CSE 374 Programming concepts and tools

Winter 2024 Instructor: Alex McKinney

Buffer Overflow

Disclaimer

Before we begin the lecture, please note that my expertise is not in security.

Consider this as an introductory overview to spark your interest and understanding.

For comprehensive and specialized knowledge, you can take CSE 484 Computer Security or conduct further research beyond this lecture.

Feel free to ask questions; I'll do my best to address them within my knowledge.

Review: General Memory Layout

Stack

- Local variables (procedure context)

Heap

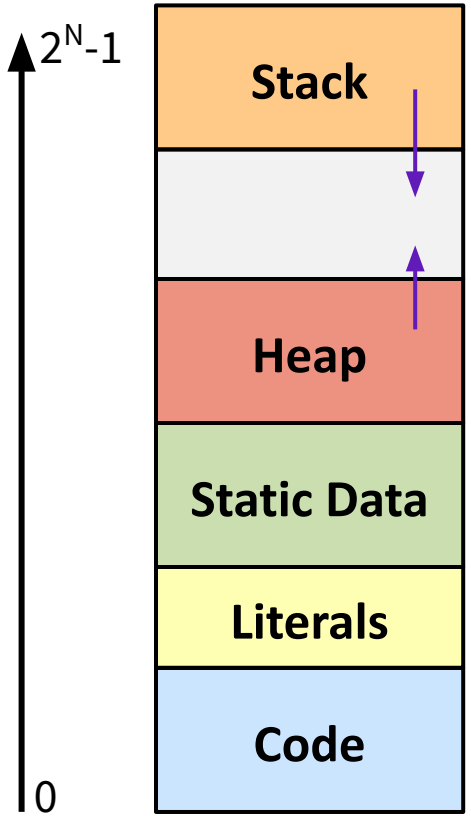
- Dynamically allocated as needed
- `malloc(),calloc(),new,...`

Statically allocated Data

- Read/write: global variables (Static Data)
- Read-only: string literals (Literals)

Code/Instructions

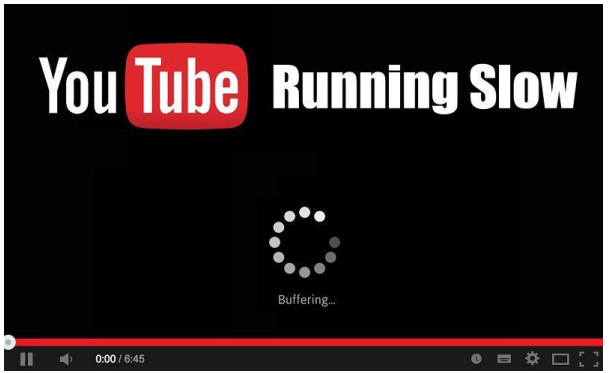
- Executable machine instructions
- Read-only



not drawn to scale

What Is a Buffer?

- A buffer is an array used to temporarily store data
- You've probably seen "video buffering…"
  - The video is being written into a buffer before being played
- Buffers can also store user input



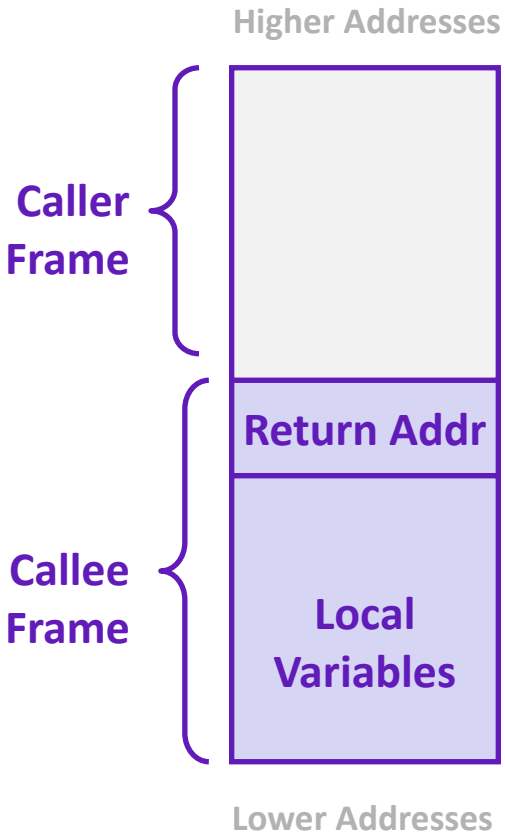
Linux Stack Frame

Stack stores active functions & local variables.

Each function call creates a frame:

- Caller's Stack Frame
- Current/ Callee Stack Frame
  - Return address: the next instruction after the function call in the program
    - This is how the callee returns to the caller!
  - Local variables (if they can't be kept in CPU registers)

This general idea is also applicable to Windows and macOS



Buffer Overflow

C does not check array bounds

- Many Unix/Linux/C functions don't check argument sizes
- Allows overflowing (writing past the end) of buffers (arrays)

"Buffer Overflow" = Writing past the end of an array

Characteristics of the traditional Linux memory layout provide opportunities for malicious programs

- Stack grows "backwards" in memory
- Data and instructions both stored in the same memory

Example

```c
#include <stdio.h>
void echo();
int main() {
    printf("Enter a string: ");
    echo();
    return 0;
}
void echo() {
    char buf[8];
    gets(buf);
    printf("%s", buf);
}
```

gets() documentation

Example

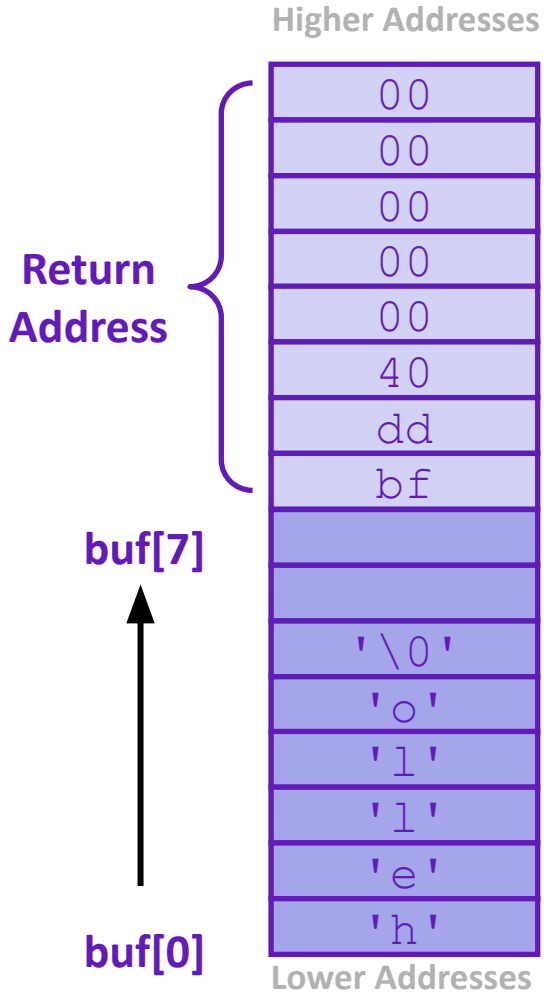
Stack grows *down* towards lower addresses

Buffer grows *up* towards higher addresses

If we write past the end of the array, we overwrite data on the stack!

```
Enter input: hello
```

No overflow! ☺️



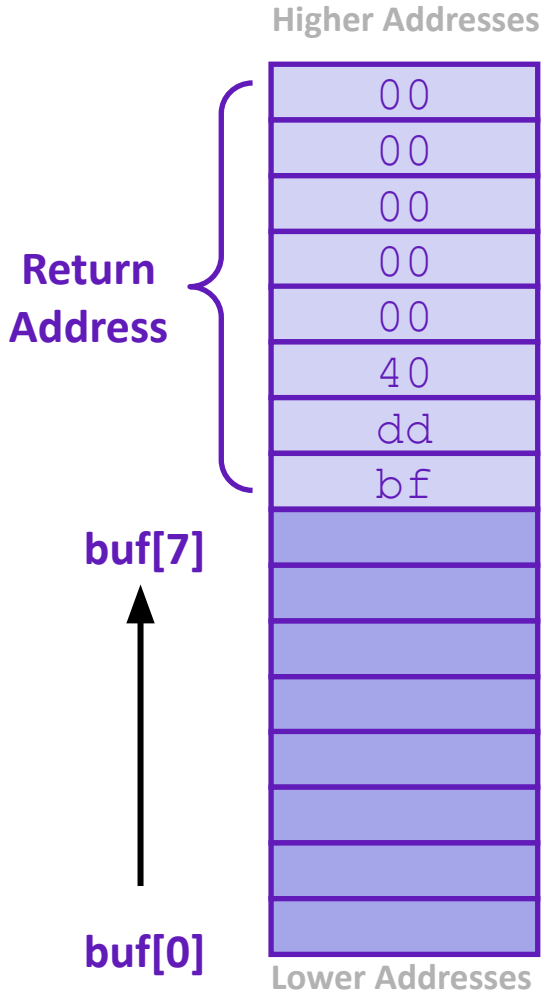
Example

Stack grows *down* towards lower addresses

Buffer grows *up* towards higher addresses

If we write past the end of the array, we overwrite data on the stack!

```
Enter input: helloabcdef
```



