Lecture 2: Introduction

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The Era We Live In

The Web 2.0 Era (1999)

- The Internet brought people closer together.
- ”Users were encouraged to provide content, rather than just viewing it.”
- You can even find early hints of ”Web 3.0”/Metaverse in this period.

What made Web 2.0 possible?

- Concurrent programming in browsers: Ajax (Asynchronous JavaScript + XML)
- HTML (DOM Tree) + CSS represented everything you could see.
  - JavaScript allowed dynamic changes to the DOM.
  - JavaScript also enabled connections between local machines and servers.

With that, you had the whole world at your fingertips!

Features and Challenges

Features:

- Not very complex
- Minimal computation required
  - The DOM tree is not too large (humans can't handle huge trees anyway)
  - The browser handles rendering the DOM tree for us
- Not too much I/O, just a few network requests

Challenges:

- Too many programmers, especially for beginners
- Expecting beginners to handle multithreading with shared memory would lead to a world full of buggy applications!

Towards the Mobile Internet Era

The Transformation of Our World

We can no longer imagine life without mobile phones.

Enjoy: Nokia Ringtone Evolution

Again and Again, Changing the World!

The first smartphone: iphone 2G, 2007.

Android

[Android Official Website]

- **Linux + Framework + JVM**
  - Is it secondary development on Linux/Java?
  - Not exactly: Android defines an application model.
- Supporting Java was a highly visionary decision.
  - **Qualcomm MSM7201:**
    - ARMv6 instruction set
    - 528MHz x 1CPU, in-order 8-stage pipeline
    - TSMC 90nm
- "Even running a map app would lag..."
  - But Moore's Law came to the rescue!

The first Android phone: HTC G1, 2008

Android Apps: Write Once, Run Anywhere

An application running on the Java Virtual Machine (Android Runtime):

- **Platform (Framework)**
- **NDK (Native Development Kit)**
- **Java Native Interface (C/C++ Code)**

Official Documentation (RTFM):

- **Kotlin**
- **Platform**
  - **android.view.View:** "the basic building block for user interface components"
  - **android.webkit.WebView:** Embedding web pages in your app
  - **android.hardware.camera2:** Camera
  - **android.database.database:** Database

Symbian (C++) vs. Android (Java)

Symbian (C++):

- Powerful and performance-oriented but requires expert-level skills.
- Higher error rates due to manual memory management and pointer issues.

Android (Java):

- Developer-friendly with built-in safety mechanisms.
- Automatic garbage collection simplifies memory management.
- Encourages faster application development and wider adoption.

Conclusion: Java's design prioritizes developer productivity and safety, making it a better fit for large-scale mobile application ecosystems.

The Strategic Bet on Java and Moore's Law

Challenges at the time:

- Limited processing power on mobile chips.
- Java's higher demands on hardware made it seem risky.

Key Assumption:

- Inspired by Intel's Pentium and multi-core advancements in PCs.
- *What happened in PC chip development will repeat in mobile chips.*

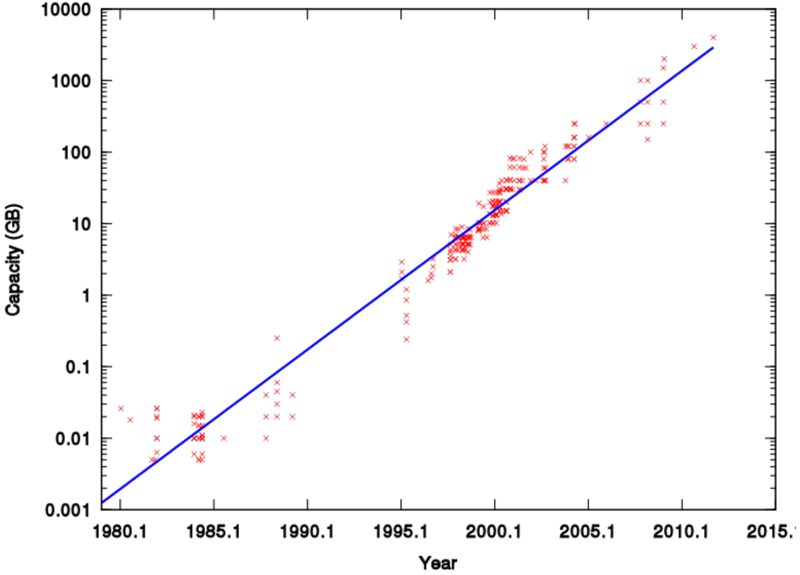
Vision:

