



# Lab 7: Caches

Deadline: Friday, October 29, 04:00:00 PM PT

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## Goals

- Analyze how memory access patterns determine cache hit rates
  - Analyze and discover which memory access patterns produce **GOOD** hit rates
  - Analyze hit rates for caches and be able to optimize code accesses to produce good hit rates
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## Review - Hit and Miss Policies

The Venus cache simulator currently simulates a **write-through, write-allocate** cache. Here's a reminder about the three different cache hit policies you should know about:

- **Write-back** means that on a write hit, data is exclusively written to the cache. In addition, after the write, the dirty bit for the block that was just written becomes 1 (mental check: what does having a dirty bit of 1 mean?). Writing to the cache is quite fast, so the write latency in write-back caches is usually quite small. However, when a block is evicted from a write-back cache, if its dirty bit is 1, then the memory must be updated with the contents of that block, as it currently contains changes that are not reflected in memory. Thanks to this, write-back caches tend to be more difficult to implement in hardware.
- **Write-through** means that on a write hit, data is written to both the cache and main memory. Writing to the cache is fast, but writing to main memory is slow; this makes the write latency in write-through caches slower than in a write-back cache. However, the significant upside of a write-through cache is that simpler hardware can be used, since whenever the cache is written to, the memory automatically updates as well.
- **Write-around** means that in every situation, data is written to main memory only, kind of like an opposite version of the write-back policy. An important thing to keep in mind is if the block we just updated in the main memory is also in our cache, then we need to change the cache block's valid bit to invalid. This is because our cache no longer has the most up-to-date memory. In addition, under the Write-Around policy, there is no such thing as a write-hit, as it effectively does the exact same thing as a write-miss.

There are also two miss policies you should know about:

- **Write-allocate** means that on a write miss, you also pull the block you missed on into the cache. For example, for write-back, write-allocate caches, memory is never written to directly. This is because we are only ever writing to the cache (thanks to the write-back policy), and we only end up updating the memory upon eviction of the (potentially) updated block.
- **No write-allocate** means that on a write miss, you do not pull the block you missed on into the cache. Only memory is updated.

There are two common combinations of cache hit/miss policies:

- **Write-through/no-write allocate:** When there are hits, the policy writes back to cache **and** main memory, keeping both updated. On write misses, the block in main memory gets updated as the main memory access has to occur anyways. Thanks to the no-write allocate policy, the updated block is not brought back into the cache, and subsequent writes always write to main memory regardless of cache status. This situation applies solely for writes; upon read hits and misses, the cache behaves as usual. With this setup, should a read of the same block occur after the write-miss, the no-write allocate would cause an unnecessary miss (mental check: why is this?).
- **Write-back/write allocate:** on hits, it writes back to the cache, updating the dirty bit without updating main memory; on misses, the corresponding block is brought into the cache. If the same block gets accessed, all subsequent writes would be hits and the dirty bit would be set until the block is evicted, at which point it would be moved back to main memory. This policy ends up eliminating all write hit main memory accesses, making it much more efficient than the write-through/write allocate policy.

Additionally, in this course, we talk about several replacement policies, in order from most useful to least useful (normally):

- **LRU** (Least Recently Used) — When we decide to evict a cache block to make space, we select the block that has been used the furthest back in time of all the blocks.
- **Random** - When we decide to evict a cache block to make space, we randomly select one of the blocks in the cache to evict.
- **MRU** (Most Recently Used) — When we decide to evict a cache block to make space, we select the block that has been used the most recently of all the blocks.

The important takeaway concerning Venus here: **in a write-through cache (like in Venus), even though you are updating memory on writes, because we also write to the cache, we consider writes to blocks we have in the cache to be write hits.**

Common question(s):

1. **Don't we usually pair write-back with write-allocate and write-through with no write-allocate?** Yes, we learned in class that the ordinary pairing of hit policy/miss policy is write-back/write-allocate and write-through/no write-allocate. However, with respect to the cache, write-through and write-back caches behave similarly on hits (both write to the cache), so the hit/miss patterns you see in the Venus cache simulator would be the same even if Venus simulated a write-back cache.
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## Setup

In your `labs` directory, pull the files for this lab with:

```
$ git pull starter main
```

For this lab, record your answers to the Tasks questions in [the Lab 7 Google Form](#).

