15-213 Recitation 6: C and Cache Lab

15 Feb 2016
Ralf Brown and the 15-213 staff

Agenda

- Reminders
- Lessons from Attack Lab
- C Assessment
- Caches
- Cache Lab Overview
- Appendix: Programming Style
- Appendix: valgrind
- Appendix: Contech

Reminders

- Attack Lab is due **tomorrow!**
  - "But if you wait until the last minute, it only takes a minute!" - ***NOT!***
- Cache Lab will be released **tomorrow!**

Image credit: pixabay.com

Lessons from Attack Lab

- **Never**, **ever** use `gets`
  - use `fgets` instead if you need that functionality
- Use functions that pass an explicit buffer length if possible
  - `strncpy/strncat` instead of `strcpy/strcat`, `snprintf` instead of `sprintf`
- Limit `scanf/fscanf` input lengths with `%123s`
- Or use a function that dynamically allocates a large-enough buffer
  - `asprintf` (GNU library) instead of `sprintf`
- If none of those is possible, be **very** careful about checking input size
- Stack protections make it harder to exploit a buffer overflow – but not impossible

C Assessment

- Can you **easily** answer all of the problems on the following slides?
- If not, please come to the C Bootcamp:
  - Time, Location TBA
- You need this for the rest of the course. **If in doubt, come to the C Bootcamp!**

C Assessment 1: Spot the Errors

```
int main() {
   int *a = malloc(100 * sizeof(int));
   for (int i=0; i<100; i++) {
      if (a[i] == 0) a[i]=i;
      else a[i]=0;
   }
   free(a);
   return 0;
}
```

C Assessment 1: Spot the Errors

malloc can return NULL – segmentation violation!

```
int main() {
   int *a = malloc(100 * sizeof(int));
   for (int i=0; i<100; i++) {
      if (a[i] == 0) a[i]=i;
      else a[i]=0;
   }
   free(a);
   return 0;
}
```

C Assessment 1: Spot the Errors

malloc can return NULL – segmentation violation!

returned memory is
uninitialized – undefined results

```
int main() {
   int *a = malloc(1      sizeof(int));
   for (int i=0; i<100; i++) {
      if (a[i] == 0) a[i]=i;
      else a[i]=0;
   }
   free(a);
   return 0;
}
```

C Assessment 1: Spot the Errors

```
int main() {
   int *a = calloc(100, sizeof(int));
   if (a == NULL){...handle error...}
   for (int i=0; i<100; i++) {
      if (a[i] == 0) a[i]=i;
      else a[i]=0;
   }
   free(a);
   return 0;
}
```

- Fixes
  - use `calloc` to get zeroed-out memory
  - check `a` before using it
- Note: variable declaration in the “for” statement requires --std=c99 flag to gcc – you'll get an error without it

C Assessment 2: Macros

```
#define IS_GREATER(a, b) a > b

int is_greater(int a, int b) {
   return a > b;
}

int A = IS_GREATER(1, 0) + 1;
int B = is_greater(1, 0) + 1;
```

- What is A?
- What is B?

C Assessment 2: Macros

```
#define IS_GREATER(a, b) a > b

int is_greater(int a, int b) {
   return a > b;
}

int A = IS_GREATER(1, 0) + 1;
int B = is_greater(1, 0) + 1;
```

- What is A?
  - 0
- What is B?
  - 2

C Assessment 2: Macros

```
#define IS_GREATER(a, b) a > b

int is_greater(int a, int b) {
   return a > b;
}

int A = IS_GREATER(1, 0) + 1;
int B = is_greater(1, 0) + 1;
```

macros are pure textual substitution

- What is A?
  - 0
  - int A = 1 > 0 + 1;
  - 1 > 1 is false
- What is B?
  - 2
  - is_greater(1,0) returns 1, then we add 1 to that as expected

C Assessment 3: Find the Errors

```
int *foo(int *allocate) {
   int a = 3;
   allocate = malloc(sizeof(int));
   if (allocate == NULL) abort();
   return &a;
}
```

C Assessment 3: Find the Errors

Memory leak!
allocate is a local copy of the pointer that goes away when the function returns

```
int *foo(int *allocate) {
   int a = 3;
   allocate = malloc(sizeof(int));
   if (allocate == NULL) abort();
   return &a;
}
```

C Assessment 3: Find the Errors

Memory leak!
allocate is a local copy of the pointer that goes away when the function returns