- Moore's Law predicted rapid improvement in chip performance.
- As hardware evolved, Java's demands would no longer be a bottleneck.

Lessons from History: Design for the future, not for the present.

The Trend

The Prophet of the Era: Google Is No Coincidence



Redundant Array of Inexpensive Disks (RAID)

Growing Demand for Persistent Storage

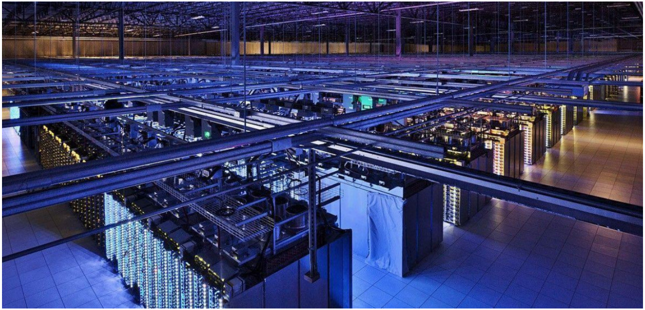
The storage device industry: As long as the CPU (DMA) can handle it, we can provide sufficient bandwidth!

- The tradition of the computer system ”industry” — creating practical, efficient, reliable, and cost-effective systems.

EMC VNX5300 Unified Storage (Disk) Array

Performance VS. Reliability

- Any physical storage medium has the potential to fail.
  - Extremely low-probability events:
    - Earthquake, war, alien invasion
  - Low-probability events: Hard drive failure
    - Large-scale redundancy = inevitable occurrence
- But we still hope the system continues running (data integrity even when storage devices fail)



Google Data Center

RAID: Virtualization of Storage Devices

So, can we achieve both performance and reliability?

Redundant Array of Inexpensive (Independent) Disks (RAID)

- Virtualize multiple (unreliable and cheap) disks into a highly reliable and high-performance virtual disk.
  - *A case for redundant arrays of inexpensive disks (RAID)* (SIGMOD '88)

RAID is a "reverse" form of virtualization

- Process: Virtualize one CPU into multiple virtual CPUs
- Virtual Memory: Virtualize one memory unit into multiple address spaces
- File System: Virtualize one drive into multiple virtual drives

RAID Fault Model: Fail-Stop

Disks may suddenly become completely inaccessible at any time.

- Mechanical failure, chip malfunction...
  - The disk seems to ”disappear suddenly” (data completely lost)
  - Assume the disk can report this issue.

The Golden Age in that Era

- 1988: Combine a few disks and disrupt the entire industry!
  - ”Single Large Expensive Disks” (IBM 3380) vs.
  - ”Redundant Array of Inexpensive Disks”

RAID 0 - Disk Striping

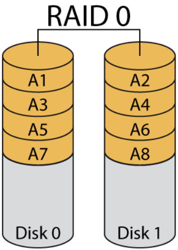
- Breaks data into **striped units** and spreads it across multiple drives.

Advantages:

- **High Performance:** High throughput (parallel I/O)
- **Cost-effective:** Better performance compared to a single large disk with similar capacity.

Disadvantages:

- **No Redundancy:** No backups; data loss occurs if any drive fails.
- **Increased Risk:** More drives mean a higher likelihood of failure.



RAID 0 – Striping

What do we *also* want?

Reliability: Data fetched is what you stored.
Availability: Data is there when you want it.

- More disks means higher probability of some disk failing.
- Striping reduces reliability
  - **N disks:** $1/n$th mean time between failures (MTBF) of 1 disk.