- The Tasks questions are shown on the spec and the form for your convenience.
  - The Google Form is very simple and thus incapable of recognizing typos or incorrectly formatted answers.
  - However, it features response validation and the ability to view your score. Please use these to verify your submission.
  - You also have the ability to edit your response, in case you leave answers blank, but wish to save your progress and return to them later.
  - We suggest you have a single tab with this form open alongside the spec as you work on Lab 7.
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## Tools for Cache Visualization in Venus

Working of caches is one of the most conceptually involved topics in 61C. This exercise will use some cool cache visualization tools to get you more familiar with cache behavior and performance terminology with the help of the file `cache.s` provided in the starter files. **This is not an actual exercise, but more of an explanation on how to use Venus as a cache visualization tool!**

At this point, read through `cache.s` to get a rough idea of what the program does. Make sure you go through what the pseudocode does and what the argument registers hold before you proceed to analyze cache configurations on it.

- The most important thing to understand is the section labeled "PSEUDOCODE" at the top of the file. When you run `cache.s`, the instructions that perform this pseudocode will be executed.

Basically, you'll just either zero out some elements of some array (option 0) or increment them (option 1).

- Which elements you access is determined by the *Step Size* (a1) and *how many times you do so* is determined by the *Rep Count* (a2). **These two parameters will most directly affect how many cache hits vs. misses will occur.** The *Option* (a3) will also change stuff, and of course the cache parameters themselves will too.

For **each** of the scenarios below, you'll be repeating these steps:

1. Paste the contents of cache.s into [Venus](#)
2. In the code for `cache.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. Simulator-->Cache.
4. Set the appropriate Cache Parameters as indicated at the beginning of each scenario.
5. As you execute code in Venus, any DATA memory access (load or store) will show up (instruction fetches not shown because instructions are loaded into a separate instruction cache that is not shown in Venus).

The Cache Simulator will show the state of your data cache. If you reset your code, you will also reset the cache hit/miss rate as well!

**IMPORTANT:** If you run the code all at once, you will get the final state of the cache and hit rate. A useful strategy might be setting a **breakpoint** in the **loop** `wordLoop` right before or after each memory access to see exactly where the hits and misses are coming from.

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## Exercise 1 - Memory Accesses

**Action Item:** Simulate the following scenarios in Venus and record the final cache hit rates with the program in `cache.s`. 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!

**Submission:** Your answers should go into the corresponding section of the Lab 7 Google Form; all answers should be lowercased.

**Do not hesitate to ask questions** if you feel confused! This is perfectly **normal** and the staff is there to help you out! Caches are a tricky topic, and asking questions is the best way to learn :).

**THE FOLLOWING** are good questions to ask yourself as you do these exercises:

- How big is your cache block?

- How many consecutive accesses (taking into account the step size) fit within a single block?
- How much data fits in the WHOLE cache?
- How far apart in memory are blocks that map to the same set (and could create conflicts)?
- What is your cache's associativity?
- Where in the cache does a particular block map to?
- When considering why a specific access is a miss or hit: Have you accessed this piece of data before? If so, is it still in the cache or not?

## Scenario 1

**Program Parameters:** (set these by initializing the a registers in the code)

- **Array Size (a0):** 128 (bytes)
- **Step Size (a1):** 8
- **Rep Count (a2):** 4
- **Option (a3):** 0

**Cache Parameters:** (set these in the Cache tab)

- **Cache Levels:** 1
- **Block Size:** 8
- **Number of Blocks:** 4
- **Enable?:** Should be green
- **Placement Policy:** Direct Mapped
- **Associativity:** 1 (Venus won't let you change this with your placement policy, why?)
- **Block Replacement Policy:** LRU

**Tip:** If it's hard for you to visualize what's getting pulled into the cache on each memory access just from staring at the code, try getting out some paper and a pencil. Write down what the tag:index:offset (TIO) breakdown of the 32-bit addresses would be, figure out which memory addresses map to which set in the cache with the index bits, and see if that helps.

## Tasks

1. What combination of parameters is producing the hit rate you observe? Write your answer in the form "[parameter A], [parameter B]" where [parameter A] and [parameter B] complete the following response: "Because [parameter A] in bytes is exactly equal to [parameter B] in bytes."

**Note:** Don't forget that 'cache size' is a valid parameter that you implicitly set by choosing the block size and the # of blocks.

2. What is the hit rate if we increase Rep Count arbitrarily? Write your answer as a decimal (e.g. "1.0" if the HR is 100%).
3. **[PRACTICE]** How could we modify one program parameter to get an increased hit rate? Write your answer in the form "[parameter], [value]" where [parameter] is the program parameter you want to change and [value] is the value you want to change it to. **Note:** We don't care if we access the same array elements. Just give us a program parameter modification that would increase the hit rate. However, do make sure that your proposed value is valid.

