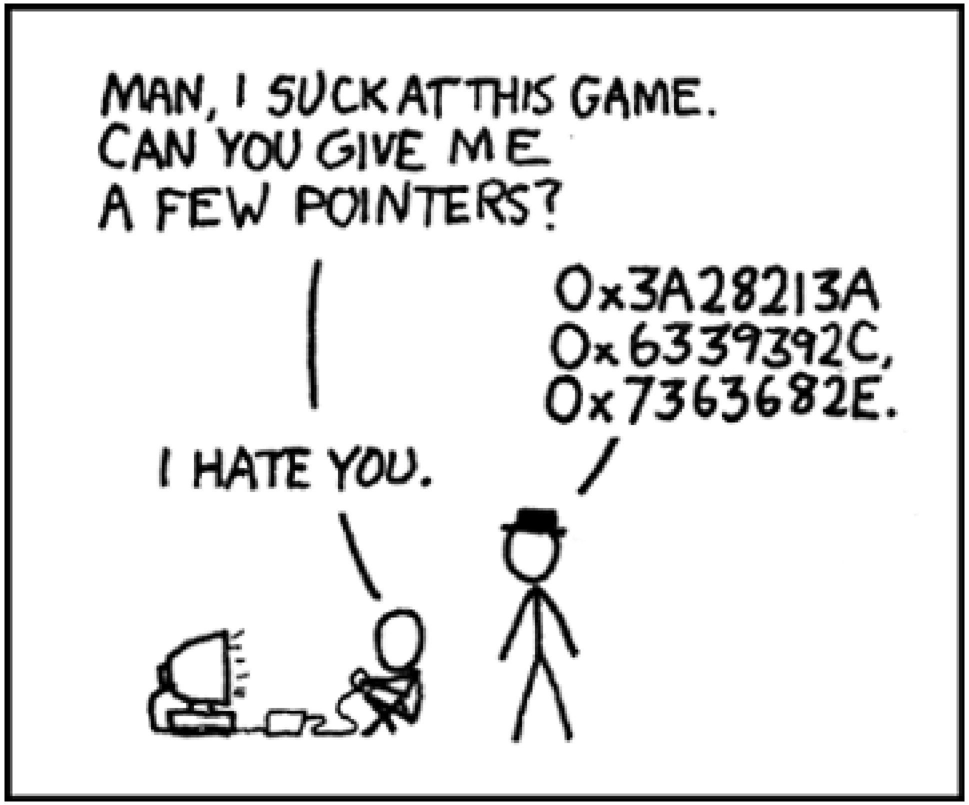
Cache Lab Implementation and Blocking

Slides courtesy of:
Aditya Shah, CMU

Welcome to the World of Pointers !


MAN, I SUCK AT THIS GAME. CAN YOU GIVE ME A FEW POINTERS?
0x3A28213A 0x6339392C, 0x7363682E.
I HATE YOU.

Outline

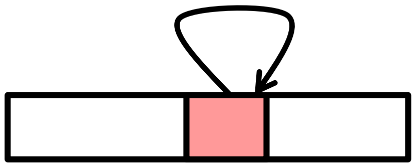
- **Schedule**
- **Memory organization**
- **Caching**
  - Different types of locality
  - Cache organization
- **Cache lab**
  - Part (a) Building Cache Simulator
  - Part (b) Efficient Matrix Transpose
  - Blocking