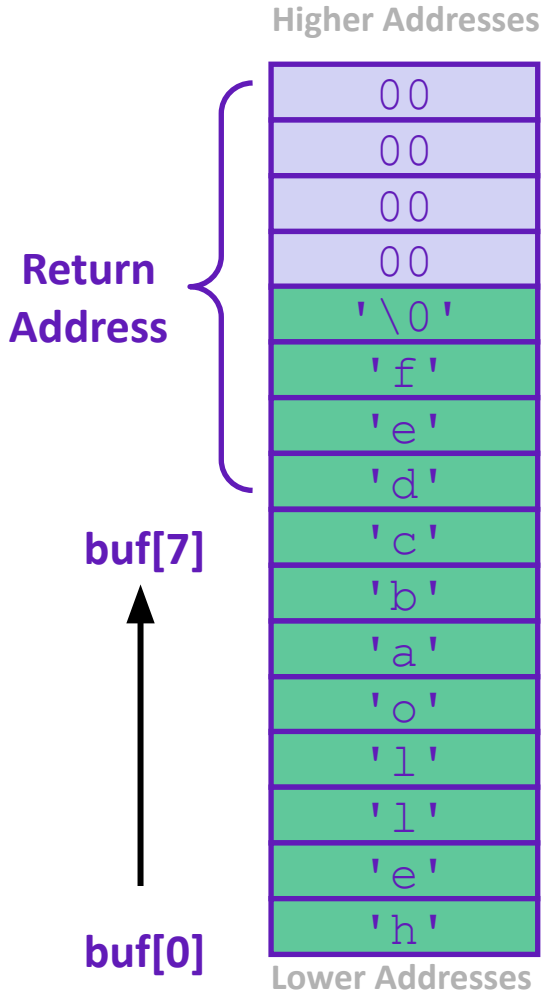
Example

If we write past the end of the array, we overwrite data on the stack!

- The data overwritten can be quite arbitrary. If the data overwritten is stack frame “bookkeeping” data or something like a function pointer, things could go bad.

```
Enter input: helloabcdef
```

Buffer overflow! ☹



Buffer Overflow in a Nutshell

Buffer overflows on the stack can overwrite “interesting” data

- Attackers just choose the right inputs

Simplest form (sometimes called “stack smashing”)

- Unchecked length on string input into bounded array causes overwriting of stack data
- Return-oriented programming
- Try to change the return address of the current procedure

Why is this a big deal?

- It was the #1 *technical* cause of security vulnerabilities
    - #1 *overall* cause is social engineering / user ignorance