What can we do to improve Disk Reliability?

RAID 1 – Disk Mirroring

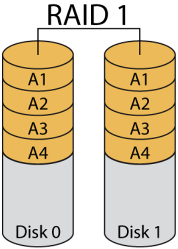
- Duplicates data and stores a copy on each drive (redundancy).
  - Requires at least two drives.
  - If one drive fails, data is still available on the other drive.
  - Supports **hot-swapping**: replace failed drives while the system is running.

Advantages:

- **Data Reliability:** Ensures no data loss even if a drive fails.
- **Redundancy:** Creates a mirror image of your data.

Disadvantages:

- **Storage Overhead:** Only 50% of total capacity is usable.



RAID 1 – Mirroring

Recovering from Failures with Parity

RAID-10: Sometimes can tolerate two disk failures, sometimes not. If we have many disks, can we reduce waste?

Reframe the Question

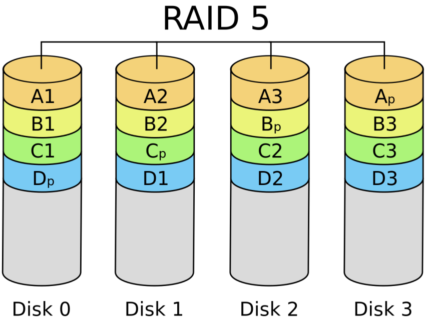
- Given n bits $b_1, b_2, \ldots, b_n$
- How many bits of information do we need to store at minimum so that we can recover any missing b_i (given that we know i)?
  - Parity (or error-correcting code)!
  - $x \oplus x = 0$
- ***n*-input XOR** gives bit-level parity:
  - $1 = \text{odd parity}, \;\; 0 = \text{even parity}$
- Example:

$$1101 \oplus 1100 \oplus 0110 = 0111 \quad \text{(parity block)}$$

- Can reconstruct any missing block using XOR with others.

RAID 5: Rotating Parity

"Interleaved" parity block!



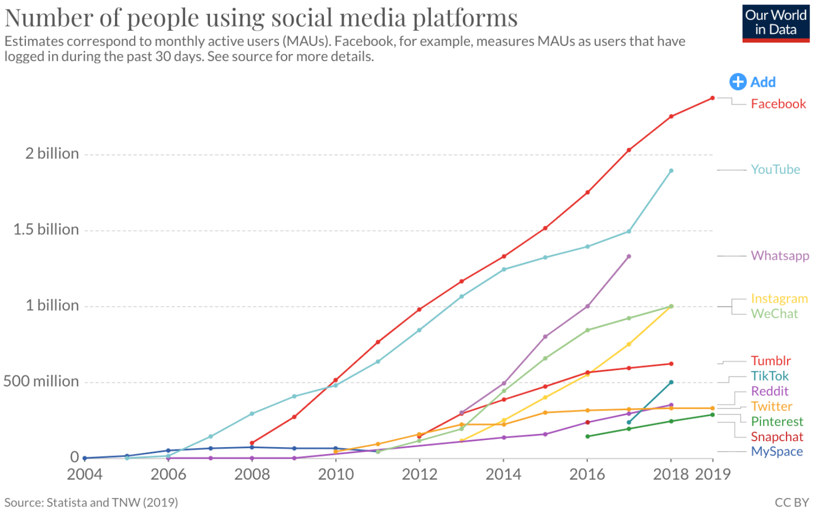
- In RAID 5, parity blocks are distributed across all disks to avoid a single parity disk bottleneck.
- This setup provides fault tolerance while maximizing disk performance.

RAID: Discussion

Faster, more reliable, and nearly free high-capacity disks.

- Revolutionized the concept of ”high-reliability disks”
  - Became the standard configuration for today’s servers
- Similar milestones
  - *The Google File System* (SOSP ’03)
  - *MapReduce: Simplified Data Processing on Large Clusters* (OSDI ’04)
    - Transformed a collection of unreliable, commodity computers into a reliable, high-performance server.
    - Launched the ”Big Data” era!
- What is next?