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

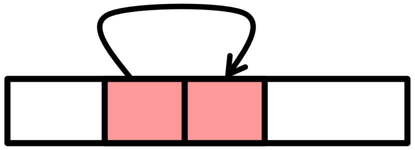
Locality

- **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

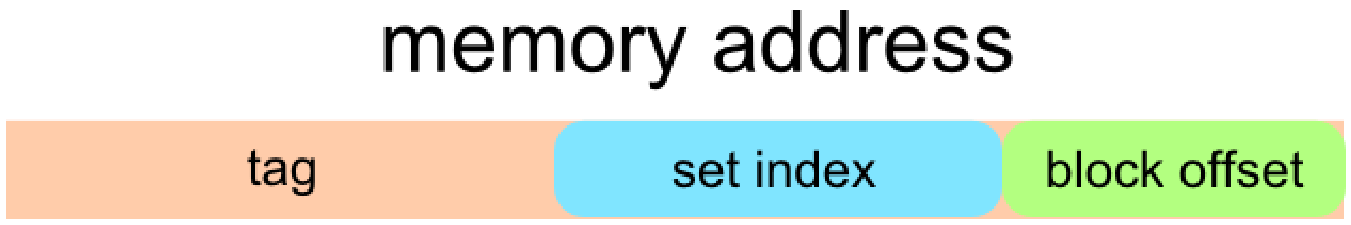
- **Spatial locality**
  - Items with nearby addresses tend to be referenced close together in time