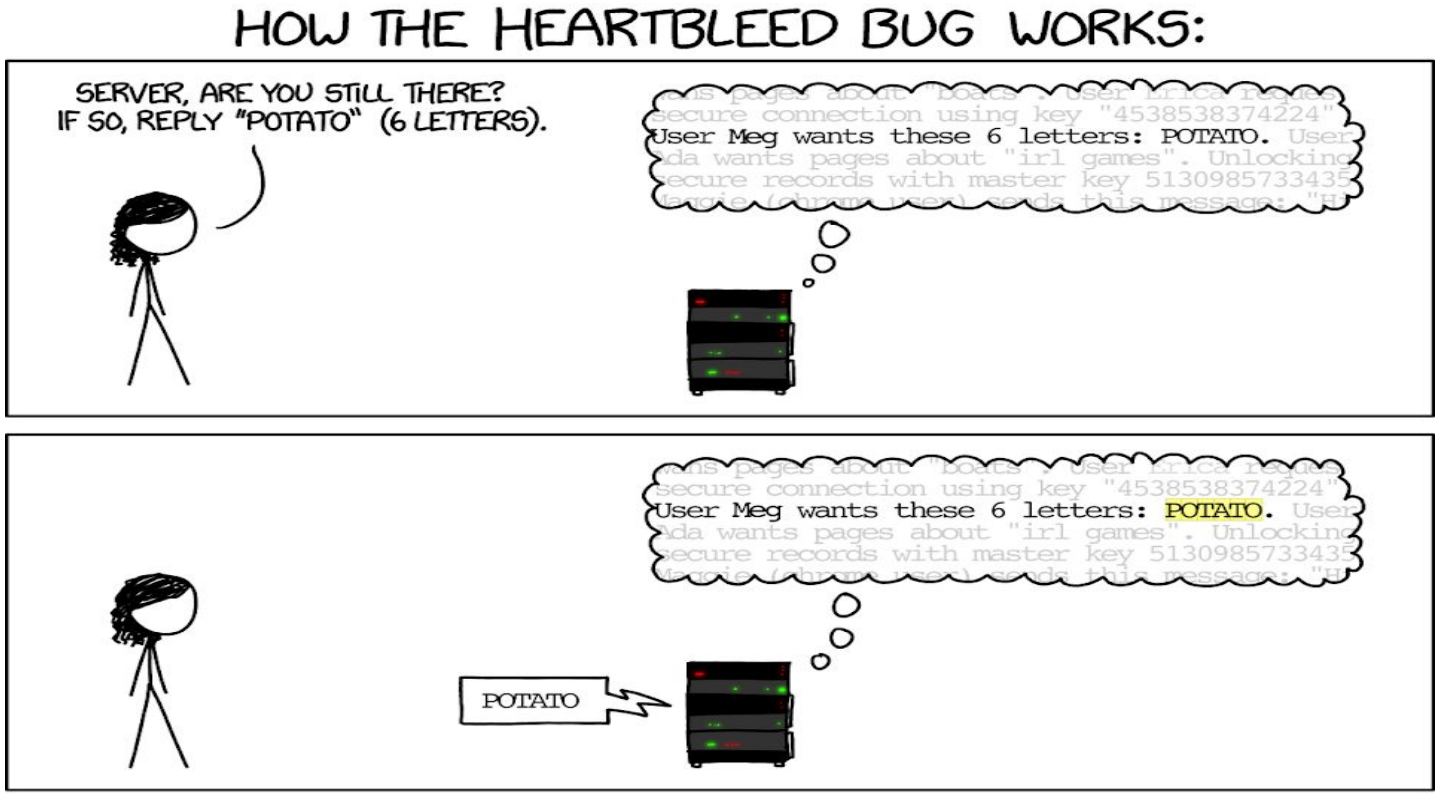
Exploits Based on Buffer Overflows

Examples across the decades

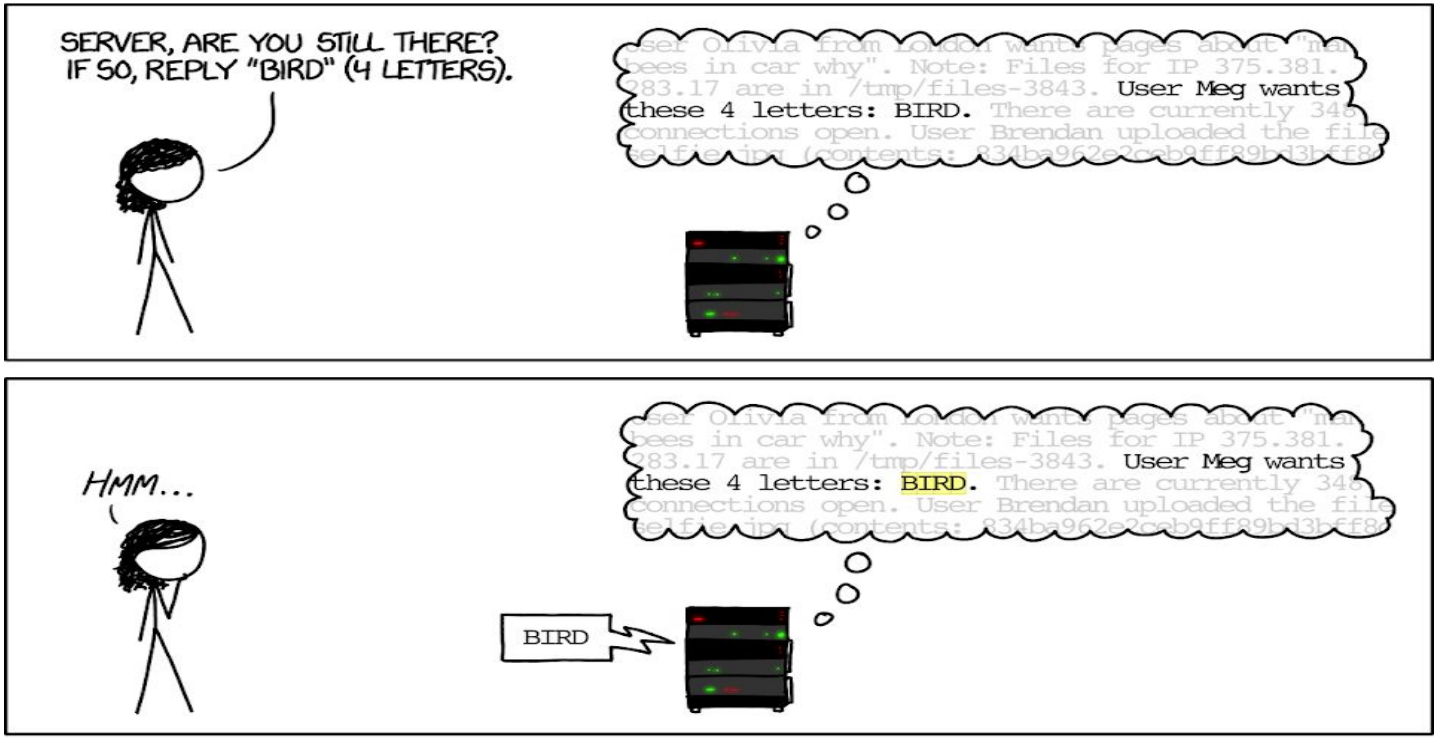
- Original “Internet worm” (aka Morris Worm) (1988)
  - Later became one of the founders of YCombinator.
- Heartbleed (2014, affected 17% of servers)
  - Similar issue in Cloudbleed (2017)
- Hacking embedded devices
  - Cars, Smart homes, Planes

Buffer overflow bugs can allow attackers to execute arbitrary code on victim machines

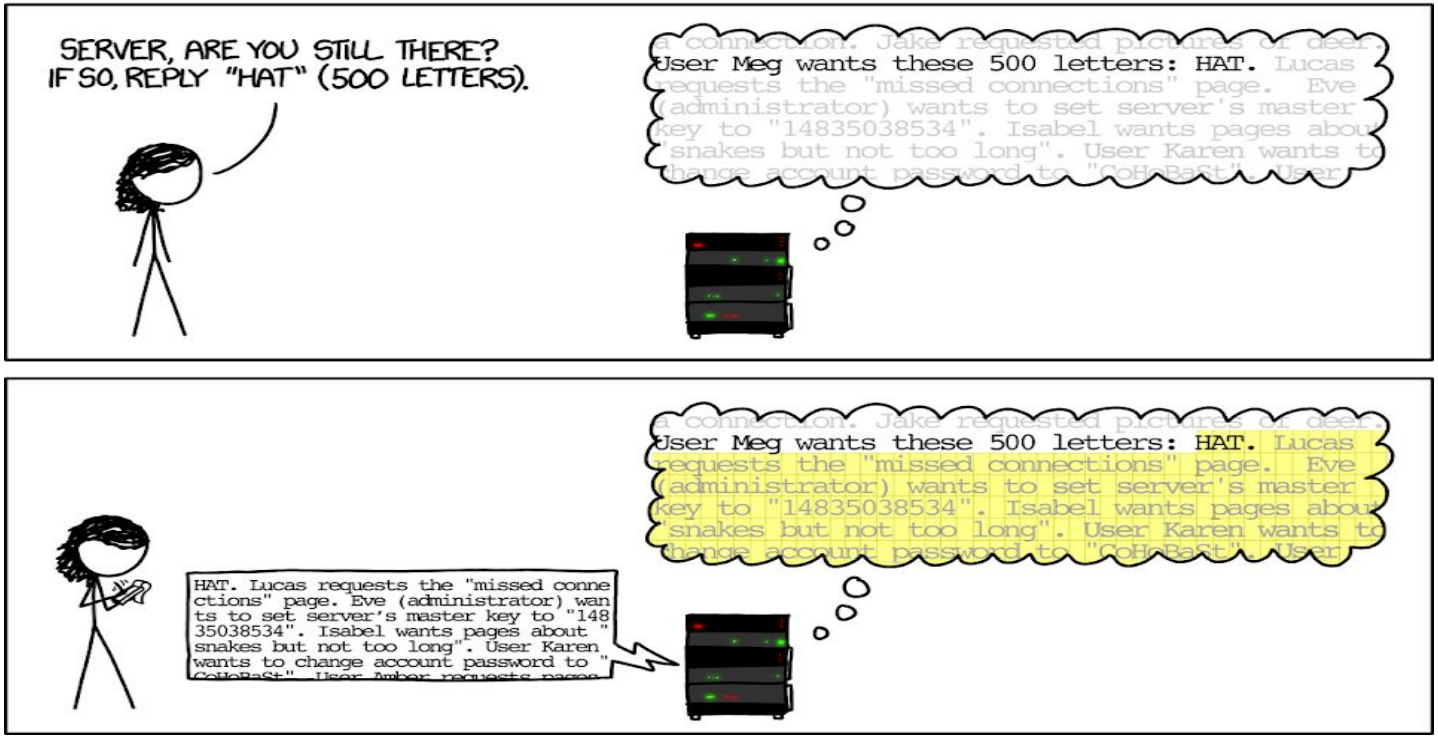
Example: Heartbleed



Example: Heartbleed



Example: Heartbleed



Heartbleed (2014)

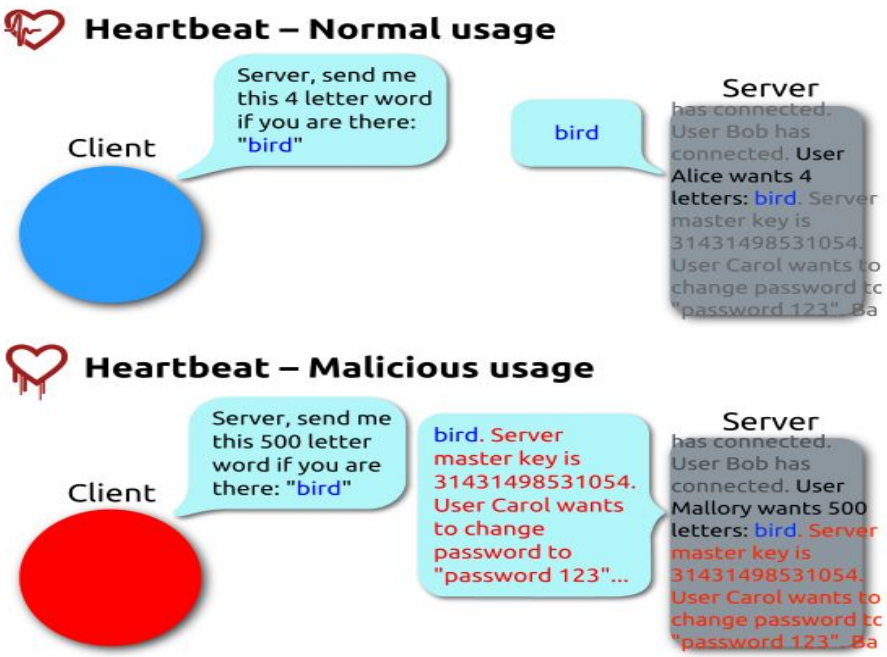
Buffer over-read in OpenSSL

- Open source security library
- Bug in a small range of versions

“Heartbeat” packet (part of Heartbeat ext.)

