15-213 Recitation 7: Caches and Blocking

22 Feb 2016

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Agenda

- Reminders
- Revisiting caching
- getopt() and fscanf()
- Blocking to reduce cache misses

Reminders

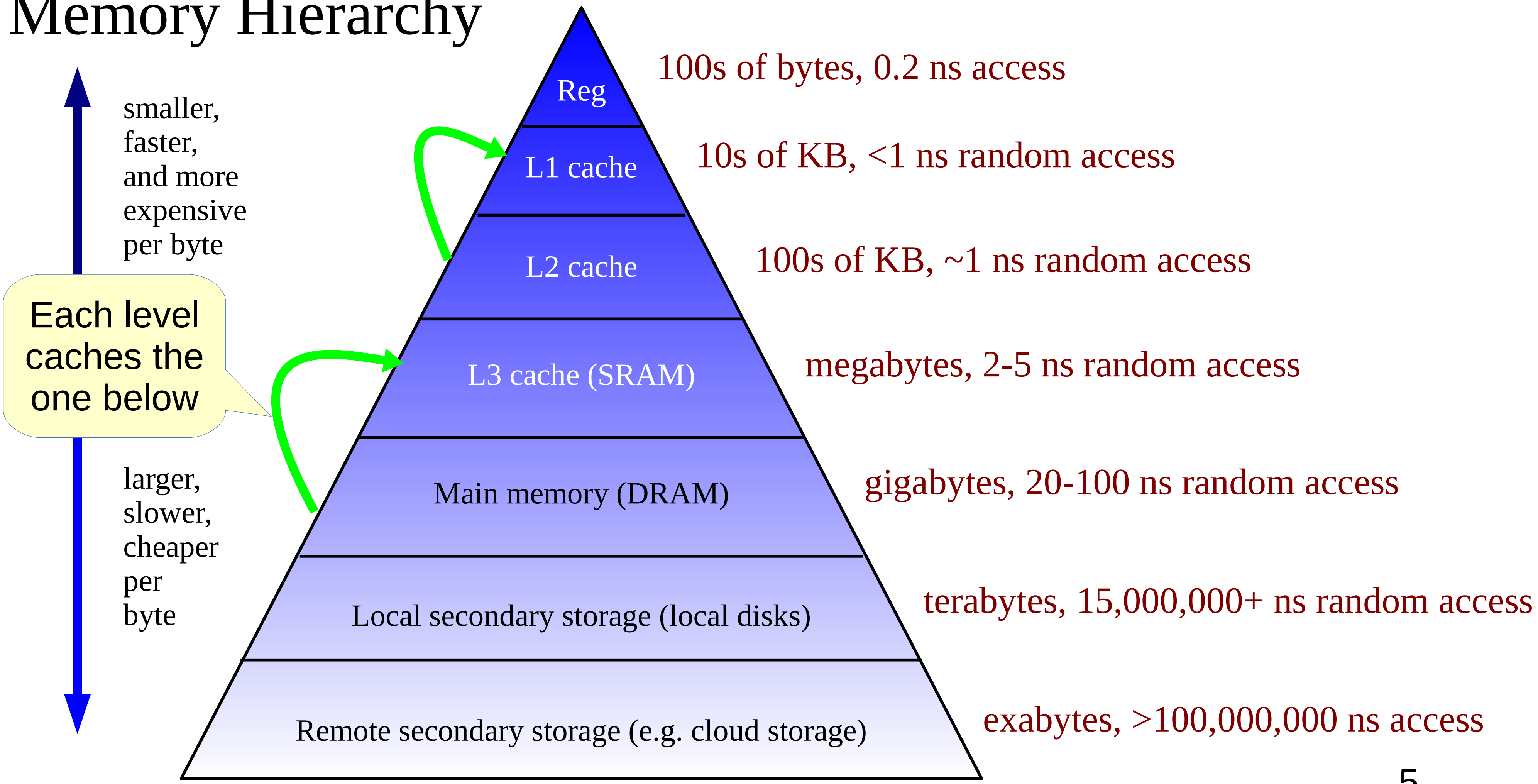
- Cache Lab is due **Thursday!**
- tshlab will be released **Thursday.**
- Exam1 is just a week away!
    - Start doing practice problems.
    - Come to the review session.