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

Memory Address

- 64-bit on shark machines

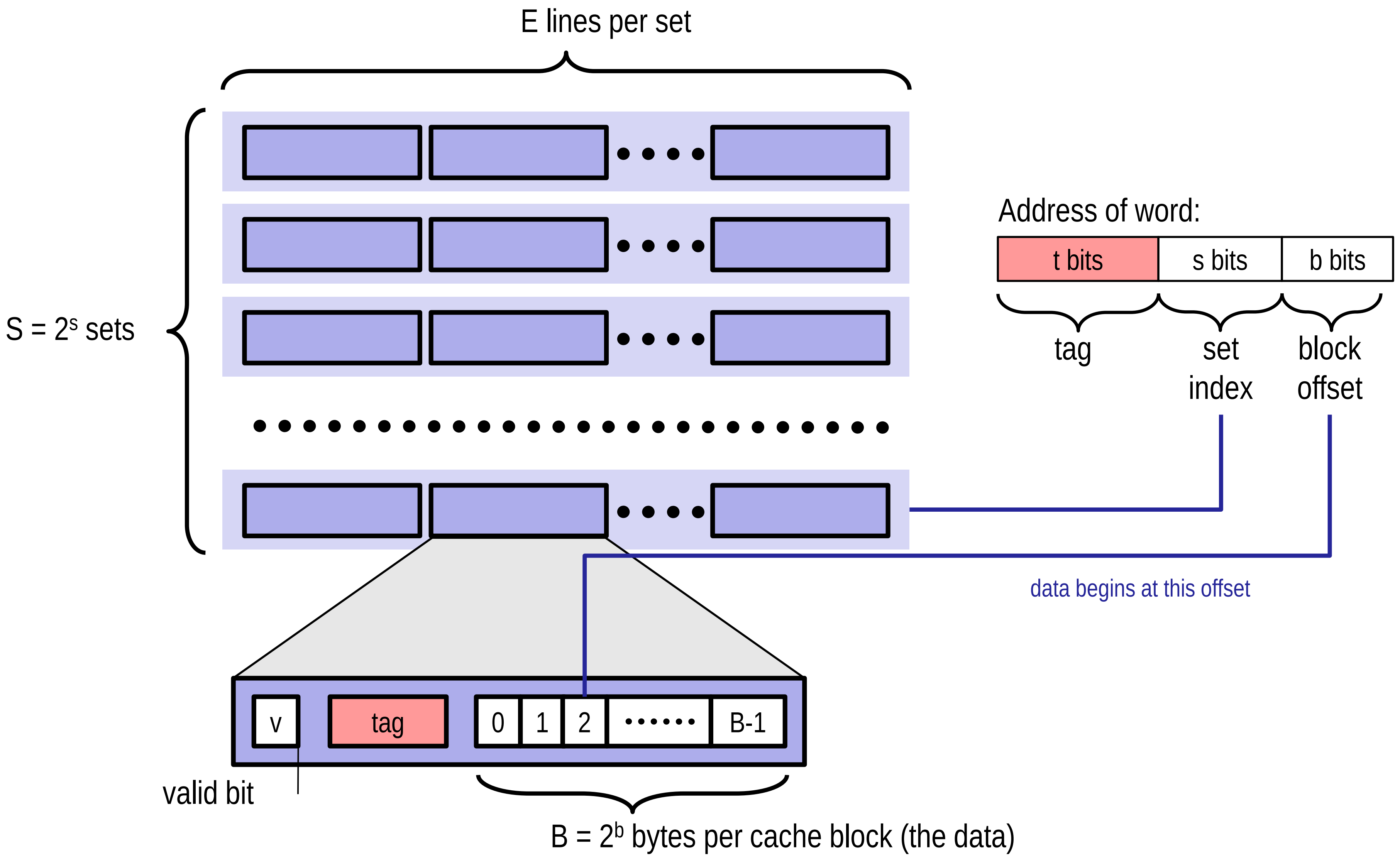


- Block offset: b bits
- Set index: s bits
- Tag Bits: (Address Size – b – s)

Cache

- **A cache is a set of 2^s *cache sets***
- **A *cache set* is a set of E *cache lines***
  - E is called associativity
  - If E=1, it is called “direct-mapped”
- **Each *cache line* stores a block**
  - Each block has B = 2^b bytes
- **Total Capacity = S*B*E**

Visual Cache Terminology



Cache Lab

- **Part (a) Building a cache simulator**
- **Part (b) Optimizing matrix transpose**

Part (a) : Cache simulator

- **A cache simulator is NOT a cache!**
  - Memory contents 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 s, b, E, given at run time.**

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

Part (a) : Hints

- **A cache is just 2D array of *cache lines*:**
  - struct cache_line cache[S][E];
  - S = 2^s, is the number of sets
  - E is associativity

- **Each cache_line has:**
  - Valid bit
  - Tag
  - LRU counter (only if you are not using a queue)

Part (a) : getopt

- **getopt() automates parsing elements on the unix command line If function declaration is missing**
  - Typically called in a loop to retrieve arguments
  - Its return value is stored in a local variable
  - When getopt() returns -1, there are no more options

#include <getopt.h>.

Part (a) : getopt

- **A switch statement is used on the local variable holding the return value from getopt()**
  - Each command line input case can be taken care of separately
  - “optarg” is an important variable – it will point to the value of the option argument

- **Think about how to handle invalid inputs**

- **For more information,**
  - look at man 3 getopt
  - http://www.gnu.org/software/libc/manual/html_node/Getopt.html

Part (a) : getopt Example

```
int main(int argc, char** argv){
    int opt,x,y;
    /* looping over arguments */
    while(-1 != (opt = getopt(argc, argv, “x:y:"))){
        /* determine which argument it’s processing */
        switch(opt) {
            case 'x':
                x = atoi(optarg);
                break;
            case ‘y':
                y = atoi(optarg);
                break;
            default:
                printf(“wrong argument\n");
                break;
        }
    }
}
```

- Suppose the program executable was called “foo”. Then we would call “./foo -x 1 –y 3“ to pass the value 1 to variable x and 3 to y.

Part (a) : fscanf

- **The fscanf() function is just like scanf() except it can specify a stream to read from (scanf always reads from stdin)**
  - parameters:
    - A stream pointer
    - format string with information on how to parse the file
    - the rest are pointers to variables to store the parsed data
  - You typically want to use this function in a loop. It returns -1 when it hits EOF or if the data doesn’t match the format string
- **For more information,**
  - man fscanf
  - http://crasseux.com/books/ctutorial/fscanf.html
- **fscanf will be useful in reading lines from the trace files.**
  - L 10,1
  - M 20,1

Part (a) : fscanf example

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

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

char identifier;
unsigned address;
int size;
// Reading lines like " M 20,1" or "L 19,3"

while(fscanf(pFile,“ %c %x,%d”, &identifier, &address, &size)>0)
{
   // Do stuff
}

