Cache Lab
Implementation and Blocking

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Section A
October 7^{th}, 2013

Welcome to the World of Pointers !

Class Schedule

- **Cache Lab**
  - Due Thursday.
  - Start now (if you haven't already).
- **The Midterm Starts in <10 Days!**
  - Wed Oct 16th – Sat Oct 19
  - Start now (if you haven't already).

  - No, really. Start now.

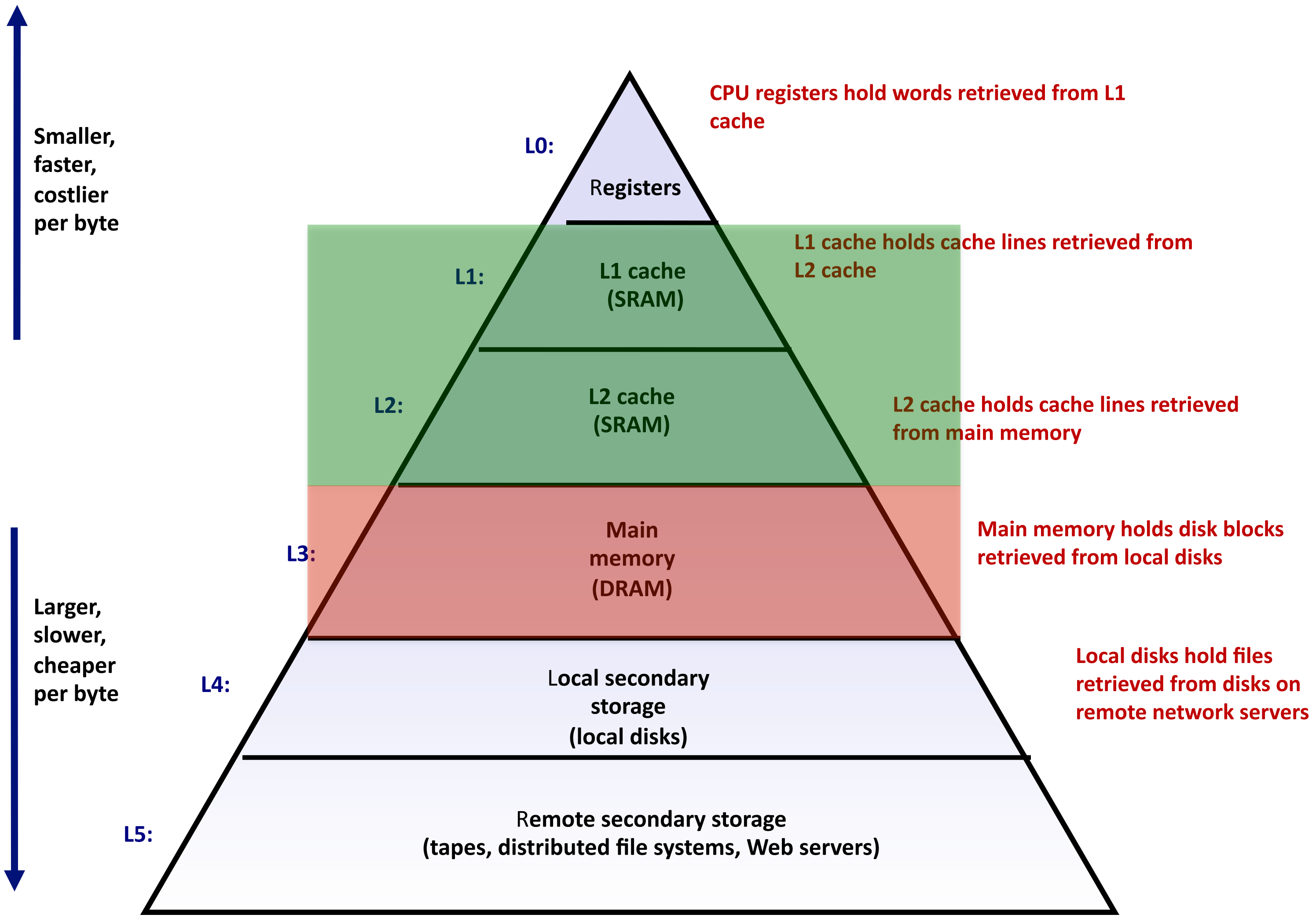
Outline

- **Memory organization**

- **Caching**
  - Different types of locality
  - Cache organization

- **Cachelab**
  - Part (a) Building Cache Simulator
  - Part (b) Efficient Matrix Transpose

Memory Hierarchy



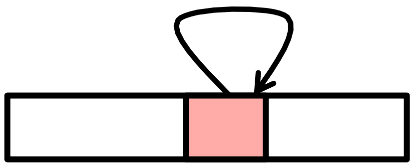
SRAM vs. DRAM tradeoff

- **SRAM (cache)**
  - Faster: L1 cache = 1 CPU cycle
  - Smaller: Kilobytes (L1) or Megabytes (L2)
  - More expensive and “energy-hungry”

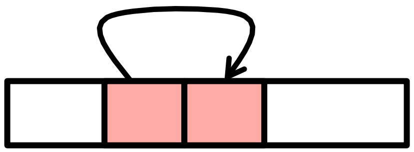
- **DRAM (main memory)**
  - Relatively slower: hundreds of CPU cycles
  - Larger: Gigabytes
  - Cheaper

Locality

- **The key concept that makes caching work:**
  - If you use a piece of data, you'll probably use **it** and/or **nearby data** again soon. So it's worth taking the time to move that whole chunk of data to SRAM, so subsequent access to that block will be fast.
- **Temporal locality**
  - Recently referenced items are likely to be referenced again in the near future