Image credit: flickr.com / kellt825@yahoo.com

Reminders: Cache Lab

- Two parts
  - write a cache simulator – hopefully you've started this part by now
  - optimize some code to minimize cache misses – we'll talk about this today
- Programming style will be graded starting now
  - worth about a letter grade on this assignment
  - a summary slide is included as an appendix to this recitation, but be sure to **carefully** read the style guide
- Details are in the writeup!

Memory Hierarchy



Cache Miss Types

- First access is a *cold miss*
- Remember this example? We had to evict a line despite having unused cache lines
  - this causes a *conflict miss* when we later want to access the evicted line
- If we repeatedly read 1024 consecutive bytes, the first byte will have been evicted by the time we read it again
  - this is called a *capacity miss*

	V	LRU	Tag	Data
Set0	1	1	0x15212 **EVICT**	A B C D
	1	0	0x15213	I J K L
Set1	0	-	--	- - - -
	0	-	--	- - - -
Set2	1	1	0x15212	E F G H
	1	0	0x15213	M N O P
Set3	0	-	--	- - - -
	0	-	--	- - - -

Cache Replacement Policies

- When we need to evict a cache line, which one do we choose?
  - Least Recently Used – replace the data which has gone unused longest
  - Least Frequently Used
  - First-In, First Out – replace the oldest data
  - Random
  - (no choice for direct-mapped)
- Policy is implemented in hardware for speed

Cache Lab: Cache Simulator Hints

- You are simply **counting** hits, misses, and evictions
- Use LRU (Least Recently Used) replacement policy
- Structs are a great way to bundle up the different parts of a cache line (valid bit, tag, LRU counter, etc.)
- A cache is just a 2D array of *cache lines*
  - one dimension represents associativity E, the other the number of sets S:
    `struct cache_line cache[S][E];`
- Your simulator needs to handle different values of S, E, and b (block size) given at run time

Cache Lab: Parsing Commandline Options

./myprog -a -n myarg

- getopt() is a standard way to extract items from the command line
  - usually called in a loop until it returns -1 (no more inputs)
  - returns the flag it has just parsed ("a", "n", etc.)
    - use a switch statement to handle each flag separately
    - if the flag has an associated argument ("myarg"), its **string** value is stored in the global variable `optarg`
  - See `man 3 getopt` for more information
- **Your program must** `#include <unistd.h>` **to use getopt**

getopt Example

```
#include <stdio.h>  /* for printf */
#include <unistd.h> /* for getopt */

int main(int argc, char **argv) {
   int opt, aflag=0, nflag=0;
   float xflag=0.0;
   /* loop over arguments */
   while (-1 != (opt = getopt(argc, argv, “an:y:”))) {
      /* determine which argument was found */
      switch (opt) {
         case 'a':  aflag=1;                      break;
         case 'n':  nflag=atoi(optarg);           break;
         case 'x':  xflag=atof(optarg);           break;
         default:   printf(“unknown argument”); break;
      }
   }
   return 0;
}
```

getopt Example

```
#include <stdio.h>   /                */
#include <unistd.h>  /                *

int main(int argc, ch
   int opt, aflag=0, nflag=0;
   float xflag=0.0;
   /* loop over arguments */
   while (-1 != (opt = getopt(argc, argv, "an:y:"))) {
      /* determine which argument was found */
      switch (opt) {
         case 'a':  aflag=1;                     break;
         case 'n':  nflag=atoi(optarg);          break;
         case 'x':  xflag=atof(optarg);          break;
         default:   printf("unknown argument"); break;
      }
   }
   return 0;
}
```

repeat until all flags have been handled

commandline data (arg count and args)

valid flag letters. an appended colon means the flag takes an argument to be put in `optarg`

handle the individual flags

always handle the unexpected

convert string to integer or float

Cache Lab: Parsing Input with fscanf

- fscanf() is exactly like scanf() except that you specify the stream to use (i.e. an open file) instead of always reading from standard input
- its parameters are
  1. a stream pointer of type FILE*, e.g. from fopen()
  2. a format string specifying how to parse the input