## Scenario 2

**Program Parameters:** (set these by initializing the a registers in the code)

- **Array Size (a0):** 256 (bytes)
- **Step Size (a1):** 2
- **Rep Count (a2):** 1
- **Option (a3):** 1

**Cache Parameters:** (set these in the Cache tab)

- **Cache Levels:** 1
- **Block Size:** 16
- **Number of Blocks:** 16
- **Enable?:** Should be green
- **Placement Policy:** N-Way Set Associative
- **Associativity:** 4
- **Block Replacement Policy:** LRU

## Tasks

1. How many **memory accesses** are there per iteration of the **inner loop** (not the one involving Rep Count)?
2. What is the **repeating hit/miss pattern**? Write your answer in the form "mmhhmh" and so on, where your response is the **shortest** pattern that gets repeated.
3. Keeping everything else the same, what does our hit rate approach as Rep Count goes to infinity? Try it out by changing the appropriate program parameter and letting the code run! Write your answer as a decimal.

You should have noticed that our hit rate was pretty high for this scenario, and your answer to the previous question should give you a good understanding of why. If you are not sure why, consider the size of the array and compare it to the size of the cache. Now, consider the following:

Suppose we have a program that iterates through a very large array (i.e. way bigger than the size of the cache) Rep Count times. During each Rep, we map a different function to the elements of our array (e.g. if Rep Count = 1024, we map 1024 different functions onto each of the array elements, one per Rep). For reference, in this scenario, we just had one function (incrementation) and one Rep.

**HINT:** You **do not** want to iterate through the entire array at once because it's much bigger than your cache. Doing so would reduce the amount of temporal locality your program exhibits, which makes cache hit rate suffer. We want to exhibit more locality so that our caches can take advantage of our predictable behavior. **SO**, instead, we should try to access \_\_\_\_ of the array at a time and apply all of the \_\_\_\_ to that \_\_\_\_ so we can be completely done with it before moving on, thereby keeping that \_\_\_\_ hot in the cache and not having to circle back to it later on! (The 1st, 3rd, and 4th blanks should be the same. It's not some vocabulary term you should use to fill them in. It's more of an idea that you should have.)

## Scenario 3

**Program Parameters:** (set these by initializing the a registers in the code)

- **Array Size (a0):** 128 (bytes)
- **Step Size (a1):** 1
- **Rep Count (a2):** 1
- **Option (a3):** 0

**Cache Parameters:** (set these in the Cache tab)

- **Cache Levels:** 2

**NOTE:** Make sure the following parameters are for the L1 cache! (Select L1 in the dropdown right next to the replacement policy)

- **Block Size:** 8
- **Number of Blocks:** 8
- **Enable?:** Should be green
- **Placement Policy:** Direct Mapped
- **Associativity:** 1
- **Block Replacement Policy:** LRU

**NOTE:** Make sure the following parameters are for the L2 cache! (Select L2 in the dropdown right next to the replacement policy)

- **Block Size:** 8
- **Number of Blocks:** 16

- **Enable?:** Should be green
- **Placement Policy:** Direct Mapped
- **Associativity:** 1
- **Block Replacement Policy:** LRU

## Tasks

1. What is the hit rate of the L1 cache? The L2 cache? Overall? Each hit rate is a decimal rounded to two places.
  2. How many accesses do we have to the L1 cache total? How many of them are misses?
  3. How many accesses do we have to the L2 cache total? **HINT:** Think about what the L1 cache has to do in order to make us access the L2 cache.
  4. What program parameter would allow us to increase the L2 hit rate, but keep the L1 hit rate the same?
  5. Do our L1 and L2 hit rates decrease (-), stay the same (=), or increase (+) as we (1) increase the number of blocks in L1, or (2) increase the L1 block size?
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## Exercise 2 - Loop Ordering and Matrix Multiplication

**NOTE:** For this exercise, using the **hive machines** is recommended! This exercise depends on certain performance characteristics that may be different on your local machine.

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 (the one that increments **k**), we see that it...

- moves through B with stride 1
- moves through A with stride n
- moves through C with stride 0



Remember: To compute the matrix multiplication correctly, **the loop order doesn't matter**.

**BUT**, 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 take advantage of spatial and temporal locality, utilizing blocks already contained within our cache. 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.

**Action Item:** Think about what the strides are for the nested loops in the other five implementations.

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 the code with the following command, and then answer the questions below:

```
$ make ex2
```

This will run some matrix multiplications according to the six different implementations in the file, and it will tell you the speed at which each implementation executed the operation. The unit "Gflops/s" reads, "Giga-floating-point-operations per second." **THE BIGGER THE NUMBER THE FASTER IT IS RUNNING!**

## Tasks

Your answers to the following questions should go into the corresponding section of the Lab 7 Google Form; all answers should be lowercased.

1. Which 2 orderings perform best for these 1000-by-1000 matrices? Write your answer in the form "[Ordering1], [Ordering2]" (e.g. "ijk, ijk").
2. Which 2 orderings perform the worst?