- Specifies length of message
- Server echoes it back
- Library just “trusted” this length
- Allowed attackers to read contents of memory anywhere they wanted

Est. 17% of Internet affected



Hacking Cars

UW CSE research from 2010 demonstrated wirelessly hacking a car using buffer overflow

Overwrote the onboard control system's code

- Disable brakes
- Unlock doors
- Turn engine on/off

Hacking DNA Sequencing Tech

- Potential for malicious code to be encoded in DNA!
- Attacker can gain control of DNA sequencing machine when malicious DNA is read
- Ney et al. (2017)
  - https://dnasec.cs.washington.edu/

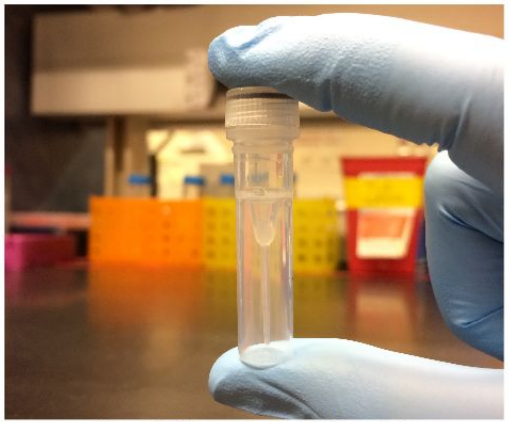


Figure 1: Our synthesized DNA exploit

Computer Security and Privacy in DNA Sequencing

Paul G. Allen School of Computer Science & Engineering, University of Washington

There has been rapid improvement in the cost and time necessary to sequence and analyze DNA. In the past decade, the cost to sequence a human genome has decreased 100,000 fold or more. This rapid improvement was made possible by faster, massively parallel processing. Modern sequencing techniques can sequence hundreds of millions of DNA strands simultaneously, resulting in a proliferation of new applications in domains ranging from personalized medicine, ancestry, and even the study of the microorganisms that live in your gut.

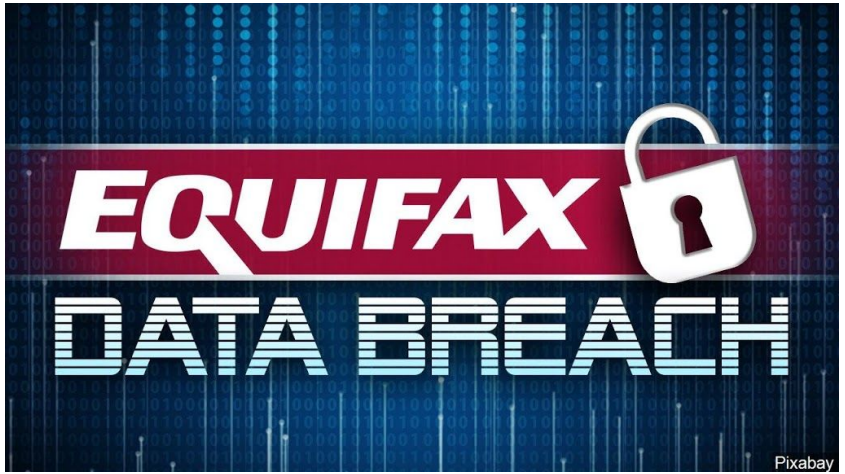
Equifax (2017)

Very similar to Heartbleed.

Exploited the Content-Type HTTP header that would cause a buffer overflow.

Attackers gained access to ~147 million people's worth of personal information!

- Names
- Birth dates
- SSNs
- Driver's license
- Credit card information



Dealing with Buffer Overflow Attacks

Avoid vulnerabilities in the first place

- Use library functions that limit string lengths
  - `fgets` instead of `gets`
  - `strncpy` instead of `strcpy`
- Use a language that makes them impossible

```
-bash@17[main]$ gcc -Wall -std=c11 -o echo echo.c
echo.c:13:5: warning: 'gets' is deprecated: This function is provid
ed for compatibility reasons only.  Due to security concerns inhere
nt in the design of gets(3), it is highly recommended that you use
fgets(3) instead. [-Wdeprecated-declarations]
    gets(buf);
    ^
```

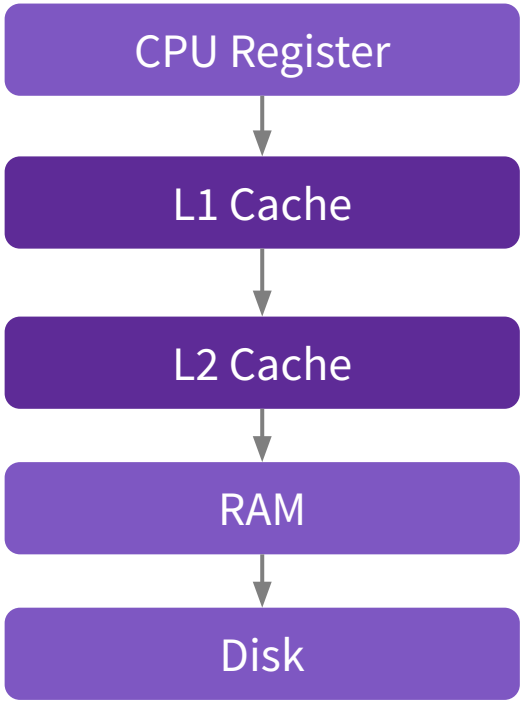
System-level protections

- Make stack non-executable
- Have compiler insert “stack canaries” (just like a networking header checksum)
- Put a special value between buffer and return address
- Check for corruption before leaving function
- Randomized Stack offsets

Questions?

Memory Hierarchy

Review: Memory Architecture

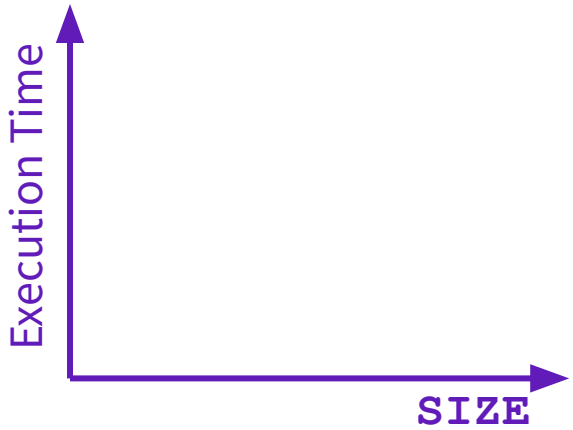


What is this?	Typical Size	Time
Part of the brain of the computer!	64 bits	≈free
Extra memory to make accessing it faster	128KB	0.5 ns
Extra memory to make accessing it faster	2MB	7 ns
Working memory, what your program need	8GB	100 ns
Large, longtime storage	1TB	8,000,000 ns

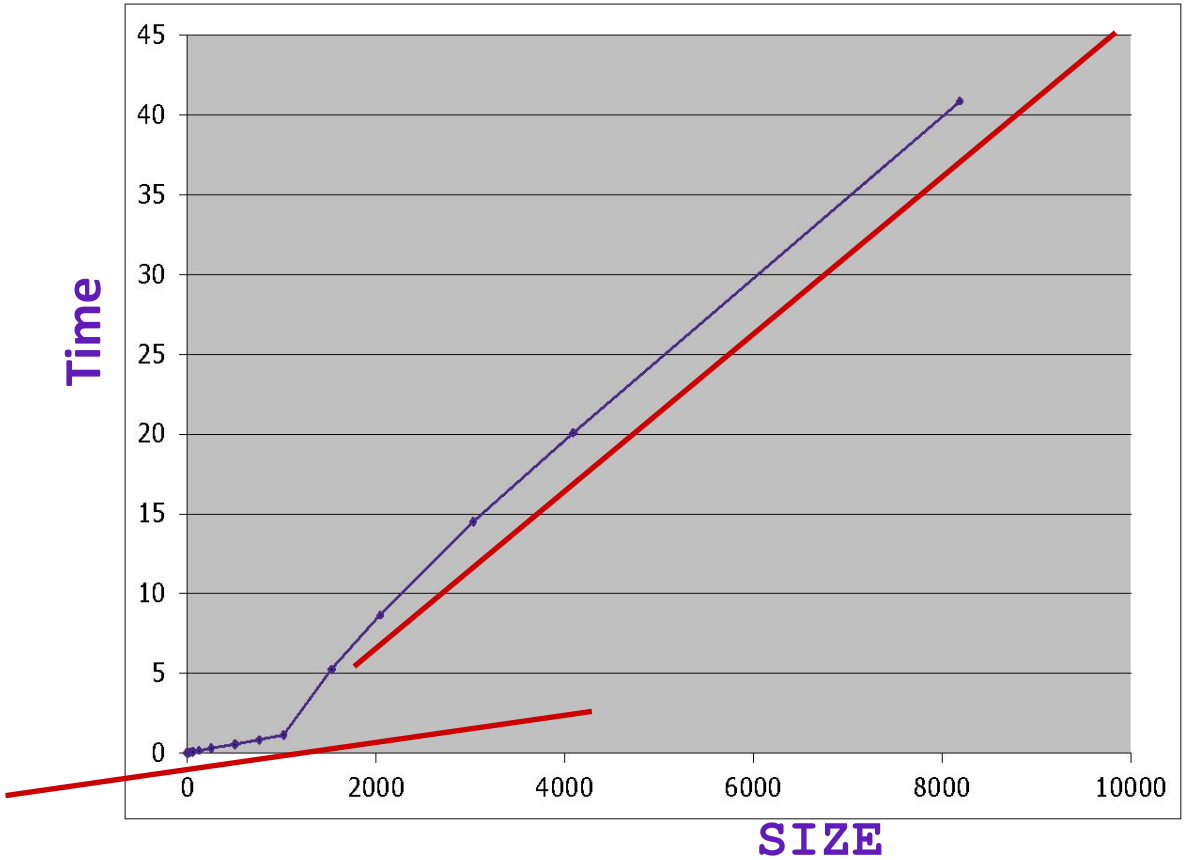
How does execution time grow with SIZE?

```
int array[SIZE];
// initialize array somewhere else
int sum = 0;
for (int i = 0; i < 200000; i++)
    for (int j = 0; j < SIZE; j++)
        sum += array[j];
```

