Software Security Foundations

CS 6335: Language Based Security

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Fall 2023

Tales of Woe:

Seven Deadly Vulnerabilities

GHOST ● Heartbleed ● Conficker ● Stagefright ● Shellshock ● Java Deserialization ● VENOM

Tale #1: GHOST (Gnu HOST bug)

- Bug in the Linux glibc library
- Discovered by Qualys researchers during a routine code audit in 2015
- Affects all code that uses glibc for host-lookups (i.e., nearly all Linux networking software) between 2000-2013
- Can you spot the bug?

```
int __nss_hostname_digits_dots( … ) {
 …

 size_needed = sizeof(*host_addr) + sizeof(*h_addr_ptrs) + strlen(name) + 1;
 *buffer = (char*) malloc(size_needed);

… 35 lines of code …

 host_addr = (host_addr_t*) *buffer;
 h_addr_ptrs = (host_addr_list_t*) ((char*) host_addr + sizeof(*host_addr));
 h_alias_ptr = (char**) ((char*) h_addr_ptrs + sizeof(*h_addr_ptrs));
 hostname = (char*) h_alias_ptr + sizeof(*h_alias_ptr);

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 hostname = (char*) h_alias_ptr + sizeof(*h_alias_ptr);

…
```

Is it really that big a deal?

```
…
if (isdigit(name[0])) {
   for (cp=name;; ++cp) {
      if (*cp == ‘\0’) {
         if (*--cp == ‘.’) break;
         if ((af == AF_INET) ? inet_aton(name, host_addr) : inet_pton(af, name, host_addr))
            result_buf->h_name = strcpy(hostname, name);
         goto done;
      }
      if (!isdigit(*cp) && *cp != ‘.’) break;
   }
}
…
```

- Qualys was able to take complete remote control of affected Linux machines merely by sending them a maliciously crafted email (unread!).
- Can you figure out how they did it?

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Tale #2: Heartbleed

- Bug in the OpenSSL (secure web communications!) library discovered by Codenomicon in 2014
- Buffer over-read error in implementation of Heartbeat TLS protocol:
  - read-loop trusts length bound provided by user
  - over-read data sent directly back to attacker
- Vulnerability exposed ~66% of the internet to theft of encryption keys between 2011-2014.
- Still highly exploitable because OpenSSL is so pervasive, cannot always be patched in the wild.
- Heartbeat packets deemed so innocuous, they were not even logged during the zero-day window.

```
int dtls1_process_heartbeat(SSL *s) {
  unsigned char *p = &s->s3->rrec.data[0];
  unsigned int payload;
  n2s(p, payload);
  …
  buffer = OPENSSL_malloc(1 + 2 + payload + padding);
  bp = buffer;
  *bp++ = TLS1_HB_RESPONSE;
  s2n(payload, bp);
  memcpy(bp, p, payload);
  bp += payload;
  …
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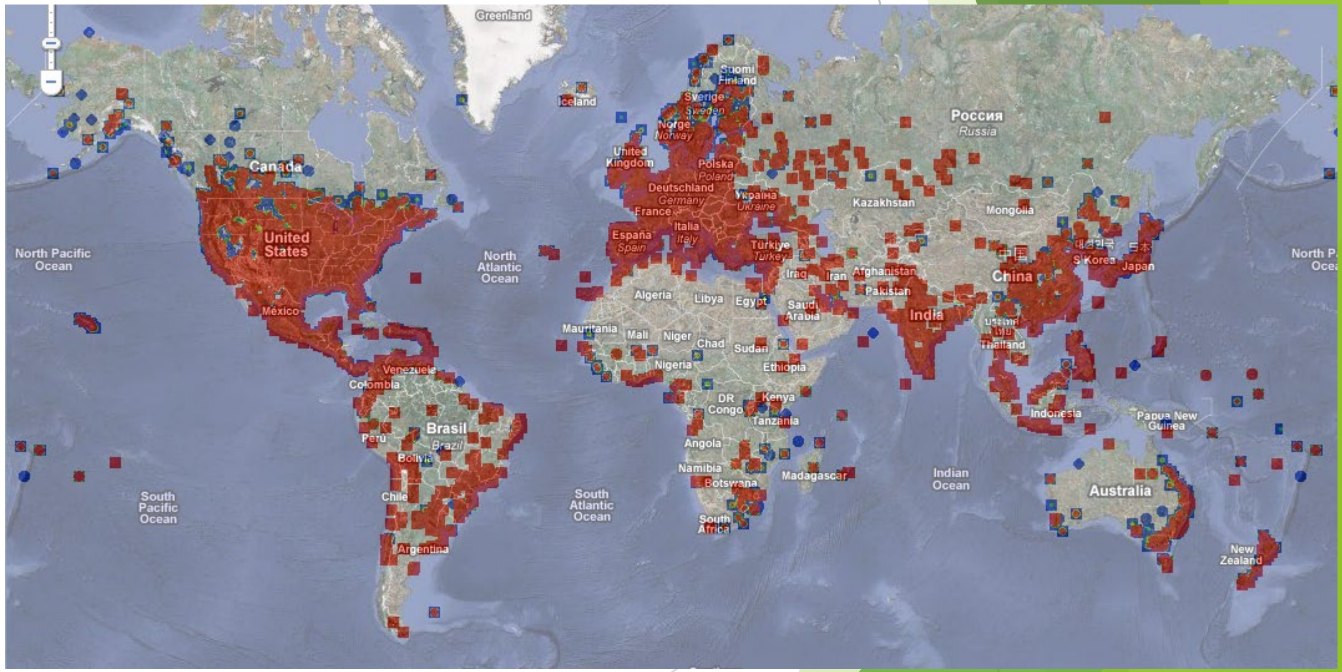
Tale #3: MS08-067 (Conficker Exploit)

- Bug in Windows netapi32.dll lib first discovered in 2008
- Allows complete remote compromise of all (then) Windows Servers
- Exploited by Confiker worm to infect ~1.7 million machines in ~190 countries, including national defense networks across Europe