To return the memory, we need a pointer to a pointer, and an extra dereference on assignment

```
int *foo(int *allocate) {
   int a = 3;
   allocate = malloc(sizeo
   if (allocate == NULL) a
   return &a;
}
```

```
int *foo(int **allocate) {
   int a = 3;
   *allocate = malloc(sizeof(int));
   if (*allocate == NULL) abort();
   return &a;
}
```

C Assessment 3: Find the Errors

returning the address of a local variable yields unpredictable results (**why?**)

```
int *foo(int *allocate) {
   int a = 3;
   allocate = malloc(sizeof(int));
   if (allocate == NULL) abort();
   return &a;
}
```

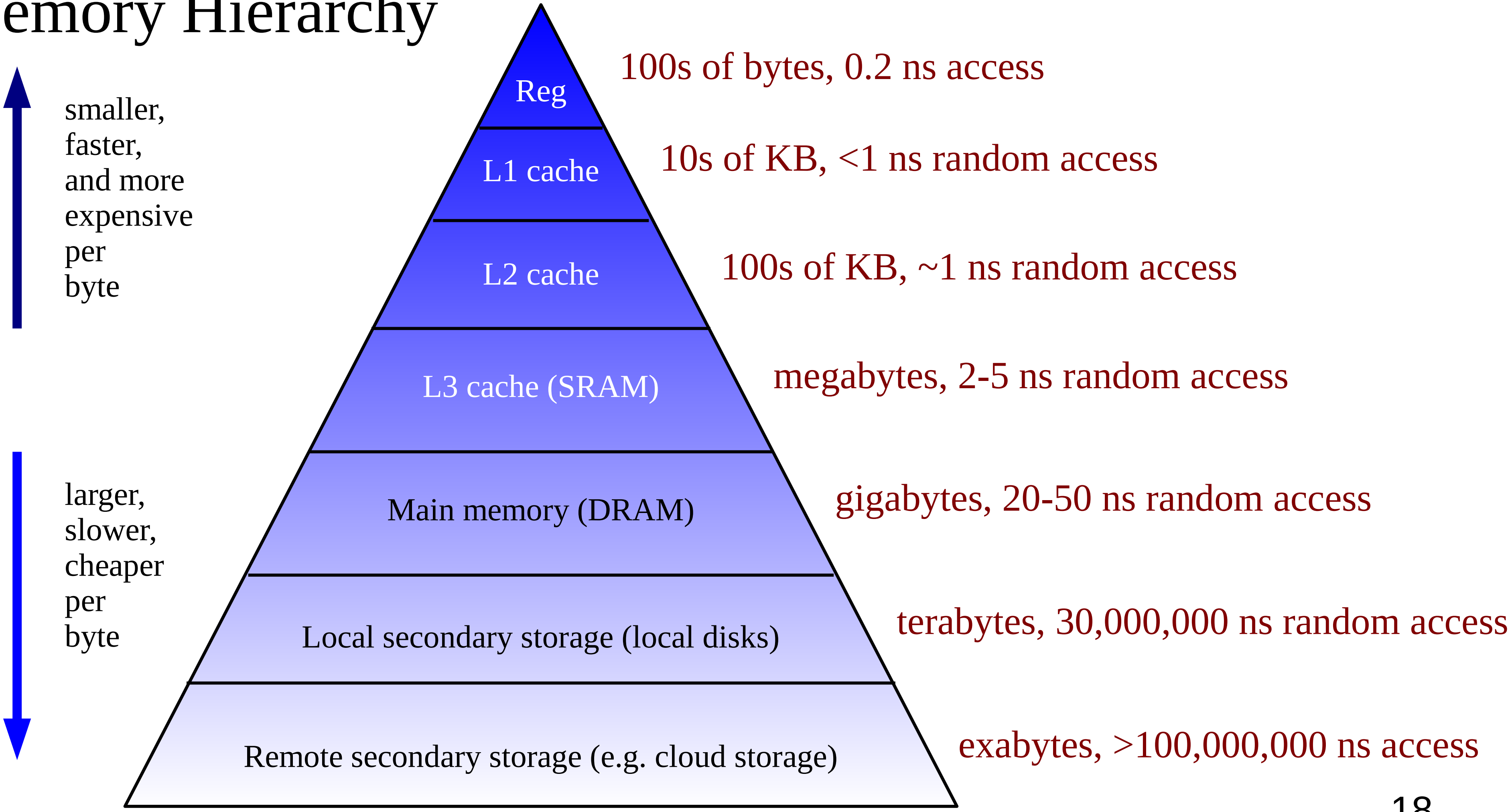
C Assessment

- Did you know the answers to all of the problems? If not,

  COME TO THE C BOOTCAMP

-

Memory Hierarchy



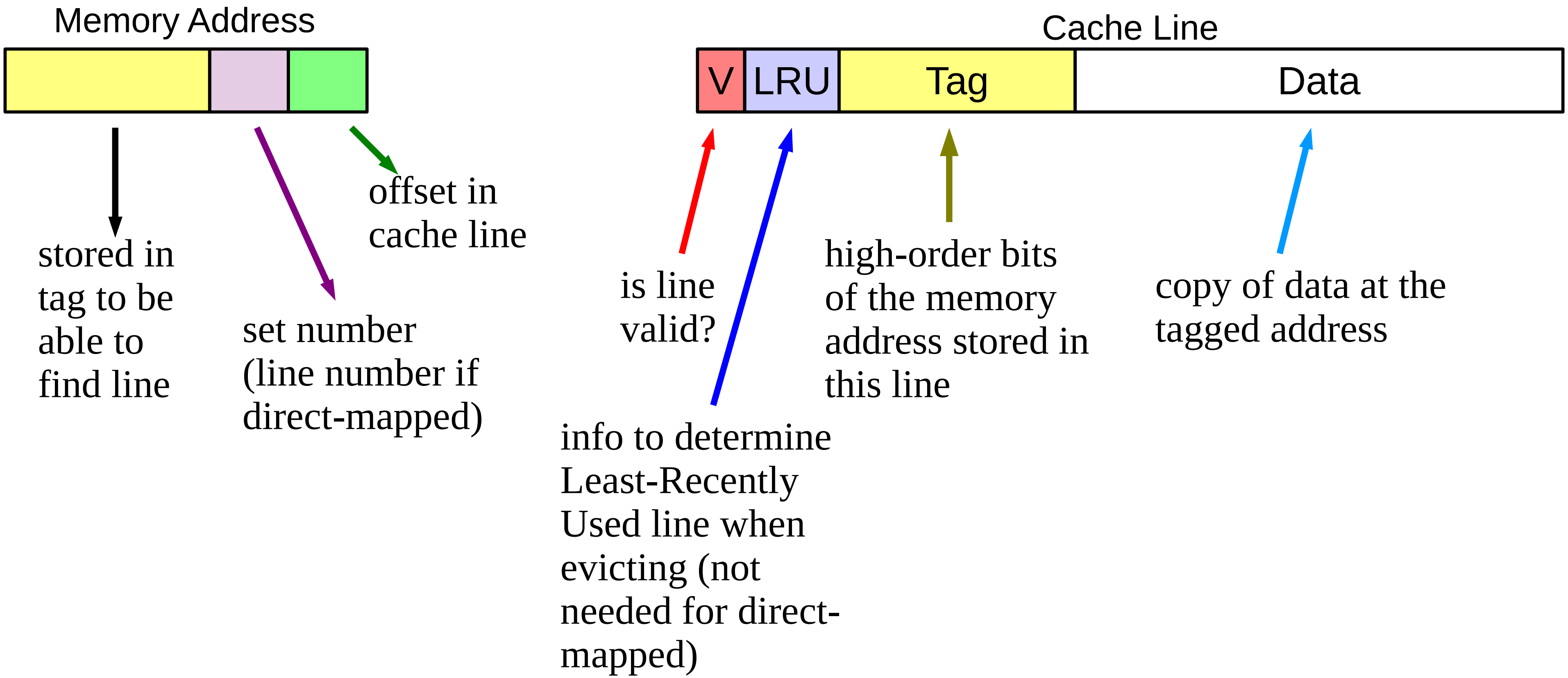
Caching

- Copy a subset of data from slower storage into faster as it is accessed
- If requested data is not yet cached and must first be copied, that is a “cache miss”
- If requested data is already available in the faster storage, that is a “hit”
- If the cache is full, a miss causes an existing entry to be discarded (“evicted”)

Cache Types

- **Fully-associative cache:** any memory location can be stored in any cache line
  - impractical to build in reasonably large size
- **Direct-mapped cache:** each memory location must be stored in a specific cache line
  - easiest to implement, but has poorer performance
- **N-way set-associative cache:** each memory location is associated with a set of N cache lines (typically 2, 4, 8, or 16), and can be stored in any one of the cache lines within that set
  - compromise – easier to implement than fully-associative, better performance than direct-mapped

Direct-Mapped and Set-Associative Caches



Set-Associative Cache: 2-way Example

- Consider the following eight-entry 2-way associative cache with 64 bytes per cache line
- Address bits 0-5 become the index into the line's data
- Address bits 7-6 are the set number
- Remaining address bits become the tag

