Designing and Writing Secure Application Code

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Outline

- General principles
  - Least privilege, defense in depth, …
- Example
  - Sendmail vs qmail
- Tools for secure coding
  - Type-safe programming languages
  - Purify
  - Perl tainting
  - Code analysis algorithms
  - Run-time monitoring (another lecture)

General topics in this course

- Vulnerabilities
  - How hackers break into systems
    - Circumvent security mechanisms (e.g., dictionary attack)
    - Use code for purpose it was not intended (buffer overflow)
- Defensive programming
  - Build *all* software with security in mind
  - Make sure video game is not a boot loader
- Security Mechanisms
  - Authentication
  - Access control
  - Network protocols

This lecture

Before you start building …

- What are the security requirements?
  - Confidentiality (secrets remain secret)
  - Integrity (meaning preserved)
  - Availability
  - Accountability
- What threats are possible?
- Who do you trust / not trust?

Security = preserve properties against attack

General advice

- Compartmentalization
  - Principle of least privilege
  - Minimize trust relationships
- Defense in depth
  - Use more than one security mechanism
  - Secure the weakest link
  - Fail securely
- Keep it simple
- Consult experts
  - Don't build what you can easily borrow/steal
  - Open review is effective and informative

Compartmentalization

- Divide system into modules
  - Each module serves a specific purpose
  - Assign different access rights to different modules
    - Read/write access to files
    - Read user or network input
    - Execute privileged instructions (e.g., Unix root)
- Principle of least privilege
  - Give each module only the rights it needs

Compartmentalization (II)

- Example
  - Sendmail runs as root
    - Root privilege needed to bind port 25
    - No longer needed after port bind established
      - But most systems keep running as root
    - Root privileges needed later to write to user mailboxes
  - Will look at qmail for better security design
- Minimize trust relationships
  - Clients, servers should not trust each other
    - Both can get hacked
  - Trusted code should not call untrusted code

Example: .NET

```
class NativeMethods
{
   // This is a call to unmanaged code. Executing this method requires
   // the UnmanagedCode security permission. Without this permission,
   // an attempt to call this method will throw a SecurityException:
   [DllImport("msvcrt.dll")]
   public static extern int puts(string str);
   [DllImport("msvcrt.dll")]
   internal static extern int _flushall();
}
```

Code denies permission not needed

```
[SecurityPermission(SecurityAction.Deny, Flags =
    SecurityPermissionFlag.UnmanagedCode)]
private static void MethodToDoSomething()
{   try
    {
       Console.WriteLine(" … ");
       SomeOtherClass.method();
     }
    catch (SecurityException)
    {
       …
    }
}
```

Defense in Depth

- Failure is unavoidable – plan for it
- Have a series of defenses
  - If an error or attack is not caught by one mechanism, it should be caught by another
- Examples
  - Firewall + network intrusion detection
  - SSH + Tripwire
- Fail securely
  - Many, many vulnerabilities are related to error handling, debugging or testing features, error messages

Secure the weakest link

- Think about possible attacks
  - How would someone try to attack this?
  - What would they want to accomplish?
- Find weakest link(s)
  - Crypto library is probably pretty good
  - Is there a way to work around crypto?
    - Data stored in encrypted form; where is *key* stored?
- Main point
  - Do security analysis of the whole system
  - Spend your time where it matters

Keep It Simple

- Use standard, tested components
  - Don't implement your own cryptography
- Don't add unnecessary features
  - Extra functionality $\Rightarrow$ more ways to attack
- Use simple algorithms that are easy to verify
  - A trick that may save a few instructions may
    - Make it harder to get the code right
    - Make it harder to modify and maintain code

Promote Privacy

- Discard information when no longer needed
  - No one can attack system to get information
- Examples
  - Don't keep log of old session keys
  - Delete firewall logs
  - Don't run unnecessary services (fingerd)
- Hiding sensitive information is hard
  - Information in compiled binaries can be found
  - Insider attacks are common
  - Security by obscurity doesn't work!!!