```
void _NetpwPathCanonicalize(wchar_t* Path) {
  if (!_function_check_length(Path)) return;
  …
  _CanonicalizePathName(Path);
  …
}

void _CanonicalizePathName(wchar_t* Path) {
  wchar _wcsBuffer[0x420];
  …
  wcscat(wcsBuffer, Path);
  …
  _ConvertPathMacros(wcsBuffer);
…
```



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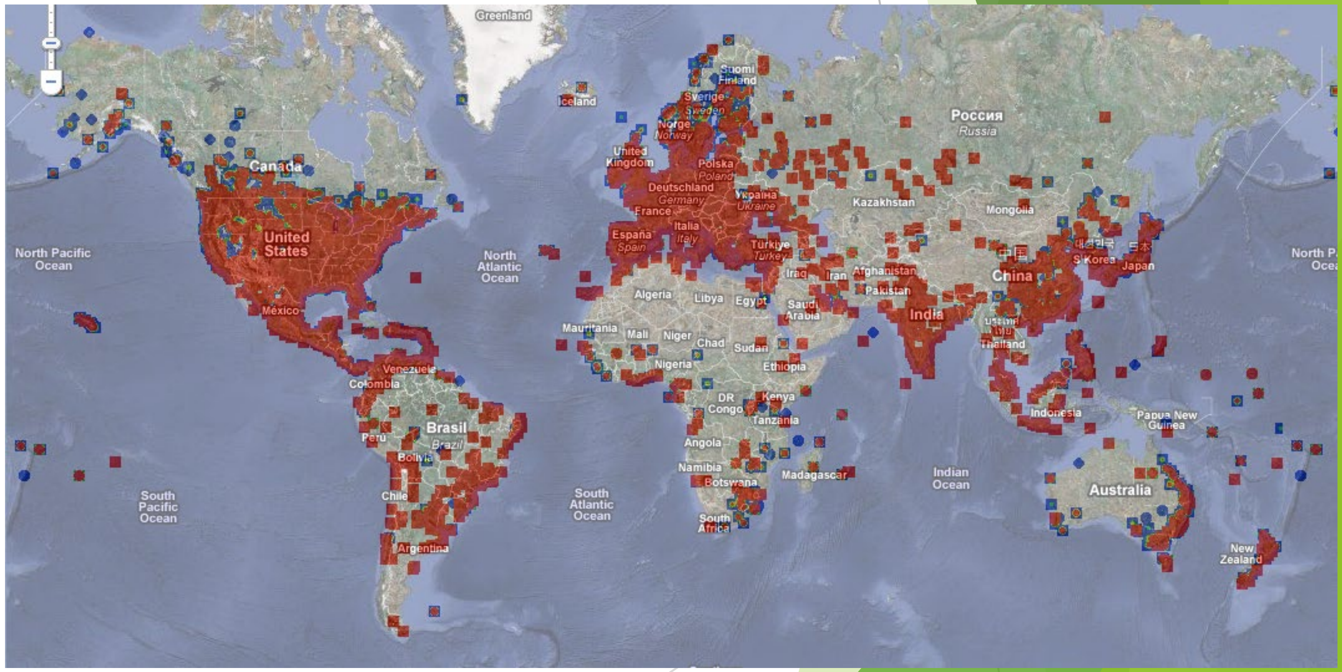

Tale #4: Stagefright

- Series of 8 critical vulnerabilities discovered in Android OS 2014-2015
- Allows complete remote hijacking of 95% of Android devices
- No user interaction required! (merely receiving a malformed MMS message triggers bug)

```
status_t SampleTable::setTimeToSampleParams(…) {
  uint32_t mTimeToSampleCount = U32_AT(&header[4]);
  uint64_t allocSize = mTimeToSampleCount * 2 * sizeof(uint32_t);
  if (allocSize > SIZE_MAX) return ERROR_OUT_OF_RANGE;
  mTimeToSample = new uint32_t[mTimeToSampleCount * 2];
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```

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```

STAGEFRIGHT

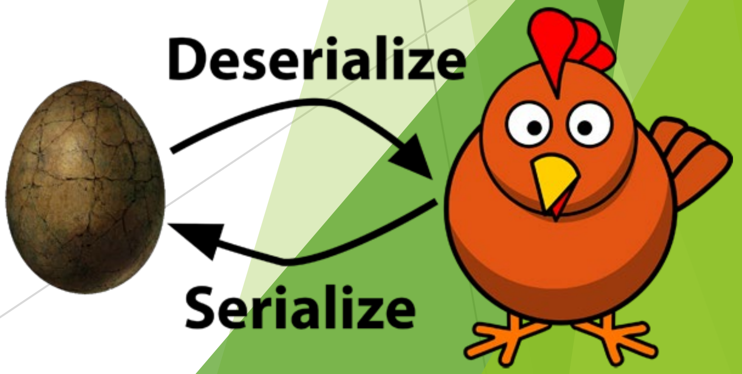
Tale #5: Shellshock (Linux Bash Bug)