Plot:



Actual Data



Incorrect Assumptions

Accessing memory is a quick and constant-time operation

Sometimes accessing memory is cheaper and easier than at other times

Sometimes accessing memory is very slow

Aside: Moore's Law

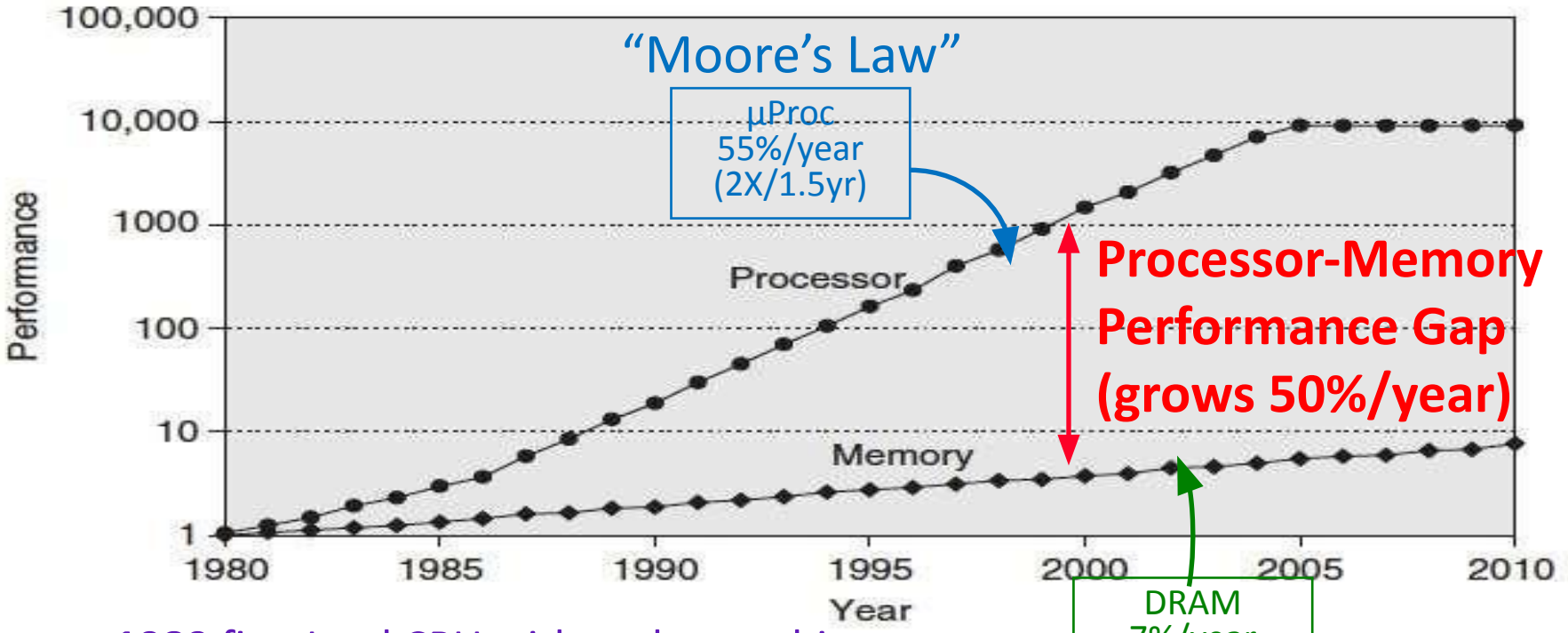
The claim that the number of transistors in an integrated circuit doubles approximately every two years.

- Had a huge impact on computing innovation and advancement.
- Was held true for decades (i.e. 1965-2010)

Nvidia CEO Jensen Huang claimed that Moore's law is dead in 2022.

- There is a physical limit for the amount of space on the device.
- Not everyone agrees (e.g. Intel's CEO, Pat Gelsinger)

Processor-Memory Gap



1989 first Intel CPU with cache on chip

1998 Pentium III has two cache levels on chip

Problem: Processor-Memory Bottleneck

Processor performance doubled about every 18 months

Bandwidth evolved much slower

Core 2 Duo:
Can process at least
256 Bytes/cycle

Core 2 Duo:
Bandwidth
2 Bytes/cycle
Latency
100-200 cycles (30-60ns)

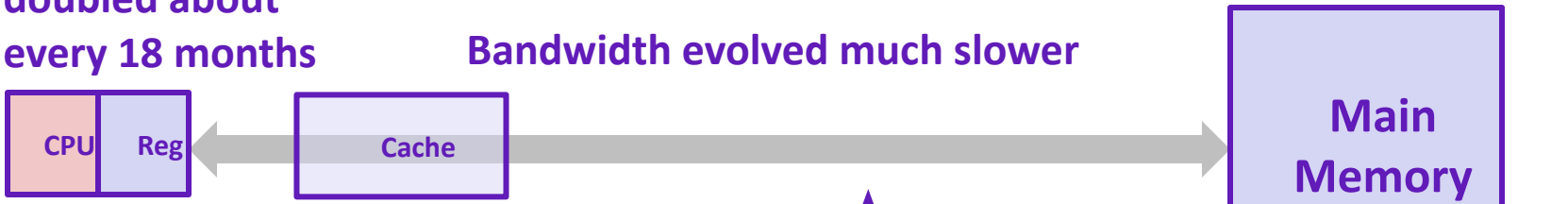
Problem: lots of waiting on memory

***cycle**: single machine step (fixed-time)*

Problem: Processor-Memory Bottleneck

Processor performance doubled about every 18 months

Bandwidth evolved much slower



Core 2 Duo:
Can process at least
256 Bytes/cycle

Core 2 Duo:
Bandwidth
2 Bytes/cycle
Latency
100-200 cycles (30-60ns)

Solution: caches

***cycle**: single machine step (fixed-time)*

Cache 💰

Pronunciation: “cash”

- We abbreviate this as “$”