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

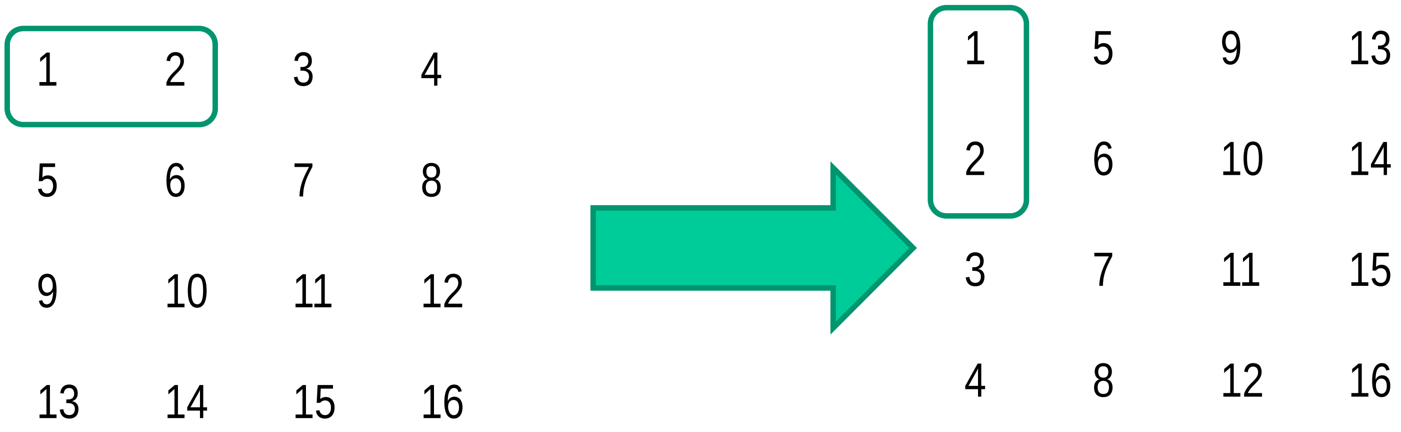
Part (a) : Malloc/free

- **Use malloc to allocate memory on the heap**
- **Always free what you malloc, otherwise may get memory leak**
  - some_pointer_you_malloced = malloc(sizeof(int));
  - Free(some_pointer_you_malloced);
- **Don’t free memory you didn’t allocate**

Part (b) Efficient Matrix Transpose

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

Matrix A **Matrix B**

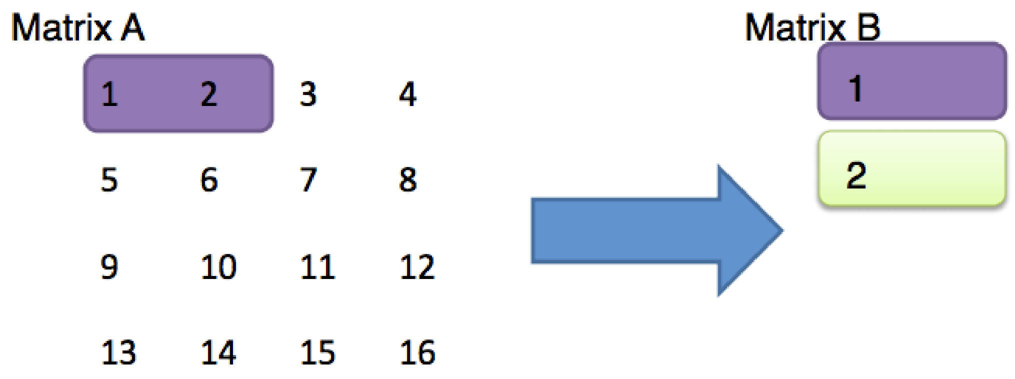


$$\begin{array}{cccc} \boxed{1 \quad 2} & & 3 & 4 \\ 5 & 6 & 7 & 8 \\ 9 & 10 & 11 & 12 \\ 13 & 14 & 15 & 16 \end{array} \Longrightarrow \begin{array}{cccc} \boxed{\begin{array}{c} 1 \\ 2 \end{array}} & \begin{array}{c} 5 \\ 6 \end{array} & \begin{array}{c} 9 \\ 10 \end{array} & \begin{array}{c} 13 \\ 14 \end{array} \\ 3 & 7 & 11 & 15 \\ 4 & 8 & 12 & 16 \end{array}$$