  3-n. a **pointer** to each of the variables that will store the parsed data
- fscanf() returns -1 if the data does not match the format string or there is no more input
- Use it to parse the trace files

fscanf() Example

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

pFile = fopen(“trace.txt”,”r”); /* open trace file for reading */
/* verify that pFile is non-NULL! */

char access_type;
unsigned long address;
int size;

/* line format is “ S 2f,1” or “ L 7d0,3” */
/* so we need to read a character, a hex number, and a decimal number */
/* put those in the format string along with the fixed formatting */
while (fscanf(pFile,” %c %lx,%d”, &access_type, &address, &size) > 0) {
   /* do stuff */
}

fclose(pFile);  /* always close file when done */
```

Cache Lab: malloc/free

- You will need to allocate memory that can persist across functions
- Use malloc() to get some memory from the heap
- Use free() to de-allocate that memory:

```
int *malloced_pointer = malloc(sizeof(int));
```

... do something with malloced_pointer ...

```
free(malloced_pointer);
```

- **Never free memory you didn't allocate:** this can cause strange behavior or crashes with no obvious cause later in the program
- **Always free what you malloc:** if you forget, you get a memory leak

Cache Lab: Helpful Information

- getopt
  - `man 3 getopt`
  - http://www.gnu.org/software/libc/manual/html_node/Getopt.html
- fscanf
  - `man fscanf`
  - http://crasseux.com/books/ctutorial/fscanf.html
  - http://www.gnu.org/software/libc/manual/html_node/Table-of-Input-Conversions.html

Cache-Friendly Code

- Keep memory accesses bunched together
  - in both time and space (address)
  - the *working set* at any time should be smaller than the cache
- Avoid access patterns that cause conflict misses
  - memory *strides* in powers of two that cause all accesses to use only a few (or just one!) cache set

Temporal Locality

- Q: Which of the functions on the right has fewer cache misses when `n` is large?

```
void fn1(int *a, int *b, int n){
   for (int i=0; i<n; i++)
      b[i] *= a[i];
   for (int i=0; i<n; i++)
      a[i] += b[i];
}

void fn2(int *a, int *b, int n){
   for (int i=0; i<n; i++) {
      b[i] *= a[i] ;
      a[i] += b[i];
   }
}
```

Temporal Locality

- Q: Which of the functions on the right has fewer cache misses when `n` is large?
- A: `fn2`, because the repeated element accesses happen together
- In `fn1`, each array element will have been evicted by the time the second loop accesses it again (a *capacity miss* because the working set is larger than the cache)

```
void fn1(int *a, int *b, int n){
    for (int i=0; i<n; i++)
        b[i] *= a[i];
    for (int i=0; i<n; i++)
        a[i] += b[i];
}

void fn2(int *a, int *b, int n){
    for (int i=0; i<n; i++) {
        b[i] *= a[i] ;
        a[i] += b[i];
    }
}
```

Spatial Locality

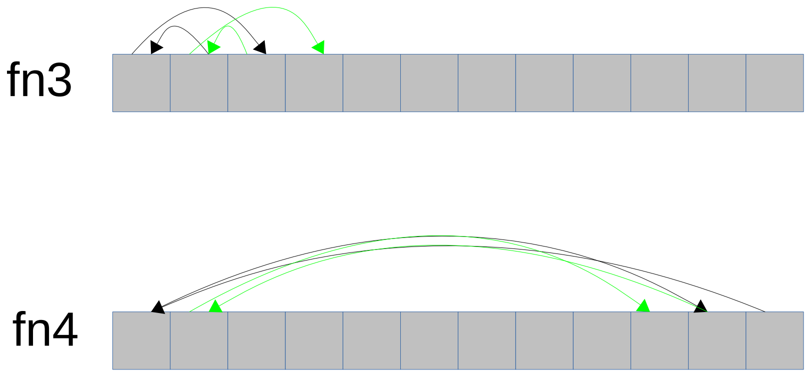
- Q: Which of the functions on the right has fewer cache misses when `n` is large?

