CS61C Lab 8 - Caches

Setup

Copy the lab skeleton into your workspace:

```
$ cp -r ~cs61c/labs/08 ~/lab08
```

Exercise 1: Cache Visualization

Caches is typically one of the hardest topics for students in 61C to grasp at first. This exercise will use some cool cache visualization tools in MARS to get you more familiar with cache behavior and performance terminology with the help of the file `cache.s` and `wackycache.s`. At this point, read through `cache.s` to get a rough idea of what the program does.

To get started with each of the scenarios below:

1. Open the designated file in MARS. (cache.s or wackycache.s)
2. In the code for cache.s or wackycache.s, set the appropriate Program Parameters as indicated at the beginning of each scenario (by changing the immediates of the commented `li` instructions in `main`)
3. Run Tools-->Data Cache Simulator.
4. Set the appropriate Cache Parameters as indicated at the beginning of each scenario.
5. Enable the Runtime Log and then click "Connect to MIPS".
6. Run Tools-->Memory Reference Visualizer and click "Connect to MIPS".
7. As you execute code in MARS, any *DATA* memory access (load or store) will show up (instruction fetches not shown).

The Data Cache Simulator will show the state of your data cache and the Memory Reference Visualization will show you what parts of memory you are accessing and how many times. Please remember that these are running independently from your code, so if you reset your code, you should also reset the cache and memory!

If you run the code all at once, you will get the final state of the cache and hit rate. You will probably benefit the most from setting breakpoints at each memory access to see exactly where the hits and misses are coming from.

Simulate the following scenarios and record the final cache hit rates. Try to reason out what the hit rate will be BEFORE running the code. After running each simulation, make sure you understand WHY you see what you see (the TAs will be asking)!

Do not heistate to ask questions if you feel confused! This is perfectly normal and the staff is there to help you out!

Good questions to ask yourself as you do these exercises:

- How big is your cache block? How many consecutive accesses fit within a single block?
- How big is your cache? How many jumps do you need to make before you "wrap around?"
- What is your cache's associativity? Where can a particular block fit?
- Have you accessed this piece of data before? If so, is it still in the cache or not?

Scenario 1: (using cache.s)

Cache Parameters:

- **Placement Policy:** Direct Mapping
- **Block Replacement Policy:** LRU
- **Set size (blocks):** 1 (MARS won't let you change this, why?)
- **Number of blocks:** 4
- **Cache block size (words):** 2

Program Parameters:

- **Array Size:** 128
- **Step Size:** 8
- **Rep Count:** 4
- **Option:** 0

Questions:

1. What combination of parameters is producing the hit rate you observe? (Hint: Your answer should be of the form: "Because parameter A == parameter B")
2. What is our hit rate if we increase Rep Count arbitrarily? Why?
3. How could we modify our program parameters to maximize our hit rate?

Scenario 2: (using cache.s)

Cache Parameters:

- **Placement Policy:** N-way Set Associative
- **Block Replacement Policy:** LRU
- **Set size (blocks):** 4
- **Number of blocks:** 16
- **Cache block size (words):** 4

Program Parameters:

- **Array Size:** 256
- **Step Size:** 2
- **Rep Count:** 1
- **Option:** 1

Questions:

1. Explain the hit rate in terms of the parameters of the cache and the program.

2. What happens to our hit rate as Rep Count goes to infinity? Why?
3. Suppose we have a program that uses a very large array and during each Rep, we apply a different operator to the elements of our array (e.g. if Rep Count = 1024, we apply 1024 different operations to each of the array elements). How can we restructure our program to achieve a hit rate like that achieved in this scenario? (Assume that the number of operations we apply to each element is very large and that the result for each element can be computed independently of the other elements.) What is this technique called? (Hint)

Scenario 3:

For the final scenario, we'll be using a new file: wackycache.s. Open it up in MARS and read through the pseudocode to make sure you understand what's happening.

Cache Parameters:

- **Placement Policy:** N-way Set Associative
- **Block Replacement Policy:** LRU
- **Set size (blocks):** 4
- **Number of blocks:** 16
- **Cache block size (words):** 4

Program Parameters:

- **Array Size:** 256
- **Step Size:** 8
- **Rep Count:** 2

Questions:

1. Run the simulation a few times. Note that the hit rate is non-deterministic. Why is this the case? Explain in terms of the cache parameters and our access pattern. ("The program is accessing random indicies" is not a sufficient answer).
2. Which Cache parameter can you modify in order to get a constant hit rate? Record the parameter and its value (and be prepared to show your TA a few runs of the simulation). How does this parameter allow us to get a constant hit rate?

Check-off

- Answer the numbered questions above for each of the scenarios.
- Ensure that you thoroughly understand each answer. Your TA may ask for a dditional explanation.

Exercise 2: Loop Ordering and Matrix Multiplication

If you recall, matrices are 2-dimensional data structures wherein each data element is accessed via two indices. To multiply two matrices, we can simply use 3 nested loops, assuming that matrices A, B, and C are all n-by-n and stored in one-dimensional column-major arrays:

```
for (int i = 0; i < n; i++)
    for (int j = 0; j < n; j++)
        for (int k = 0; k < n; k++)
            C[i+j*n] += A[i+k*n] * B[k+j*n];
```

Matrix multiplication operations are at the heart of many linear algebra algorithms, and efficient matrix multiplication is critical for many applications within the applied sciences.