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

Part (b) : Efficient Matrix Transpose

- Suppose Block size is 8 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

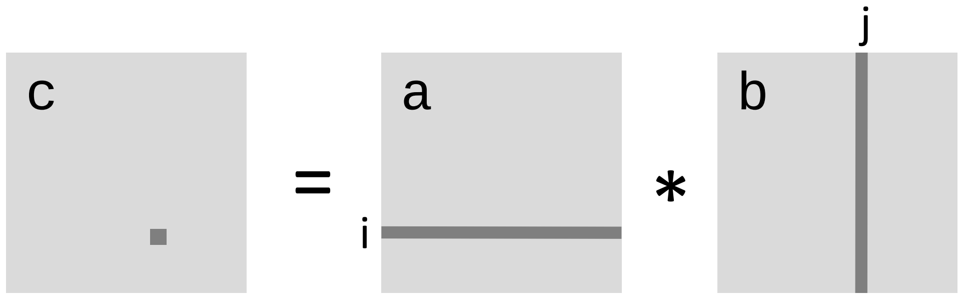
Should we handle 3 & 4 next or 5 & 6 ?

Part (b) : Blocking

- Blocking: divide matrix into sub-matrices.
- Size of sub-matrix depends on cache block size, cache size, input matrix size.
- Try different sub-matrix sizes.

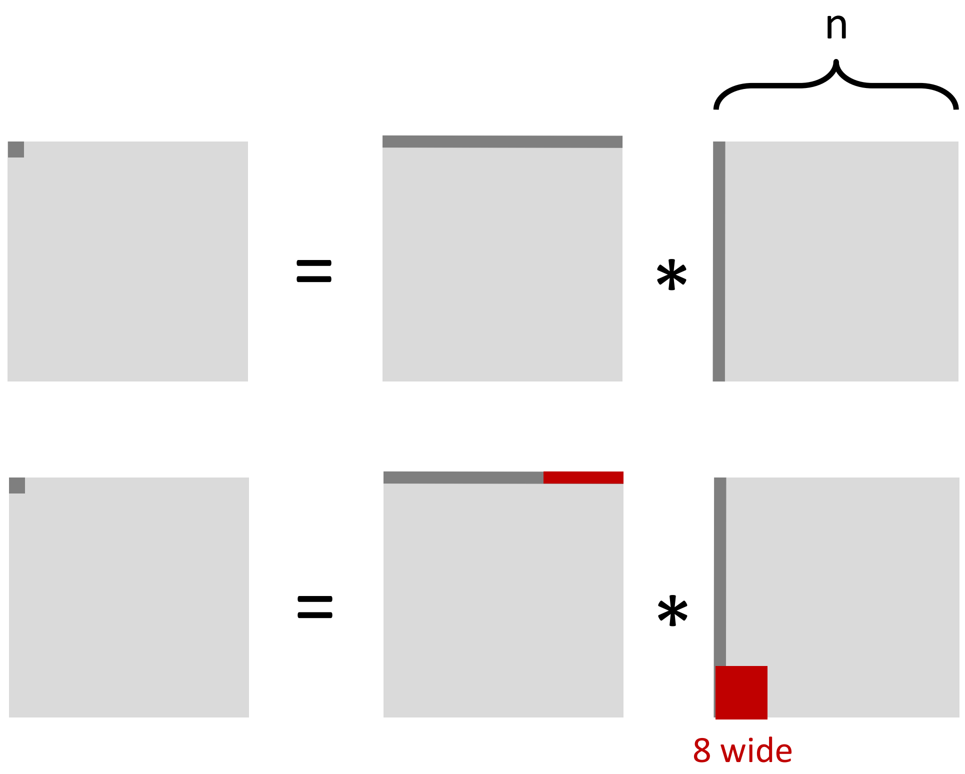
Example: Matrix Multiplication

```
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) {
    int i, j, k;
    for (i = 0; i < n; i++)
     for (j = 0; j < n; j++)
             for (k = 0; k < n; k++)
              c[i*n + j] += a[i*n + k] * b[k*n + j];
}
```



