 1 Points]

These policy simulations take a long time. Once you implement them, you would need **nearly a week to simulate** these different policies. So please start your implementation today itself!

2.1. Policies

1. **[0.5 Points]** Implement a replacement policy that randomly chooses (**random**) the lines to evict. You may ONLY edit the file **replacement/random/random.cc** for this. You can compile your implementation using **./compile_champsim.sh random** command. You can then attach your **tmux** session and run this using the **./run_champsim.sh random** command.

2. **[0.5 Point]** Implement a replacement policy that chooses the least frequently used (**LFU**) lines to evict. You have the following design constraints.

   - You can use only 4 bits per cacheline (per way) to count the frequency.
   - If there is a tie in frequency among victim lines, you will evict a random line among the tied lines.
   - If ALL ways in the set have the same non-zero frequency during an eviction, you will initialize the 4 bits for ALL cachelines (ways) in the set to zero.
   - The 4 bits per cacheline (per way) is a saturating counter.

You may ONLY edit the file **replacement/lfu/lfu.cc** for this. You can compile your implementation using **./compile_champsim.sh lfu** command. You can then attach your **tmux** session and run this using the **./run_champsim.sh lfu** command.

3. **[1 Point]** Implement the Tree-Based Pseudo-LRU (**pLRU**) policy. You may ONLY edit the file **replacement/plru/plru.cc** for this. You can compile your implementation using **./compile_champsim.sh plru** command. You can then attach your **tmux** session and run this using the **./run_champsim.sh plru** command.

4. **[1 Point]** Implement the Bimodal Insertion Policy (**BIP**) with an epsilon (ϵ) of 5%. You may ONLY edit the file **replacement/bip/bip.cc** for this. You can compile your implementation using **./compile_champsim.sh bip** command. You can then attach your **tmux** session and run this using the **./run_champsim.sh bip** command.

5. **[1 Point]** Implement the Dynamic Insertion Policy (**DIP**) that uses BIP with epsilon (ϵ) of 5% and LRU. You may use 64 leader sets per policy for set-dueling. Your PSEL is 10 bits wide and is initialized to 512. You may ONLY edit the file **replacement/dip/dip.cc** for this. You can compile your implementation using **./compile_champsim.sh dip** command. You can then attach your **tmux** session and run this using the **./run_champsim.sh dip** command.

6. **[1 Point]** – BONUS (optional) Implement your own cache replacement policy – let us call this policy (**GIMMIK**). You can ONLY use a maximum of 16KB additional overheads for the entire LLC. This can be in the form of a table, per cacheline, or however, you like. **If you exceed this limit, you will get a ZERO in the entire assignment**. Note that this needs to be a new policy. It cannot be a replica of published policies.

You may ONLY edit the file **replacement/gimmik/gimmik.cc** for this. You can compile your implementation using **./compile_champsim.sh gimmik** command. You can then attach your **tmux** session and run this using the **./run_champsim.sh gimmik** command.

To get this BONUS point, (i) Your policy must be among the top 5 IPCs from the **gimmik** submissions in the class *AND* (ii) Your policy should provide 2%+ speedup (geomean) compared to the SHIP replacement policy. *We will start an anonymous tracking sheet for this soon.*

7. **[1 Point]** Write a report in pdf format explaining how you implemented **random**, **lfu**, **plru**, **bip**, **dip**, and **gimmik** (optional) policies. This pdf should also have graphs that compare IPC (normalized and actual IPC across policies), hit rates, and other key metrics you deem fit. You should be able to explain your results convincingly, exhaustively, and logically in this document. There is a page limit of 5 pages. **Place your report within the ChampSim folder**.

2.2. A Few Pro Tips

1. If you have <1 week remaining and have not started your simulations, you may struggle to complete this assignment (if you use an ECE server). So start early!

2. Please learn how to track your jobs using the **top** and/or **htop** commands.

3. You DO NOT need to run your simulations only on **ssh-linux4** or whatever server you get during login. You can use **htop** and check if this server is busy with other jobs from other students. If so, you can ssh to other servers. This will help balance the load. We have **ssh-linux1**, **ssh-linux2**, **ssh-linux3** and **ssh-linux4** servers. For instance, once you login, can ssh into **ssh-linux1** from **ssh-linux4** by typing the command as follows:

```
jeonghyunwoo@Jeonghyuns-Laptop.local:~/OneDrive - UBC/TA/CPEN 411/2024/Assignemnts/Assignment2 $ ssh jhwoo36@ssh-linux1.ece.ubc.ca
```

4. Please kill your simulations before you restart a run. Otherwise, your simulations will stack up, and that will cause **immense slowdowns** for you.