	V	LRU	Tag	Data
Set0	0	-	--	- - - - -
	0	-	--	- - - - -
Set1	0	-	--	- - - - -
	0	-	--	- - - - -
Set2	0	-	--	- - - - -
	0	-	--	- - - - -
Set3	0	-	--	- - - - -
	0	-	--	- - - - -

Set-Associative Cache: 2-way Example

- Let's read every 128th byte starting at 0x1521200
- 0x1521200 is

  0001 0101 0010 0001 0010 0000 0000
- that's the first byte of a line in set 0, with tag 0x15212
- it's a miss, so read from main memory and store in an available line in set 0

	V	LRU	Tag	Data
Set0	1	0	0x15212	A B C D
	0	-	--	- - - -
Set1	0	-	--	- - - -
	0	-	--	- - - -
Set2	0	-	--	- - - -
	0	-	--	- - - -
Set3	0	-	--	- - - -
	0	-	--	- - - -

Set-Associative Cache: 2-way Example

- Next, we read 0x1521280

  0001 0101 0010 0001 0010 1000 0000
- that's the first byte of a line in set 2, with tag 0x15212
- it's a miss, so read from main memory and store in set 2

	V	LRU	Tag	Data
Set0	1	0	0x15212	A B C D
	0	-	--	- - - -
Set1	0	-	--	- - - -
	0	-	--	- - - -
Set2	1	0	0x15212	E F G H
	0	-	--	- - - -
Set3	0	-	--	- - - -
	0	-	--	- - - -

Set-Associative Cache: 2-way Example

- 0x1521300:

  0001 0101 0010 0001 0011 0000 0000

- that's the first byte of a line in set 0, with tag 0x15213
- it's once again a miss, so read from main memory and store in an empty line in set 0
- also update the LRU info

Set	V	LRU	Tag	Data
Set0	1	1	0x15212	A B C D
	1	0	0x15213	I J K L
Set1	0	-	--	- - - -
	0	-	--	- - - -
Set2	1	0	0x15212	E F G H
	0	-	--	- - - -
Set3	0	-	--	- - - -
	0	-	--	- - - -

Set-Associative Cache: 2-way Example

- 0x1521380:

  0001 0101 0010 0001 0011 1000 0000
- that's the first byte of a line in set 2, with tag 0x15213
- yet another miss, so read from main memory and store in an empty line in set 2
- also update the LRU info

	V	LRU	Tag	Data
Set0	1	1	0x15212	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	-	--	- - - -

Set-Associative Cache: 2-way Example

- 0x1521400:

  0001 0101 0010 0001 0100 0000 0000
- that's the first byte of a line in set 0, with tag 0x15214
- missed yet again, so read from main memory and store in an empty line in set 0
- but set 0 is full, so we need to evict someone
- tag 0x15212 was least-recently used, so it goes

	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	-	--	- - - -

Set-Associative Cache: 2-way Example

- Note how we had to evict a line even though the cache still has empty entries

	V	LRU	Tag	Data
Set0	1	0	0x15214	Q R S T
	1	1	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 Lab

- Two parts
  - write a cache simulator
  - optimize some code to minimize cache misses
- 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!

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 valgrind`, `man gdb`, gdb's `help` command

KEEP
CALM
and
READ
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

Appendix: valgrind

- A suite of tools for debugging and profiling memory use, among other things
  - find where memory that wasn't freed was allocated
  - track origin of uninitialized values
  - show heap usage over time
  - detect reads and writes of invalid locations
  - detect illegal and double frees
  - trace individual memory accesses (used for cachelab)
  - report on race conditions in multi-threaded programs (useful later in the semester)

valgrind: Finding Memory Leaks

- valgrind --leak-resolution=high --leak-check=full --show-reachable=yes --track-fds=yes *./my_prog <args>*
- your program runs as normal, though much, **much** slower
  - read/write errors and uses of uninitialized values are reported as they occur
  - un-freed memory is reported on program termination

valgrind: Tracing Memory Accesses

- valgrind --log-fd=1 --tool=lackey -v --trace-mem=yes <*prog*> <*args*>
- writes a line to stdout for each memory operation the program makes
  - instruction fetches
  - data loads
  - data stores
  - data modifies (read followed by write, e.g. from `add $8,(%rsp)`)
- The writeup has details on the output format

Appendix: Contech

- We are rolling out a new method for generating memory traces
- Contech relies on specially-compiled executables that record their memory accesses to a file
  - this is much faster than Valgrind
  - outputs trace in same format as Valgrind, but omits instruction fetches
- More information on using Contech is coming soon
  - cachelab uses a simplified version of the original, which can be found at http://bprail.github.io/contech/