Cache Miss Analysis

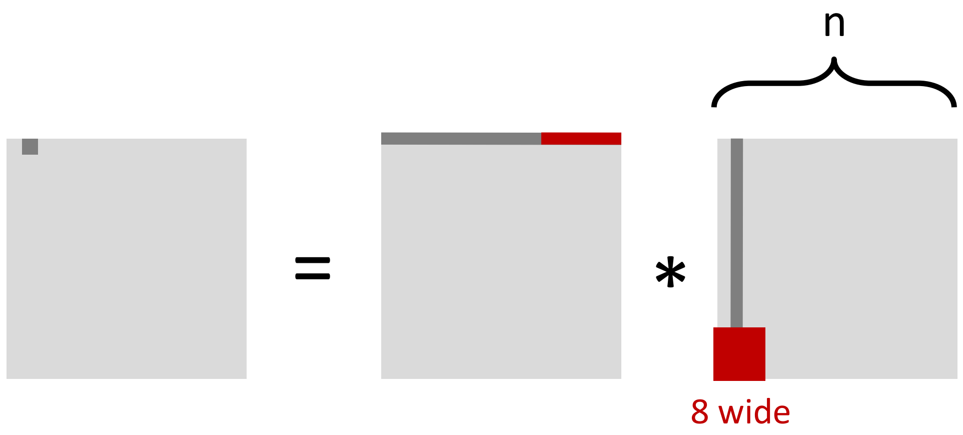
- **Assume:**
  - Matrix elements are doubles
  - Cache block = 8 doubles
  - Cache size C << n (much smaller than n)
- **First iteration:**
  - n/8 + n = 9n/8 misses
  - Afterwards in cache: (schematic)



Cache Miss Analysis

- **Assume:**
  - Matrix elements are doubles
  - Cache block = 8 doubles
  - Cache size C << n (much smaller than n)

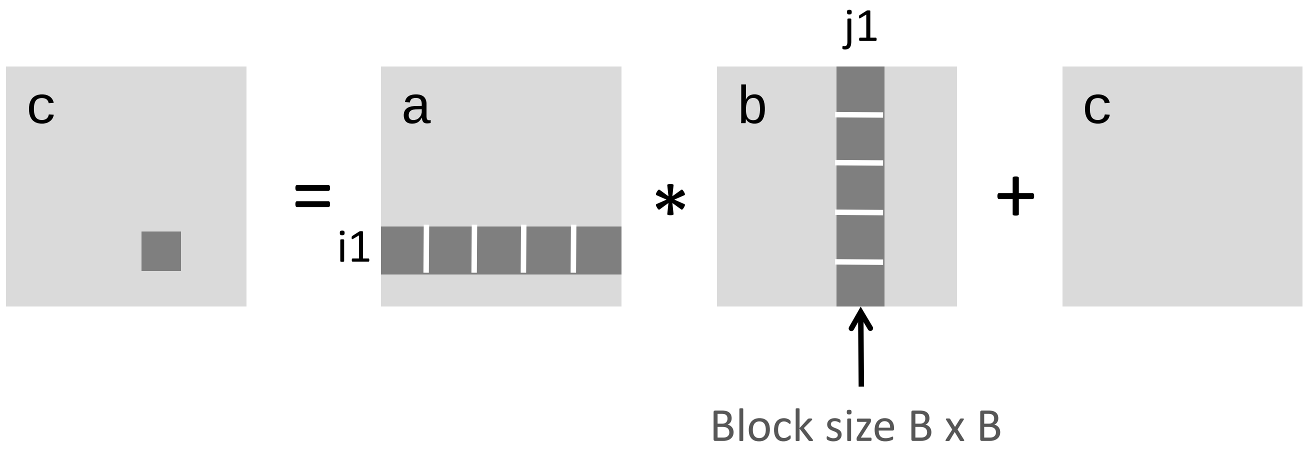
- **Second iteration:**
  - Again:
    n/8 + n = 9n/8 misses