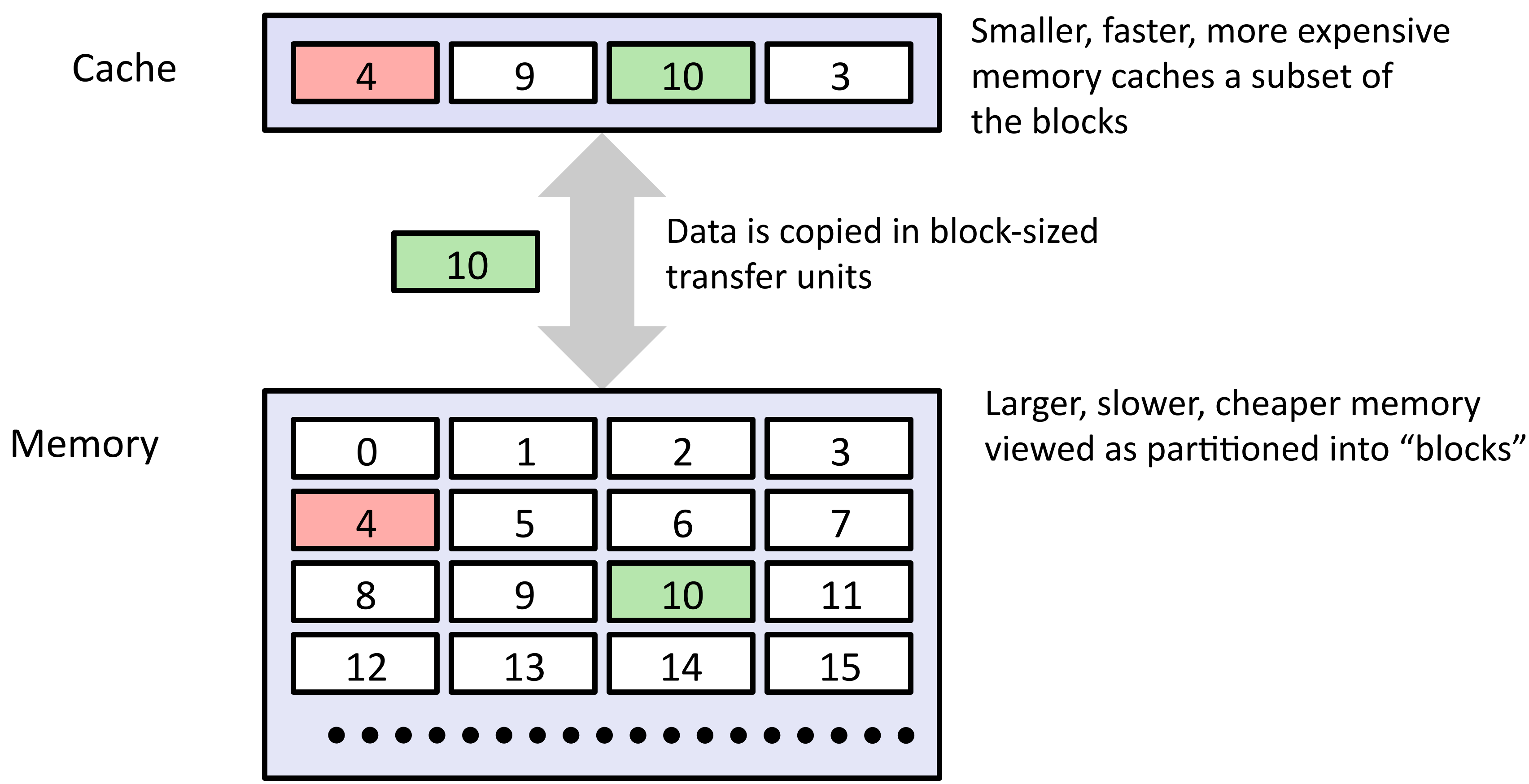


  - After accessing address X in memory, save the bytes in cache for future access
- **Spatial locality**
  - Items with nearby addresses tend to be referenced close together in time

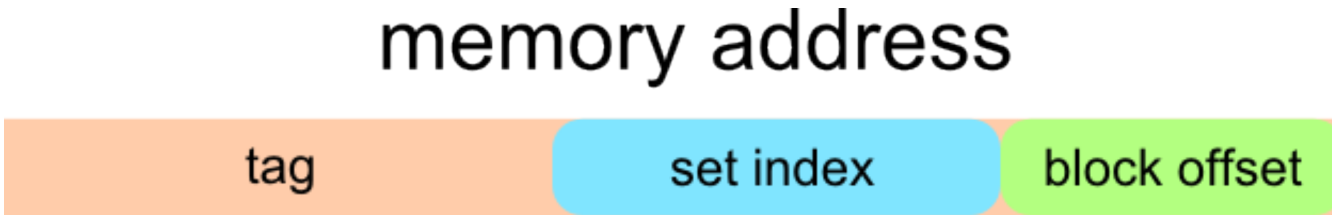


  - After accessing address X, save the block of memory around X in cache for future access

General Cache Concepts



Memory Address

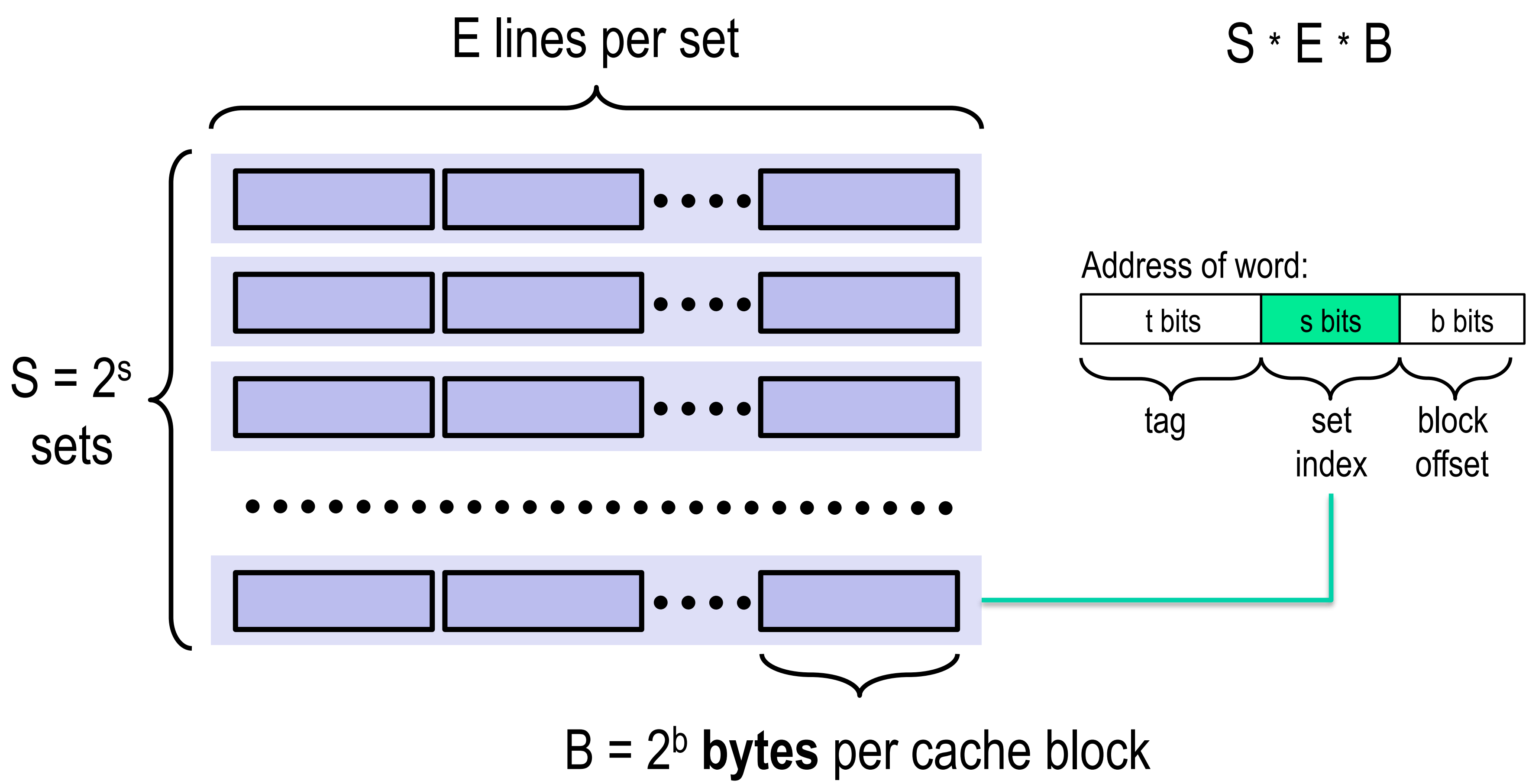


- Block offset: **b** bits ⟷ Size of block **B** = 2^b
- Set index: **s** bits ⟷ Number of sets **S** = 2^s
- Tag Bits: **t** bits = {address size} – b – s
  (On shark machines, address size = 64 bits.)

- **Key point:** if the data at a given address is in the cache, it **has** to be in the *block offset*th byte of the *set index*th set – but it can be in any line in that set.