- Bug (undocumented feature?) discovered in Linux bash shell (by IT manager Stephane Chazelas in his spare time!) in 2014
- Bash command-parser interprets certain text in environment variables as code and executes it during parsing(?!)
- Impact: All Linux software storing user-provided data in environment variables susceptible to complete remote compromise.
- Zero-day window: 25 years(!!) (198?-2014)

```
void initialize_shell_variables(char **env, int privmode) {
  …
  for (string_index = 0; string = env[string_index++]; ) {
    …
    if (privmode==0 && read_but_dont_execute == 0 && STREQN("() {", string, 4)) {
      …
      parse_and_execute(temp_string, name, SEVAL_NONINT|SEVAL_NOHIST);
      …
```

Tale #6: Java Deserialization

- Logical flaw in how many Java applications receive objects as input
- Examples dating back to 2010 and before, but popularized in 2015-2018 by successful attacks against WebSphere, WebLogic, JBoss, etc. [FoxGlove'15]
- millions of Java apps estimated to be currently vulnerable to complete remote compromise
- The Problem:
  - Java apps must deserialize input stream to object before they know what kind of object they received.
  - JVM deserializes stream to whatever object it says it is.
  - Some built-in JVM objects execute code at object initialization.
  - Executed code is supplied by attacker!

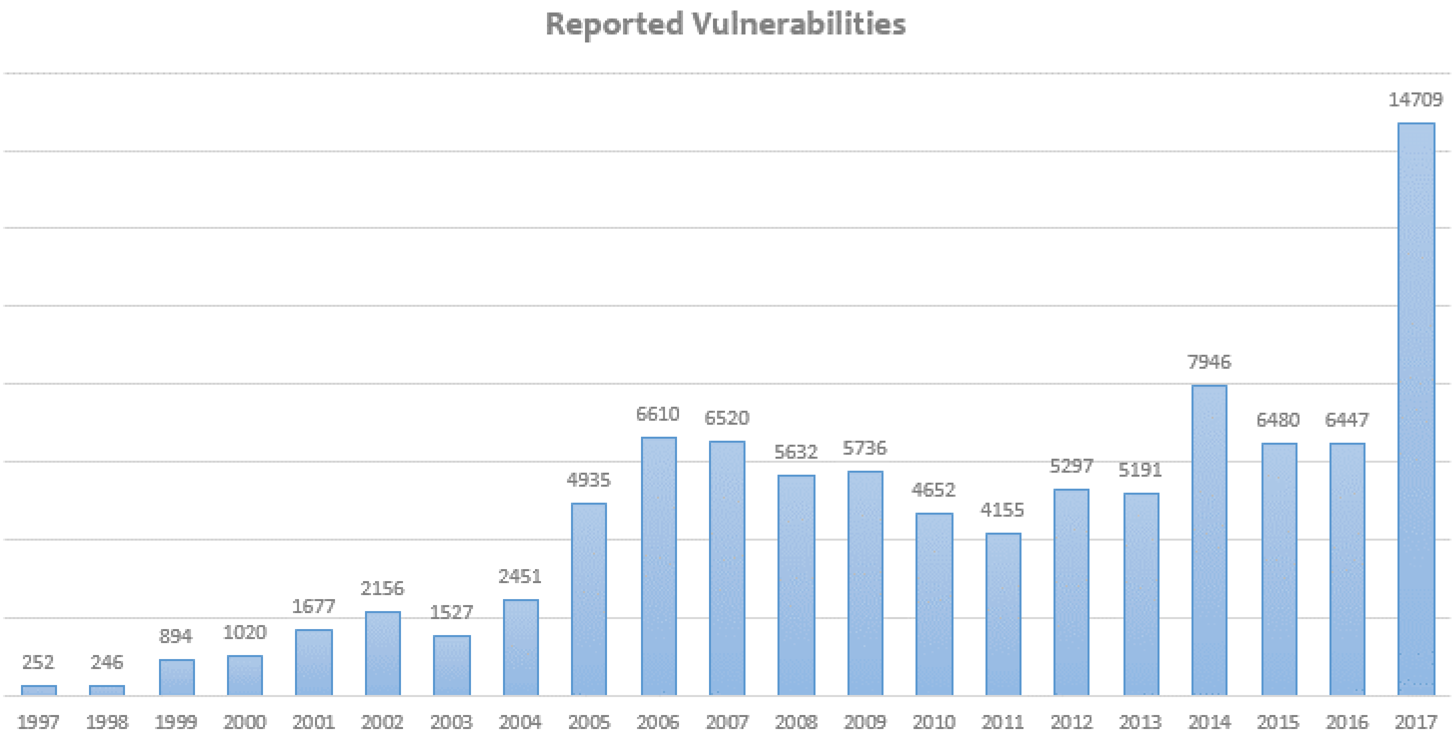


Tale #7: VENOM (Virtualized Environment Neglected Operations Manipulation)

