15-213 Recitation 7: Style, Valgrind, Blocking

Your TAs

Monday, October 11th, 2021

Agenda

- Logistics
- Code Reviews
- Blocking
- Valgrind / Intro to Git
- Looking Ahead: Cache Lab

Logistics

- Cache lab is due **tomorrow**!
  - Come to office hours for help
  - NO Midterm!

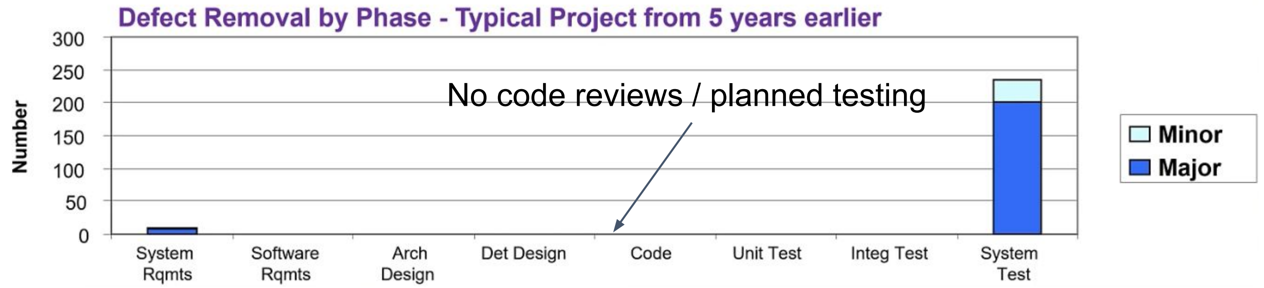
Code Reviews

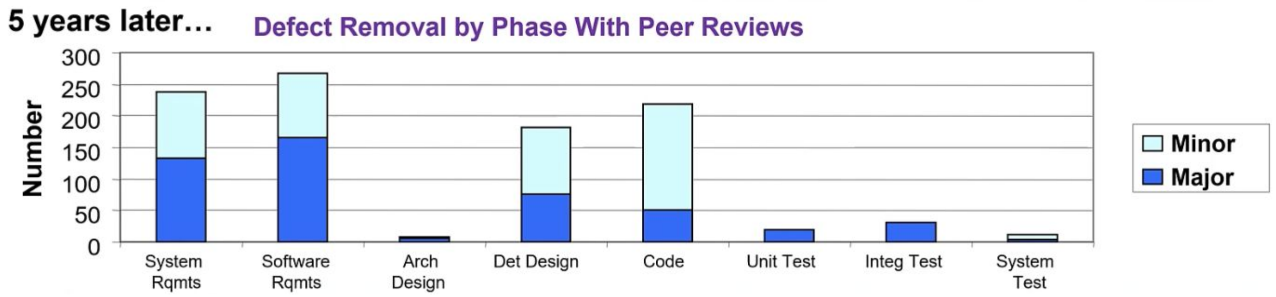
Code Reviews

- Why code reviews?
  - Used in industry - Nearly all companies utilize code reviews
  - Systematic code reviews are highly effective at finding bugs efficiently and effectively.

Code Reviews

- Industry example from an embedded system machine critical pipeline flow device requiring high software quality



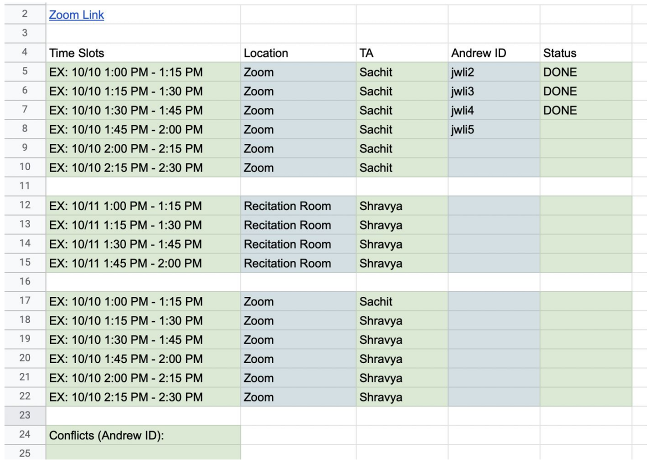


The same team implemented testing and code reviews. This is a similar project done 5 years later.

Example from CMU 18-642 https://course.ece.cmu.edu/~ece642/ , Sourced from Roger G. 2005

Code Review Signup

- All students in the course will receive an email with a link to signup for a code review timeslot.
- All students will receive a final style score from 0-4 points
- 213 code reviews will be short (<= 15 minutes) and cover code style and code quality.



2	Zoom Link				
3					
4	Time Slots	Location	TA	Andrew ID	Status
5	EX: 10/10 1:00 PM - 1:15 PM	Zoom	Sachit	jwli2	DONE
6	EX: 10/10 1:15 PM - 1:30 PM	Zoom	Sachit	jwli3	DONE
7	EX: 10/10 1:30 PM - 1:45 PM	Zoom	Sachit	jwli4	DONE
8	EX: 10/10 1:45 PM - 2:00 PM	Zoom	Sachit	jwli5	
9	EX: 10/10 2:00 PM - 2:15 PM	Zoom	Sachit		
10	EX: 10/10 2:15 PM - 2:30 PM	Zoom	Sachit		
11					
12	EX: 10/11 1:00 PM - 1:15 PM	Recitation Room	Shravya		
13	EX: 10/11 1:15 PM - 1:30 PM	Recitation Room	Shravya		
14	EX: 10/11 1:30 PM - 1:45 PM	Recitation Room	Shravya		
15	EX: 10/11 1:45 PM - 2:00 PM	Recitation Room	Shravya		
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17	EX: 10/10 1:00 PM - 1:15 PM	Zoom	Sachit		
18	EX: 10/10 1:15 PM - 1:30 PM	Zoom	Shravya		
19	EX: 10/10 1:30 PM - 1:45 PM	Zoom	Shravya		
20	EX: 10/10 1:45 PM - 2:00 PM	Zoom	Shravya		
21	EX: 10/10 2:00 PM - 2:15 PM	Zoom	Shravya		
22	EX: 10/10 2:15 PM - 2:30 PM	Zoom	Shravya		
23					
24	Conflicts (Andrew ID):				
25					

Code Style

- Properly document your code
  - Function + File header comments, overall operation of large blocks, any tricky bits
- Write robust code – check error and failure conditions
- Write modular code
  - Use interfaces for data structures, e.g. create/insert/remove/free functions for a linked list
  - No magic numbers – use `#define` or `static const`
- Formatting
  - 80 characters per line (use Autolab's highlight feature to double-check)
  - Consistent braces and whitespace
- No memory or file descriptor leaks

Valgrind

- Finding memory leaks - part of the style

  -
    ```
    $ valgrind –leak-resolution=high –leak-check=full
    –show-reachable=yes –track-fds=yes ./myProgram arg1 arg
    ```
- Remember that Valgrind can be used for other things, like finding invalid reads and writes!

Activity: Valgrind

Activity Setup

- Split up into groups of 2-3 people
- One person needs a laptop
- Log in to a Shark machine, and type:

```
$ wget https://www.cs.cmu.edu/~213/activities/rec7.tar
$ tar -xvf rec7.tar
$ cd rec7
```

213_exam_answers.c

Blocking

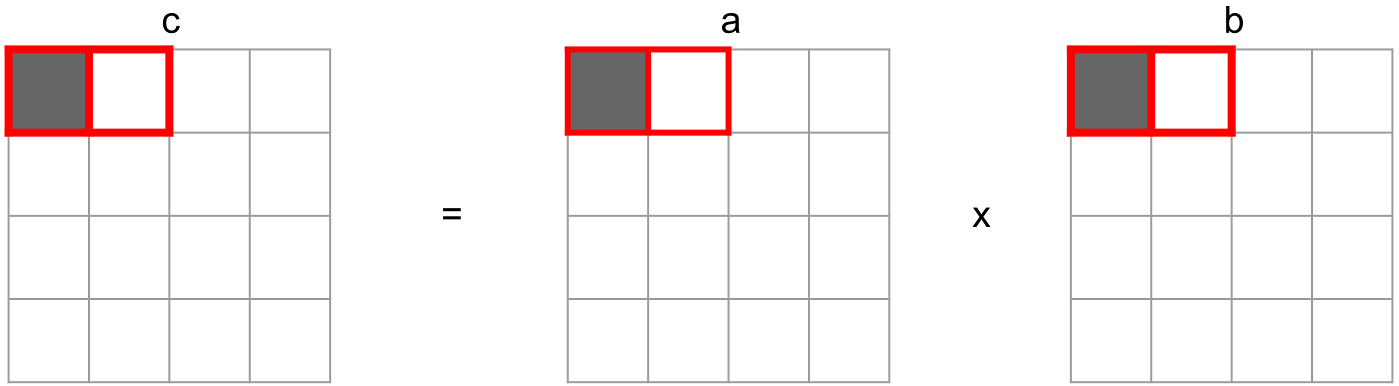
Example: Matrix Multiplication