Cache Terminology

Total cache size = $S * E * B$



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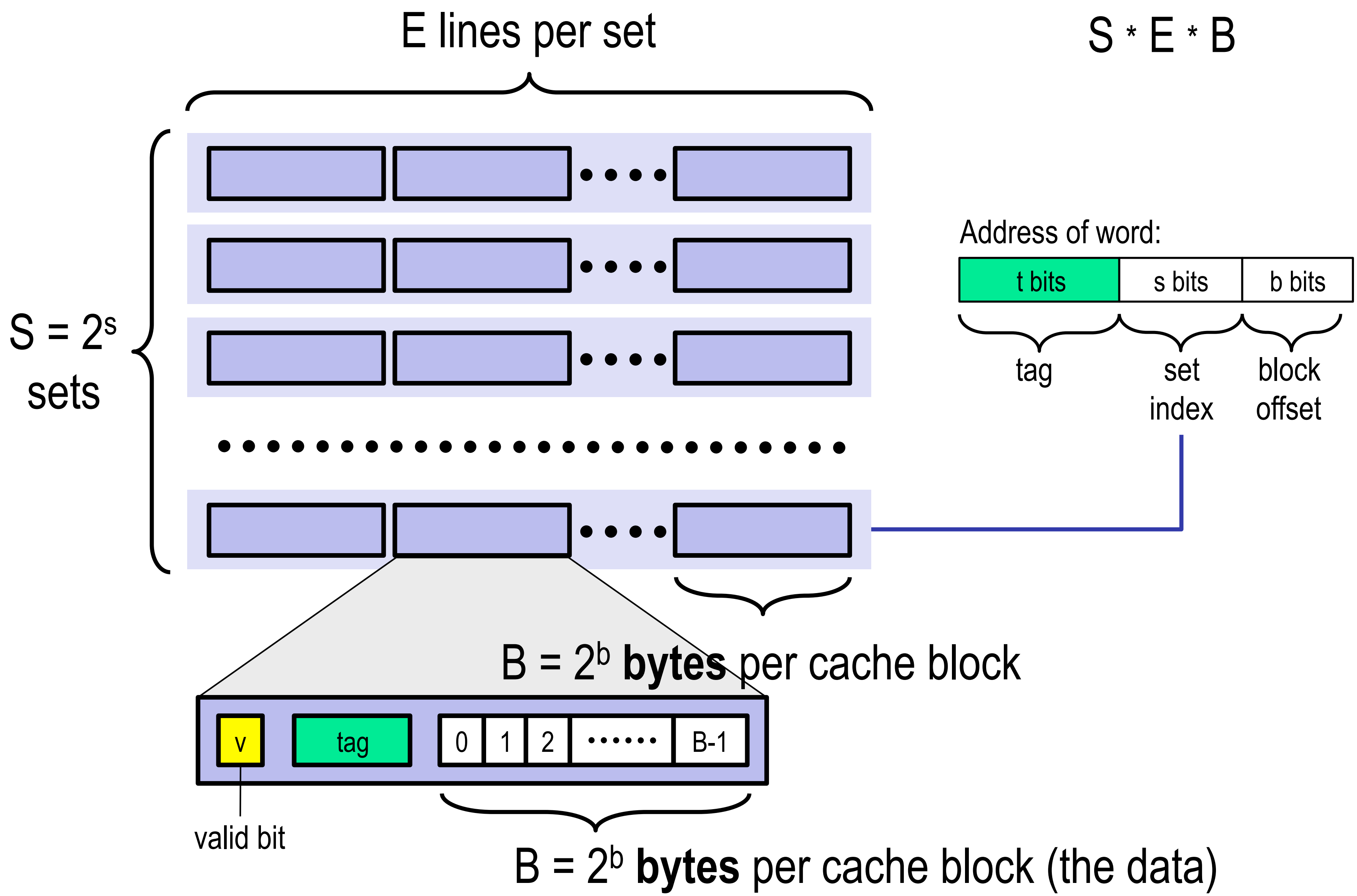