- floppy disk controller bug discovered in 2015
- affects many VMs and hypervisors: QEMU, Xen, KVM, VirtualBox, …
- allows guest OS to escape the VM sandbox and run code on the host
- millions of data centers at risk
- existed for 10 years(!) before patched
- buffer overwrite error

```
void fdctrl_write_data(FDCtrl *fdctrl, uint32_t value) {
  …
  fdctrl->fifo[fdctrl->data_pos++] = value;
  …
```

The Software Security Crisis



- MITRE CVE Top "Unforgivable Vulnerabilities"
  - buffer overflow
  - XSS
  - SQL injection
  - directory traversal
  - world-writable files
  - direct admin script requests
  - homegrown crypto
  - authentication bypass
  - large check-use windows (TOCTOU)
  - privilege escalation
  - undocumented account
  - integer overflow
- Why do these still occur? Why do standard approaches fail?

Misguided Solutions

- People who haven't studied the field think the solution is "obvious":
  - Naïve idea #1: "If everyone just used [Linux | Java | Mac | …]"
  - Naïve idea #2: "Stop hiring stupid programmers."
  - Naïve idea #3: "Prioritize security testing more. Don't release too soon."
  - Naïve idea #4: "Just configure your permissions properly."
- IT approaches today:
  - Patch early, patch often…
  - Monitor network packets, monitor syscalls, monitor phone calls (NSA)…
  - Penetration testing (red-teaming)
  - Source code review

Science of Software Security

- Goals
  - Find **long-term, universal** solutions to software security crisis
  - Obtain **mathematical, quantifiable guarantees** for security of software products
    - machine-checked proofs, reliable metrics
  - **Automate** rigorous checking processes
    - no human in the loop!
- Two main domains of research
  - new languages/tools for creating secure software from scratch
  - securing legacy code
- Three stages of enforcement
  - static (find & fix vulnerabilities before runtime)
  - dynamic (detect and block attacks at runtime)
  - audit (recover and assign blame after an attack)

Important LBS Technologies

- Automated theorem-provers
  - machine-assisted, machine-checked proofs of security
- In-lined Reference Monitors
  - insert dynamic security checks into untrusted code
- Type-checkers
  - advanced type systems can encode security properties
- Model-checkers
  - statically verify that code model obeys a security property
- Certifying Compilers
  - transform source code into object code and an independently verifiable proof that the object code is safe to execute

At Least Three Hard Issues Involved

- Minimal Trusted Computing Base (TCB)
- Principle of Least Privilege
- The Model Problem:
  - Trust Model
  - Attacker Model
  - System Model

TCB Minimization

- Let’s play a game: I’m thinking of a piece of software.
  - Most of you have it and have used it.
  - If it fails, it could delete or divulge all your personal files.
  - Microsoft makes it.
  - Can you guess which software I’m thinking of?