```
/* multiply 4x4 matrices */
void mm(int a[4][4], int b[4][4], int c[4][4]) {
    int i, j, k;
    for (i = 0; i < 4; i++)
        for (j = 0; j < 4; j++)
            for (k = 0; k < 4; k++)
                c[i][j] += a[i][k] * b[k][j];
```

Let’s step through this to see what’s actually happening

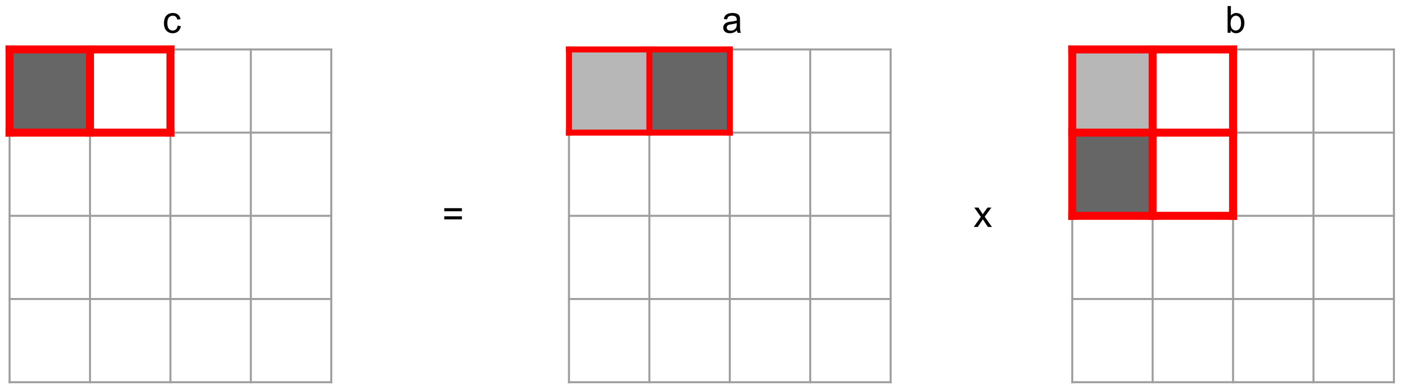
Example: Matrix Multiplication

- Assume a tiny cache with 4 lines of 8 bytes (2 ints)
  - S = 1, E = 4, B = 8
- Let's see what happens if we don't use blocking



iter	i	j	k	operation
0	0	0	0	c[0][0] += a[0][0] * b[0][0]

Key:
Grey = accessed
Dark grey = currently accessing
Red border = in cache



iter	i	j	k	operation
0	0	0	0	c[0][0] += a[0][0] * b[0][0]
1	0	0	1	c[0][0] += a[0][1] * b[1][0]

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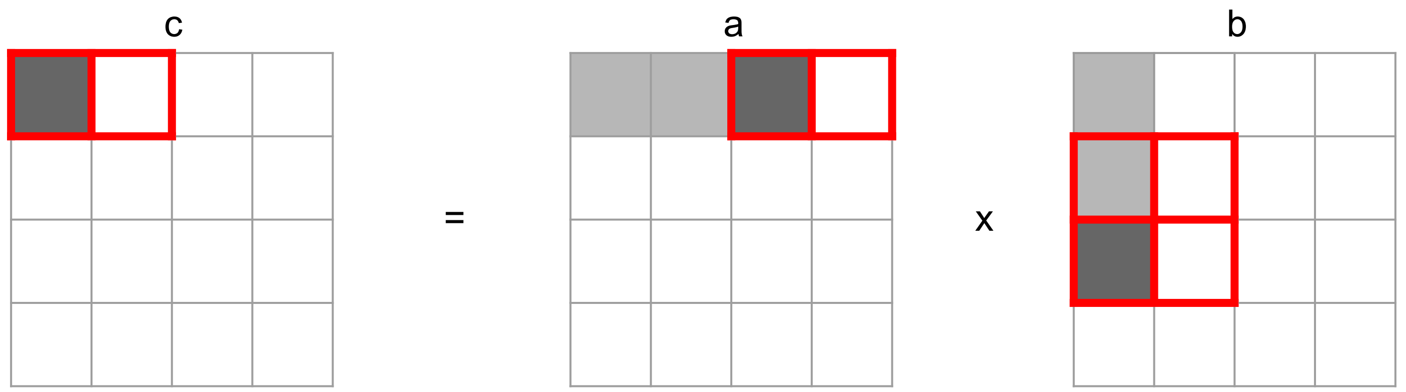

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0	0	0	0	c[0][0] += a[0][0] * b[0][0]
1	0	0	1	c[0][0] += a[0][1] * b[1][0]
2	0	0	2	c[0][0] += a[0][2] * b[2][0]

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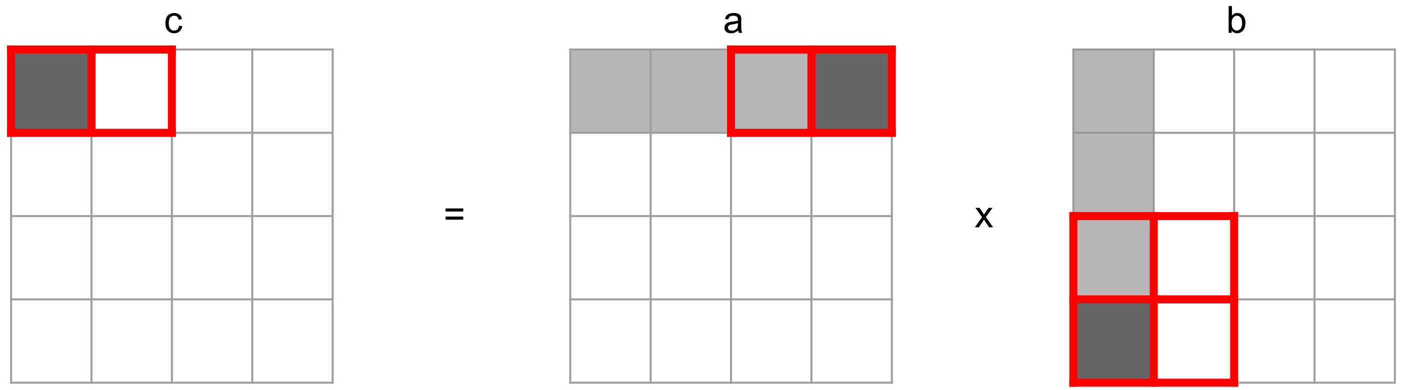

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1	0	0	1	c[0][0] += a[0][1] * b[1][0]
2	0	0	2	c[0][0] += a[0][2] * b[2][0]
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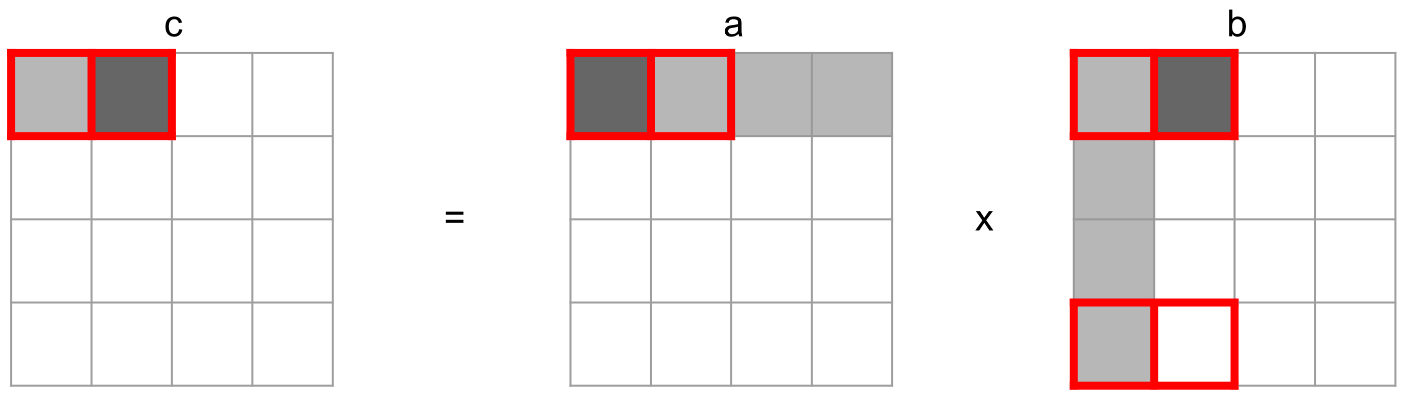

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1	0	0	1	c[0][0] += a[0][1] * b[1][0]
2	0	0	2	c[0][0] += a[0][2] * b[2][0]
3	0	0	3	c[0][0] += a[0][3] * b[3][0]
4	0	1	0	c[0][1] += a[0][0] * b[0][1]

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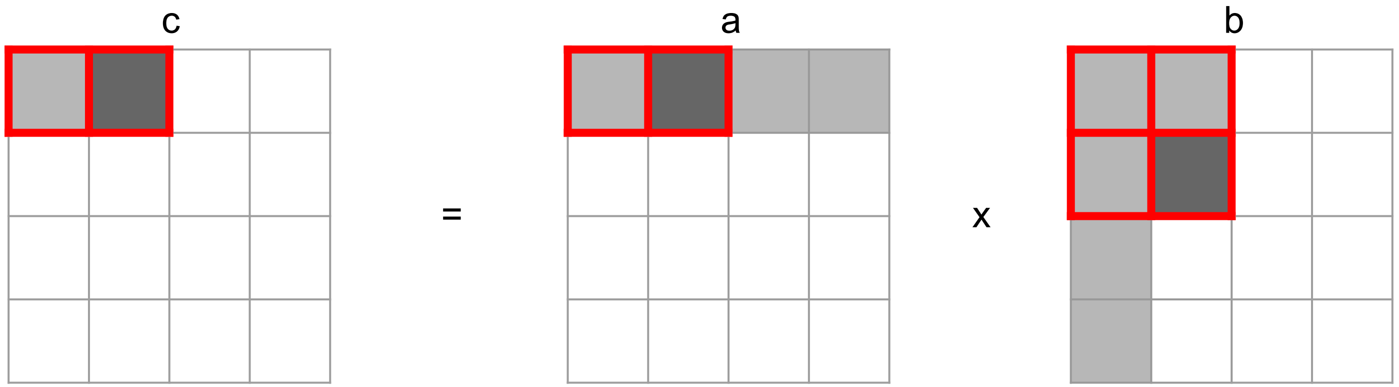

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2	0	0	2	c[0][0] += a[0][2] * b[2][0]
3	0	0	3	c[0][0] += a[0][3] * b[3][0]
4	0	1	0	c[0][1] += a[0][0] * b[0][1]
5	0	1	1	c[0][1] += a[0][1] * b[1][1]

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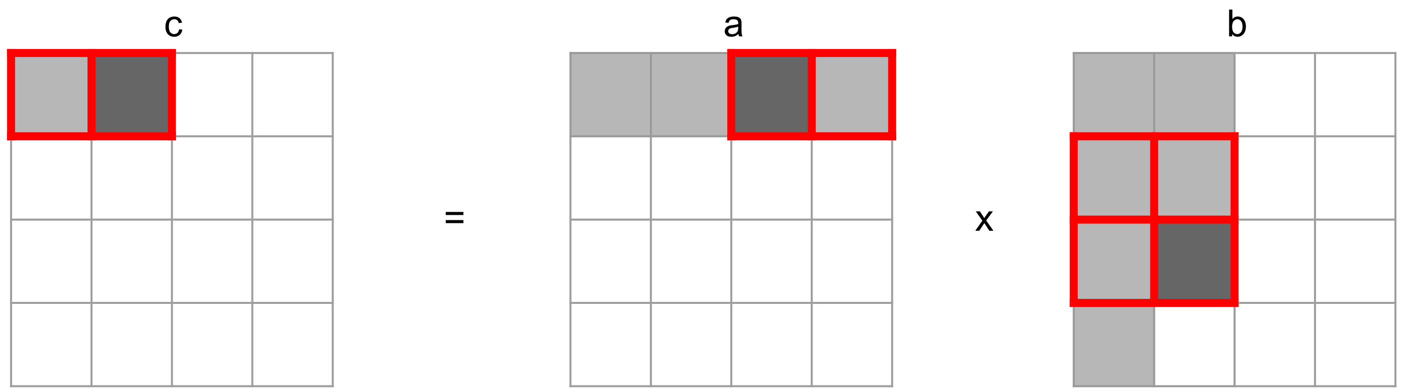

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1	0	0	1	c[0][0] += a[0][1] * b[1][0]
2	0	0	2	c[0][0] += a[0][2] * b[2][0]
3	0	0	3	c[0][0] += a[0][3] * b[3][0]
4	0	1	0	c[0][1] += a[0][0] * b[0][1]
5	0	1	1	c[0][1] += a[0][1] * b[1][1]
6	0	1	2	c[0][1] += a[0][2] * b[2][1]

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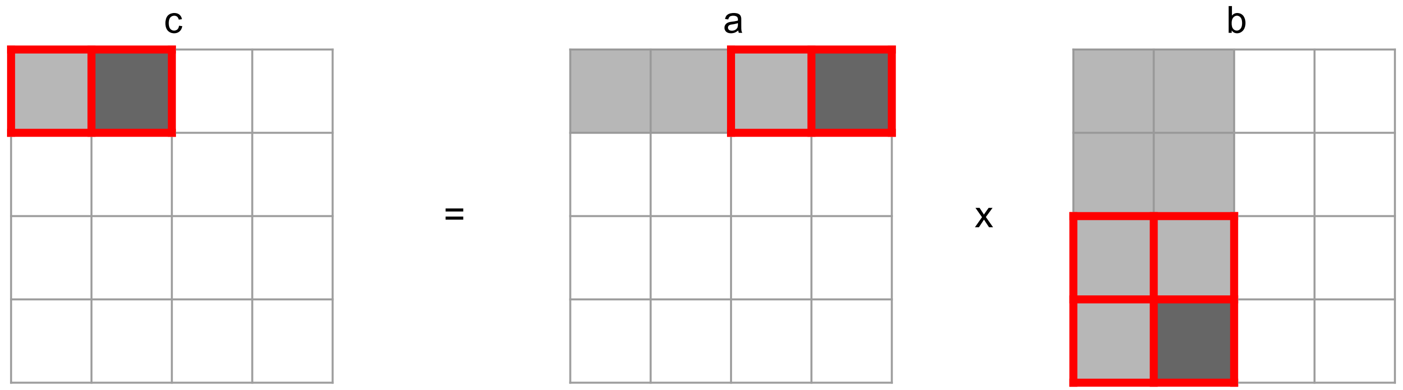

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0	0	0	0	c[0][0] += a[0][0] * b[0][0]
1	0	0	1	c[0][0] += a[0][1] * b[1][0]
2	0	0	2	c[0][0] += a[0][2] * b[2][0]
3	0	0	3	c[0][0] += a[0][3] * b[3][0]
4	0	1	0	c[0][1] += a[0][0] * b[0][1]
5	0	1	1	c[0][1] += a[0][1] * b[1][1]
6	0	1	2	c[0][1] += a[0][2] * b[2][1]
7	0	1	3	c[0][1] += a[0][3] * b[3][1]

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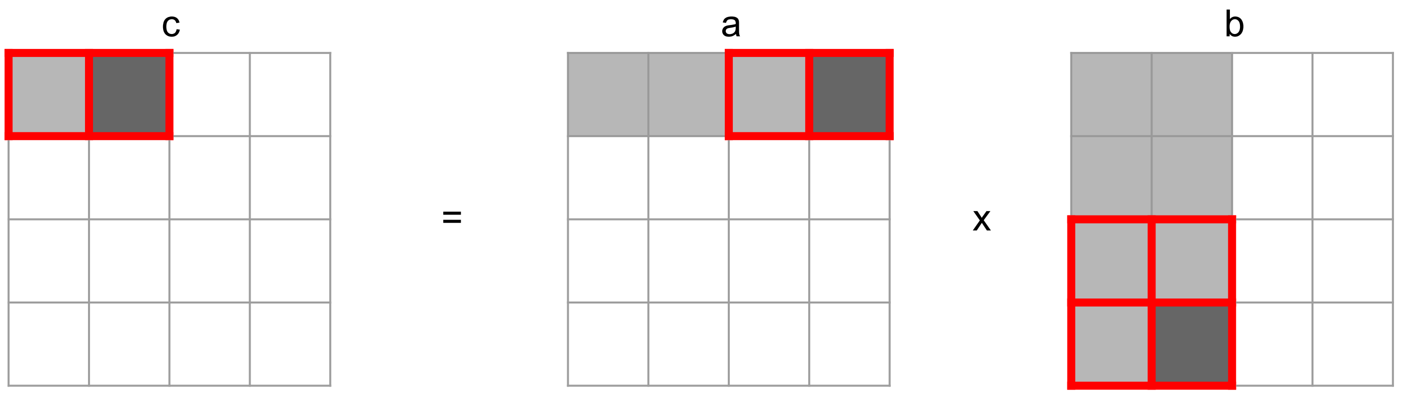

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1	0	0	1	c[0][0] += a[0][1] * b[1][0]
2	0	0	2	c[0][0] += a[0][2] * b[2][0]
3	0	0	3	c[0][0] += a[0][3] * b[3][0]
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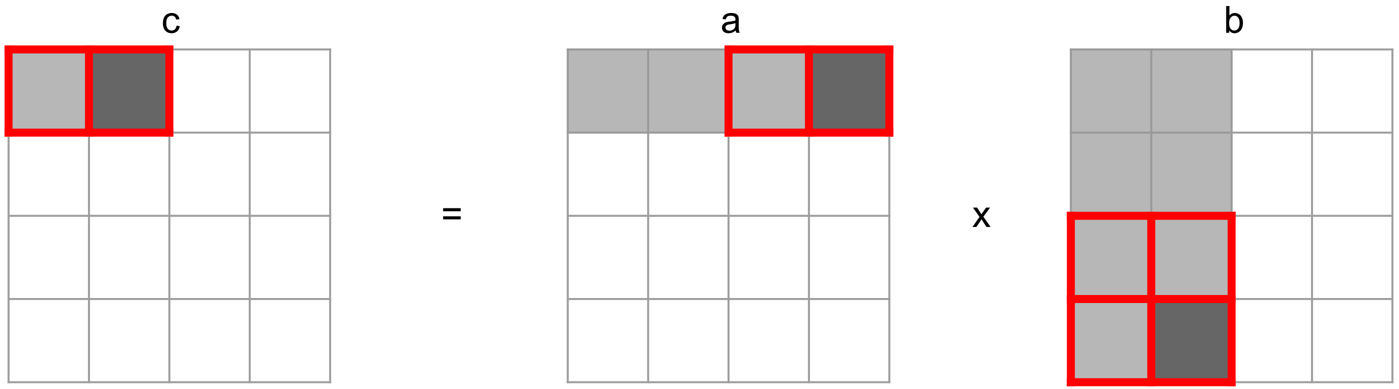
What is the miss rate of a?



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0	0	0	0	c[0][0] += a[0][0] * b[0][0]
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7	0	1	3	c[0][1] += a[0][3] * b[3][1]

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What is the miss rate of a?

What is the miss rate of b?

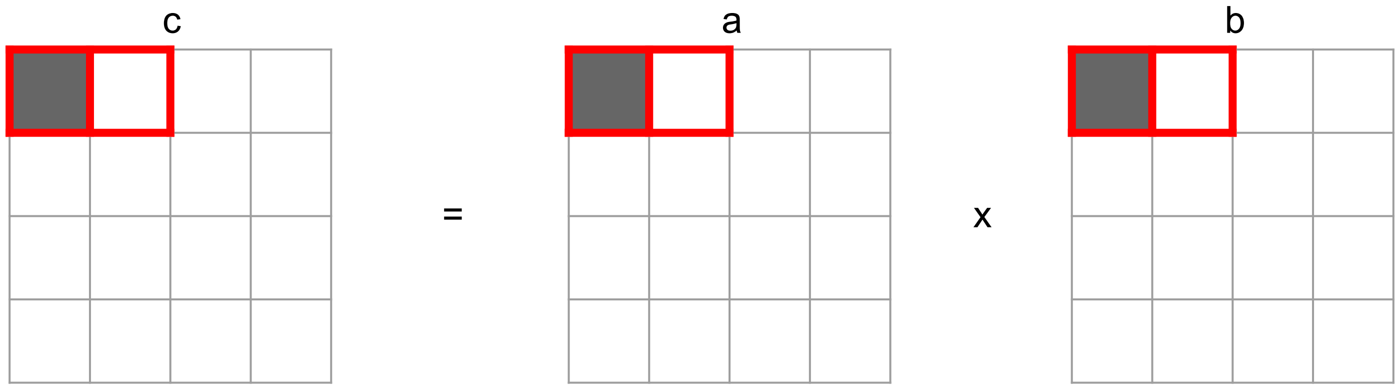
Example: Matrix Multiplication (blocking)