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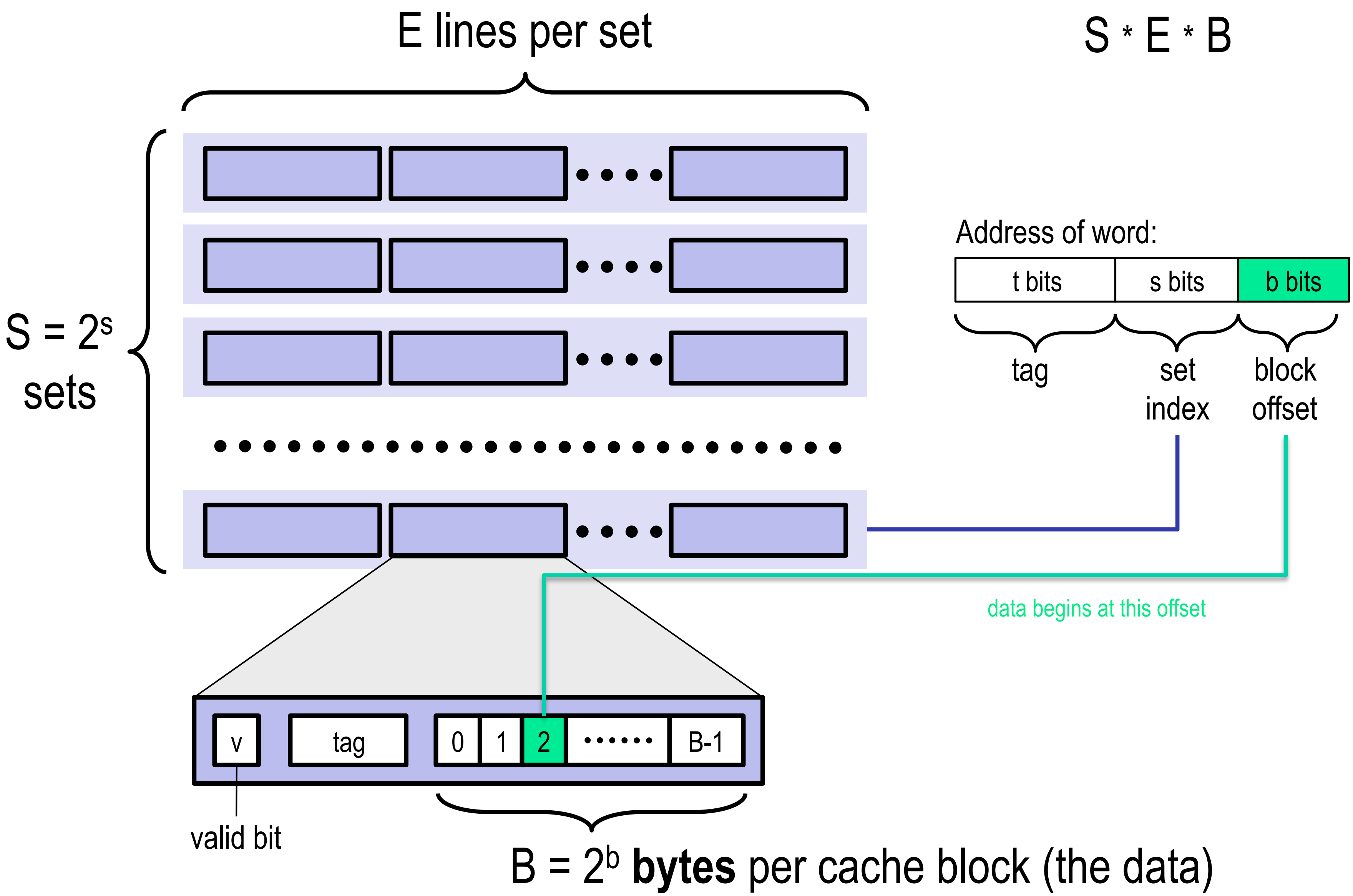
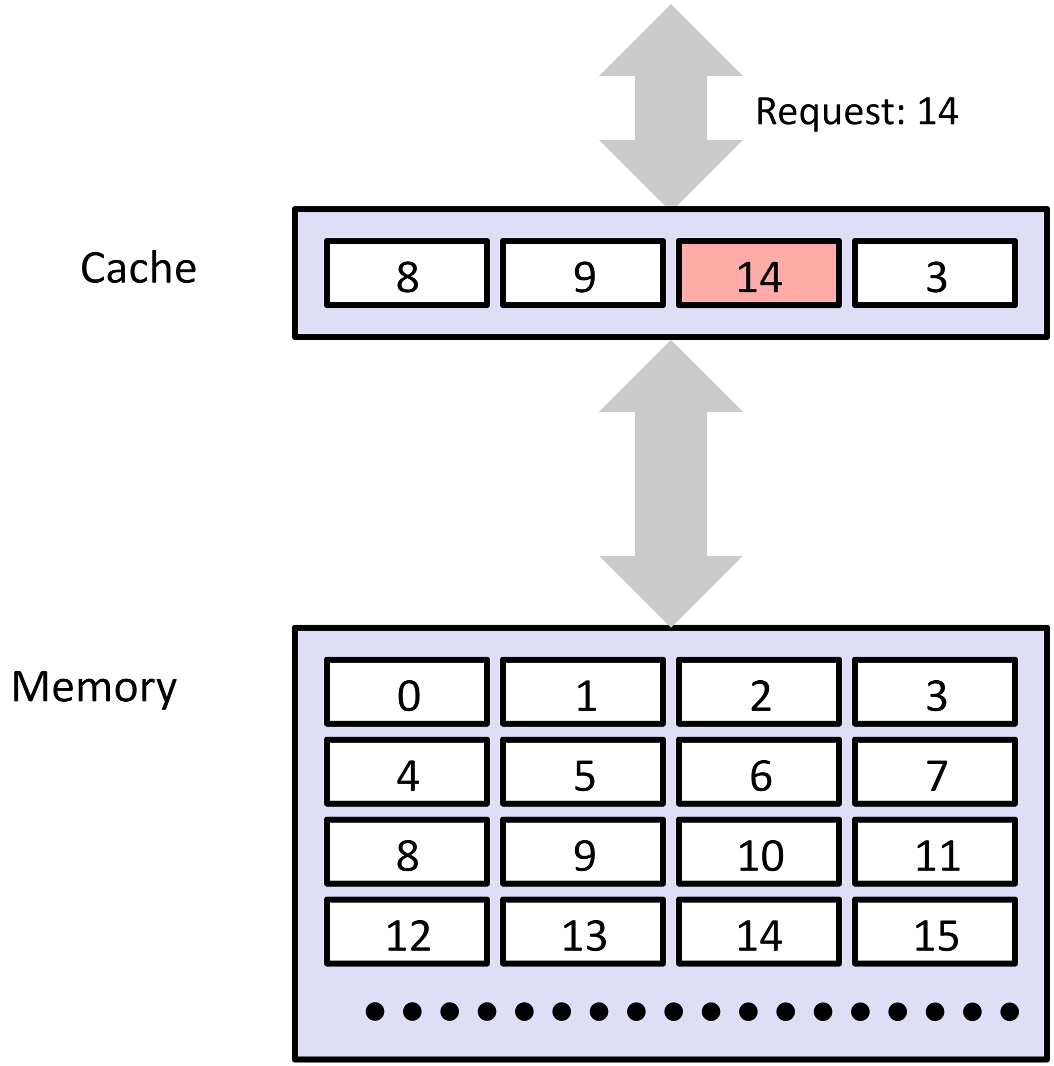


General Cache Concepts: Hit

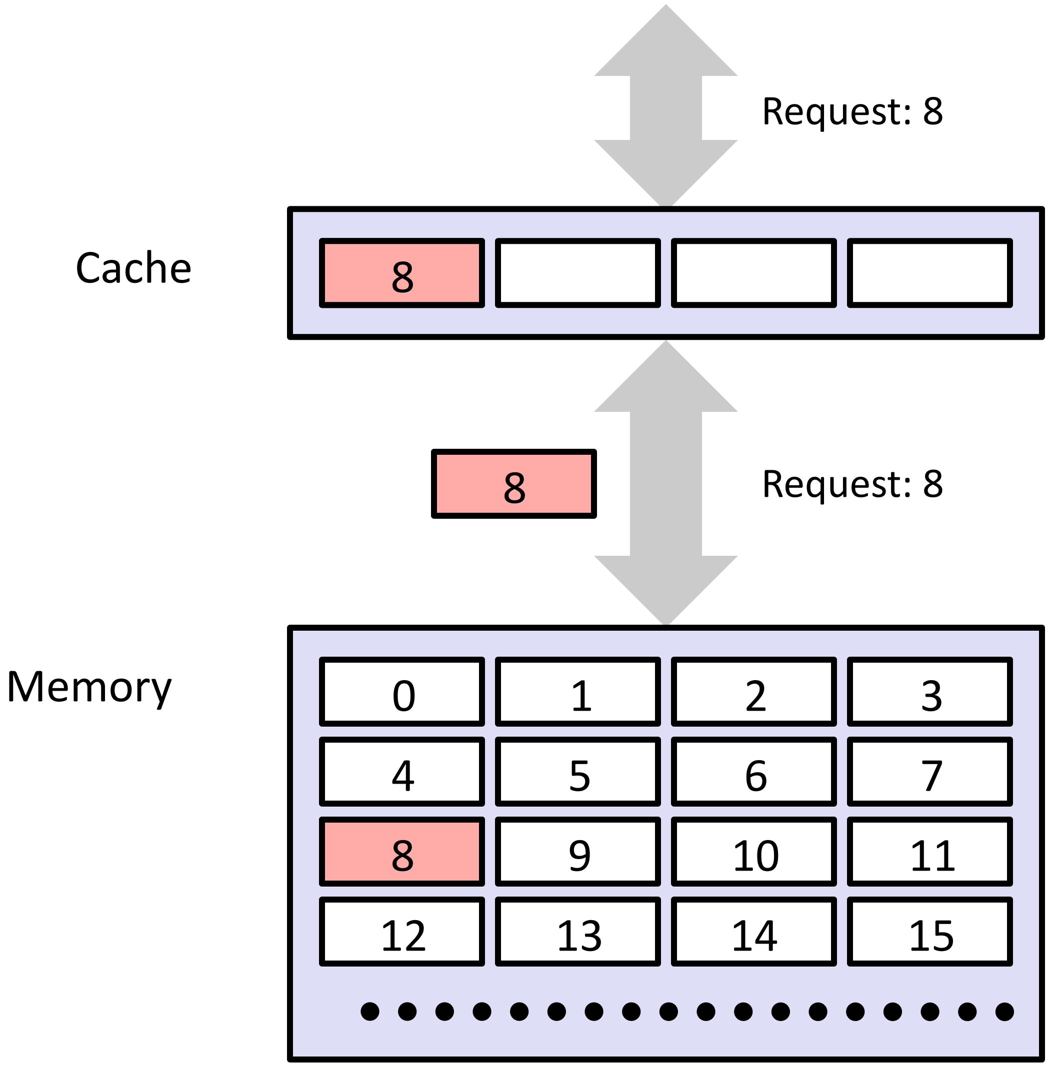


Data in block x is needed

Block x is in cache and is valid: Hit!