```
void fn3(int *a, int n) {
   for (int i=1; i<n; i++) {
      a[i] *= 2;
      a[i-1] *= 3;
   }
}

void fn4(int *a, int n) {
   for (int i=1; i<=n; i++) {
      a[n-i] *= 2; /*reverse order*/
      a[i-1] *= 3;
   }
}
```

Spatial Locality

- Q: Which of the functions on the right has fewer cache misses when `n` is large?
- A: `fn3`, because successive array accesses are adjacent to each other




```
void fn3(int *a, int n) {
    for (int i=1; i<n; i++) {
        a[i] *= 2;
        a[i-1] *= 3;
    }
}

void fn4(int *a, int n) {
    for (int i=1; i<=n; i++) {
        a[n-i] *= 2; /*reverse order*/
        a[i-1] *= 3;
    }
}
```

Cache Lab: Efficient Matrix Transpose

- Transposing a matrix essentially swaps its two dimensions:

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

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

- a[i][j] becomes a[j][i]

- How do we minimize the number of cache misses while performing this operation?

Efficient Matrix Transpose

A:

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

B:

1	-	-	-
2	-	-	-
-	-	-	-
-	-	-	-

- If a cache line holds 2 doubles, copying 1 and 2 causes
  - A[0][0] miss
  - B[0][0] miss
  - A[0][1] hit
  - B[1][0] miss
- Will it be better to copy 3&4 or 5&6 next?

Efficient Matrix Transpose

A:

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

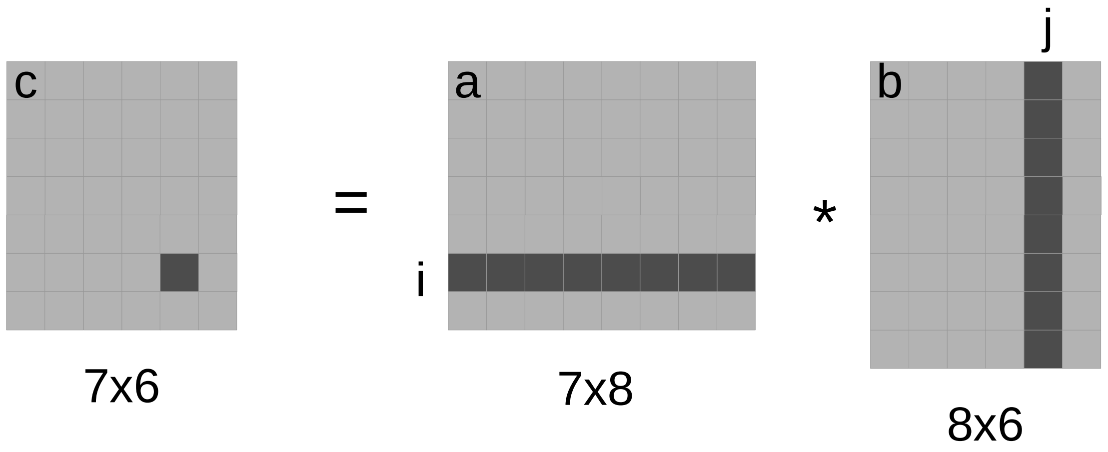
B:

1	-	-	-
2	-	-	-
-	-	-	-
-	-	-	-

- Copying 3&4:
  - A[0][2] miss
  - B[2][0] miss
  - A[0][3] hit
  - B[3][0] miss
- Copying 5&6:
  - A[1][0] miss
  - B[0][1] hit
  - A[1][1] hit
  - B[1][1] hit

Blocking Example: Matrix Multiplication

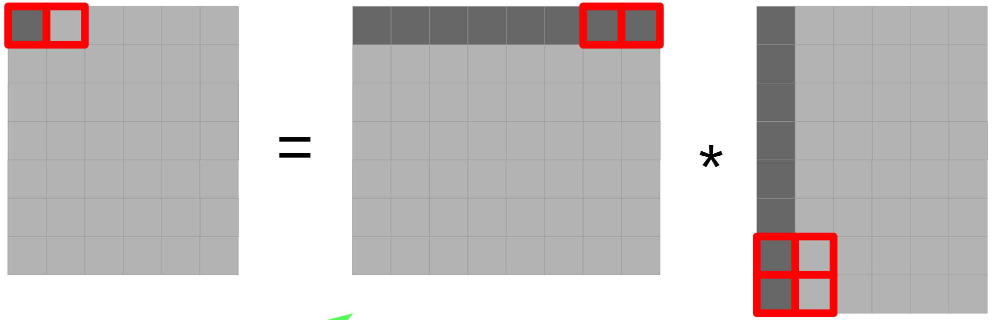