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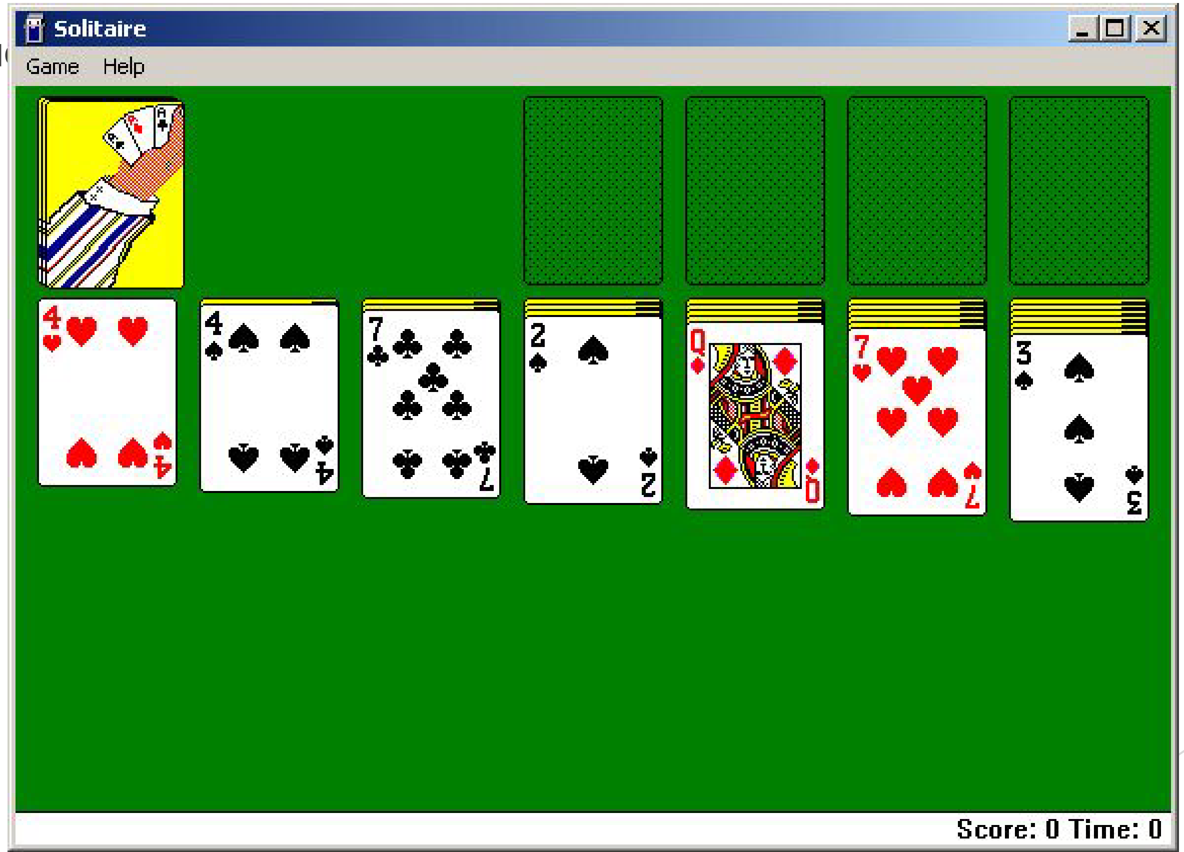
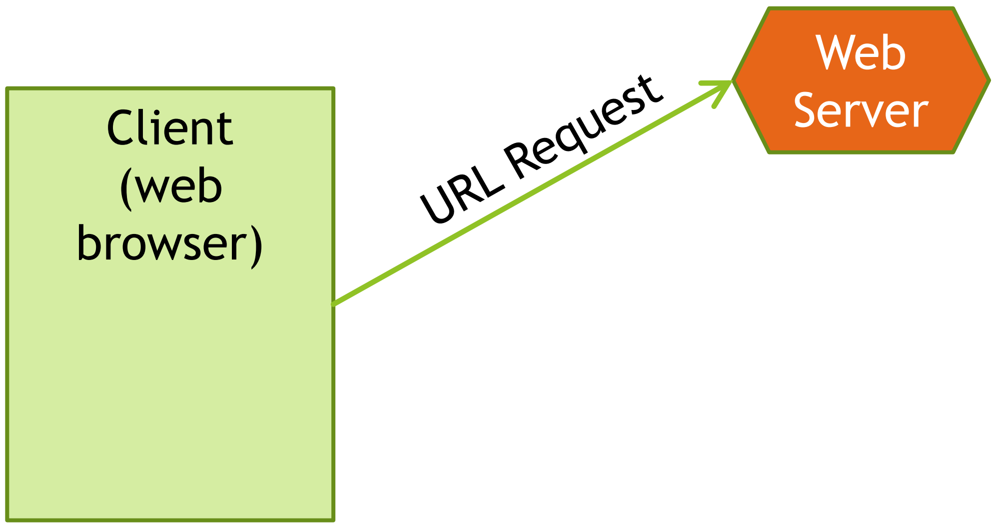


Least Privilege

- Principle of Least Privilege: *"Every program and every user of the system should operate using the least set of privileges necessary to complete the job."* [Saltzer & Schroeder, 1975]
- Hard problem: What is the least set of privileges necessary to complete the job? How do we compute it?
- No finite set of roles or permission options suffices to meet PoLP in all cases!
- Richer classes of enforceable policies get us closer, though.

Trust Modeling



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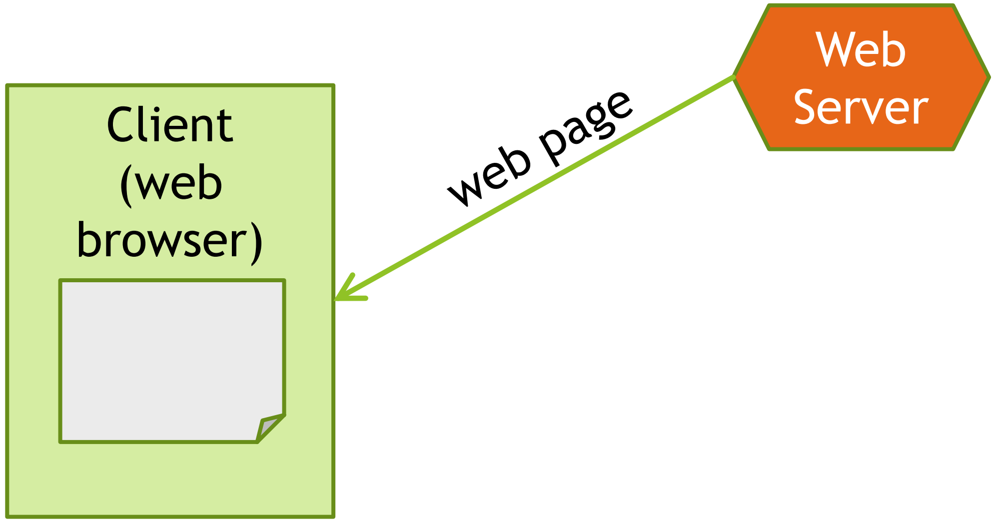