Memory isn't touched (yay!)

General Cache Concepts: Miss



Data in block y is needed

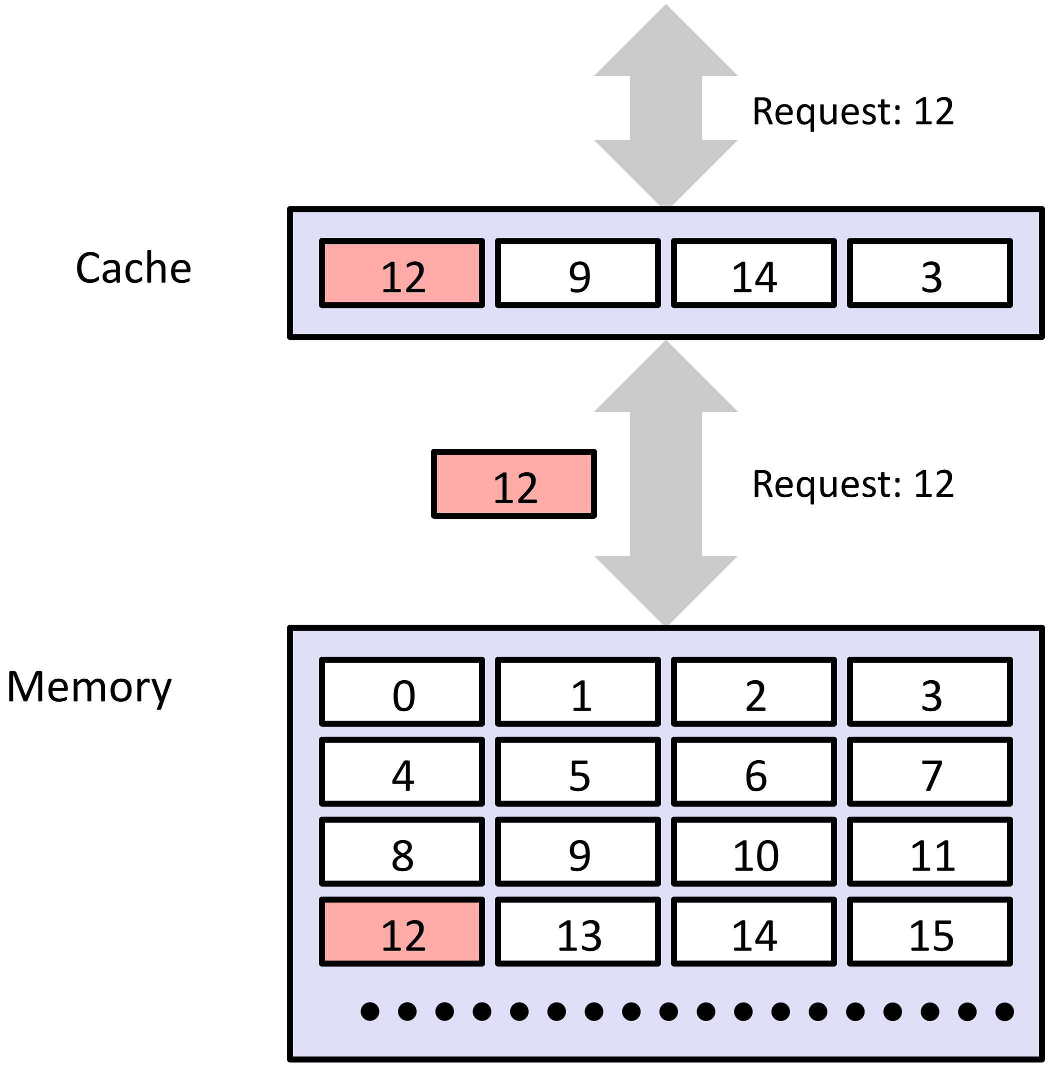
Block y is not in cache:
Miss!

Block y is fetched from *memory*

Block y is stored in cache

- Placement policy: determines where b goes

General Cache Concepts: Miss & Evict



Data in block z is needed

Block z is not in cache:
Miss!

Block z is fetched from *memory*

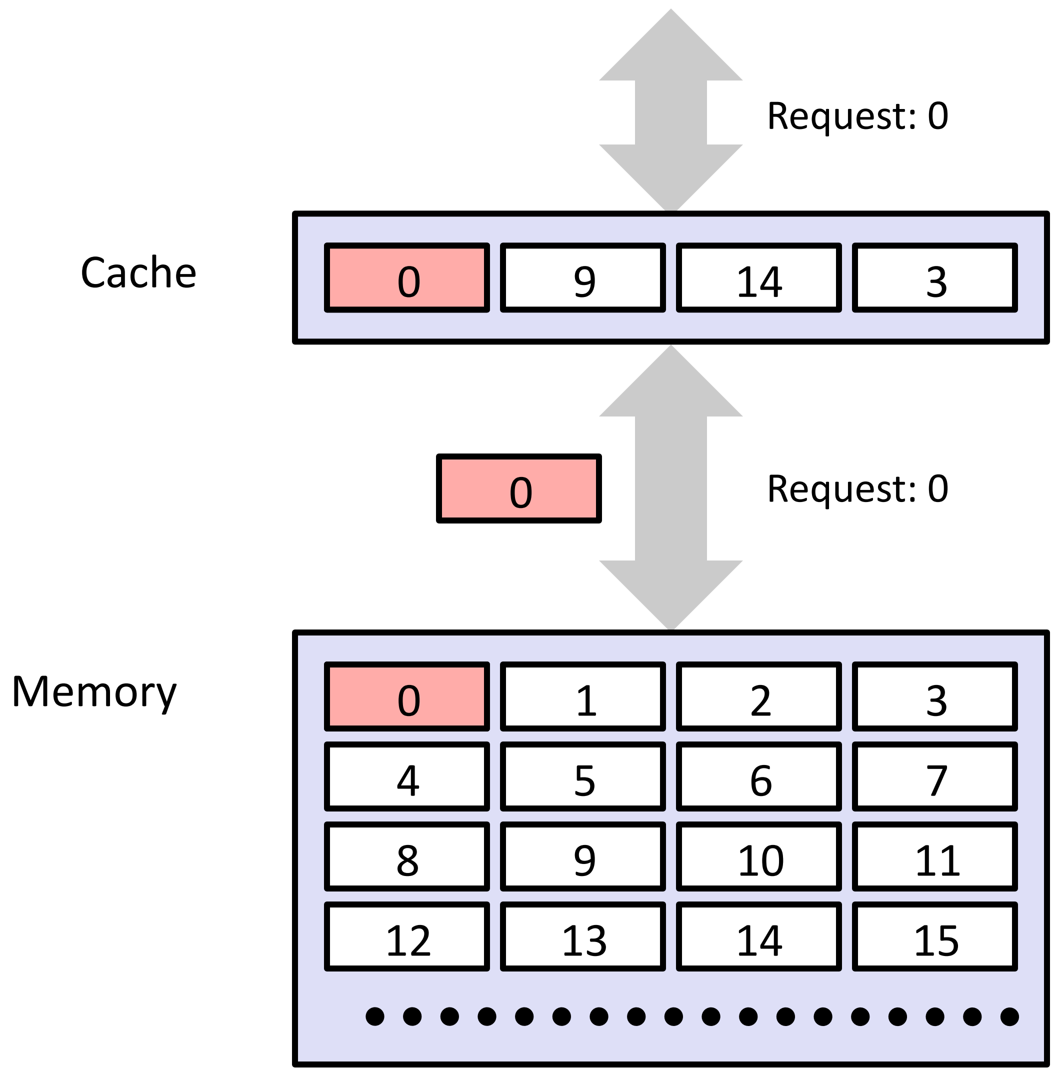
Block z is stored in cache:
Evict!