In the above code, note that the loops are ordered i, j, k. If we examine the innermost loop (k), we see that it moves through B with stride 1, A with stride n and C with stride 0. To compute the matrix multiplication correctly, the loop order doesn't matter. However, the order in which we choose to access the elements of the matrices can have a large impact on performance. Caches perform better (more cache hits, fewer cache misses) when memory accesses exhibit spatial and temporal locality. Optimizing a program's memory access patterns is essential to obtaining good performance from the memory hierarchy.

Take a glance at matrixMultiply.c. You'll notice that the file contains multiple implementations of matrix multiply with 3 nested loops.

Note that the compilation command in the Makefile uses the '-O3' flag. *It is important here that we use the '-O3' flag to turn on compiler optimizations*.Compile and run this code with the following command, and then answer the questions below:

```
$ make ex2
```

a. Which ordering(s) perform best for 1000-by-1000 matrices?
b. Which ordering(s) perform the worst?
c. How does the way we stride through the matrices with respect to the innermost loop affect performance?

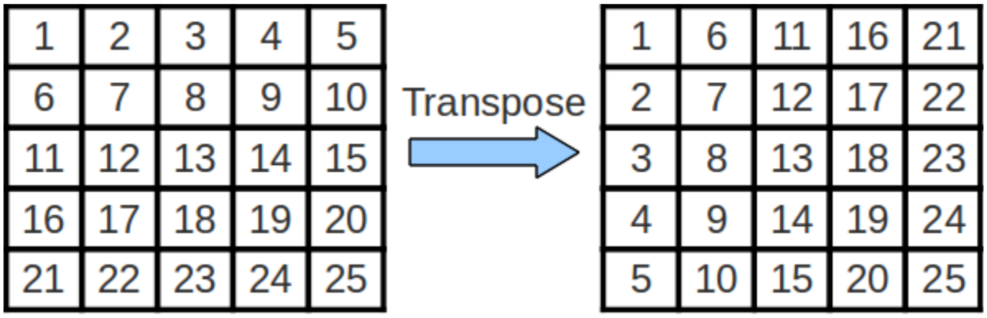
Checkoff: Be prepared to explain your responses to the above questions to your TA.

Exercise 3: Cache Blocking and Matrix Transposition

Note: The term cache blocking is not referring to the same thing as the cache blocks we talked about when discussing the structure of caches.

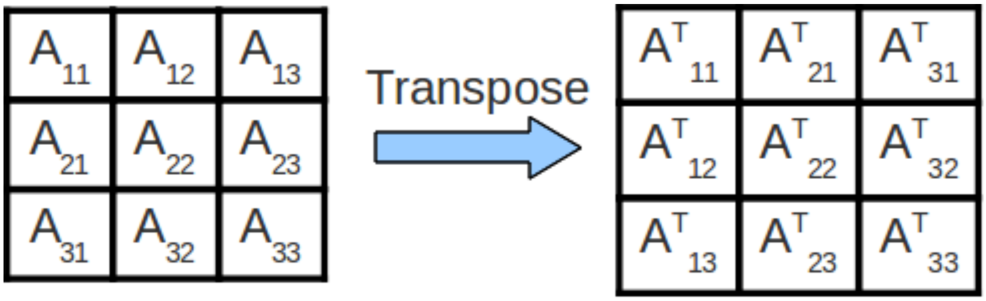
Matrix Transposition

Sometimes, we wish to swap the rows and columns of a matrix. This operation is called a "transposition" and an efficient implementation can be quite helpful while performing more complicated linear algebra operations. The transpose of matrix A is often denoted as A^T.



Cache Blocking

In the above code for matrix multiplication, note that we are striding across the entire A and B matrices to compute a single value of C. As such, we are constantly accessing new values from memory and obtain very little reuse of cached data! We can improve the amount of data reuse in the caches by implementing a technique called cache blocking. More formally, **cache blocking is a technique that attempts to reduce the cache miss rate by improving the temporal and/or spatial locality of memory accesses**. In the case of matrix transposition we consider performing the transposition one block at a time.


A_{11} A_{12} A_{13}
A_{21} A_{22} A_{23}
A_{31} A_{32} A_{33}
Transpose
A^T_{11} A^T_{21} A^T_{31}
A^T_{12} A^T_{22} A^T_{32}
A^T_{13} A^T_{23} A^T_{33}

In the above image, we transpose each block A_{ij} of matrix A into its final location in the output matrix, one block at a time. With this scheme, we significantly reduce the magnitude of the working set in cache during the processing of any one block. This (if implemented correctly) will result in a substantial improvement in performance. For this lab, you will implement a cache blocking scheme for matrix transposition and analyze its performance. You may also find this technique useful for Project 3.

Your task is to implement cache blocking in the `transpose_blocking()` function inside transpose.c. By default, the function does nothing, so the benchmark function will report an error. **You may NOT assume that the matrix width (`n`) is a multiple of the blocksize.** After you have implemented cache blocking, you can run your code by typing:

```
$ make ex3
$ ./transpose <n> <blocksize>
```

Where `n`, the width of the matrix, and `blocksize` are parameters that you will specify. You can verify that your code is working by setting `n`=1000 and `blocksize`=33 Once your code is working, complete the following exercises and record your answers (we will ask about it during checkoff).

Part 1: Changing Array Sizes

Fix the `blocksize` to be 20, and run your code with `n` equal to 100, 1000, 2000, 5000, and 10000. At what point does cache blocked version of transpose become faster than the non-cache blocked version? Why does cache blocking require the matrix to be a certain size before it outperforms the non-cache blocked code?

Part 2: Changing Blocksize

Fix `n` to be 10000, and run your code with `blocksize` equal to 50, 100, 500, 1000, 5000. How does performance change as the blocksize increases? Why is this the case?

Checkoff: Be prepared to explain your responses to the above questions to your TA.