Don't reinvent the wheel

- Consult experts
- Allow public review
- Use software, designs that other have used
- Examples
  - Bad use of crypto: 802.11b
  - Protocols without expert review: 802.11i
  - Use standard url parser, crypto library, good random number generater, …

Example: Mail Transport Agents

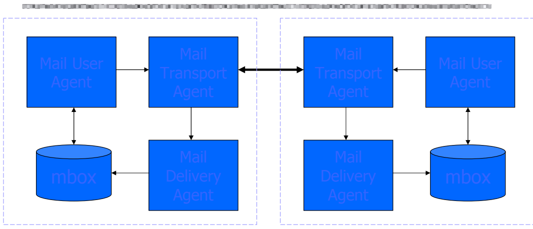
- Sendmail
  - Complicated system
  - Source of many vulnerabilities
- Qmail
  - Simpler system designed with security in mind
  - Gaining popularity

Qmail was written by Dan Bernstein, starting 1995
$500 reward for successful attack; no one has collected

Market share

Year	Sendmail	Qmail
1996	80%	
1997	76%	
1998	63%	
2000	55%	
2001	47%	9%
2002	42%	17%

Simplified Mail Transactions



- Message composed using an MUA
- MUA gives message to MTA for delivery
  - If local, the MTA gives it to the local MDA
  - If remote, transfer to another MTA

Stanford Sendmail Vulnerability

Sent: Tuesday, March 04, 2003 1:12 PM
To: unix-info@lists.Stanford.EDU
Subject: Stanford ITSS Security Alert: sendmail Header Processing Vulnerability

sendmail is the most popular Mail Transfer Agent (MTA) program in use on the Internet, …

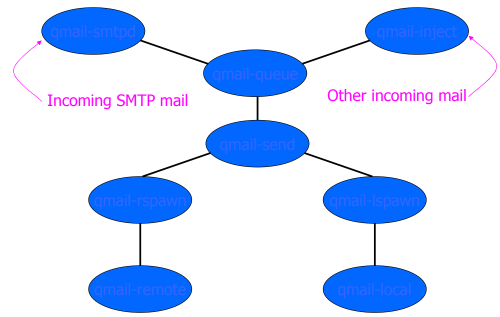
sendmail contains an error in one of the security checks it employs on addresses in its headers, which may allow an attacker to execute malicious code within the sendmail security context, usually root…

All users of sendmail should patch immediately …

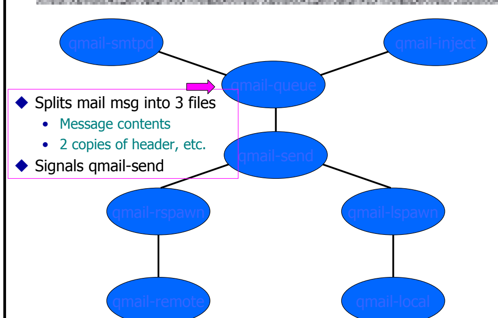
Example: qmail

- Least privilege
  - Each module uses least privileges necessary
  - Only one setuid program
    - setuid to one of the other qmail user IDs, not root
    - No setuid root binaries
  - Only one run as root
    - Spawns the local delivery program under the UID and GID of the user being delivered to
    - No delivery to root
    - Always changes effective uid to recipient before running user-specified program
- Other secure coding ideas

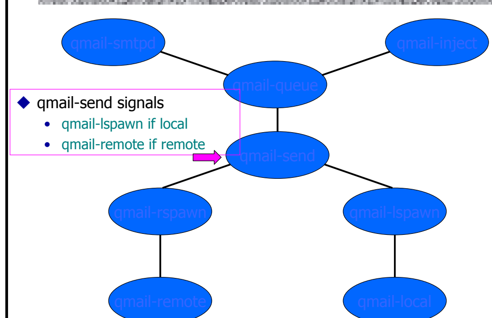
Structure of qmail



Structure of qmail



Structure of qmail



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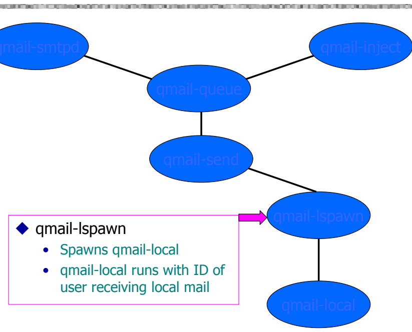

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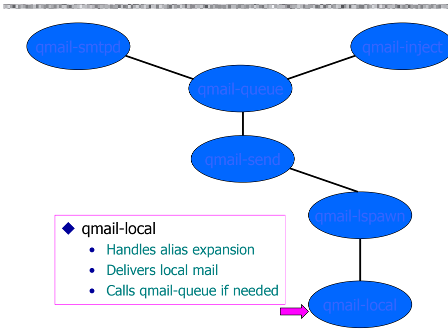
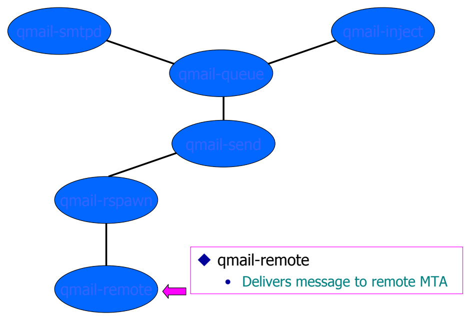
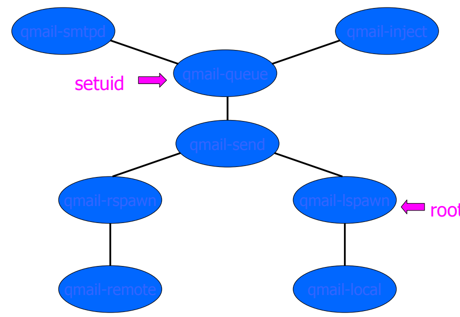