The Prophet of the Era: Facebook Is No Coincidence



Data Center

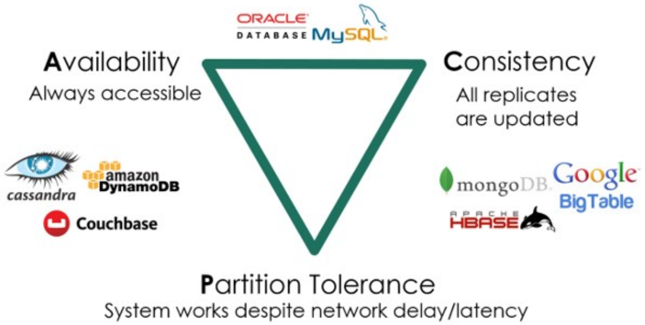
Data Center

"A network of computing and storage resources that enable the delivery of shared applications and data." (CISCO)

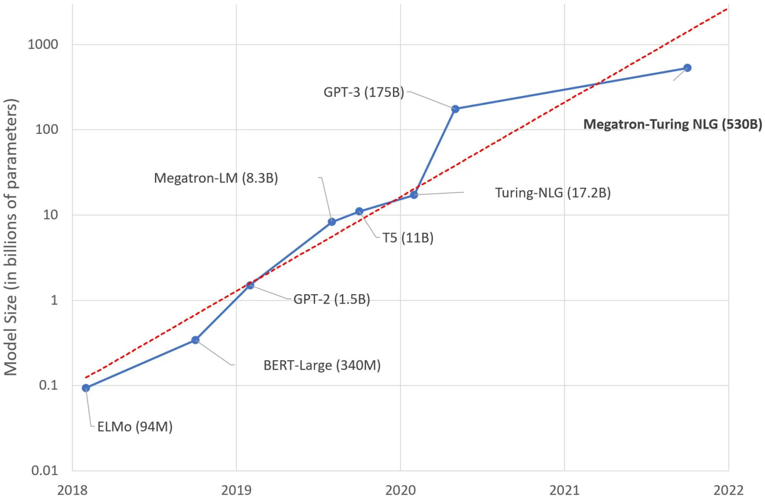
- Data-Centric (Storage-Focused) Approach
  - Originated from internet search (Google), social networks (Facebook/Twitter)
  - Powers various internet applications: Gaming/Cloud Storage/ WeChat/Alipay/...
- The Importance of Algorithms/Systems for HPC and Data Centers
  - You manage 1,000,000 servers
  - A 1% improvement in an algorithm or implementation can save 10,000 servers

Main Challenges of Data Center

- Serving massive, geographically distributed requests
- Data must remain consistent (Consistency)
- Services must always be available (Availability)
    - Must tolerate machine failures (Partition Tolerance)

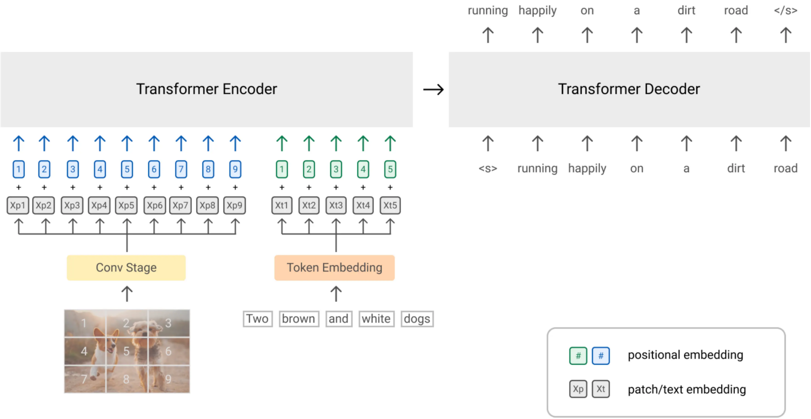


The Prophet of the Era: OpenAI Is No Coincidence



AGI is approaching rapidly:

- *Everything is an embedding.* (Below: SimVLM)



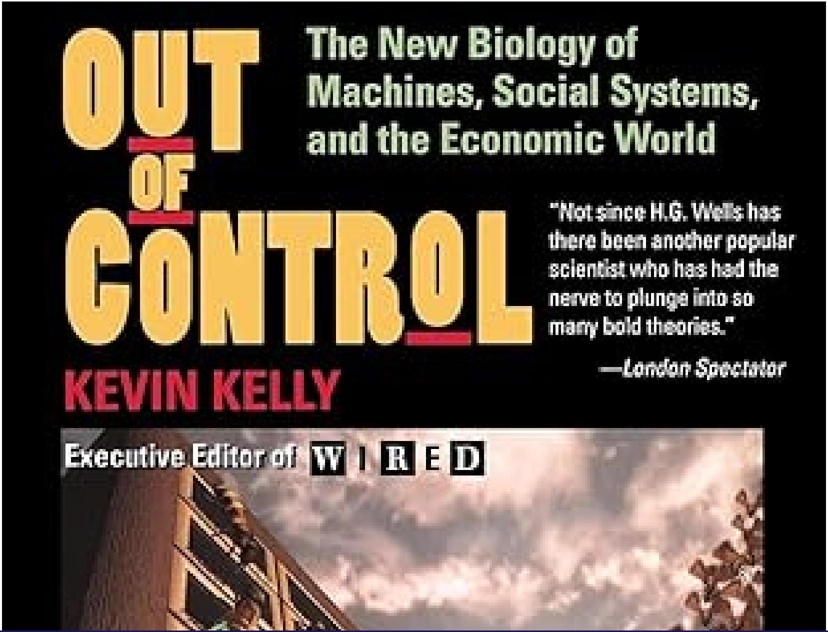
A. C. (Anno. ChatGPT) Year 3

We Begin Using LLMs for Complex Programming Tasks

- Explore GCC/LLVM to uncover 100+ bugs.
  - Use ChatGPT to generate test cases.
  - Use ChatGPT to generate Clang AST Transformer.

```
  class ModifyFunctionReturnTypeToVoid : ... {
-   vector<ReturnStmt *> TheReturns;
-   vector<CallExpr *> TheCalls;
+   map<FunctionDecl *, vector<ReturnStmt *>> FuncReturns;
+   map<FunctionDecl *, vector<CallExpr *>> FuncCalls;
  };

  bool ModifyFunctionReturnTypeToVoid::mutate() {
    TraverseAST(getASTContext());
    if (TheFunctions.empty()) return false;

    FunctionDecl *func = randElement(TheFunctions);

    // Change the return type to void
    QualType voidType = getASTContext().VoidTy;
    std::string voidTypeStr = formatAsDecl(voidType, "");

    SourceRange typeRange =
      func->getReturnTypeSourceRange();
    getRewriter().ReplaceText(typeRange, voidTypeStr);
```

The Era We Live In



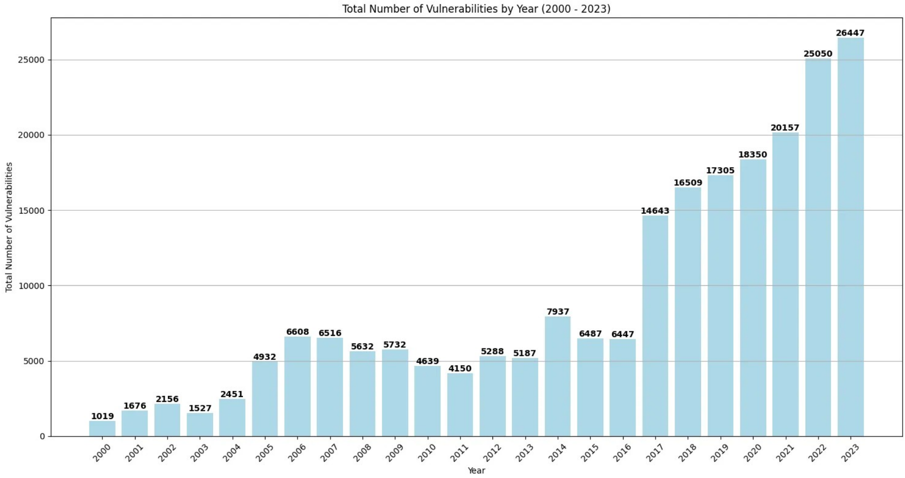
Current State of Computer Security

- Lots of **buggy software** (and gullible users)
- Money can be made from vulnerabilities