- **Total misses:**
  - $9n/8 * n^2 = (9/8) * n^3$

Blocked Matrix Multiplication

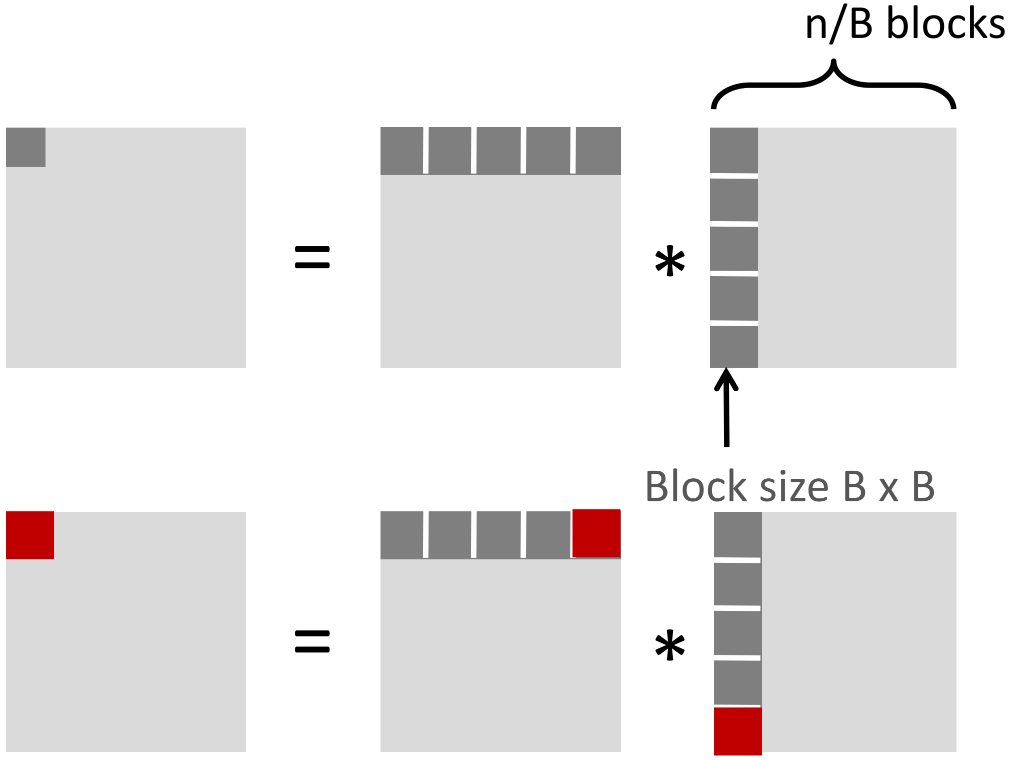
```
c = (double *) calloc(sizeof(double), n*n);

/* Multiply n x n matrices a and b  */
void mmm(double *a, double *b, double *c, int n) {
    int i, j, k;
    for (i = 0; i < n; i+=B)
     for (j = 0; j < n; j+=B)
             for (k = 0; k < n; k+=B)
         /* 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];
}
```



Cache Miss Analysis

- **Assume:**
  - Cache block = 8 doubles
  - Cache size C << n (much smaller than n)
  - Three blocks ■ fit into cache: $3B^2 < C$