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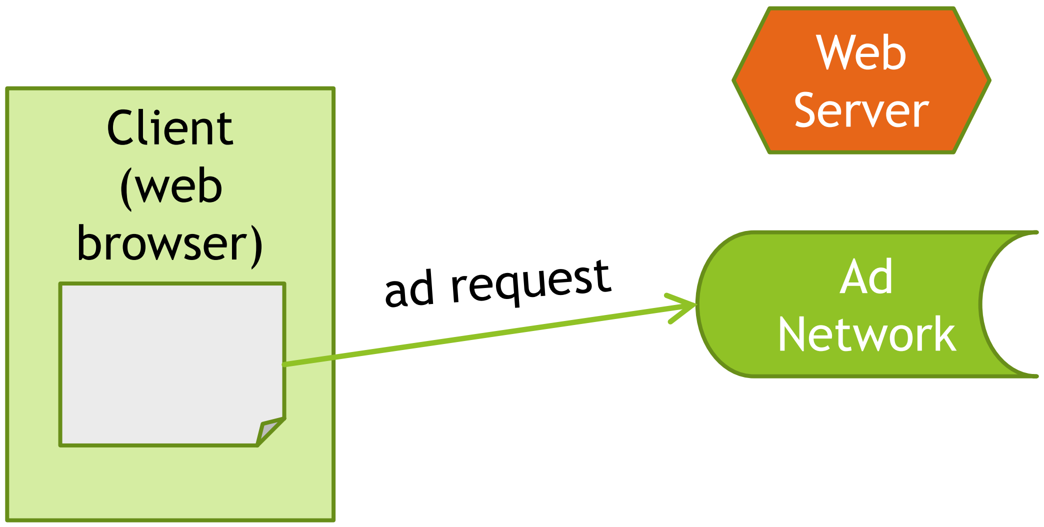

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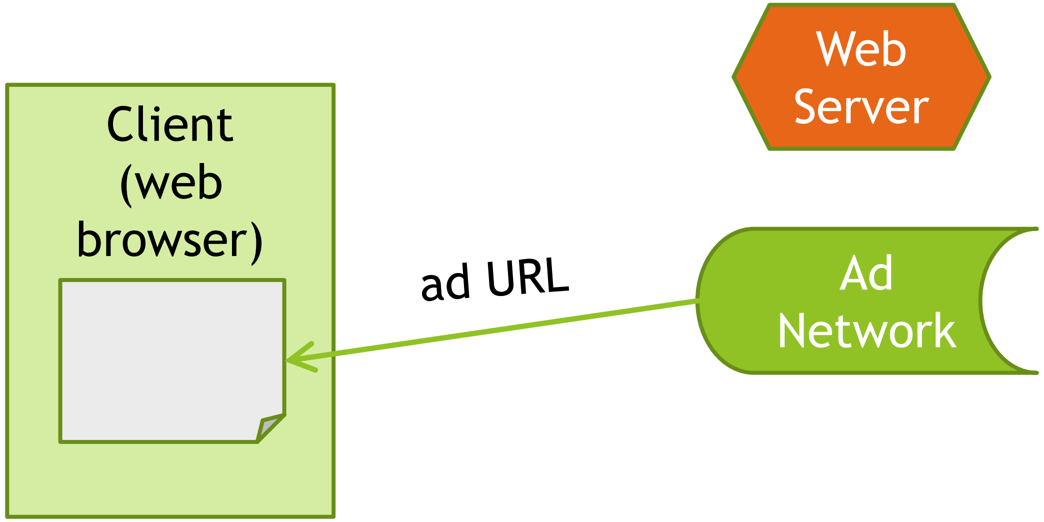

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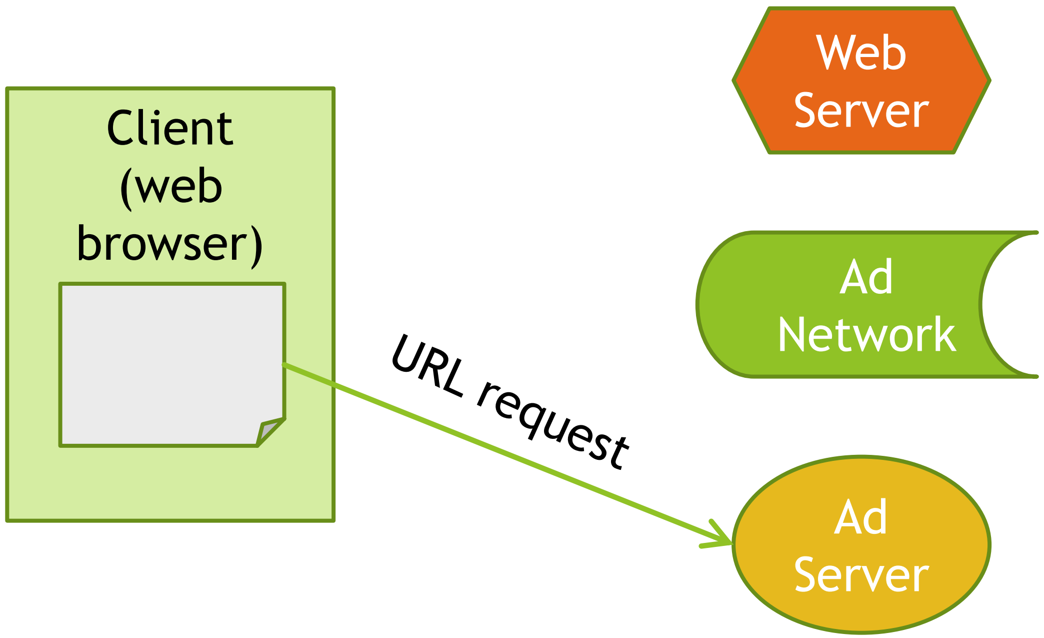