Marketplace

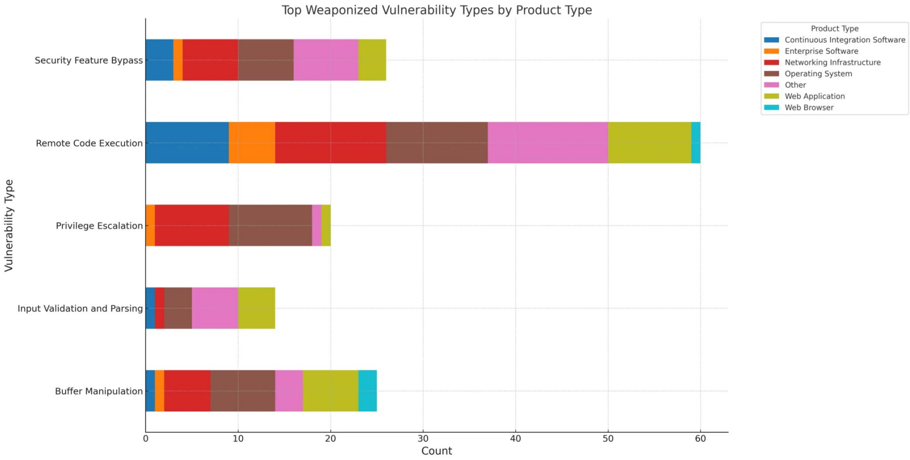
- Marketplace for vulnerabilities
- Marketplace for owned machines (PPI)
- Many methods to profit from owned client machines

Vulnerability Disclosures Tracked by MITRE



MITRE (https://cve.mitre.org/) is a nonprofit organization that operates federally funded research and development centers (FFRDCs) and manages programs like CVE (Common Vulnerabilities and Exposures), helping to track and classify software vulnerabilities.

Prevalence of Key Vulnerability Types in Various Product Types



Vulnerabilities and Exploits

- A **bug** is a place where real behavior may **deviate** from expected behavior.
  - A vulnerability is a security-sensitive bug.
- An **exploit** is an **input** that gives an attacker an advantage.

Method	**Objective**
Control flow hijacking	Gain control of the instruction pointer %eip
Denial of service	Cause program to crash or stop servicing clients
Information disclosure	Leak private information, e.g., saved password

Top Targeted High-risk Vulnerabilities

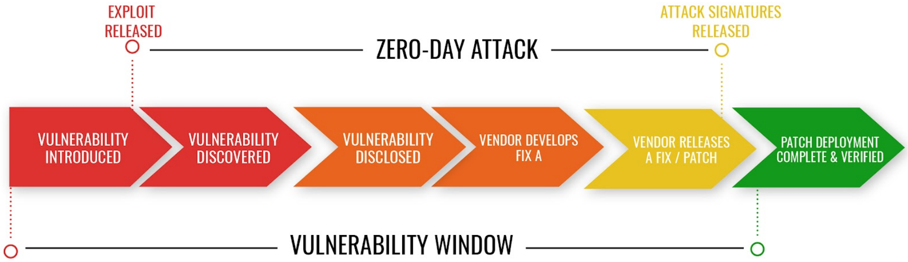
- There are plenty of bugs in common programs
  - Fact: Ubuntu Linux has over **99,000** known bugs
- Old vulnerabilities, even fixed, still exist in user systems
  - CVE-2006-3227 is a top threat after almost **10 years**!