```
/* multiply 4x4 matrices using blocks of size 2 */
void mm_blocking(int a[4][4], int b[4][4], int c[4][4]) {
    int i, j, k;
    int i_c, j_c, k_c;
    int B = 2;
    // control loops
    for (i_c = 0; i_c < 4; i_c += B)
        for (j_c = 0; j_c < 4; j_c += B)
            for (k_c = 0; k_c < 4; k_c += B)
                // block multiplications
                for (i = i_c; i < i_c + B; i++)
                    for (j = j_c; j < j_c + B; j++)
                        for (k = k_c; k < k_c + B; k++)
                            c[i][j] += a[i][k] * b[k][j];
```

Let’s step through this to see what’s actually happening

Example: Matrix Multiplication (blocking)

- Assume a tiny cache with 4 lines of 8 bytes (2 ints)
  - S = 1, E = 4, B = 8
- Let’s see what happens if we now use blocking



iter	i	j	k	operation
0	0	0	0	c[0][0] += a[0][0] * b[0][0]

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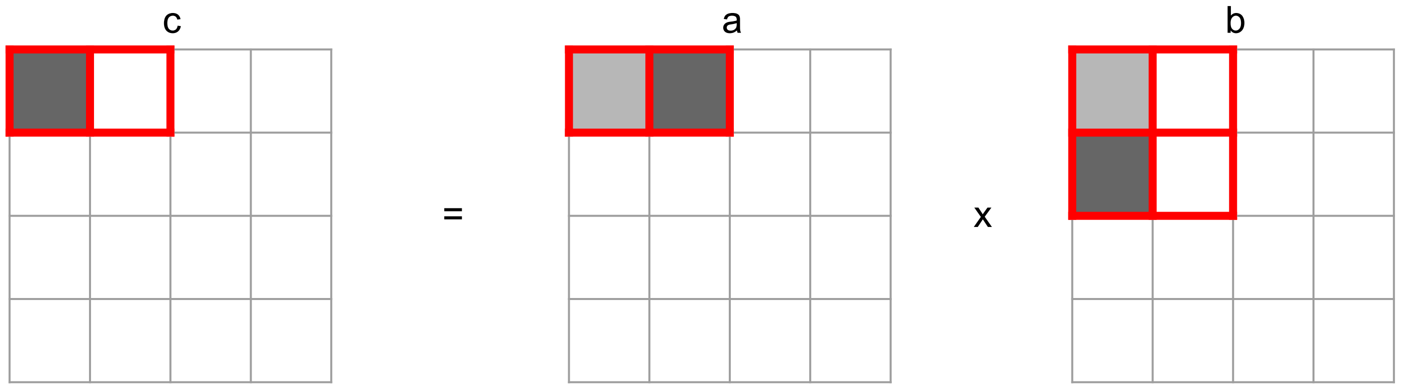

iter	i	j	k	operation
0	0	0	0	c[0][0] += a[0][0] * b[0][0]
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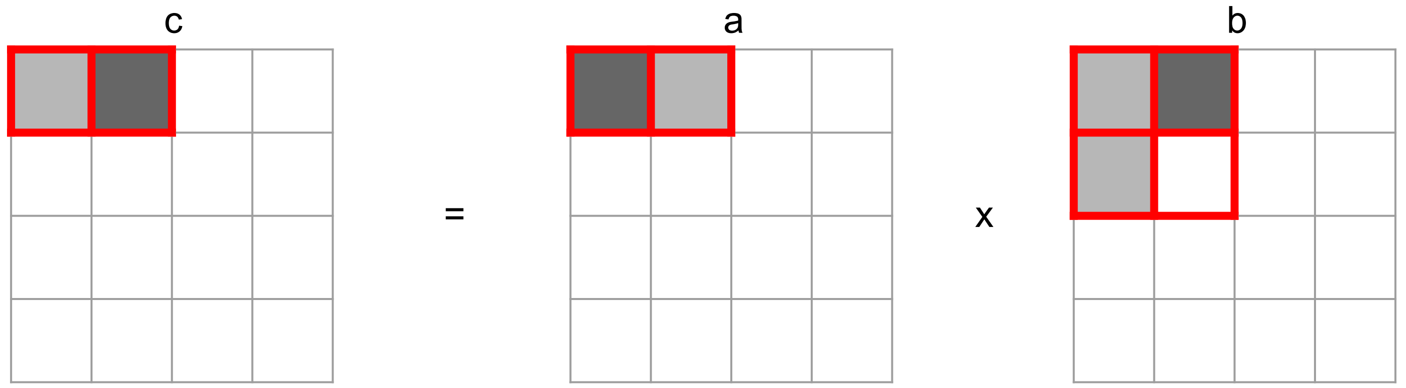

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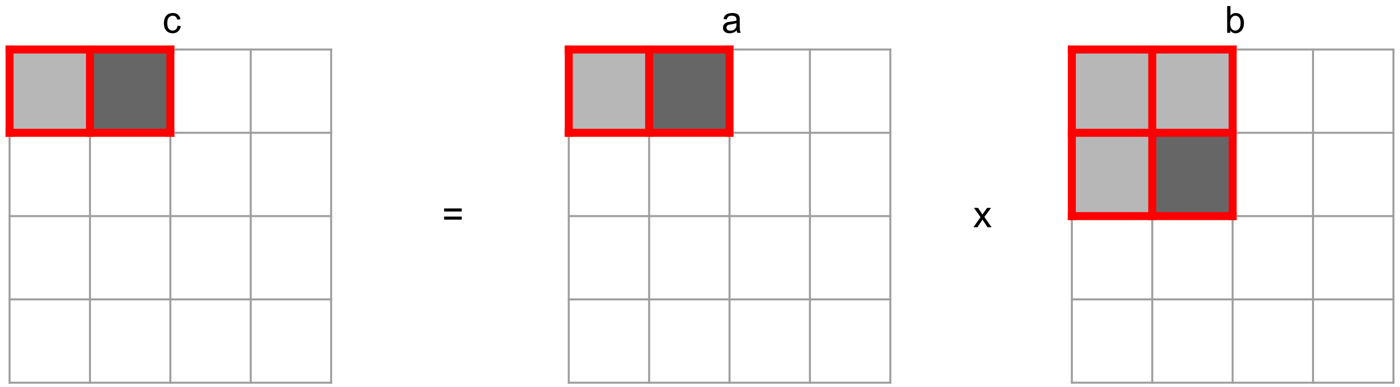

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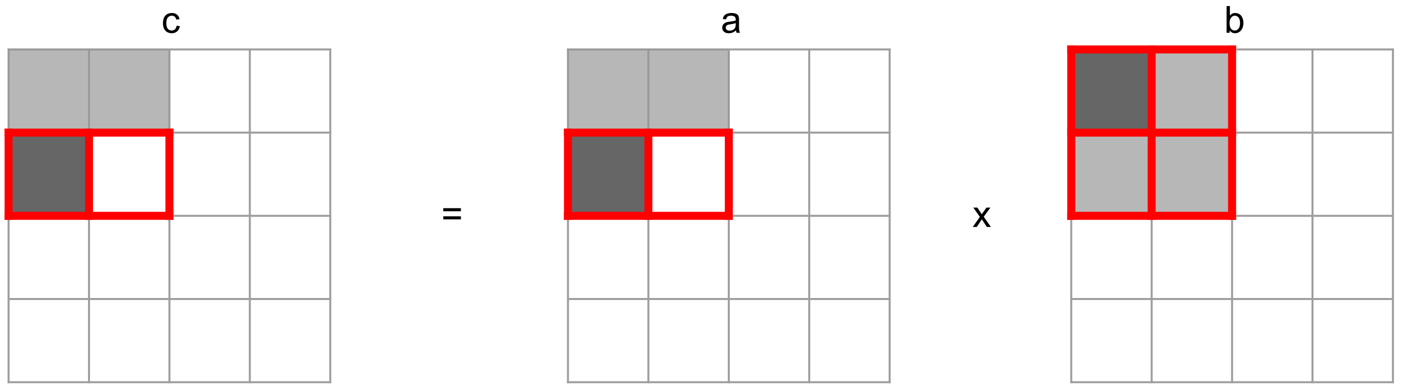

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3	0	1	1	c[0][1] += a[0][1] * b[1][1]
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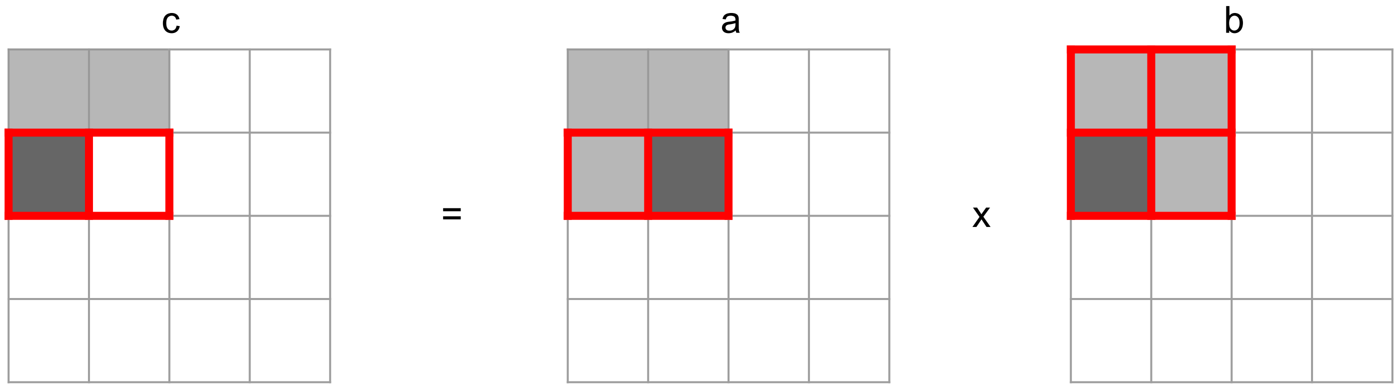

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3	0	1	1	c[0][1] += a[0][1] * b[1][1]
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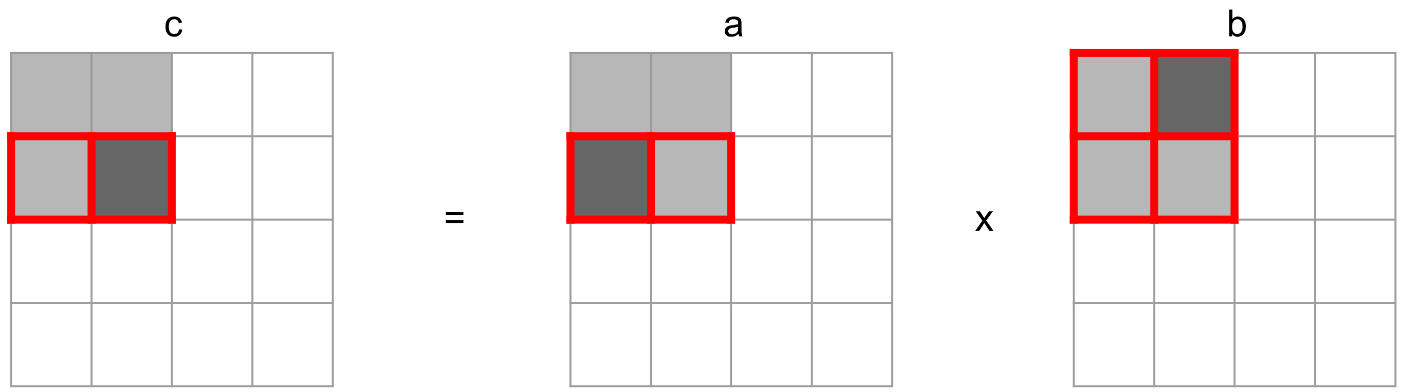

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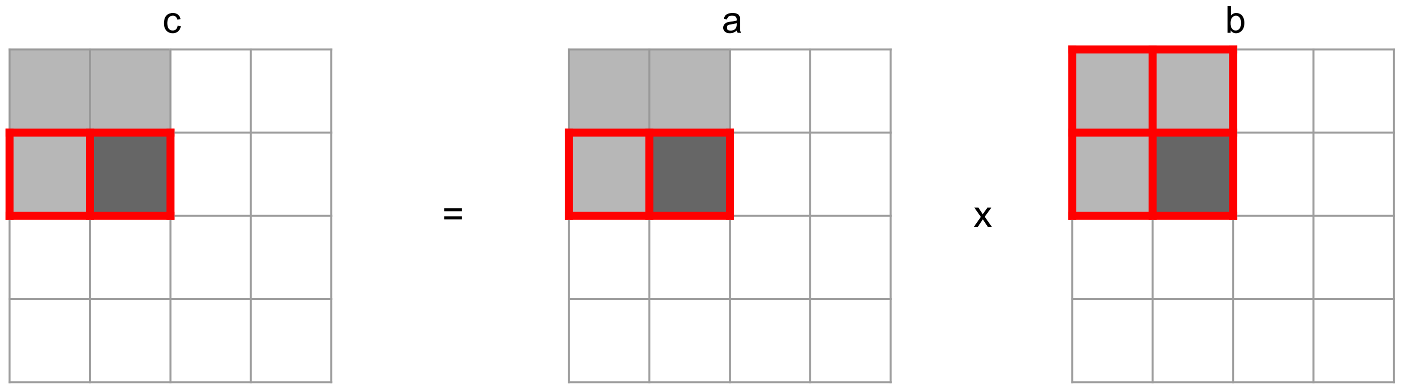

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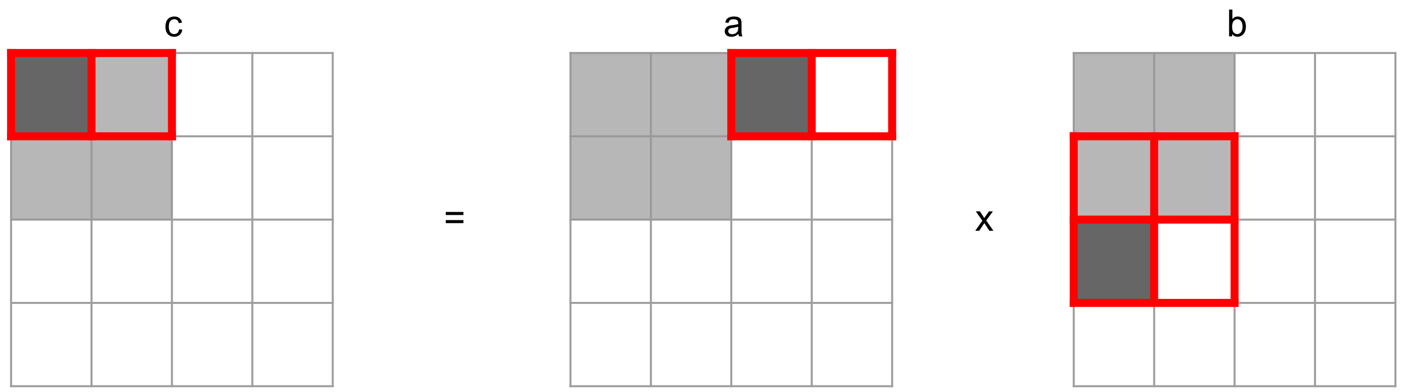

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3	0	1	1	c[0][1] += a[0][1] * b[1][1]
4	1	0	0	c[1][0] += a[1][0] * b[0][0]
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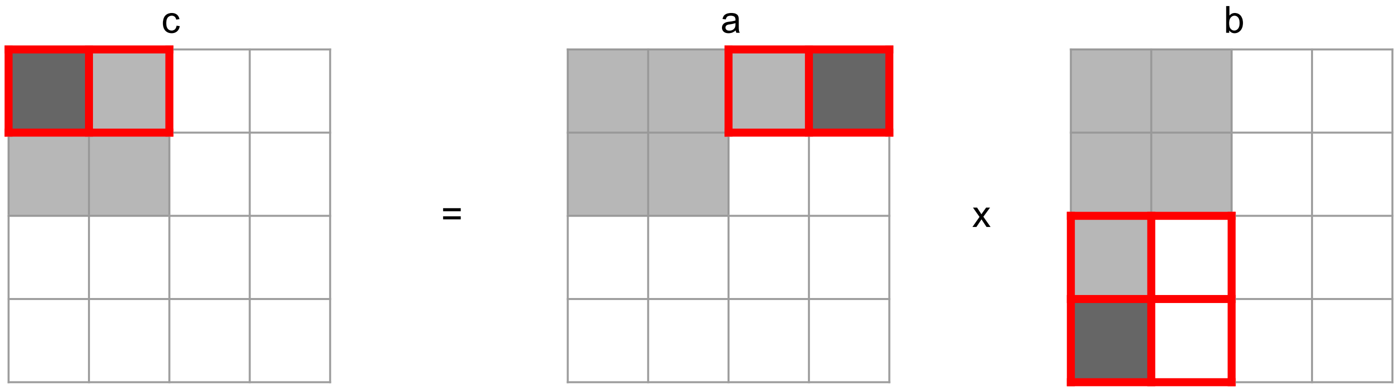
7	1	1	1	c[1][1] += a[1][1] * b[1][1]

iter	i	j	k	operation
8	0	0	2	c[0][0] += a[0][2] * b[2][0]



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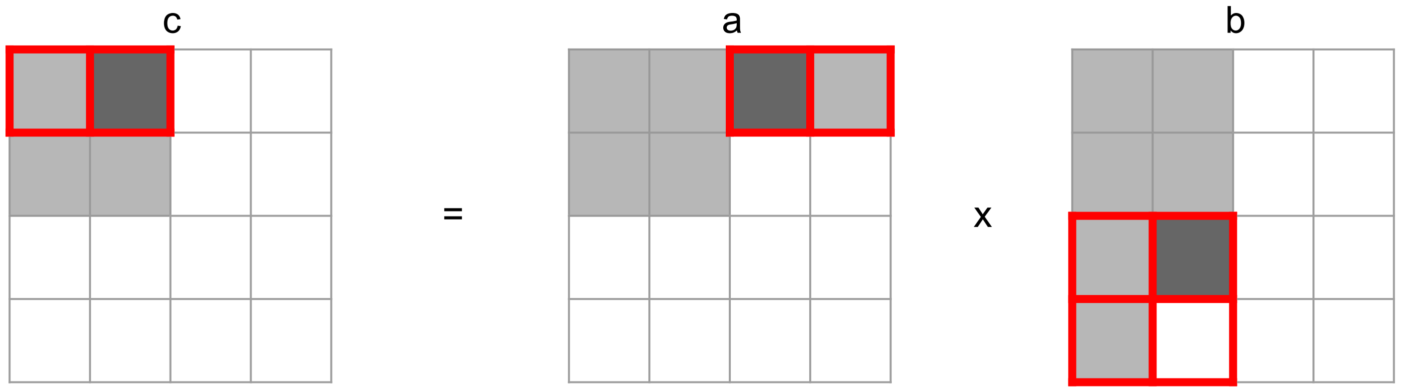

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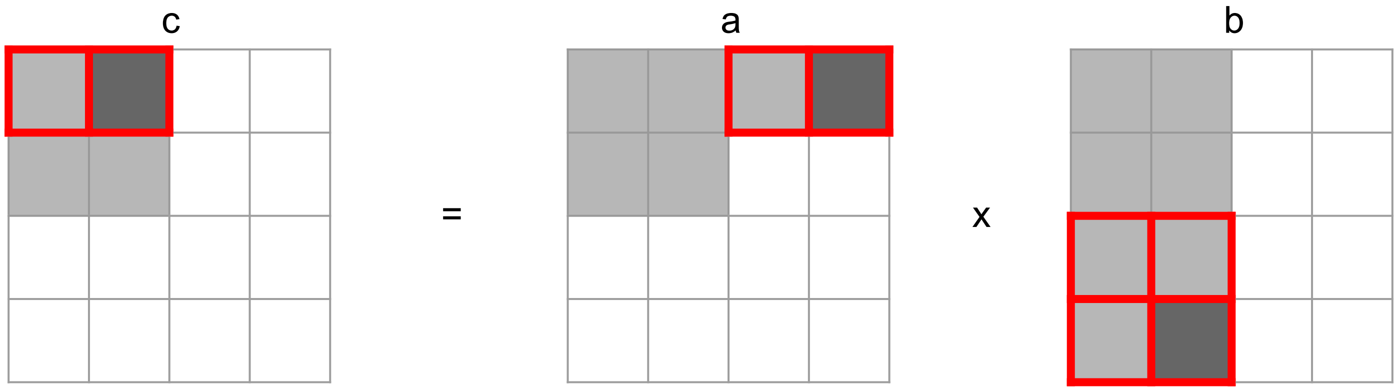
2	0	1	0	c[0][1] += a[0][0] * b[0][1]
3	0	1	1	c[0][1] += a[0][1] * b[1][1]
4	1	0	0	c[1][0] += a[1][0] * b[0][0]