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## Exercise 3 - Cache Blocking and Matrix Transposition

**NOTE:** For this exercise, using the **hive machines** is recommended! This exercise depends on certain performance characteristics that may be different on your local machine.

### 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  $A^T$ .

1	2	3	4	5
6	7	8	9	10
11	12	13	14	15
16	17	18	19	20
21	22	23	24	25

Transpose

1	6	11	16	21
2	7	12	17	22
3	8	13	18	23
4	9	14	19	24
5	10	15	20	25

## Cache Blocking

In the above code for matrix multiplication, note that we are striding across the entirety of the  $A$  and  $B$  matrices to compute a single value of  $C$ . As such, we are constantly accessing new values from memory and reuse very little 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 further 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

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

**Things to note:** In the above image, we transpose each submatrix  $A_{ij}$  of matrix  $A$  into its final location in the output matrix, one submatrix at a time. It is important to note that transposing each individual subsection is equivalent to transposing the entire matrix.

Since we operate on and finish transposing each submatrix sequentially, we consolidate our memory accesses to that smaller chunk of memory when transposing that particular submatrix. This increases our degree of spatial locality, making our cache performance and thus our program run faster.

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.

Your task is to implement cache blocking in the `transpose_blocking()` function inside `transpose.c`. **You may NOT assume that the matrix width ( $n$ ) is a multiple of the block size.** By default, the

function does nothing, so the benchmark function will report an error. After you have implemented cache blocking, you can run your code by typing:

```
$ make ex3
$ ./transpose <n> <block size>
```

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=10000` and `blocksize=33`. The blocked version should finish significantly faster.

The following section is meant to serve as a guideline for you if you have no idea how to start. If you think you know how to use the parameter `blocksize`, then just jump right in and get started.

Some tips to get started:

Start by looking at the `transpose_naive` function included in the file. Notice that the index `y` strides vertically across the WHOLE `src` matrix in one iteration of the outer loop before resetting to 0. Another way to say this is that the index `x` only updates after `y` is done going from 0 all the way to `n`. This is the behavior which we want to change. We want to step not stride across the array indices.

tl;dr: fill out `dst` square chunks at a time, where each square chunk is of dimension `blocksize` by `blocksize`.

Instead of updating `x` only when `y` goes through ALL of 0 through `n`, we want to jump down to the next row of `dst` after we stride across the width (horizontal axis) of just a single block. How big is a block? Exactly the number of integers specified by the parameter `blocksize`. In addition, we only want to stride vertically through the height (vertical axis) of a block before we move on to the next block. We don't want to make `x` stride all the way down `n` rows of `dst` before we move on to the next block.

**Hint:** A standard solution needs 4 (four) for loops.

Finally, since we can't assume that `n` is a multiple of `blocksize`, the final block column for each block row will be a little bit cut-off, i.e. it won't be a full `blocksize` by `blocksize` square. In addition, the final block row will all be truncated. To fix this problem, you can do the exercise assuming that `n` is a multiple of the `blocksize` and then add in a special case somewhere to do nothing when your indices reach out of bounds of the array.

Once your code is working, complete the following exercises and record your answers.

## Tasks

Record your results and responses to the questions below in the corresponding section of the Lab 7 Google Form, but note that responses to the following questions are not autograded.

## 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.

**Question 1:** At what point does cache blocked version of transpose become faster than the non-cache blocked version?

**Question 2:** Why does cache blocking require the matrix to be a certain size before it outperforms the non-cache blocked code?

(Sanity check: the blocked version isn't faster than the naive version until the matrix size is sufficiently big.)

## Part 2 - Changing Block Size

Fix `n` to be 10000, and run your code with `blocksize` equal to 50, 100, 500, 1000, 5000.

**Question 3:** How does performance change as `blocksize` increases? Why is this the case?

(Sanity check: as you increase `blocksize`, the amount of speedup should change in one direction, then change in the other direction.)

Notice that in neither of the last two exercises did we actually know the cache parameters of our machine. We just made the code exhibit a higher degree of locality, and this magically made things go faster! This tells us that caches, regardless of their specific parameters, will always benefit from operating on code which exhibits a high degree of locality.

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## Exercise 4 - Feedback Form

We are working to improve the labs for next semester, so please fill out [this survey](#) to tell us about your experience with Lab 7. The survey will be collecting your email to verify that you have submitted it, but your responses will be anonymized before the data is analyzed. Thank you!

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## Submission

Please submit the **Lab 7 Google Form**. Then save, commit, and push your work, and submit to the **Lab 7** assignment on Gradescope.

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# Checkoff

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☐ Dark Mode