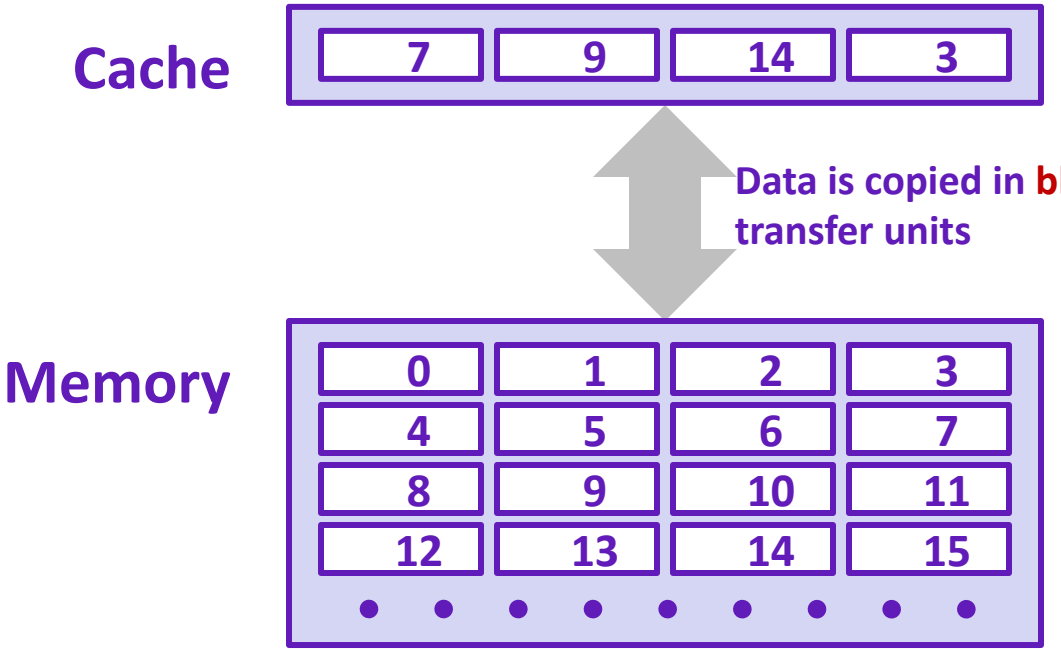
English: A hidden storage space

- for provisions, weapons, and/or treasures

Computer: Memory with short access time used for the storage of frequently or recently used data

- *More generally:* Used to optimize data transfers between any system elements with different characteristics (network interface cache, I/O cache, etc.)

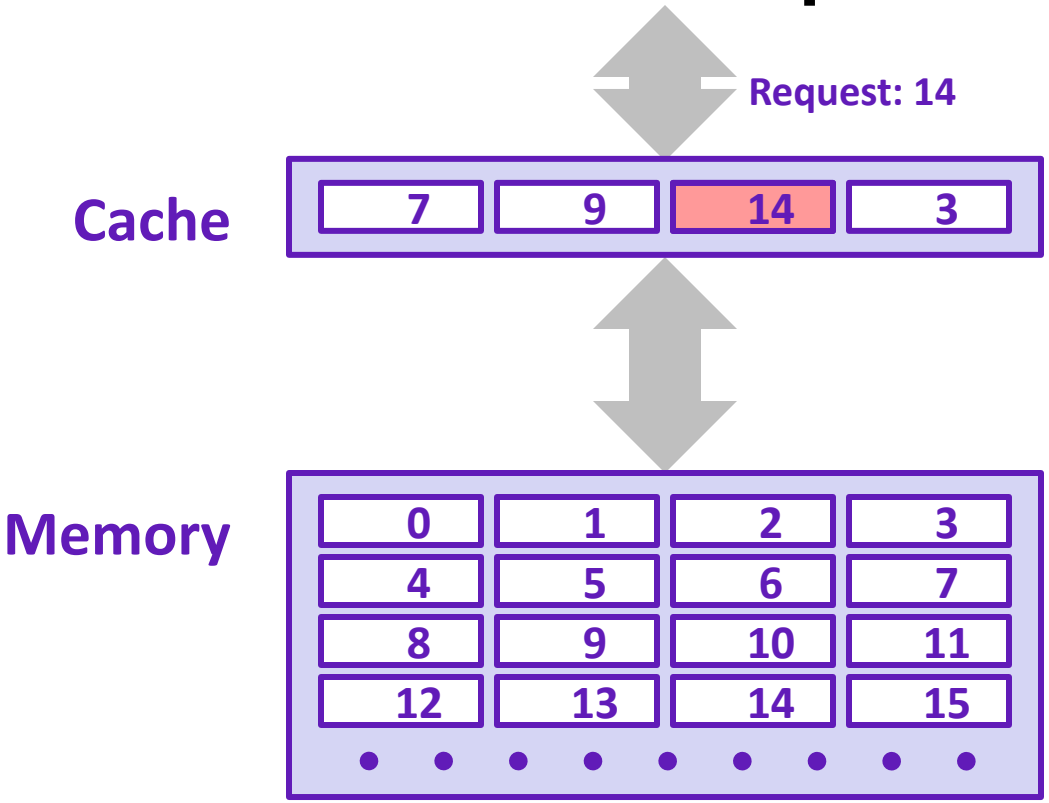
General Cache Mechanics



- Smaller, faster, more expensive memory
- Caches a subset of the blocks

- Larger, slower, cheaper memory.
- Viewed as partitioned into “blocks”

General Cache Concepts: Hit

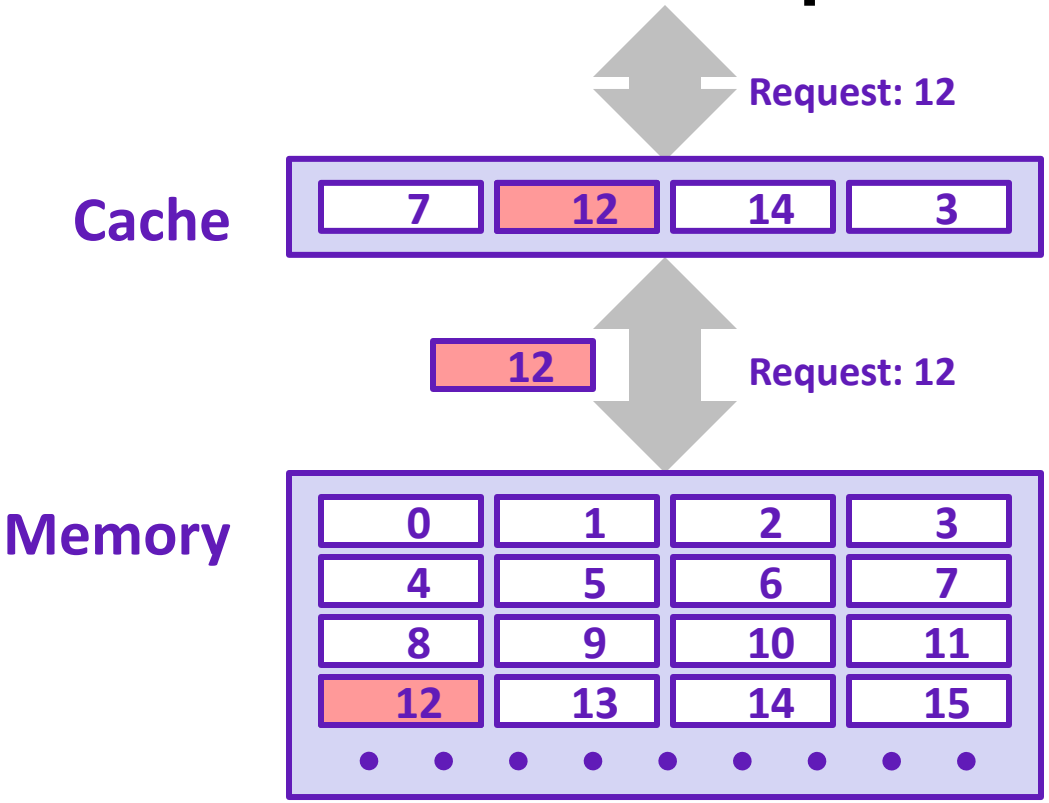


Data in block b is needed

Block b is in cache:
Hit!

Data is returned to CPU

General Cache Concepts: Miss



Data in block b is needed

Block b is not in cache: Miss!

Block b is fetched from memory

Block b is stored in cache

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

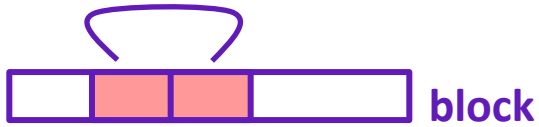
Data is returned to CPU

Why Caches Work

Locality: Programs tend to use data and instructions with addresses near or equal to those they have used recently

- *Temporal* locality:
  - Recently referenced items are *likely* to be referenced again in the near future

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



Analogy: took a bite of sandwich, probably going to take a bite out of other half of sandwich (as opposed to a new sandwich)

How do caches take advantage of this?