5	1	0	1	c[1][0] += a[1][1] * b[1][0]
6	1	1	0	c[1][1] += a[1][0] * b[0][1]
7	1	1	1	c[1][1] += a[1][1] * b[1][1]

iter	i	j	k	operation
8	0	0	2	c[0][0] += a[0][2] * b[2][0]
9	0	0	3	c[0][0] += a[0][3] * b[3][0]
10	0	1	2	c[0][1] += a[0][2] * b[2][1]



iter	i	j	k	operation
0	0	0	0	c[0][0] += a[0][0] * b[0][0]
1	0	0	1	c[0][0] += a[0][1] * b[1][0]
2	0	1	0	c[0][1] += a[0][0] * b[0][1]
3	0	1	1	c[0][1] += a[0][1] * b[1][1]
4	1	0	0	c[1][0] += a[1][0] * b[0][0]
5	1	0	1	c[1][0] += a[1][1] * b[1][0]
6	1	1	0	c[1][1] += a[1][0] * b[0][1]
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iter	i	j	k	operation
8	0	0	2	c[0][0] += a[0][2] * b[2][0]
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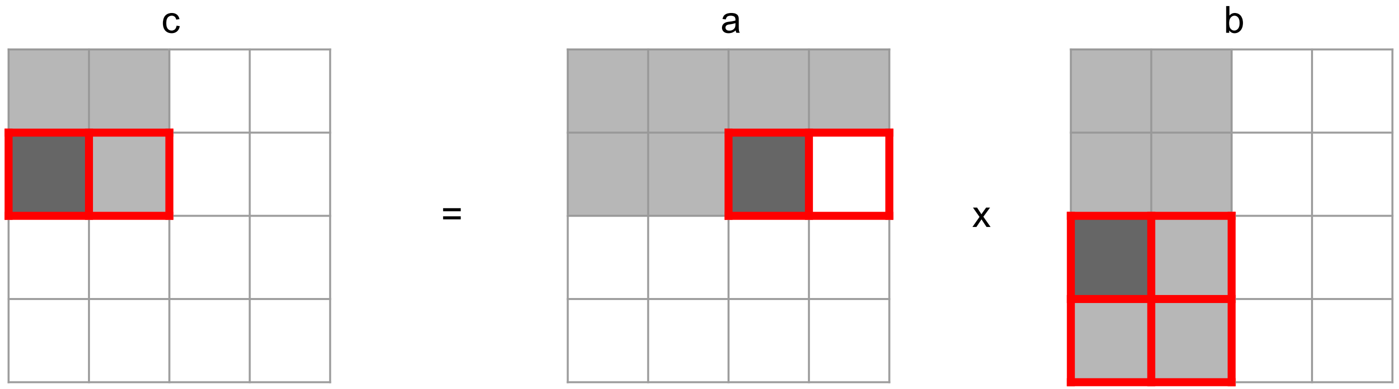
10	0	1	2	c[0][1] += a[0][2] * b[2][1]
11	0	1	3	c[0][1] += a[0][3] * b[3][1]



iter	i	j	k	operation
0	0	0	0	c[0][0] += a[0][0] * b[0][0]
1	0	0	1	c[0][0] += a[0][1] * b[1][0]
2	0	1	0	c[0][1] += a[0][0] * b[0][1]
3	0	1	1	c[0][1] += a[0][1] * b[1][1]
4	1	0	0	c[1][0] += a[1][0] * b[0][0]
5	1	0	1	c[1][0] += a[1][1] * b[1][0]
6	1	1	0	c[1][1] += a[1][0] * b[0][1]
7	1	1	1	c[1][1] += a[1][1] * b[1][1]

iter	i	j	k	operation
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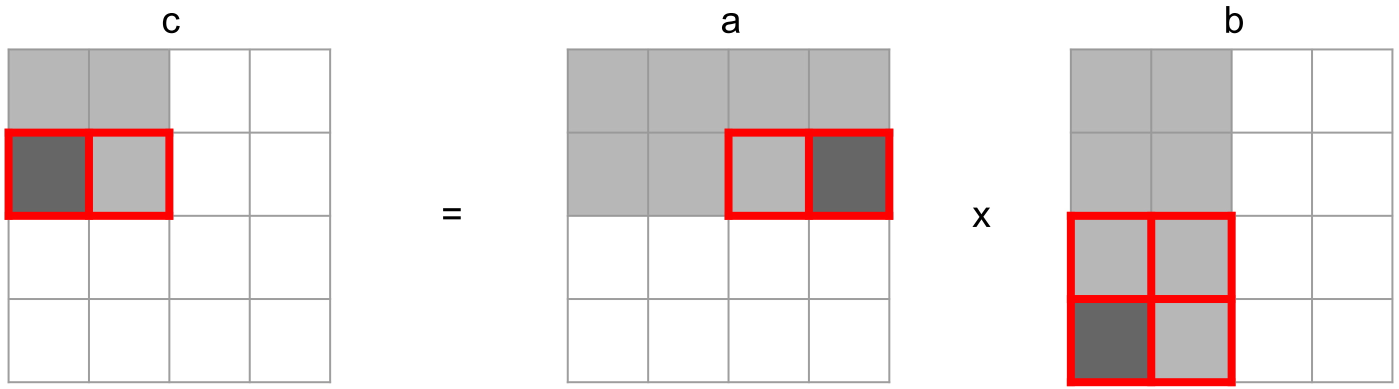
10	0	1	2	c[0][1] += a[0][2] * b[2][1]
11	0	1	3	c[0][1] += a[0][3] * b[3][1]
12	1	0	2	c[1][0] += a[1][2] * b[2][0]



iter	i	j	k	operation
0	0	0	0	c[0][0] += a[0][0] * b[0][0]
1	0	0	1	c[0][0] += a[0][1] * b[1][0]
2	0	1	0	c[0][1] += a[0][0] * b[0][1]
3	0	1	1	c[0][1] += a[0][1] * b[1][1]
4	1	0	0	c[1][0] += a[1][0] * b[0][0]
5	1	0	1	c[1][0] += a[1][1] * b[1][0]
6	1	1	0	c[1][1] += a[1][0] * b[0][1]
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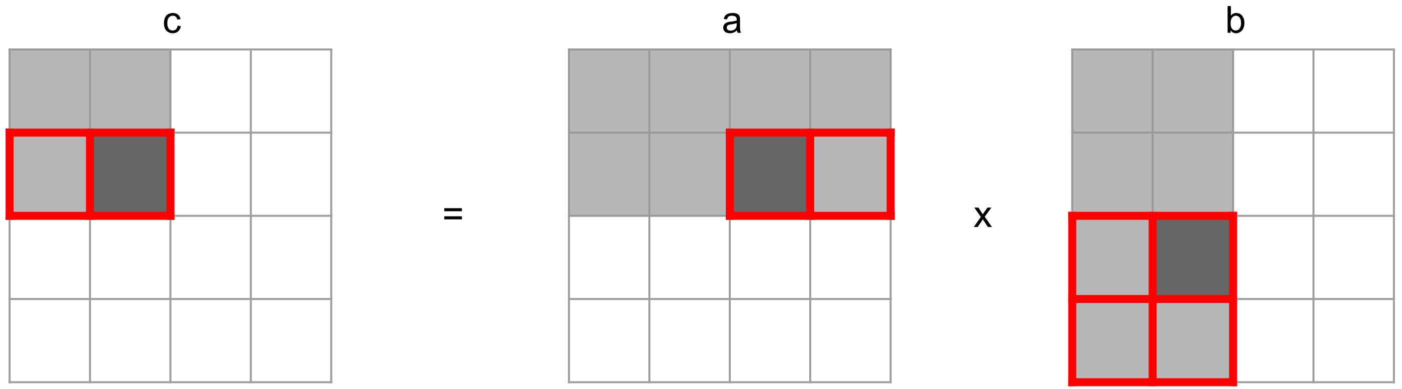
10	0	1	2	c[0][1] += a[0][2] * b[2][1]
11	0	1	3	c[0][1] += a[0][3] * b[3][1]
12	1	0	2	c[1][0] += a[1][2] * b[2][0]
13	1	0	3	c[1][0] += a[1][3] * b[3][0]



iter	i	j	k	operation
0	0	0	0	c[0][0] += a[0][0] * b[0][0]
1	0	0	1	c[0][0] += a[0][1] * b[1][0]
2	0	1	0	c[0][1] += a[0][0] * b[0][1]
3	0	1	1	c[0][1] += a[0][1] * b[1][1]
4	1	0	0	c[1][0] += a[1][0] * b[0][0]
5	1	0	1	c[1][0] += a[1][1] * b[1][0]
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iter	i	j	k	operation
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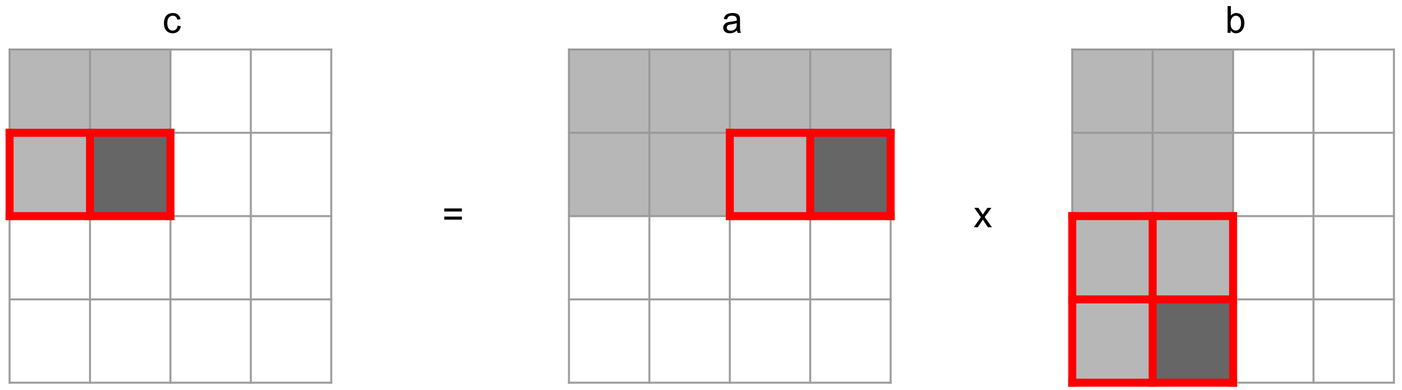
11	0	1	3	c[0][1] += a[0][3] * b[3][1]
12	1	0	2	c[1][0] += a[1][2] * b[2][0]
13	1	0	3	c[1][0] += a[1][3] * b[3][0]
14	1	1	2	c[1][1] += a[1][2] * b[2][1]