Product	**CVE**
Internet Explorer	CVE-2006-3227, CVE-2009-3674, CVE-2010-0806, CVE-2012-4792, CVE-2013-1347, CVE-2014-0322/1776
Microsoft Office	CVE-2008-2244, CVE-2009-3129, CVE-2010-3333, CVE-2011-0101, CVE-2012-0158/1856, CVE-2014-1761
JAVA	CVE-2012-172, CVE-2013-2465

Source: https://www.us-cert.gov/ncas/alerts/TA15-119A (Sep 2016)

Vulnerability Lifecycle

- Patch deployment could take a long time to complete
  - Different versions, shared code, compatibility (enterprise)
  - Automated update can reduce the vulnerability life span
- A patch reveals the details of the fixed vulnerabilities
  - **Patch-based exploit generation** is possible



Zero-Day exploits, and their underlying vulnerabilities, have a 6.9 year life expectancy, on average.

CWE/SANS Top 25 Most Dangerous Software Errors

http://cwe.mitre.org/top25

CWE (Common Weakness Enumeration): A list of common software weaknesses maintained by MITRE, widely used to identify and mitigate security risks.
SANS Institute: A cybersecurity organization that collaborates with industry and government to provide training and insights on software vulnerabilities.

Insecure Interaction Between Components

Rank	CWE ID	Name
1	CWE-89	Improper Neutralization of Special Elements used in an SQL Command (**'SQL Injection'**)
2	CWE-78	Improper Neutralization of Special Elements used in an OS Command (**'OS Command Injection'**)
4	CWE-79	Improper Neutralization of Input During Web Page Generation (**'Cross-site Scripting'**)
9	CWE-434	Unrestricted Upload of File with Dangerous Type
12	CWE-352	**Cross-Site Request Forgery (CSRF)**
22	CWE-601	URL Redirection to Untrusted Site (**'Open Redirect'**)

Risky Resource Management

Rank	CWE ID	Name
3	CWE-120	Buffer Copy without Checking Size of Input (**'Classic Buffer Overflow'**)
13	CWE-22	Improper Limitation of a Pathname to a Restricted Directory (**'Path Traversal'**)
14	CWE-494	Download of Code Without Integrity Check
16	CWE-829	Inclusion of Functionality from Untrusted Control Sphere
18	CWE-676	Use of Potentially Dangerous Function
20	CWE-131	**Incorrect Calculation of Buffer Size**
23	CWE-134	**Uncontrolled Format String**
24	CWE-190	**Integer Overflow or Wraparound**

Porous Defenses

Rank	CWE ID	Name
5	CWE-306	**Missing Authentication for Critical Function**
6	CWE-862	Missing Authorization
7	CWE-798	**Use of Hard-coded Credentials**
8	CWE-311	**Missing Encryption of Sensitive Data**
10	CWE-807	**Reliance on Untrusted Inputs in a Security Decision**
11	CWE-250	**Execution with Unnecessary Privileges**
15	CWE-863	Incorrect Authorization
17	CWE-732	Incorrect Permission Assignment for Critical Resource
19	CWE-327	**Use of a Broken or Risky Cryptographic Algorithm**
21	CWE-307	Improper Restriction of Excessive Authentication Attempts
25	CWE-759	Use of a One-Way Hash without a Salt

Bugs, Bugs, Bugs

Buffer Overflow

```c
#include <stdio.h>

int main(int argc, char **argv)
{
   char buf[8];
   gets(buf);

   printf("%s\n", buf);
   return 0;
}
```

Integer Overflow

```
nresp = packet_get_int();

if (nresp > 0) {
   response = xmalloc(nresp * sizeof(char*));

   for (i = 0; i < nresp; i++) {
      response[i] = packet_get_string(NULL);
   }
}
```