Structure of qmail

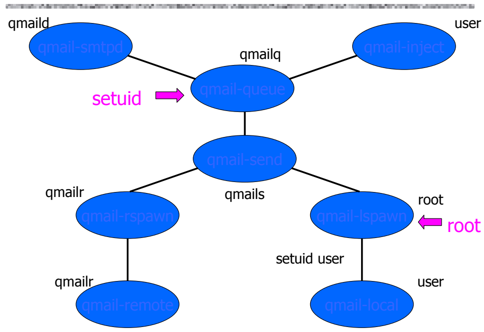


Least privilege



UIDs

qmailq – user who is allowed to read/write mail queue



Principles, sendmail vs qmail

- Do as little as possible in setuid programs
  - Of 20 recent sendmail security holes, 11 worked only because the entire sendmail system is setuid
  - Only qmail-queue is setuid
    - Its only function is add a new message to the queue
- Do as little as possible as root
  - The entire sendmail system runs as root
    - Operating system protection has no effect
  - Only qmail-start and qmail-lspawn run as root.

Principles, sendmail vs qmail

- Programs and files are not addresses
  - sendmail treats programs and files as addresses
    - "sendmail goes through horrendous contortions trying to keep track of whether a local user was responsible for an address. This has proven to be an unmitigated disaster" (DJB)
  - qmail programs and files are not addresses
    - "The local delivery agent, qmail-local, can run programs or write to files as directed by ~user/.qmail, but it's always running as that user. Security impact: .qmail, like .cshrc and .exrc and various other files, means that anyone who can write arbitrary files as a user can execute arbitrary programs as that user. That's it." (DJB)

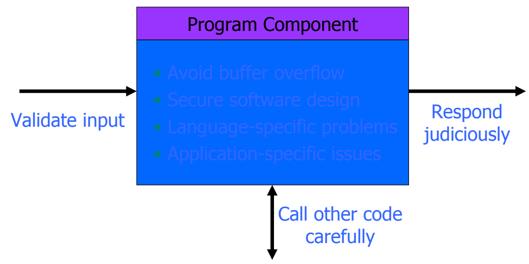
Keep it simple

- Parsing
  - Limited parsing of strings
    - Minimizes risk of security holes from configuration errors
- Libraries
  - Avoid standard C library, stdio
    - "Write bug-free code" (DJB)
- Don't repeat functionality
  - One simple mechanism handles forwarding, aliasing, and mailing lists (instead of 3)
  - Single delivery mode instead of a selection

Comparison

	Lines	Words	Chars	Files
qmail-1.01	16028	44331	370123	288
sendmail-8.8.8	52830	179608	1218116	53
zmailer-2.2e10	57595	205524	1423624	227
smail-3.2	62331	246140	1701112	151
exim-1.90	67778	272084	2092351	127

Additional general advice [Wheeler]



See Wheeler's book on web

Summary from [Wheeler]

- Validate all your inputs
  - Command line inputs, environment variables, CGI inputs, …
  - Don't just reject "bad" input, define "good" and reject all else
- Avoid buffer overflow
- Structure your program security
  - Secure the interface, minimize privileges
  - Make the initial configuration and defaults safe
  - Avoid race conditions
  - Trust only trustworthy channels
    - Most servers must not trust clients for security checks
- Carefully call out to other resources
  - Check all system calls and return values

Additional reading

- Contents
  - Contemporary security
    - Need for secure systems, proactive security process
  - Secure Coding Techniques
    - The buffer overrun
    - Determining appropriate access control
    - Running with least privilege
    - Protecting secret data
    - All input is evil
    - ….
  - More Secure Coding techniques
  - Special Topics
    - Testing, code review, secure installation, privacy

Tools for producing secure code

- C vs type safe languages
  - Buffer overflows are array bounds violations
  - Java, ML, … check array bounds, prevent overflow
- Purify
  - Find memory errors on the heap
- Perl tainting
  - Track use of untrusted input
- Automated code analysis tools
  - Can catch many kinds of errors