iter	i	j	k	operation
0	0	0	0	c[0][0] += a[0][0] * b[0][0]
1	0	0	1	c[0][0] += a[0][1] * b[1][0]
2	0	1	0	c[0][1] += a[0][0] * b[0][1]
3	0	1	1	c[0][1] += a[0][1] * b[1][1]
4	1	0	0	c[1][0] += a[1][0] * b[0][0]
5	1	0	1	c[1][0] += a[1][1] * b[1][0]
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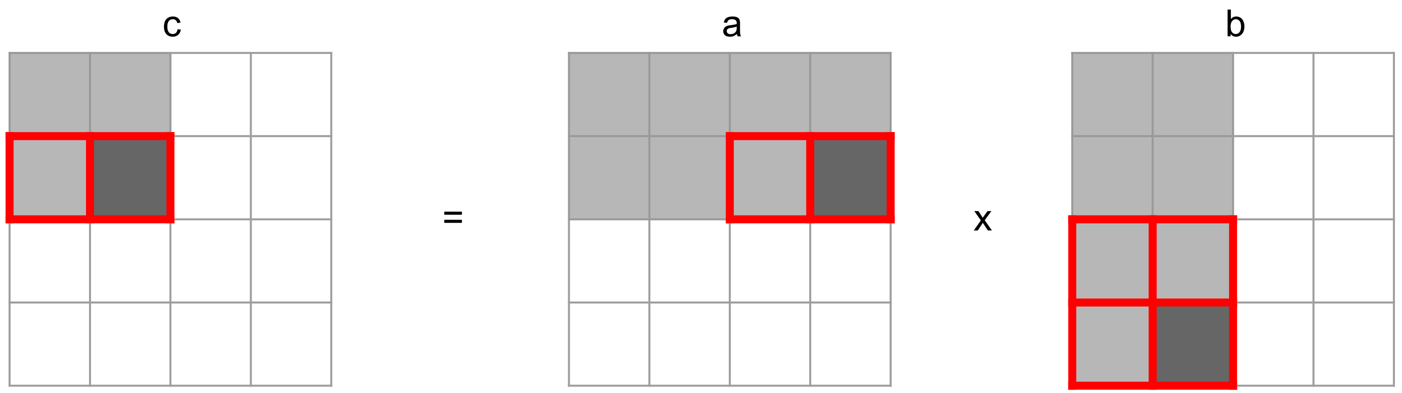
7	1	1	1	c[1][1] += a[1][1] * b[1][1]

iter	i	j	k	operation
8	0	0	2	c[0][0] += a[0][2] * b[2][0]
9	0	0	3	c[0][0] += a[0][3] * b[3][0]
10	0	1	2	c[0][1] += a[0][2] * b[2][1]
11	0	1	3	c[0][1] += a[0][3] * b[3][1]
12	1	0	2	c[1][0] += a[1][2] * b[2][0]
13	1	0	3	c[1][0] += a[1][3] * b[3][0]
14	1	1	2	c[1][1] += a[1][2] * b[2][1]
15	1	1	3	c[1][1] += a[1][3] * b[3][1]



iter	i	j	k	operation	iter	i	j	k	operation
0	0	0	0	c[0][0] += a[0][0] * b[0][0]	8	0	0	2	c[0][0] += a[0][2] * b[2][0]
1	0	0	1	c[0][0] += a[0][1] * b[1][0]	9	0	0	3	c[0][0] += a[0][3] * b[3][0]
2	0	1	0	c[0][1] += a[0][0] * b[0][1]	10	0	1	2	c[0][1] += a[0][2] * b[2][1]
3	0	1	1	c[0][1] += a[0][1] * b[1][1]	11	0	1	3	c[0][1] += a[0][3] * b[3][1]
4	1	0	0	c[1][0] += a[1][0] * b[0][0]	12	1	0		0]
5	1	0	1	c[1][0] += a[1][1] * b[1][0]	13	1	0		0]
6	1	1	0	c[1][1] += a[1][0] * b[0][1]	14	1	1	2	c[1][1] += a[1][2] * b[2][1]
7	1	1	1	c[1][1] += a[1][1] * b[1][1]	15	1	1		1]

What is the miss rate of a?

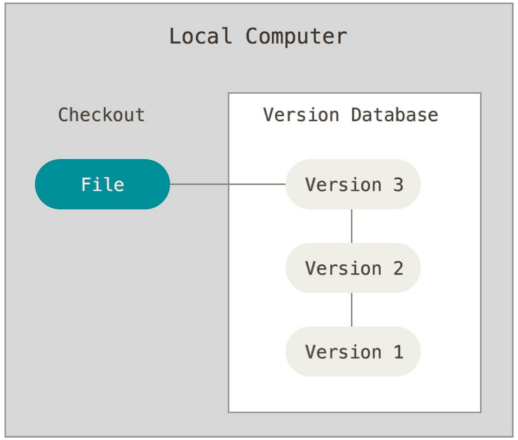
What is the miss rate of b?

Introduction to Git

Version control is your friend

What is Git?

- Most widely used version control system out there
- Version control:
  - Help track changes to your source code over time
  - Help teams manage changes on shared code



Git Commands

- Clone: git clone <clone-repository-url>
- Add: git add . or git add <file-name>
- Push / Pull: git push / git pull
- Commit: git commit -m “your-commit-message”
  - Good commit messages are key!
  - Bad:“commit”, “change”, “fixed”
  - Good: “Fixed buffer overflow potential in AttackLab”

If you get stuck…

- Reread the writeup
- Look at CS:APP Chapter 6
- Review lecture notes (http://cs.cmu.edu/~213)
- Come to Office Hours (Sunday to Friday, 6:00-10:00 PM Locations on Piazza)
- Post private question on Piazza
- `man malloc`, `man valgrind`, `man gdb`

Appendix

Practice Problems

Class Question / Discussions

- We’ll work through a series of questions
- Write down your answer for each question
- You can discuss with your classmates

What Type of Locality?

- The following function exhibits which type of locality? Consider *only* array accesses.