Example: Any Locality?

```
sum = 0;
for (i = 0; i < n; i++) {
      sum += a[i];
}
return sum;
```

- Temporal: `sum` referenced in each iteration
- Spatial: consecutive elements of array `a[]` accessed

Locality Example #1

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

Locality Example #1

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

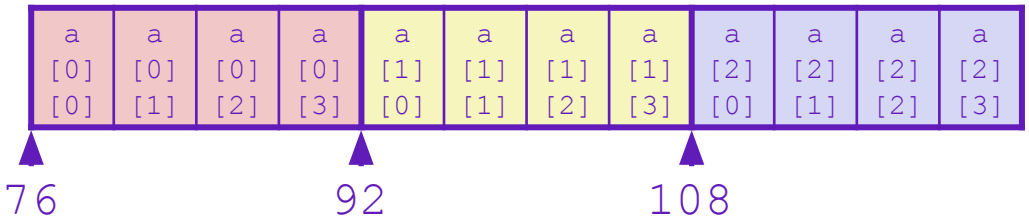
M = 3, N=4

a[0][0]	a[0][1]	a[0][2]	a[0][3]
a[1][0]	a[1][1]	a[1][2]	a[1][3]
a[2][0]	a[2][1]	a[2][2]	a[2][3]

Access Pattern:
stride = 1

1) a[0][0]
2) a[0][1]
3) a[0][2]
4) a[0][3]
5) a[1][0]
6) a[1][1]
7) a[1][2]
8) a[1][3]
9) a[2][0]
10) a[2][1]
11) a[2][2]
12) a[2][3]

Layout in Memory



Note: 76 is just one possible starting address of array a

Locality Example #2

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

Locality Example #2

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

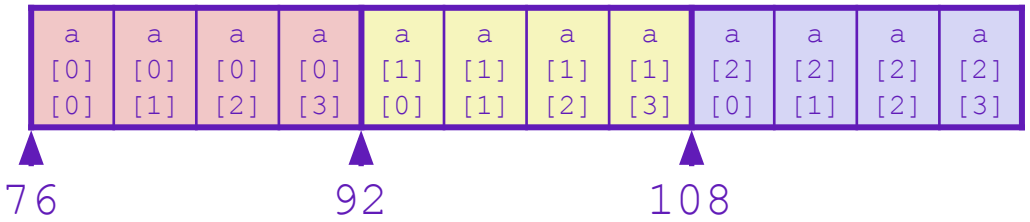
M = 3, N=4

a[0][0]	a[0][1]	a[0][2]	a[0][3]
a[1][0]	a[1][1]	a[1][2]	a[1][3]
a[2][0]	a[2][1]	a[2][2]	a[2][3]

Access Pattern:
stride = 3

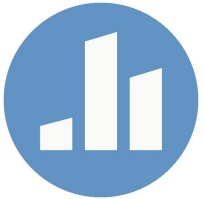
1) a[0][0]
2) a[1][0]
3) a[2][0]
4) a[0][1]
5) a[1][1]
6) a[2][1]
7) a[0][2]
8) a[1][2]
9) a[2][2]
10) a[0][3]
11) a[1][3]
12) a[2][3]

Layout in Memory



Questions?

Poll Question (PollEv.com/cs374)



Which of the following is correct?

A. To increase temporal locality, put fewer memory accesses in your loop body
B. To increase spatial locality, access the same memory several times
C. As you allocate more memory, you will get more cache hits
D. To increase temporal locality, access the same memory sooner rather than later

Which of the following is correct?

0

To increase temporal locality, put fewer memory accesses in your loop body

0%

To increase spatial locality, access the same memory several times

0%

As you allocate more memory, you will get more cache hits

0%

To increase temporal locality, access the same memory sooner rather than later

0%

Compute Points on a Line (Original)

```
// Compute y = mx + b for each point
void compute_line(float m, float b, float* points, int n) {
  for(int i = 0; i < n; i++) {
    points[i] = m * points[i];
  }
  for(int i = 0; i < n; i++) {
    points[i] = b + points[i];
  }
}
```

Compute Points on a Line (Improved)

```
// Compute y = mx + b for each point
void compute_line(float m, float b, float* points, int n) {
  for(int i = 0; i < n; i++) {
    points[i] = m * points[i];
    points[i] = b + points[i];
  }
}
```

- Better temporal locality!

Memory Hierarchies

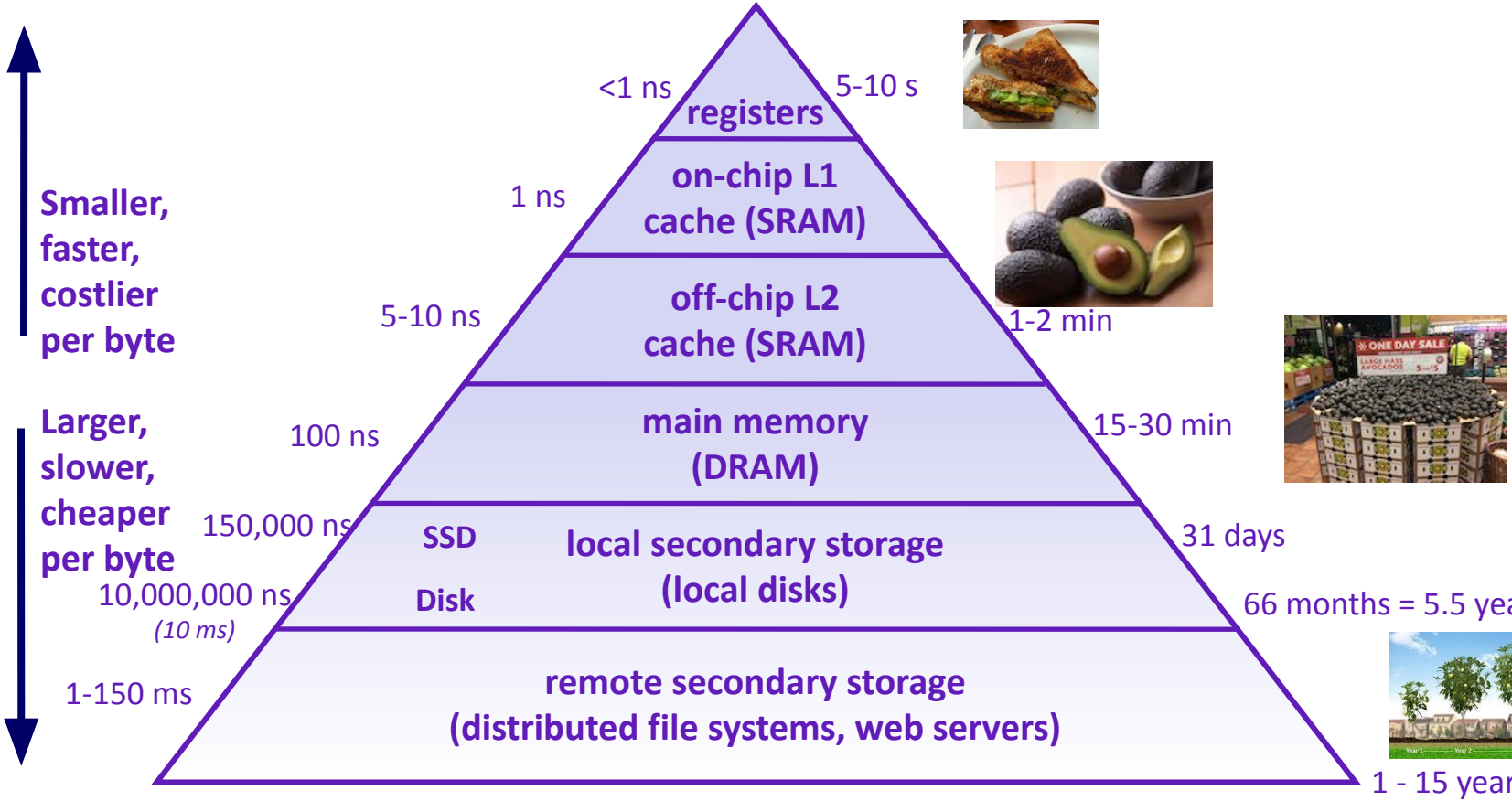
Some fundamental and enduring properties of hardware and software systems:

- Faster storage technologies almost always cost more per byte and have lower capacity
- Well-written programs tend to exhibit good locality