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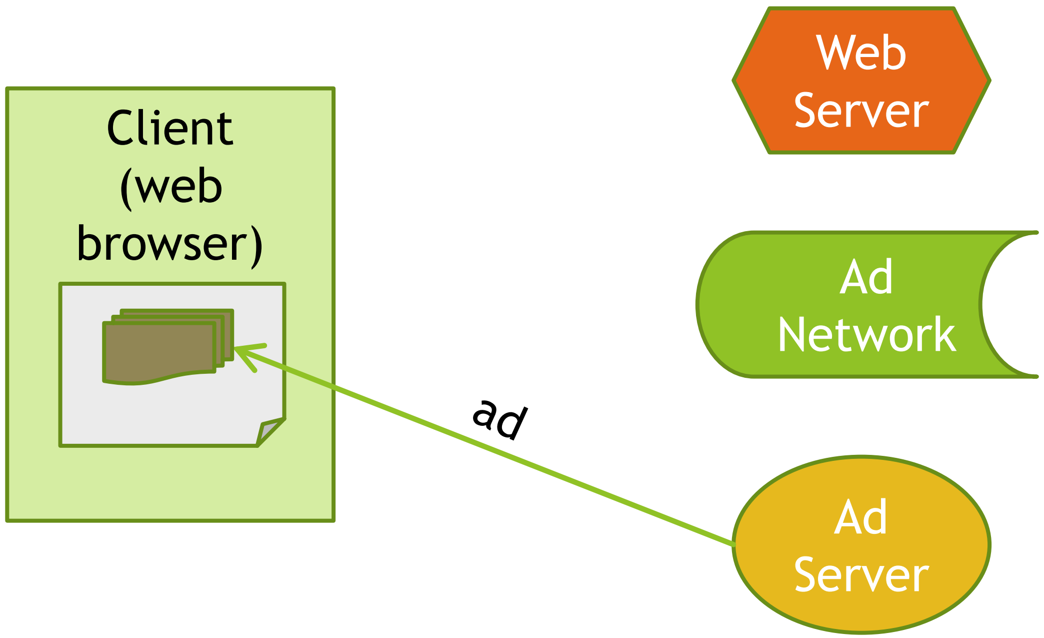

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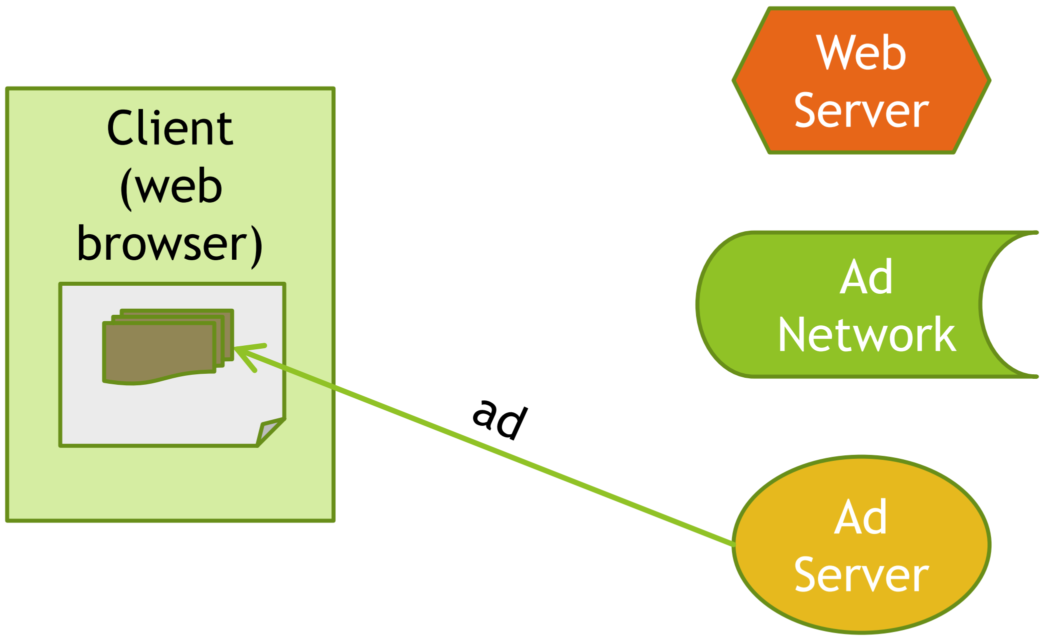


- Four principals: client, page publisher, ad network, ad publisher
- What are some security requirements each principal is likely to have?
- Which existing technologies can be used to meet those requirements?
- How can we assess/measure the “security” of the resulting system?

Trust Modeling

- Trust model: Who trusts whom to do what?
- Trusted Computing Base (TCB): The set of all system components that must be trusted in order to maintain system security
  - Security meta-goal: minimize the TCB
- What is the trust model in our web scenario?
- What is the TCB? How can we make it smaller?

Attack Modeling

- Threat model: set of assumed attacker capabilities
  - attacks outside the model may succeed!
  - threat model assumptions = security system limitations
- What is a reasonable threat model for our web scenario?