```
void who(int *arr, int size) {
  for (int i = 0; i < size-1; ++i)
    arr[i] = arr[i+1];
}
```

A. Spatial

B. Temporal

C. Both A and B

D. Neither A nor B

What Type of Locality?

- The following function exhibits which type of locality? Consider *only* array accesses.

```
void who(int *arr, int size) {
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}
```

A. Spatial

B. Temporal

[✓ C.] Both A and B

D. Neither A nor B

What Type of Locality?

- The following function exhibits which type of locality? Consider *only* array accesses.

```
void coo(int *arr, int size) {
  for (int i = size-2; i >= 0; --i)
    arr[i] = arr[i+1];
}
```

A. Spatial

B. Temporal

C. Both A and B

D. Neither A nor B

What Type of Locality?

- The following function exhibits which type of locality? Consider *only* array accesses.

```
void coo(int *arr, int size) {
  for (int i = size-2; i >= 0; --i)
    arr[i] = arr[i+1];
}
```

A. Spatial

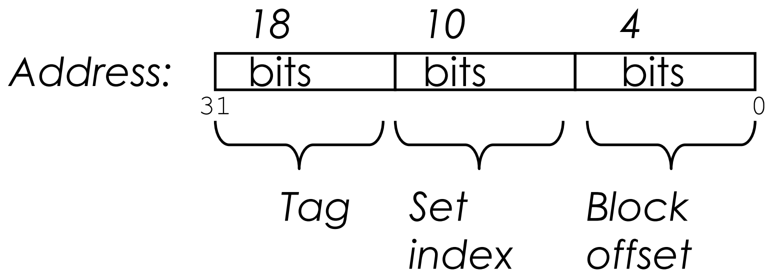
B. Temporal

[✓ C.] Both A and B

D. Neither A nor B

Calculating Cache Parameters

- Given the following address partition, how many `int` values will fit in a single data block?



# of int in block

A. 0

B. 1

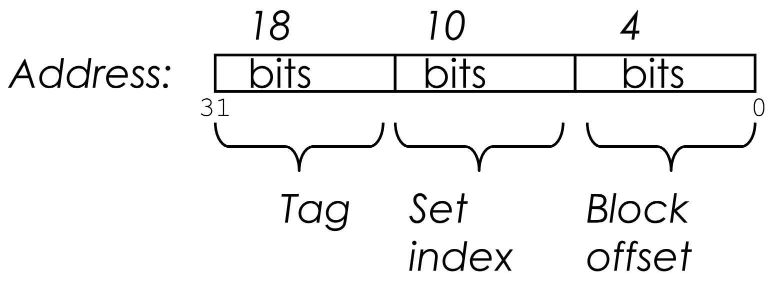
C. 2

D. 4

E. Unknown: We need more info

Calculating Cache Parameters

- Given the following address partition, how many `int` values will fit in a single data block?



# of int in block

A. 0

B. 1

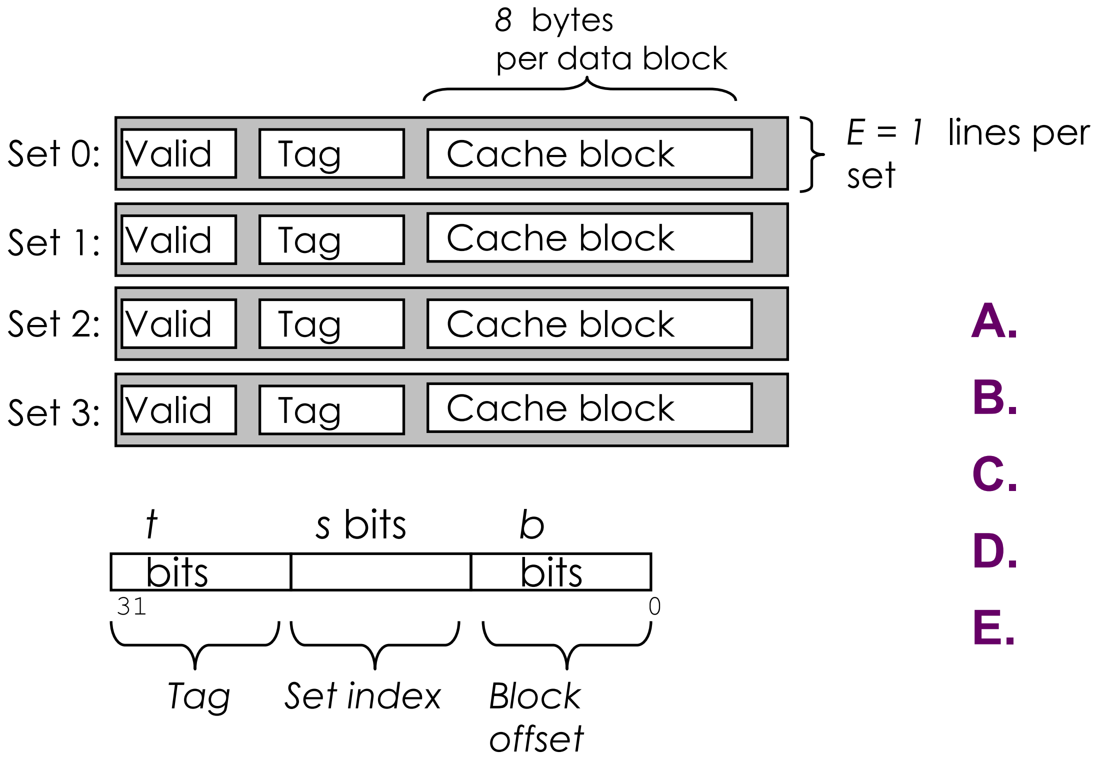
C. 2

[✓ **D.** 4]

E. Unknown: We need more info

Direct-Mapped Cache Example

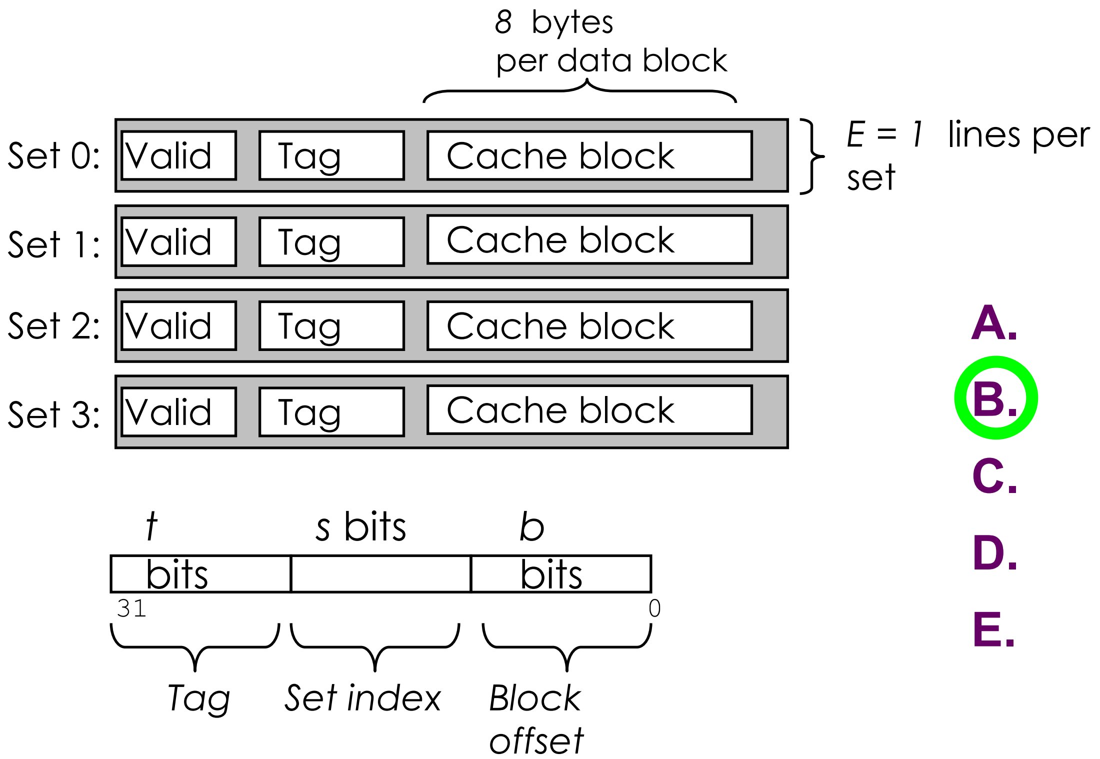
- Assuming a 32-bit address (i.e. m=32), how many bits are used for tag (t), set index (s), and block offset (b).



	t	s	b
A.	1	2	3
B.	27	2	3
C.	25	4	3
D.	1	4	8
E.	20	4	8

Direct-Mapped Cache Example

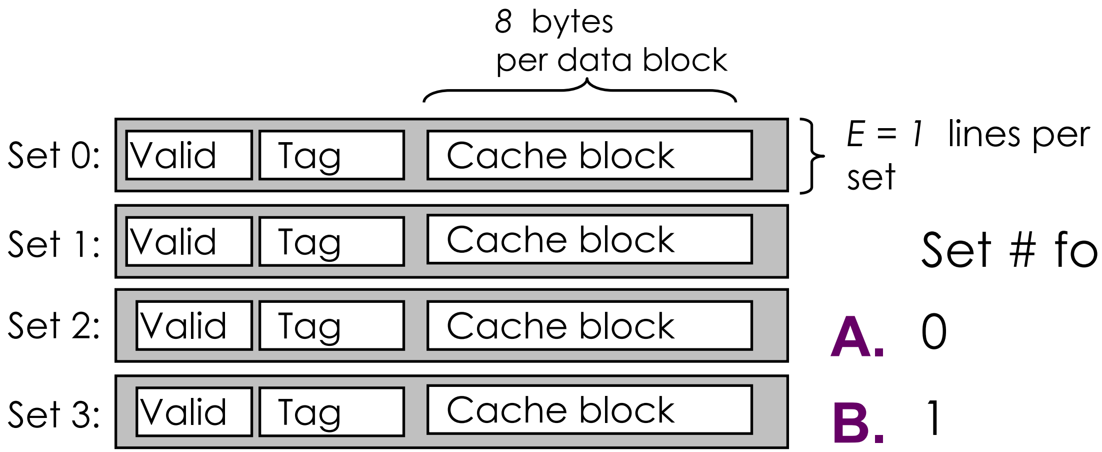
- Assuming a 32-bit address (i.e. m=32), how many bits are used for tag (t), set index (s), and block offset (b).

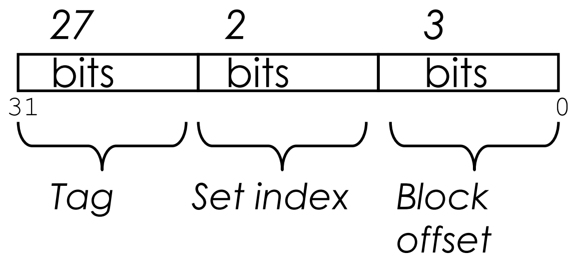


	t	s	b
A.	1	2	3
[✓ **B.**]	27	2	3
C.	25	4	3
D.	1	4	8
E.	20	4	8

Which Set Is it?

- Which set is the address **0xFA1C** located in?





Set # for 0xFA1C

A. 0

B. 1

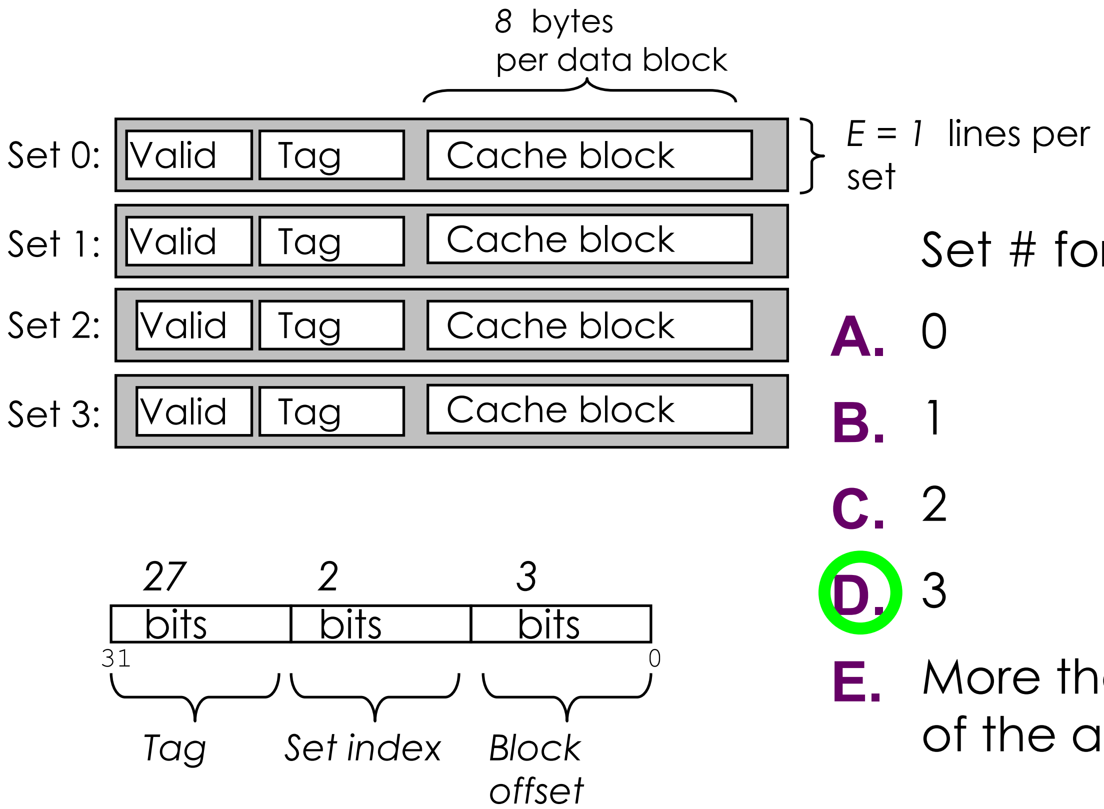
C. 2

D. 3

E. More than one of the above

Which Set Is it?

- Which set is the address **0xFA1C** located in?



Set # for 0xFA1C

A. 0

B. 1

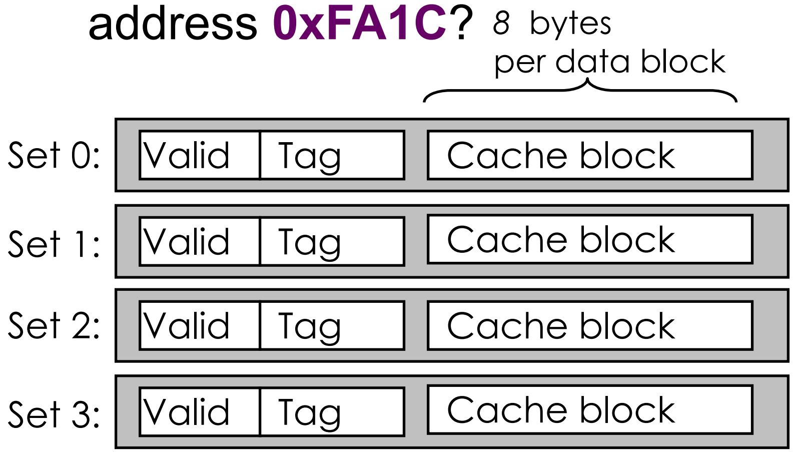
C. 2

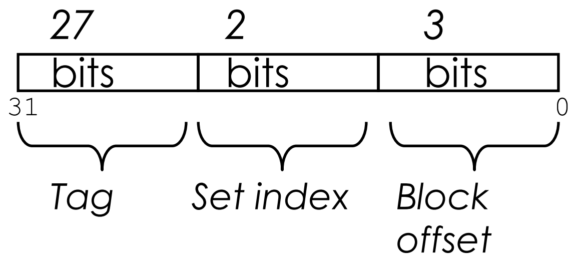
[✓ **D.** 3]

E. More than one of the above

Cache Block Range

- What range of addresses will be in the same block as address **0xFA1C**?





Addr. Range

A. 0xFA1C

B. 0xFA1C – 0xFA23

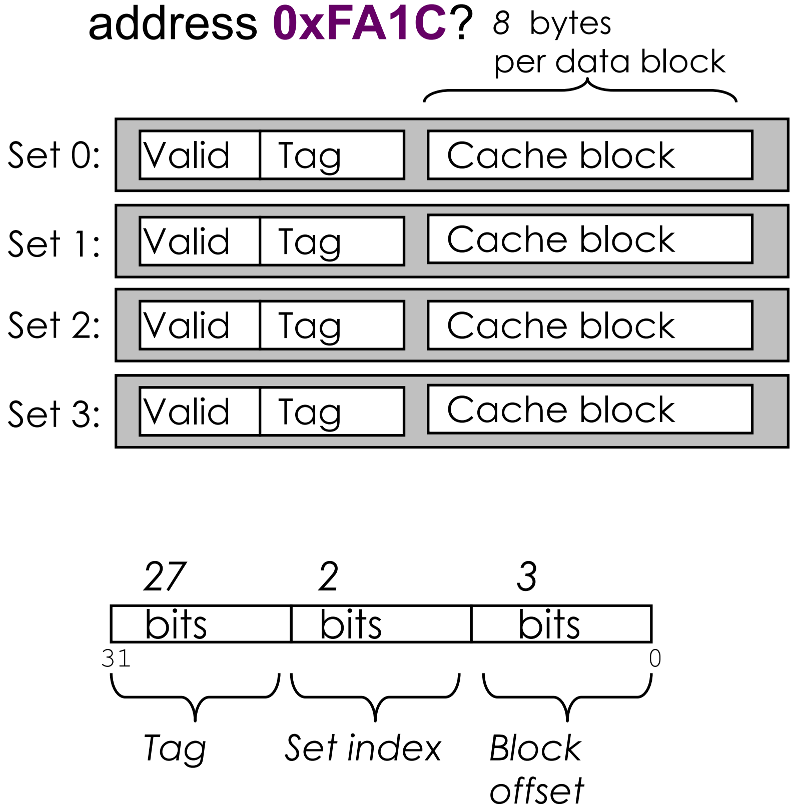
C. 0xFA1C – 0xFA1F

D. 0xFA18 – 0xFA1F

E. It depends on the access size (byte, word, etc)

Cache Block Range

- What range of addresses will be in the same block as address **0xFA1C**?



Addr. Range

A. 0xFA1C

B. 0xFA1C – 0xFA23

C. 0xFA1C – 0xFA1F

[✓ **D.**] 0xFA18 – 0xFA1F

E. It depends on the access size (byte, word, etc)

Cache Misses

If N = 16, how many bytes does the loop access of a?