- Placement policy: determines where b goes
- Replacement policy: determines which block gets evicted (victim)

General Caching Concepts: Types of Misses

- **Cold (compulsory) miss**
  - The first access to a block has to be a miss
- **Conflict miss**
  - Conflict misses occur when the cache is large enough, but multiple data objects all map to the same block
    - e.g., referencing blocks 0, 8, 0, 8, 0, 8, ... would miss every time
- **Capacity miss**
  - Occurs when the set of active cache blocks (working set) is larger than the cache

General Cache Concepts: Conflict Misses



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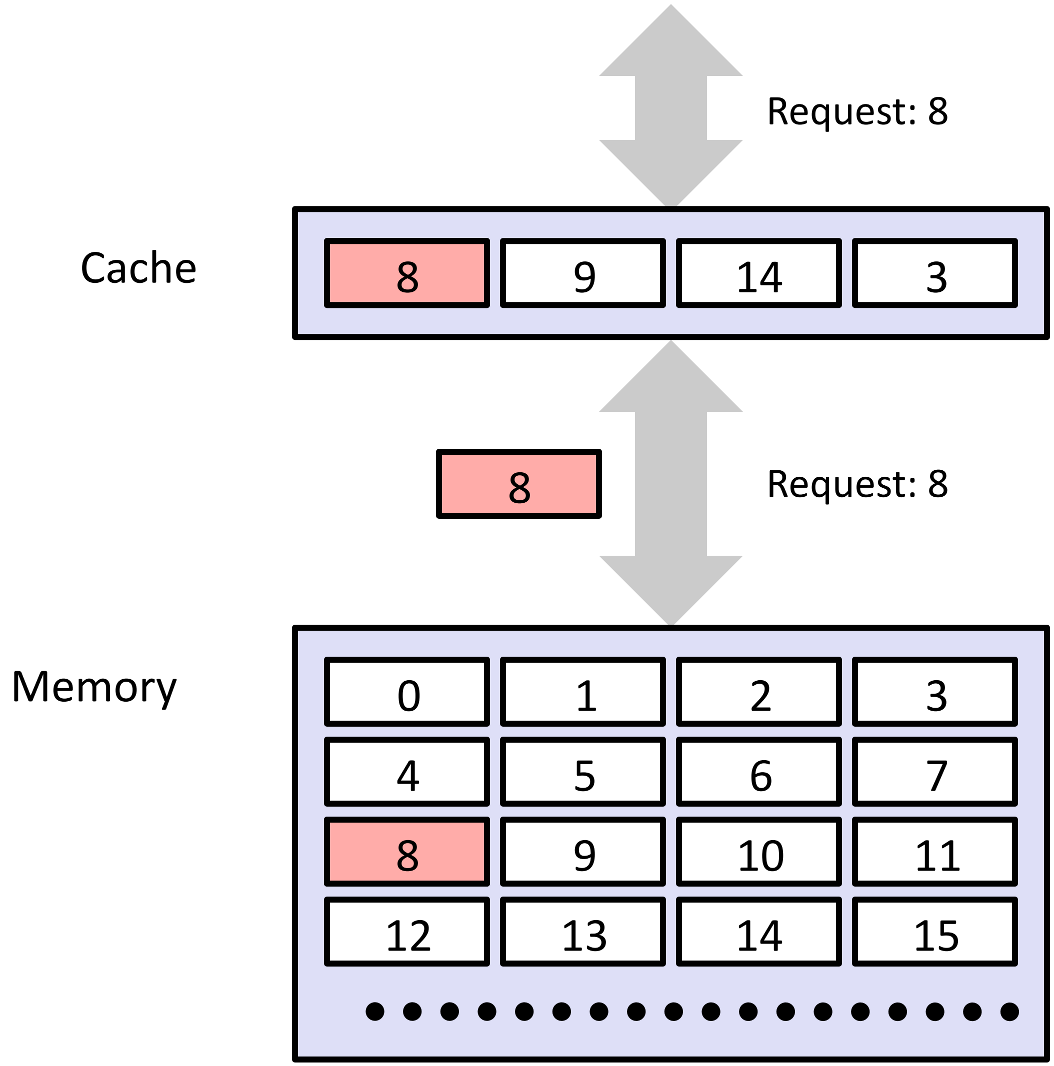

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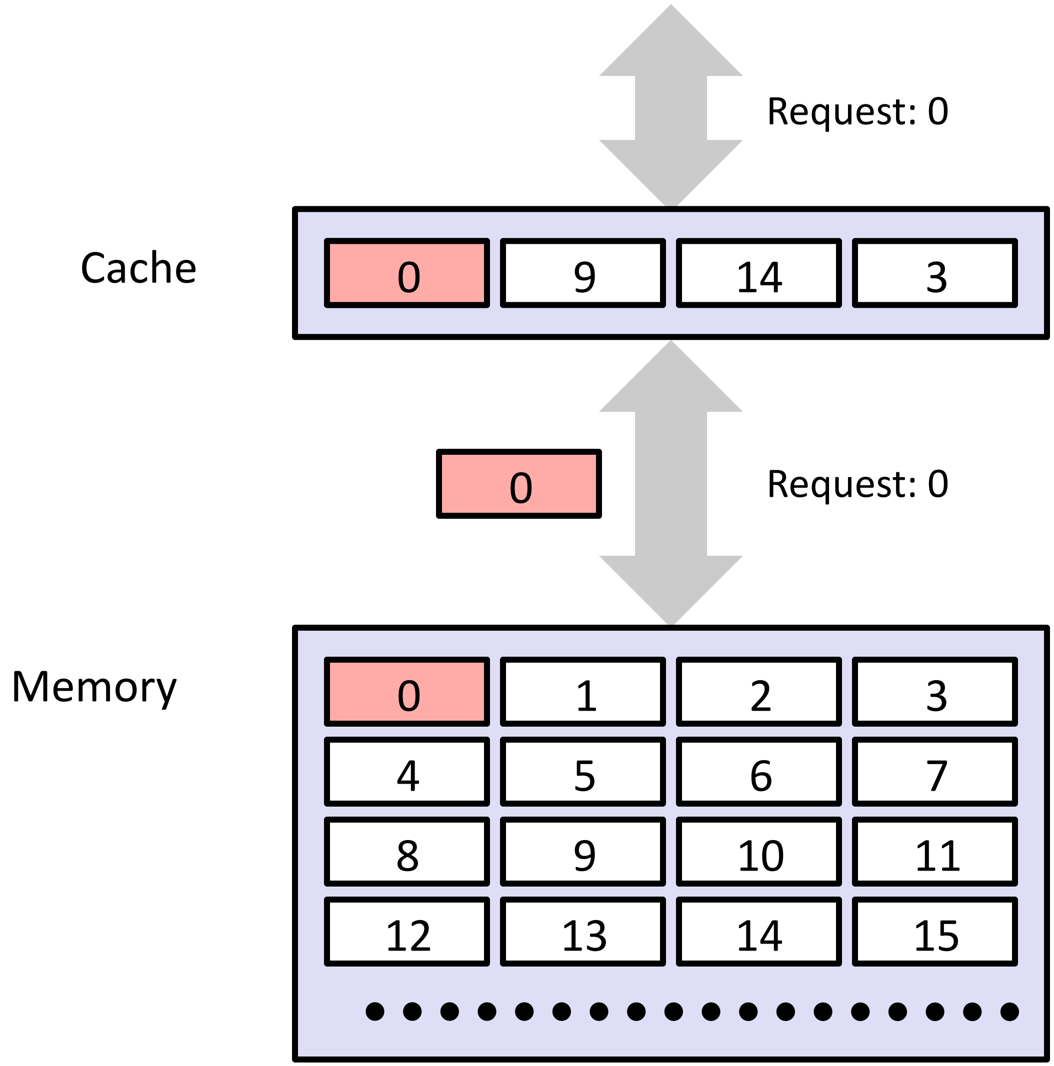