- Multiply an MxN matrix by a NxK matrix to yield an MxK matrix by taking the “dot product” of corresponding rows and columns:



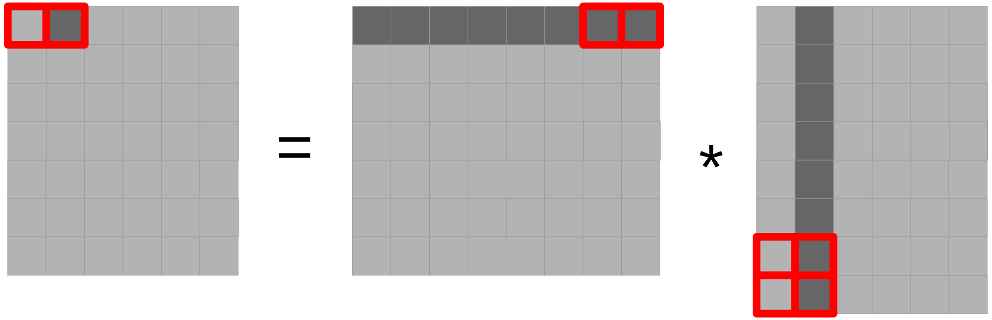
- The dot product is the sum of the products of corresponding elements:
  - for (k=0; k<n; k++) c[i][j] += a[i][k] * b[k][j];

Blocking Example: Matrix Multiplication

- Assume a really tiny cache with four lines of 16 bytes (2 doubles)
- After computing c[0][0], we will have accessed the dark gray cells, and the red-bordered cells will be in the cache:

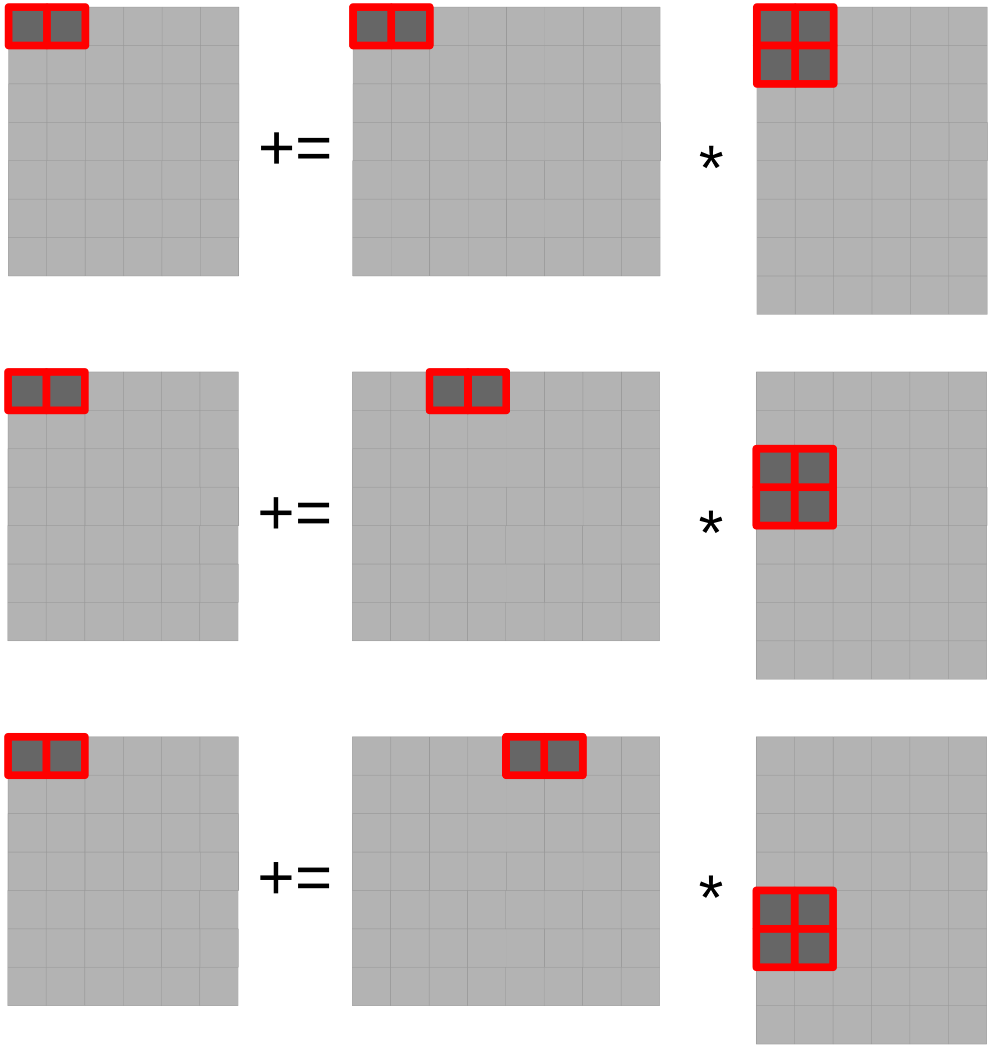


- In computing c[0][1], every single access in `b`, and half the accesses in `a`, will be capacity misses! (*why?*) Once done, the cache contents will be as shown.

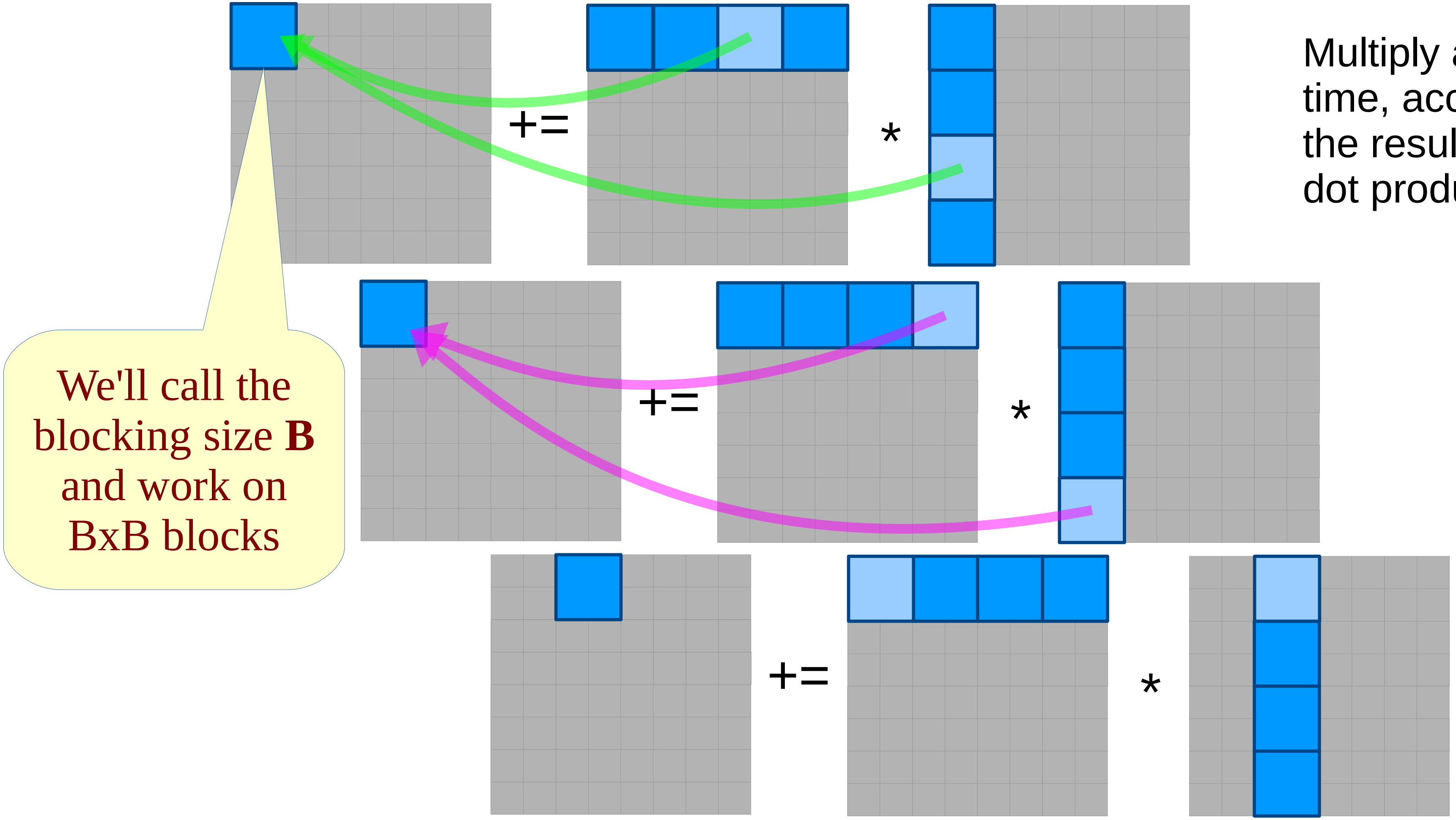


Blocked Matrix Multiplication