```
int foo(int* a, int N)
{
    int i;
    int sum = 0;
    for(i = 0; i < N; i++)
    {
        sum += a[i];
    }
    return sum;
}
```

	Accessed Bytes
A	4
B	16
C	64
D	256

Cache Misses

If N = 16, how many bytes does the loop access of a?

```
int foo(int* a, int N)
{
    int i;
    int sum = 0;
    for(i = 0; i < N; i++)
    {
        sum += a[i];
    }
    return sum;
}
```

	Accessed Bytes
A	4
B	16
[✓ C]	64
D	256

Cache Misses

Consider a 32 KB cache in a 32 bit address space. The cache is 8-way associative and has 64 bytes per block. A LRU (Least Recently Used) replacement policy is used. What is the miss rate on **‘pass 1’**?

```
void muchAccessSoCacheWow(int *bigArr){
    // 48 KB array of ints
    int length = (48*1024)/sizeof(int);

    int access = 0;

    // traverse array with stride 8

    // pass 1
    for(int i = 0; i < length; i+=8){
        access = bigArr[i];
    }

    // pass 2
    for(int i = 0; i < length; i+=8){
        access = bigArr[i];
    }
}
```

	Miss Rate
A	0 %
B	25 %
C	33 %
D	50 %
E	66 %

Cache Misses

Consider a 32 KB cache in a 32 bit address space. The cache is 8-way associative and has 64 bytes per block. A LRU (Least Recently Used) replacement policy is used. What is the miss rate on **‘pass 1’**?

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    // traverse array with stride 8

    // pass 1
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    }

    // pass 2
    for(int i = 0; i < length; i+=8){
        access = bigArr[i];
    }
}
```

	Miss Rate
A	0 %
B	25 %
C	33 %
[✓ D]	50 %
E	66 %

Cache Misses

Consider a 32 KB cache in a 32 bit address space. The cache is 8-way associative and has 64 bytes per block. A LRU (Least Recently Used) replacement policy is used. What is the miss rate on **‘pass 2’**?

```
void muchAccessSoCacheWow(int *bigArr){
    // 48 KB array of ints
    int length = (48*1024)/sizeof(int);

    int access = 0;

    // traverse array with stride 8

    // pass 1
    for(int i = 0; i < length; i+=8){
        access = bigArr[i];
    }

    // pass 2
    for(int i = 0; i < length; i+=8){
        access = bigArr[i];
    }
}
```

	Miss Rate
A	0 %
B	25 %
C	33 %
D	50 %
E	66 %

Cache Misses

Consider a 32 KB cache in a 32 bit address space. The cache is 8-way associative and has 64 bytes per block. A LRU (Least Recently Used) replacement policy is used. What is the miss rate on **‘pass 2’**?

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void muchAccessSoCacheWow(int *bigArr){
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    int length = (48*1024)/sizeof(int);

    int access = 0;

    // traverse array with stride 8

    // pass 1
    for(int i = 0; i < length; i+=8){
        access = bigArr[i];
    }

    // pass 2
    for(int i = 0; i < length; i+=8){
        access = bigArr[i];
    }
}
```

	Miss Rate
A	0 %
B	25 %
C	33 %
[✓ D]	50 %
E	66 %

Detailed explanation in Appendix!

Clang / LLVM

- Clang is a (gcc equivalent) C compiler
  - Support for code analyses and transformation
  - Compiler will check you variable usage and declarations
  - Compiler will create code recording all memory accesses to a file
  - Useful for Cache Lab Part B (Matrix Transpose)

Appendix: Git Usage

- Commit early and often!
  - At minimum at every major milestone
  - Commits don’t cost anything!
- Popular stylistic conventions
  - Branches: short, descriptive names
  - Commits: A single, logical change. Split large changes into multiple commits.
  - Messages:
    - Summary: Descriptive, yet succinct
    - Body: More detailed description on **what** you changed, **why** you changed it, and what **side effects** it may have

Appendix: Parsing Input with fscanf

- fscanf(FILE *stream, const char *format, …)
  - "scanf" but for files

- Arguments
  1. A stream pointer, e.g. from fopen()
  2. Format string for parsing, e.g "%c %d,%d"

  3+. **Pointers** to variables for parsed data
    - Can be pointers to stack variables

- Return Value
  - Success: # of parsed vars
  - Failure: EOF
- man fscanf

Appendix: fscanf() Example

```
FILE *pFile;
pFile = fopen(“trace.txt”, "r");  // Open file for reading

// TODO: Error check sys call

char access_type;
unsigned long address;
int size;

// Line format is " S 2f,1" or " L 7d0,3"
//      - 1 character, 1 hex value, 1 decimal value
while (fscanf(pFile, " %c %lx, %d", &access_type, &address, &size) > 0)
{
    // TODO: Do stuff
}

fclose(pFile); // Clean up Resources
```

Appendix: Discussion Questions

- What did the optimal transversal orders have in common?
- How does the pattern generalize to `int[8][8] A` and a cache that holds 4 lines each of 4 `int’`s?

Appendix: Blocking Example

- We have a 2D array `int[4][4] A;`
- Cache is fully associative and can hold two lines
- Each line can hold two `int` values

Consider the following:

- What is the best miss rate for traversing `A` once?
- What order does of traversal did you use?

- What other traversal orders can achieve this miss rate?

Appendix: Cache Misses

If there is a 48KB cache with 8 bytes per block and 3 cache lines per set, how many misses if foo is called twice? N still equals 16.

NOTE: This is a contrived example since the number of cache lines must be a power of 2. However, it still demonstrates an important point.