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Evict!

- Placement policy:
  determines where b goes
- Replacement policy:
  determines which block
  gets evicted (victim)

Sets vs. Lines

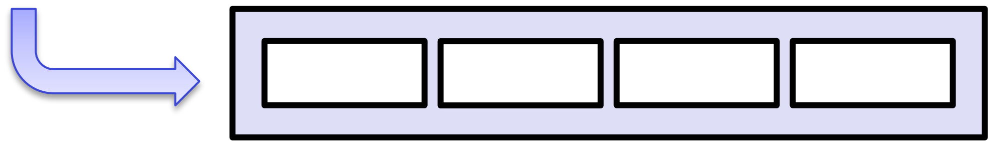
- **Why arrange cache in sets?**
  - If a block can be stored *anywhere*, then you have to search for it *everywhere*.

- **Why arrange cache in lines?**
  - If a block can can only be stored *in one place*, it'll be evicted a lot.

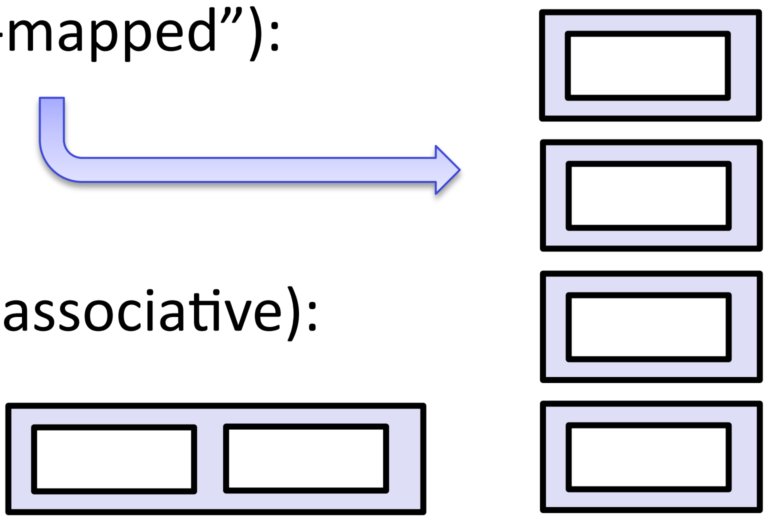
- "The rule of thumb is that doubling the associativity, from direct mapped to two-way, or from two-way to four-way, has about the same effect on hit rate as doubling the cache size." –Wikipedia, CPU_Cache

Sets vs. Lines

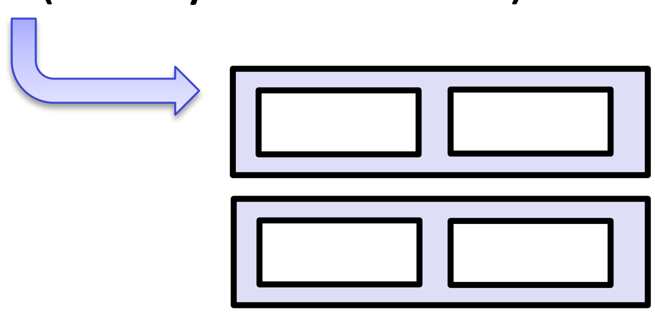
- **An 8-byte cache with 2-byte blocks could be arranged as:**
  - one set of four lines (“fully associative”):



  - four sets of one line (“direct-mapped”):



  - two sets of two lines (2-way associative):



Sets vs. Lines

Data	'a'	'b'	'c'	'd'	'e'	'f'	'g'	'h'	'I'	'j'	'k'	'l'
Address	0000	0001	0010	0011	0100	0101	0110	0111	1000	1001	1010	1011

- For each possible configuration of an 8-byte cache with 2-bytes blocks:
  - How many how many hits/misses/evictions will there be for the following sequence of operations?
  - What will be in the cache at the end?

1. L 0101
2. L 0100
3. L 0000
4. L 0010
5. L 1000
6. L 0000
7. L 0101
8. L 1011

Outline

- **Memory organization**
- **Caching**
  - Different types of locality
  - Cache organization
- **Cachelab**
  - Part (a) Building Cache Simulator
  - Part (b) Efficient Matrix Transpose

Part (a) Cache simulator

- **A cache simulator is NOT a cache!**
  - Memory contents are not stored.
  - Block offsets are not used – the b bits in your address don't matter.
  - Simply count hits, misses, and evictions.

- **Your cache simulator needs to work for different values of s, b, and E — given at run time.**

- **Use LRU – a Least Recently Used replacement policy**
  - Evict the least recently used block from the cache to make room for the next block.
  - Queues? Time stamps? Counter?

Part (a) Hints

- **Structs are a great way to represent your cache line. Each cache line has:**
  - A valid bit.
  - A tag.
  - Some sort of LRU counter (if you are not using a queue).

- **A cache is just 2D array of cache lines:**
  - struct cache_line cache[S][E];
  - Number of sets: $S = 2^s$
  - Number of lines per set: E
  - You know S and E at run time, but not at compile time. What does that mean you'll have to do when you declare your cache?

Part (a) `malloc/free`

- **Use `malloc` to allocate memory on the heap.**

- **Always `free` what you `malloc`, otherwise you will leak memory!**

```
my_pointer = malloc(sizeof(int));
… use that pointer for a while …
free(my_pointer);
```

- **Common mistake: freeing your array of pointers, but forgetting to free the objects those pointers point to.**

- **Valgrind is your friend!**

Part (a) `getopt`

```
./point -x 1 -y 3 -r
```

- **`getopt()` automates parsing elements on the Unix command line.**
  - It's typically called in a loop to deal with each flag in turn. (It returns -1 when it's out of inputs.)
  - Its return value is the flag it's currently parsing ("x", "y", "r"). You can then use a switch statement on the local variable you stored that value to.
  - If a flag has an associated argument, `getopt` **also** gives you `optarg`, a pointer to that argument ("1", "3"). Remember this argument is a **string**, not an integer.
  - Think about how to handle invalid inputs.