- Let's re-order the computation to build up the c[i][j] values a piece at a time
  - this works because they are sums of products
- Notice how each step of the calculation stays within the cache's capacity



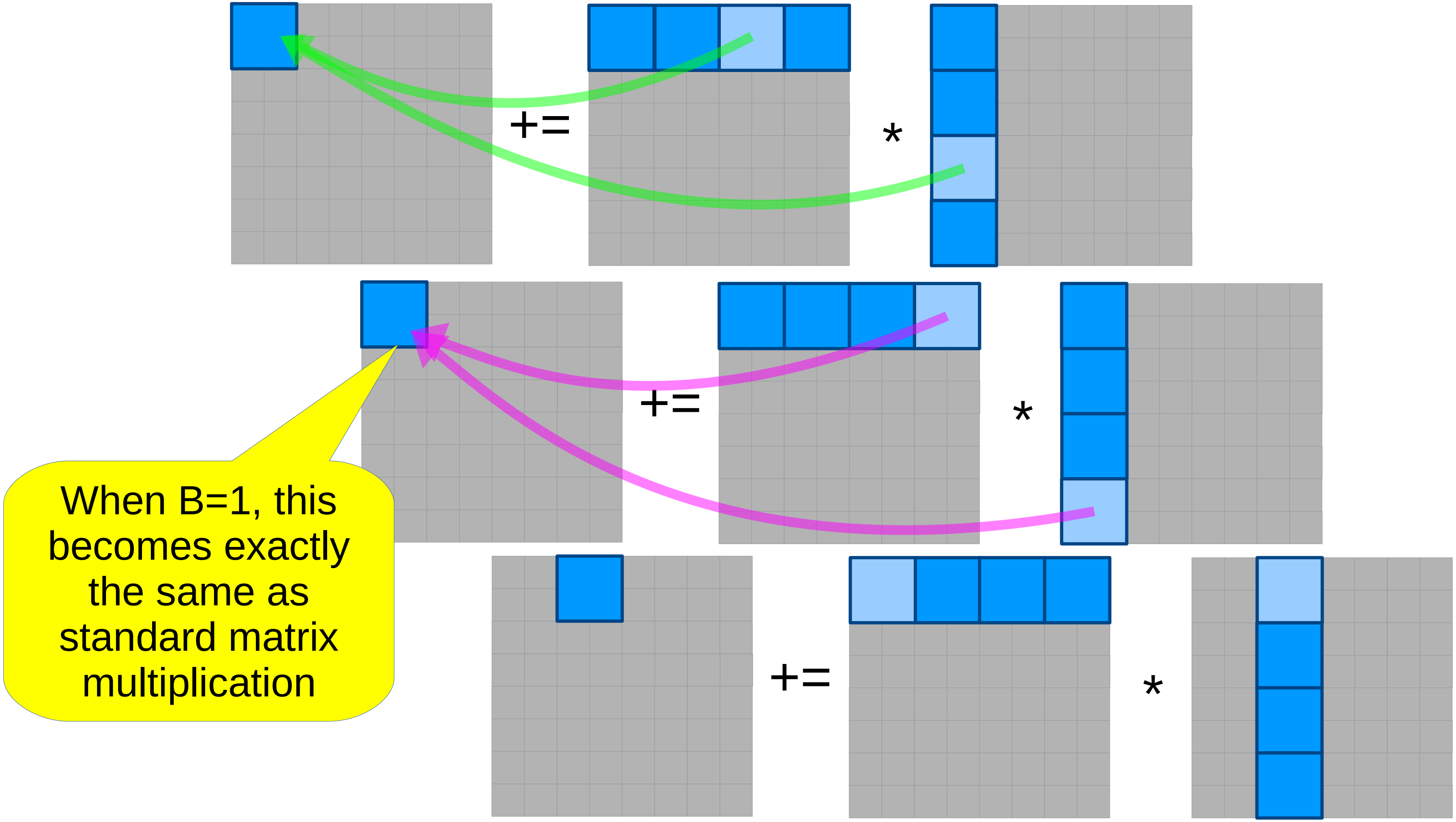
Blocked Matrix Multiplication



Multiply a block at a time, accumulating the results of the BxB dot products

Then move on to the next result block

Blocked Matrix Multiplication



Standard Matrix Multiplication: Code

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

void matrix_mult(double *a, double *b, double *c, int n) {
   int i, j, k;
   /* process each row */
   for (i=0; i<n; i++)
      /* process each column */
      for (j=0; j<n; j++)
         /* run the dot-product of the current row/column */
         for (k=0; k<n; k++)
            c[i*n+j] += a[i*n+k] * b[k*n+j];
}
```