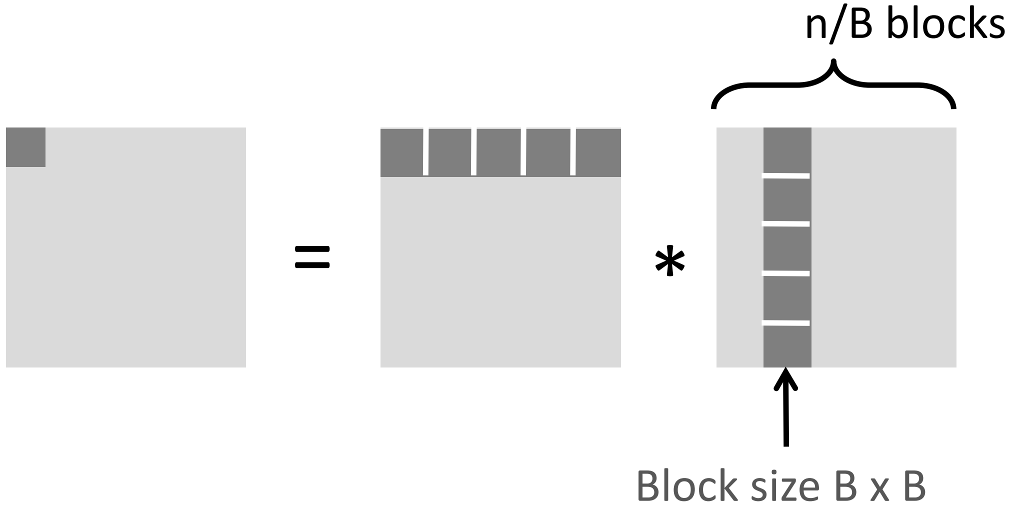
- **First (block) iteration:**
  - $B^2/8$ misses for each block
  - $2n/B * B^2/8 = nB/4$ (omitting matrix c)
  - Afterwards in cache (schematic)



Cache Miss Analysis

- **Assume:**
  - Cache block = 8 doubles
  - Cache size C << n (much smaller than n)
  - Three blocks ■ fit into cache: $3B^2 < C$

- **Second (block) iteration:**
  - Same as first iteration
  - $2n/B * B^2/8 = nB/4$



- **Total misses:**
  - $nB/4 * (n/B)^2 = n^3/(4B)$

Part(b) : Blocking Summary

- **No blocking: (9/8) * n^3**
- **Blocking: 1/(4B) * n^3**

- **Suggest largest possible block size B, but limit $3B^2 < C$!**

- **Reason for dramatic difference:**
  - Matrix multiplication has inherent temporal locality:
    - Input data: $3n^2$, computation $2n^3$
    - Every array elements used O(n) times!
  - But program has to be written properly

- **For a detailed discussion of blocking:**
  - http://csapp.cs.cmu.edu/public/waside.html

Part (b) : Specs

- **Cache:**
  - You get 1 kilobytes of cache
  - 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

Part (b)

- **Things you'll need to know:**
  - Warnings are errors
  - Header files
  - Eviction policies in the cache

Warnings are Errors

- **Strict compilation flags**

- **Reasons:**
  - Avoid potential errors that are hard to debug
  - Learn good habits from the beginning

- **Add "-Werror" to your compilation flags**

Missing Header Files

- **Remember to include files that we will be using functions from**

- **If function declaration is missing**
  - Find corresponding header files
  - Use: man <function-name>

- **Live example**
  - man 3 getopt

Eviction policies of Cache

- **The first row of Matrix A evicts the first row of Matrix B**
  - Caches are memory aligned.
  - Matrix A and B are stored in memory at addresses such that both the first elements align to the same place in cache!
  - Diagonal elements evict each other.

- **Matrices are stored in memory in a row major order.**
  - If the entire matrix can’t fit in the cache, then after the cache is full with all the elements it can load. The next elements will evict the existing elements of the cache.
  - Example:- 4x4 Matrix of integers and a 32 byte cache.
    - The third row will evict the first row!

Style

- **Read the style guideline**
  - But I already read it!
  - Good, read it again.
- **Start forming good habits now!**

Questions?