5. For faster development, learn to use **vi**, **vim**, or **emacs**.

6. **Important**: You can test your code for fewer instructions and only a few benchmarks before instantiating a full run. This can be done via the command line as follows:

```
prashantnair@ssh-linux4:~/ChampSim$ ./bin/champsim-lru --warmup-instructions 2000000 --simulation-instructions 5000000 workloads/astar.trace.xz
WARNING: physical memory size is smaller than virtual memory size.

*** ChampSim Multicore Out-of-Order Simulator ***
Warmup Instructions: 2000000
Simulation Instructions: 5000000
Number of CPUs: 1
Page size: 4096

Off-chip DRAM Size: 64 GiB Channels: 2 Width: 64-bit Data Race: 3200 MT/s
Warmup finished CPU 0 instructions: 2000001 cycles: 500046 cumulative IPC: 4 (Simulation time: 00 hr 00 min 03 sec)
Warmup complete CPU 0 instructions: 2000001 cycles: 500046 cumulative IPC: 4 (Simulation time: 00 hr 00 min 03 sec)
```

Here, we are testing the **LRU** policy on the **astar** benchmark with a warm-up of only 2 million instructions and execution of only 5 million instructions. This will be a quick run; you won't have to use **tmux**.

Note that the main submission warms up for 50 million instructions and executes an additional 50 million instructions for each benchmark.

7. If you have time, learn how to use the tracer folder to develop your **own traces** of tailored access patterns. The tracer uses **Pin**, and this strategy will help you debug with your tailored binaries. You can check if your cache policy provides the expected hit rates for your custom trace.

Chapter 3

Submission Instructions

1. Before submitting your assignment, please kill the `tmux` session as follows:

```
prashantnair@ssh-linux4:~$ tmux ls
champsim-session: 1 windows (created Tue Oct  8 19:55:27 2024)
prashantnair@ssh-linux4:~$ tmux kill-session -t champsim-session
prashantnair@ssh-linux4:~$ tmux ls
no server running on /tmp/tmux-18623/default
prashantnair@ssh-linux4:~$
```

2. To submit, please execute the following command within the ChampSim folder.

```
prashantnair@ssh-linux4:~/ChampSim$ bash create_submission.sh
```

3. You can then run **rsync** from your local computer and download the submission file.

```
prashantnair@Prashants-Mac-mini Downloads % rsync -avzh --progress --stats prashantnair@ssh.ece.ubc.ca:~/ChampSim/submission.tar.gz submis
sion.tar.gz
prashantnair@ssh.ece.ubc.ca's password:
receiving file list ...
1 file to consider
submission.tar.gz
      10.22K 100%    9.74MB/s    0:00:00 (xfer#1, to-check=0/1)

Number of files: 1
Number of files transferred: 1
Total file size: 10.22K bytes
Total transferred file size: 10.22K bytes
Literal data: 10.22K bytes
Matched data: 0 bytes
File list size: 81
File list generation time: 0.002 seconds
File list transfer time: 0.000 seconds
Total bytes sent: 38
Total bytes received: 10.34K

sent 38 bytes  received 10.34K bytes  902.78 bytes/sec
total size is 10.22K  speedup is 0.98
```

4. If and only if you have implemented `gimmik` AND it provides 2%+ speedup (geomean) compared to the `ship` replacement policy, write a comment in your submission with the speedup number. You DO NOT need to write a comment if the performance of your `gimmik` policy is less than 2% compared to the `ship` replacement policy (geomean) OR if you did not implement `gimmik`.

We will evaluate your `gimmik` implementation ONLY if we see this comment. So do not forget to write this if you did implement a high-performance policy.

5. Please upload **ONLY** the **submission.tar.gz** on Canvas. **If we find stale files and execute those, you can get "ZERO" points for this assignment**.

6. Thus, be extremely careful and double-check if your source files and other things are right! We have 80 students and will not re-evaluate your Assignment if you submit incorrect or stale work.

Bibliography

[1] Homebrew. Website Access for Homebrew. https://brew.sh/.

[2] Vscode. Website Access for Remote Development using SSH - Visual Studio Code. https://code.visualstudio.com/docs/remote/ssh.

[3] Cyberduck. Website Access for Cyberduck. https://cyberduck.io/.

[4] MobaXterm. Website Access for MobaXterm . https://mobaxterm.mobatek.net/.