Blocked Matrix Multiplication: Code

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

void matrix_mult(double *a, double *b, double *c, int n) {
   int i, j, k;
   /* process each row of blocks */
   for (i=0; i<n; i+=B)
      /* process each column of blocks */
      for (j=0; j<n; j+=B)
         /* run the dot-product of the current row/column of blocks */
         for (k=0; k<n; k+=B)
            /* perform BxB mini matrix multiplications */
            for (int i1=i; i1<i+B; i1++)
               for (int j1=j; j1<j+B; j1++)
                  for (int k1=k; k1<k+B; k1++)
                     c[i1*n+j1] += a[i1*n+k1] * b[k1*n+j1];
}
```

boldface shows changes from non-blocked

Cache Miss Analysis: Standard vs Blocked Matrix Mult

Standard:

- computing element `c[i][j]` costs*
  - n/8 misses for `a[i][k]`
  - n misses for `b[k][j]`
  - = 9n/8 misses per element
- there are n^2 elements in `c`
- total misses: $9n/8 * n^2 = (9/8) * n^3$

Blocked:

- for block size BxB such that $3B^2$ lines fit in cache
  - $B^2/8$ misses per block
  - 2n/B input blocks touched per result block
  - n^2/B^2 result blocks
- total misses: $B^2/8 * 2n/B * n^2/B^2$

  $= 1/(4B) * n^3$
- example: 4096 cache lines, B=32
  - $1/128\ n^3$ misses

* Assuming **n**x**n** matrices, 8 doubles per cache line, and cache size much smaller than **n** lines

Cache Lab: Blocking for Efficient Matrix Transposition

- Divide matrix into sub-matrices that best fit into cache
- The optimimum size depends on the cache parameters and matrix size
  - try different sub-matrix sizes
- CacheLab's cache specs:
  - 1 KB direct-mapped (E=1)
  - 32 sets (s=5) with block size 32 bytes (b=5)
- Your test matrices:
  - 32 by 32
  - 64 by 64
  - 61 by 67

It's OK to special-case each of these sizes

If You Get Stuck

- **Please read the writeup.** ***Please read the writeup.*** ***<u>Please read the writeup.</u>*** ***Please read the writeup!***
- CS:APP Chapter 6
- View lecture notes and course FAQ at http://www.cs.cmu.edu/~213
- Office hours Sunday through Thursday 5:00-9:00pm in WeH 5207
- Post a **private** question on Piazza
- `man malloc`, `man gdb`, gdb's `help` command
- http://csapp.cs.cmu.edu/public/waside/waside-blocking.pdf

If I had a penny for every time someone

asked a question answered in the writeup....

Appendix: Programming Style

- Properly document your code
  - 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
- Formatting
  - 80 characters per line
  - consistent braces and whitespace
- No memory or file descriptor leaks