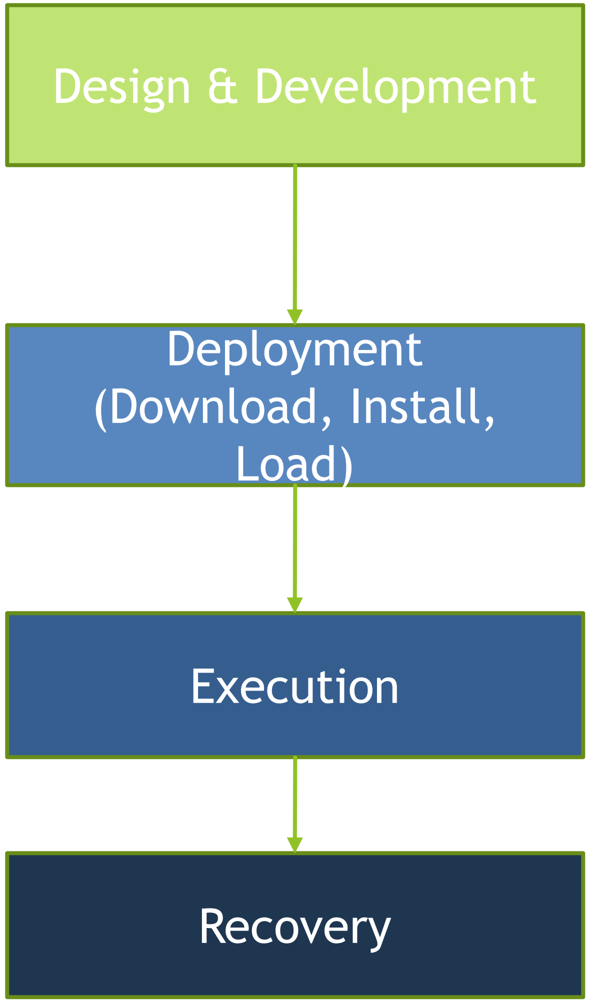
Major Classes of Security Policies

- Integrity – preventing improper or unauthorized change to data or resources
  - Example: ad may not delete your files
- Availability – continued access to data or resources
  - Example: ad may not expand to occlude the rest of the page
- Confidentiality – concealment of data or resources
  - Example: ad may not send your browsing history to your employer

Defining Security Policies Formally

- Security Policy – specification of allowed (or, equivalently, disallowed) behaviors
  - Safety Policies – some “bad” thing shouldn’t happen (integrity)
  - Liveness Policies – some “good” thing should eventually happen (availability)
- Safety + Liveness = all policies [Alpern & Schneider, 1985]

Software Lifecycle



- Security vulnerabilities in non-malicious code
  - type-safe programming languages
  - formal verification
  - code synthesis
- Malicious code (viruses, worms, etc.)

- Antivirus scanning
- Code-signing
- Type-safe target codes (e.g., Java bytecode)
- Independently verifiable certificates

- Runtime monitoring
- Automatically generated self-monitoring code

- Auditing (logging)
- Rollback (reversible computation, restore points)
- Legal action

Example: Memory Safety

- Memory Safety = ?
- Traditional security model:
  - program is a black box
  - OS/hardware intercepts every memory access
- Language-based security model:
  - program is a sequence of instructions in an architecture with known semantics
  - analyze the sequence to identify all potential violations
  - insert dynamic memory checks into the program

Example: Memory Safety

- Memory Safety = Programs may not access unallocated memory addresses
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Example: Data Confidentiality

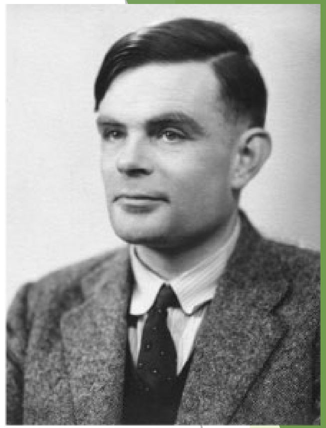
- Policy: Don’t divulge my credit card number
- Traditional approach:
  - monitor all outgoing network traffic
  - block any transmission containing the relevant bit sequence
- Language-based approach:
  - analyze the dataflow graph of the software
  - identify potential flows from high-security sources to low-security sinks
  - interpose robust declassification guards along identified flows
  - quantify the potential information disclosure as Shannon entropy

Reasons for a Language-based Approach

- Rigor
  - We have a science of programming languages!
  - Lets us prove things about how software behaves and what it can do
- Efficiency
  - enforce security "from inside" the software
  - richer context, smarter security checks, fewer context switches
- Flexibility
  - no need for custom OS/hardware
  - ship the enforcement mechanism with the product, or add it client-side
- Power/expressiveness
  - can enforce exceptionally powerful policies (e.g., history-based)
  - enforce notoriously hard policies like confidentiality and availability

Decidability


Kurt Gödel


Alan Turing


Alonzo Church

- Is this really possible with arbitrary software? What about these guys?
- The Halting Problem
  - Exercise: Reduce memory safety to the halting problem
- Escape Hatches
  - conservative rejection
  - limit the domain (e.g., constrained input language)
  - require dynamic checks on uncertainty
  - push the proof burden to the code-provider

Next Time: Software Model Checking

- Software Model Checking vs. Automated Theorem Proving

- Lists assignment also due Monday
  - Be sure you have at least a tentative solution to *matches_nil* and *rem* from Assignment 1 (even if they might have bugs).
  - probably easier than last two assignments if you have a mostly-correct Assignment 1 (but don't wait until the last second!)