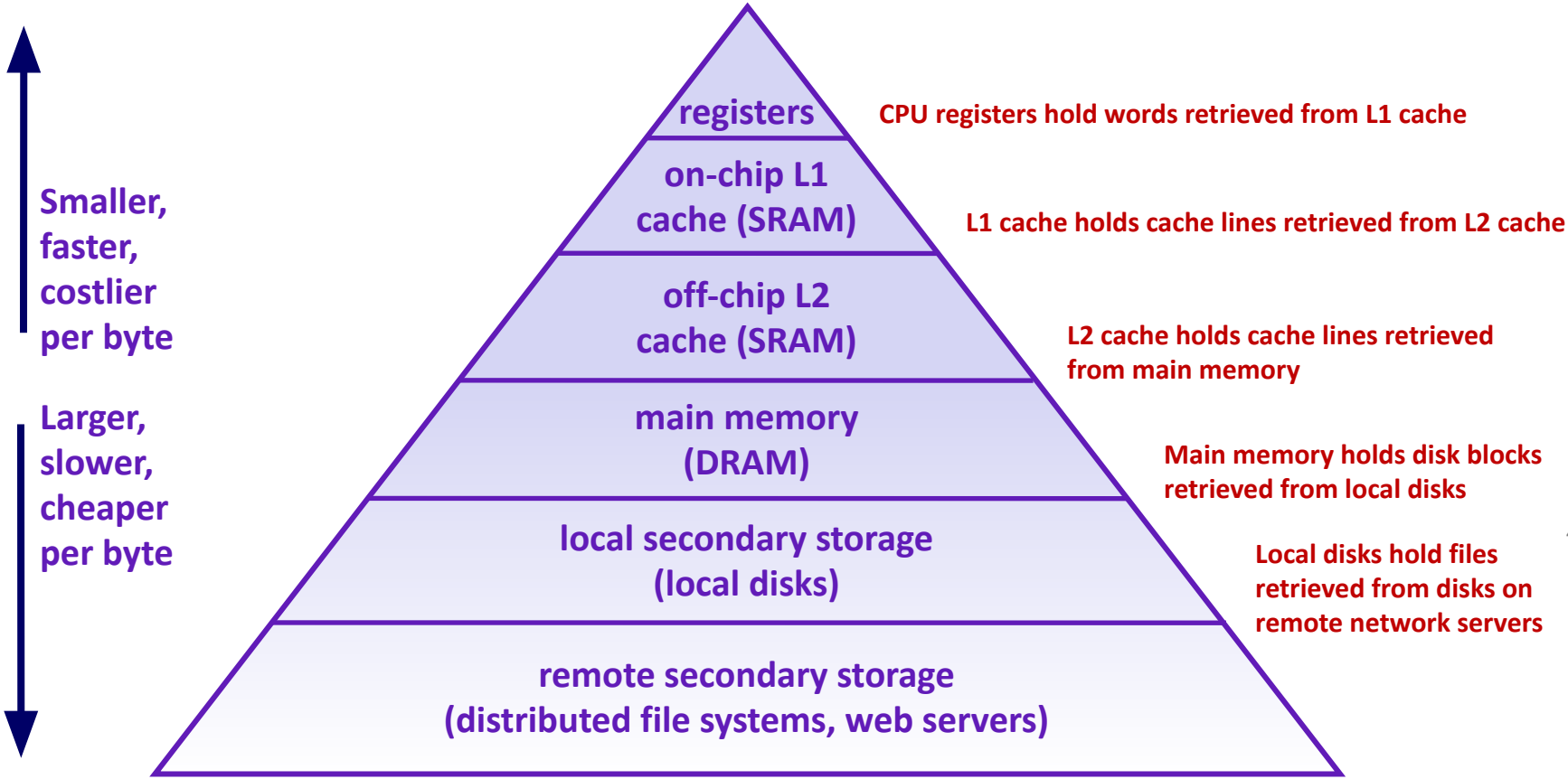
These properties complement each other beautifully

- They suggest an approach for organizing memory and storage systems known as a **memory hierarchy**
  - For each level k, the faster, smaller device at level k serves as a cache for the larger, slower device at level k+1

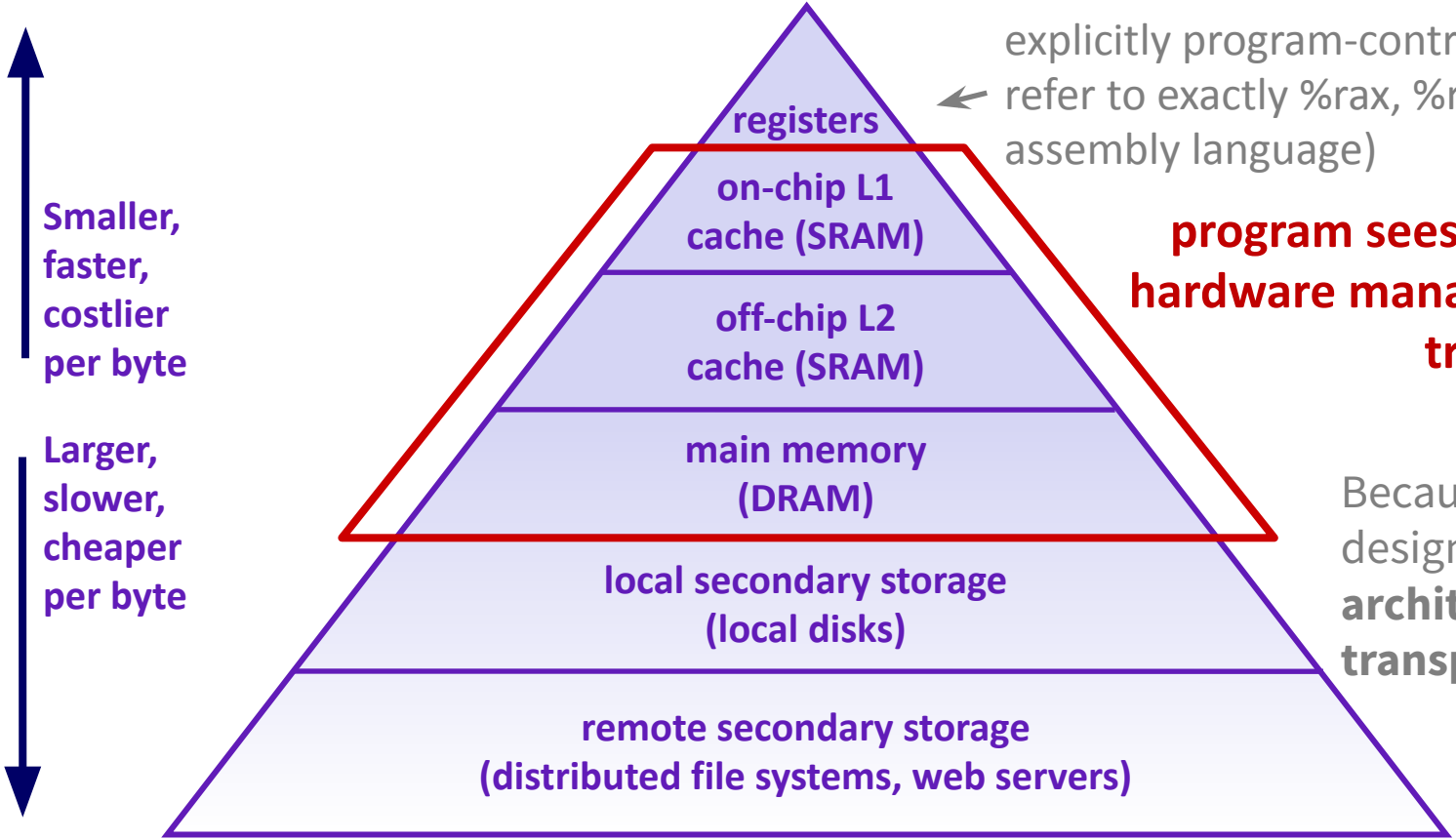
An Example Memory Hierarchy



An Example Memory Hierarchy



Why haven't we seen caches before?



explicitly program-controlled (e.g. refer to exactly %rax, %rbx in assembly language)

program sees "memory"; hardware manages caching transparently

Because they're designed to be **architecturally transparent**!

All systems favor “cache-friendly code”

Write code that has locality!

- Spatial: access data contiguously, use small strides
- Temporal: make sure access to the same data is not too far apart in time, keep working set reasonably small

How can you achieve locality?

- Adjust memory accesses in *code* (software) to improve miss rate (MR)
    - Requires knowledge of *both* how caches work as well as your system’s parameters
- Proper choice of algorithm
- Loop transformations

Summary

Memory Hierarchy

- Successively higher levels contain “most used” data from lower levels
- Accessing the disk is very slow
  - This is why we discourage excess I/O in homework assignments!
- Exploits *temporal and spatial locality*
- Caches are intermediate storage levels used to optimize data transfers between any system elements with different characteristics

Cache Performance

- Ideal case: found in cache (hit)
- Bad case: not found in cache (miss), search in next level