Integer Error

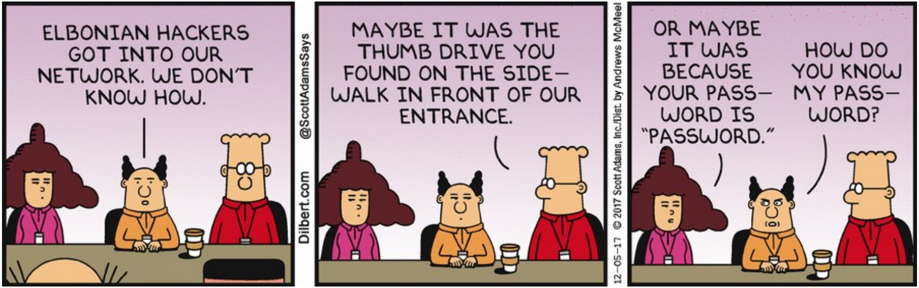
```
char* processNext(char* strm)
{
   char buf[512];

   short len = *(short*) strm;
   strm += sizeof(len);

   if (len <= 512) {
      memcpy(buf, strm, len);
      process(buf);

      return strm + len;
   } else {
      return -1;
   }
}
```

Format-string Vulnerability

```
int main(int argc, char **argv)
{
   char buf[128];
   ...
   snprintf(buf, 128, argv[1]);
}
```

SQL Injection

```
SELECT * FROM Users
WHERE Username='$username' AND Password='$password'
```



Money, Money, Money

Steal IP Address and Bandwidth

Attacker's goal: look like a random Internet user

Use the IP address of infected machine or phone for:

- Spam (e.g., the storm bonnet)
  - Spamalytics: 1:12M pharma spams lead to purchase
  - 1:260K greeting card spams lead to infection
- Denial-of-service
  - Services: 1 hour – $20, 24 hours – $100
- Click fraud (e.g., clickbot.a)

Steal User Credentials and Inject Ads

- Keylogger for banking/web/gaming passwords
- Example: SilentBanker (and many others like it e.g., Zeus bot)

Spread to Isolated Systems

Example: Stuxnet

Windows infection $\rightarrow$
Siemens PCS 7 SCADA control software on Windows $\rightarrow$
Siemens device controller on isolated network

Stuxnet was a sophisticated computer worm discovered in 2010. It was designed to target and disrupt industrial control systems (ICS), specifically Iran's nuclear program. It marked a significant milestone in cybersecurity as one of the first cyberweapons.

Server-side Attacks

- **Financial data theft** (credit card numbers)
  - Example: Target attack (2013), $\sim$140M CC numbers stolen
  - Many similar attacks since 2000
- **Political motivation**
  - Aurora (2009), Tunisia Facebook (2011), GitHub (Great Cannon 2015)
- **Infect visiting users** (waterhole attacks)

Marketplace for Vulnerabilities

- **Option 1:** bug bounty programs (many)
  - Google Vulnerability Reward Program: up to 100K $
  - Microsoft Bounty Program: up to 100K $
  - Mozilla Bug Bounty program: 500$ - 3000$
  - Pwn2Own competition: 15K $
- **Option 2:**
  - ZDI, iDefense: 2K - 25K $

Marketplace for Vulnerabilities

Option 3: black market

- Not really an option for ethical hackers

Software	Price Range
Adobe Reader	\$5,000–\$30,000
Mac OSX	\$20,000–\$50,000
Android	\$30,000–\$60,000
Flash or Java Browser Plug-ins	\$40,000–\$100,000
Microsoft Word	\$50,000–\$100,000
Windows	\$60,000–\$120,000
Firefox or Safari	\$60,000–\$150,000
Chrome or Internet Explorer	\$80,000–\$200,000
iOS	\$100,000–\$250,000

Source: Andy Greenberg (Forbes, 3/23/2012)

Marketplace for Owned Machines

Pay-per-install (PPI) services:

- Install client's malware on owned machines for a fee

PPI operation:

- Own victim's machine
- Download and install client's malware
- Charge client

US: 100–180$/1000 machines
Asia: 7–8$/1000 machines

Takeaways

Goals of this course:
In this out-of-control world, stay in control and not losing your computer.

- Be aware of exploit techniques
- Learn to defend and avoid common exploits
- Learn to architect secure systems