```
int foo(int* a, int N)
{
    int i;
    int sum = 0;
    for(i = 0; i < N; i++)
    {
        sum += a[i];
    }
    return sum;
}
```

	Misses
A	0
B	8
C	12
D	14
E	16

Appendix: Cache Misses

If there is a 48KB cache with 8 bytes per block and 3 cache lines per set, how many misses if foo is called twice? N still equals 16.

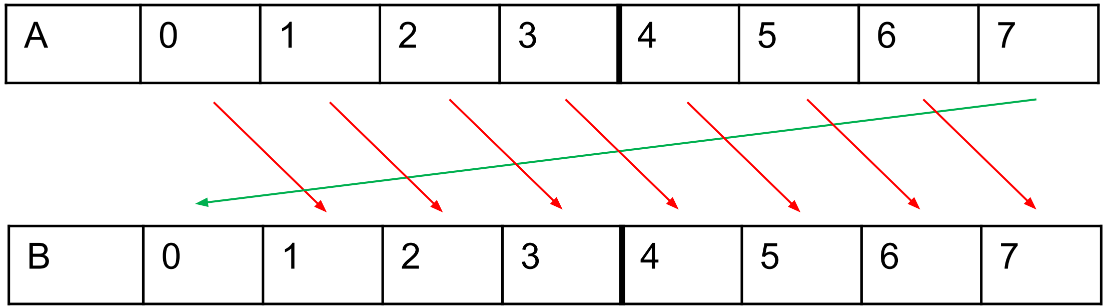
NOTE: This is a contrived example since the number of cache lines must be a power of 2. However, it still demonstrates an important point.

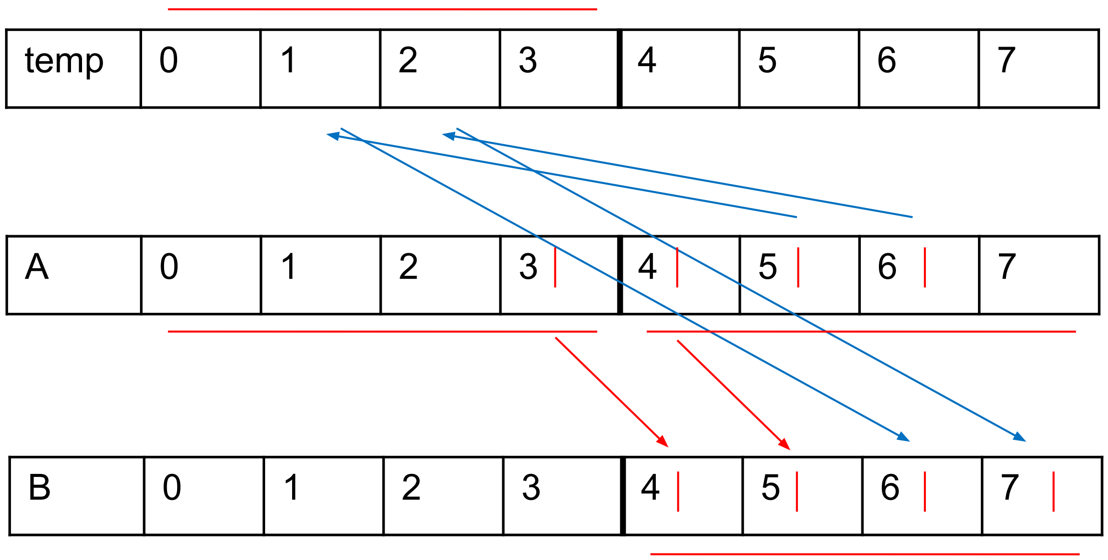
```
int foo(int* a, int N)
{
    int i;
    int sum = 0;
    for(i = 0; i < N; i++)
    {
        sum += a[i];
    }
    return sum;
}
```

	Misses
A	0
B	8
C	12
D	14
[✓ E]	16

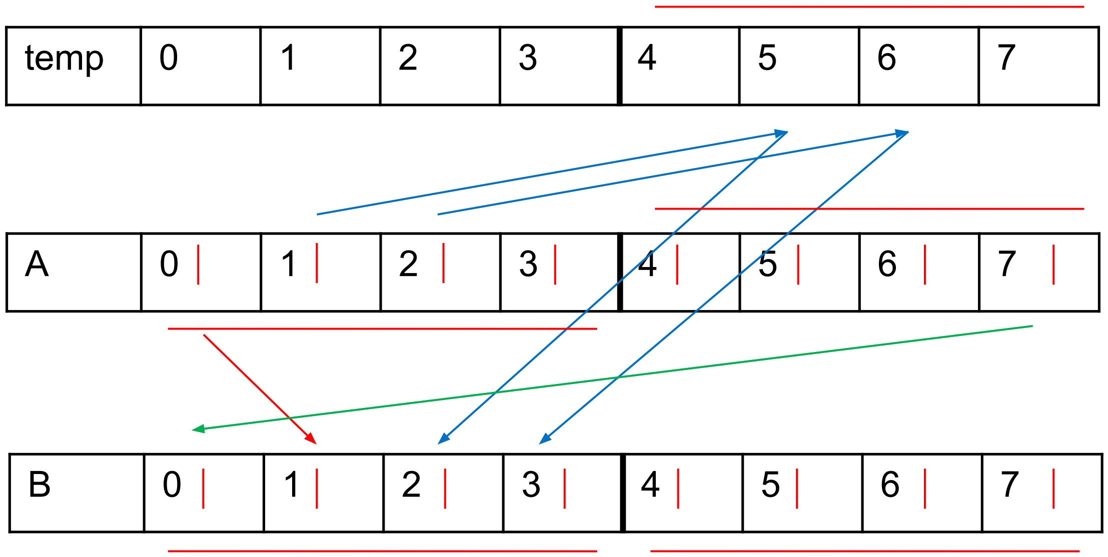
Appendix: Very Hard Cache Problem

- We will use a direct-mapped cache with 2 sets, which each can hold up to 4 `int`'s.
- How can we copy A into B, shifted over by 1 position?
  - The most efficient way? (Use `temp`!)

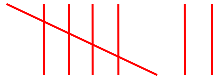




Number of misses: ||||



Number of misses:



□ Could’ve been 16 misses otherwise!
We would save even more if the block size were larger, or if `temp` were already cached

Appendix: 48KB Cache Explained (1)

We access the int array in strides of 8 (note the comment and the i += 8). Each block is 64 bytes, which is enough to hold 16 ints, so in each block:

```
| 8 ints = 32B  | 8 ints = 32B  |
+---------------+---------------+
|m| | | | | | | |h| | | | | | | |
+---------------+---------------+
|      16 ints = 64B
```

The "m" denotes a miss, and the "h" denotes a hit. This pattern will repeat for the entirety of the array.

We can be sure that the second access is always a hit. This is because the first access will load the entire 64-byte block into the cache (since the entire block is always loaded if any of its elements are accessed).

So, the big question is why the first access is always a miss. To answer this, we must understand many things about the cache.

First of all, we know that s, the number of set bits, is 6, which means there are 64 sets. Since each set maps to 64 bytes (as there are b = 6 block bits), we know that every 64 * 64 bytes = 4 kilobytes we run out of sets:

```
   64B     64B             64B      64B
+-------+-------+--...--+--------+-------+--...
| set 0 | set 1 |       | set 63 | set 0 |
+-------+-------+--...--+--------+-------+--...
|        64 * 64B = 4KB          |
```

Clearly, this pattern will repeat for the entirety of the array.

Appendix: 48KB Cache Explained (2)

```
However, note that we have E = 8 lines per set. That means that even though the next 4KB map to the same sets (0-63) as the
first 4KB, they will just be put in another line in the cache, until we run out of lines (i.e., after we've gone through 8 *
4KB = 32KB of memory). Splitting up the bigArr into 16KB chunks:

    16KB        16KB        16KB
+-----------+-----------+-----------+
| section A | section B | section C |
+-----------+-----------+-----------+
|  |  |  |  |  |  |  |  |  |  |  |  |
              4KB each

We see that section A will take up 16KB = 4 * 4KB; like we said, each of those 4KB chunks will take up 1 line each, so section
A uses 4 lines per set (and uses all 64 sets).

Similarly, section B also takes up 16KB = 4 * 4KB; again, each of those 4KB chunks will take up 1 line each, so section B also
uses 4 lines per set (and uses all 64 sets).

Note that as all of this data is being loaded in, our cache is still cold (does not contain any data from those sections), so
the previous assumption about the first of every other access missing (the "m" above) is still true.

After we read in sections A and B, the cache looks like:
line 0 1 2 3 4 5 6 7
    +-------+-------+
  0 |       |       |
  1 |       |       |
s . .       .       .
e . .   A   .   B   .
t . .       .       .
  62|       |       |
  63|       |       |
    +-------+-------+
```

Appendix: 48KB Cache Explained (3)

However, once we reach section C, we've run out of lines! So what do we have to do? We have to start evicting lines. And of course, the least-recently used lines are the ones used to store the data from A (lines 0-3), since we just loaded in the stuff from B. So, first of all, these evictions are causing misses on the first of every other read, so that "m" assumption is still true. Second, after we read in the entirety of section C, the cache looks like:

```
line 0 1 2 3 4 5 6 7
    +-------+-------+
  0 |       |       |
  1 |       |       |
s . .       .       .
e . .   C   .   B   .
t . .       .       .
  62|       |       |
  63|       |       |
    +-------+-------+
```

Thus, we know now that the miss rate for the first pass is 50%.

Appendix: 48KB Cache Explained (4)

If we now consider the second pass, we're starting over at the beginning of bigArr (i.e., now we're reading section A). However, there's a problem - section A isn't in the cache anymore! So we get a bunch of evictions (the "m" assumption is still true, of course, since these evictions must also be misses). What are we evicting? The least-recently used lines, which are now lines 4-7 (holding data from B). Thus, the cache after reading section A looks like:

```
line 0 1 2 3 4 5 6 7
    +-------+-------+
  0 |       |       |
  1 |       |       |
s . .       .       .
e . .   C   .   A   .
t . .       .       .
  62|       |       |
  63|       |       |
    +-------+-------+
```

Then, we access B. But it isn't in the cache either! So we evict the least-recently-used lines (in this case, the lines that were holding section C, 0-3) (the "m" assumption still holds); afterwards, the cache looks like:

```
line 0 1 2 3 4 5 6 7
    +-------+-------+
  0 |       |       |
  1 |       |       |
s . .       .       .
e . .   B   .   A   .
t . .       .       .
  62|       |       |
  63|       |       |
    +-------+-------+
```

Appendix: 48KB Cache Explained (5)

```
And finally, we access section C. But of course, its data isn't in the cache at all, so we again evict the least-recently used
lines (in this case, section A's lines, 4-7) (again, "m" assumption holds):

line 0 1 2 3 4 5 6 7
    +-------+-------+
  0 |       |       |
  1 |       |       |
s . .       .       .
e . .   B   .   C   .
t . .       .       .
  62|       |       |
  63|       |       |
    +-------+-------+

And so the miss rate is 50% for the second pass as well.

Thank you to Stan Zhang for coming up with such a detailed explanation!
```

Appendix: `$ man 3 getopt`

- `int getopt(int argc, char * const argv[], const char *optstring);`
  - `int argc` → argument count passed to `main()`
    - Note: includes executable, so `./a.out 1 2` has `argc=3`
  - `char * const argv` is argument string array passed to `main`
  - `const char *optstring` → string with command line arguments
    - Characters followed by colon require arguments
      - Find argument text in `char *optarg`
    - `getopt` can't find argument or finds illegal argument sets `optarg` to "?"
    - Example: "`abc:d:`"
      - a and b are boolean arguments (not followed by text)
      - c and d are followed by text (found in `char *optarg`)
- Returns: `getopt` returns -1 when done parsing