Part (a) getopt Example

```
./point -x 1 -y 3 -r
```

```
int main(int argc, char** argv){
  int opt, x, y;
  int r = 0;
  while(-1 != (opt = getopt(argc, argv, "x:y:r"))){
    switch(opt) {
      case 'x':
        x = atoi(optarg);
        break;
      case 'y':
        y = atoi(optarg);
        break;
      case 'r':
        r = 1;
        break;
      default:
        printf("Invalid argument.\n");
        break;
    }
  }
}
```

Part (a) `fscanf`

- `fscanf` **will be useful in reading lines from the trace files.**
  - `L 10,4`
  - `M 20,8`
- `fscanf()` **is just like** `scanf()` **except it can specify a stream to read from (i.e., the file you just opened).**
- **Its parameters are:**
  1. a stream pointer (e.g. your file descriptor).
  2. a format string with information on how to parse the file

  3-n. the appropriate number of **pointers** to the variables in which you want to store the data from your file.
- **You typically want to use it in a loop; it returns -1 if it hits EOF (or if the data doesn't match the format string).**

Part (a) fscanf Example

```
FILE *pFile;                              //pointer to FILE object

pFile = fopen("tracefile.txt", "r");   //open file for reading

char operation;
unsigned address;
int size;

// read a series of lines like " M 20,1" or "L 19,3"

while(fscanf(pFile, " %c %x,%d", &operation, &address, &size)>0){
   // do stuff ...
}

fclose(pFile);                            //remember to close file
```

Part (a) Header files!

- **If you use a library function, always remember to `#include` the relevant library!**

- **Use `man <function-name>` to figure out what header you need.**
  - `man 3 getopt`
  - If you're not using a shark machine, you'll need `<getopt.h>` as well as `<unistd.h>`. (So why not use a shark machine?)

- If you get a warning about a missing or implicit function declaration, you probably forgot to include a header file.

Part (a) Relevant tutorials

- `getopt`:
  - http://www.gnu.org/software/libc/manual/html_node/Getopt.html
- `fscanf`:
  - http://crasseux.com/books/ctutorial/fscanf.html
- Google is your friend!

Part (b) Efficient Matrix Transpose

- **Matrix Transpose (A -> B)**

Matrix A

1	2	3	4
5	6	7	8
9	10	11	12
13	14	15	16

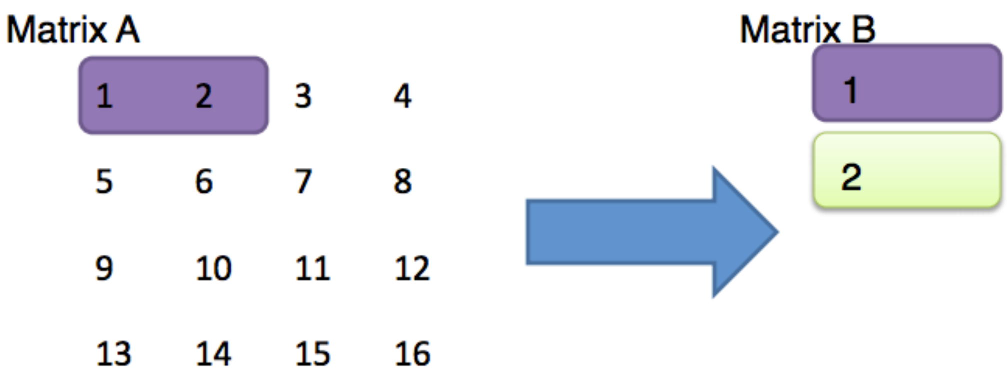
Matrix B

1	5	9	13
2	6	10	14
3	7	11	15
4	8	12	16

- **How do we optimize this operation using the cache?**

Part (b) Efficient Matrix Transpose

- Suppose block size is 8 bytes. Each int is 4 bytes.



- Access A[0][0]: cache miss
- Access B[0][0]: cache miss
- Access A[0][1]: cache hit
- Access B[1][0]: cache miss

Should we handle 3 & 4 next or 5 & 6 ?

Part (b) Blocked Matrix Multiplication

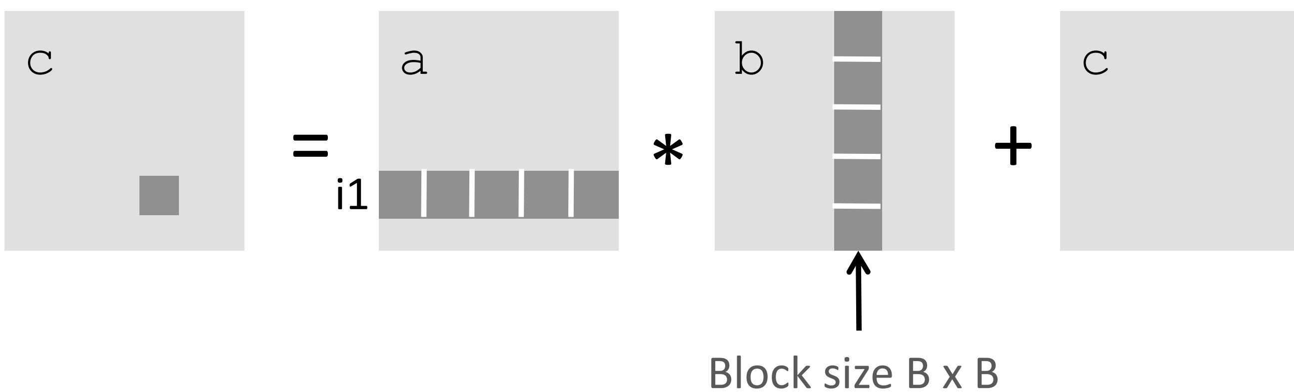
```
c = (double *) calloc(sizeof(double), n*n);

/* Multiply n x n matrices a and b */
void mmm(double *a, double *b, double *c, int n) {
```

“Sometimes it is faster to do more faster work than less slower work.”

-Greg Kesden

```
         /* B x B mini matrix multiplications */
         for (i1 = i; i1 < i+B; i++)
           for (j1 = j; j1 < j+B; j++)
             for (k1 = k; k1 < k+B; k++)
               c[i1*n+j1] += a[i1*n + k1]*b[k1*n + j1];
}
```



Part (b) Blocking

- Blocking: dividing your matrix into sub-matrices.

- The ideal size of each sub-matrix depends on your cache block size, cache size, and input matrix size.

- Try different sub-matrix sizes and see what happens!

- http://csapp.cs.cmu.edu/public/waside/waside-blocking.pdf

Part (b) Specs

- **Cache:**
  - You get 1 KB of cache
  - It's directly mapped (E=1)
  - Block size is 32 Bytes (b=5)
  - There are 32 sets (s=5)
- **Test Matrices:**
  - 32 by 32
  - 64 by 64
  - 61 by 67
  - **Your solution need not work on other size matrices.**

General Advice: Warnings are Errors!

- **Strict compilation flags:**
  - -Wall "enables all the warnings about constructions that some users consider questionable, and that are easy to avoid."
  - -Werror treats warnings as errors.
- **Why?**
  - Avoid potential errors that are hard to debug.
  - Learn good habits from the beginning.

```
#
# Student makefile for Cache Lab
#
CC = gcc
CFLAGS = -g -Wall -Werror -std=c99
...
```

General Advice: Style!!!

- The rest of the labs in this course will be hand-graded for style as well as auto-graded for correctness.

- Read the style guideline.
  - "But I already read it!"
  - Good, read it again.

- Pay special attention to failure and error checking.
  - Functions don't always work
  - What happens when a system call fails?

- Start forming good habits now!