Purify

- Goal
  - Instrument a program to detect run-time memory errors (out-of-bounds, use-before-init) and memory leaks
- Technique
  - Works on relocatable object code
    - Link to modified malloc that provides tracking tables
  - Memory access errors: insert instruction sequence before each load and store instruction
  - Memory leaks: GC algorithm

Perl tainting

- Run-time checking of Perl code
  - Perl used for CGI scripts, security sensitive
  - Taint checking stops some potentially unsafe calls
- Tainted strings
  - User input, Values derived from user input
  - Except result of matching against untainted string
- Prohibited calls
  - print $form_data{"email"} . "\n";
    - OK since print is safe (???)
  - system("mail " . $form_data{"email"});
    - Flagged system call with user input as argument

Safe Perl mail command (?)

- Check email string against pattern and parse

```
$email = $form_data{"email"};
if ( $email =~ /(\w{1}[\w-.]*)\@([\w-.]+)/) {
    $email = "$1\@$2";
} else { warn ("TAINTED DATA SENT BY ...");
    $email = ""; # successful match did not occur }
```

- What does this accomplish?
  - Only send email to address that "looks good"
  - Programmer responsible for "good" pattern
  - Perl cannot guarantee that email addr is OK

Automated code analysis for C

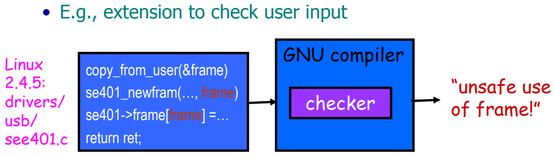
- Example tool
  - Ken Ashcraft and Dawson Engler, Using Programmer-Written Compiler Extensions to Catch Security Holes, IEEE Security and Privacy 2002
  - Used modified compiler to find over 100 security holes in Linux and BSD
  - http://www.stanford.edu/~engler/
- Benefit
  - Capture recommended practices, known to experts, in tool available to all

Checking secure software

- Many rules for writing secure code
  - "sanitize user input before using it"
  - "check permissions before doing operation X"
- How to find errors?
  - Formal verification
    - \+ rigorous
    - – costly, expensive. *Very* rare to do for software
  - Testing:
    - \+ simple, few false positives
    - – requires running code: doesn't scale & can be impractical
  - Manual inspection
    - \+ flexible
    - – erratic & doesn't scale well.
  - What to do??

Metacompilation (MC)

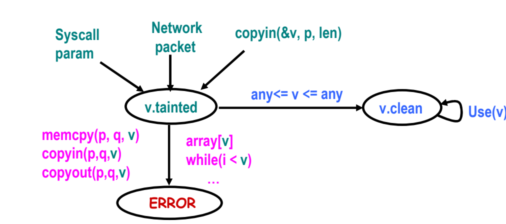
- Analyze compiler data structure to check code
  - Extensions dynamically linked into GNU gcc compiler
  - Applied down all paths in input program source
  - E.g., extension to check user input



Actual error in Linux: raid5 driver disables interrupts, and then if it fails to allocate buffer, returns with them disabled. This kernel deadlock is actually hidden by an immediate segmentation fault since the callers dereference the pointer without checking for NULL

Sanitize integers before use

Warn when unchecked integers from untrusted sources reach trusting sinks



Linux: 125 errors, 24 false; BSD: 12 errors, 4 false

Example security holes

- Remote exploit, no checks

```
/* 2.4.9/drivers/isdn/act2000/capi.c:actcapi_dispatch */
isdn_ctrl cmd;
...
while ((skb = skb_dequeue(&card->rcvq))) {
   msg = skb->data;
   ...
   memcpy(cmd.parm.setup.phone,
          msg->msg.connect_ind.addr.num,
          msg->msg.connect_ind.addr.len - 1);
```

Example security holes

- Missed lower-bound check:

```
/* 2.4.5/drivers/char/drm/i810_dma.c */
if(copy_from_user(&d, arg, sizeof(arg)))
   return -EFAULT;
if(d.idx > dma->buf_count)
   return -EINVAL;
buf = dma->buflist[d.idx];
Copy_from_user(buf_priv->virtual, d.address, d.used);
```

User-pointer inference

- Problem: which are the user pointers?
  - Hard to determine by dataflow analysis
  - Easy to tell if kernel *believes* pointer is from user!
- Belief inference
  - "*p" implies safe kernel pointer
  - "copyin(p)/copyout(p)" implies dangerous user ptr
  - Error: pointer p has both beliefs.
- Implementation: 2 pass checker

  inter-procedural: compute all tainted pointers

  local pass to check that they are not dereferenced

Results for BSD and Linux

- All bugs released to implementers; most serious fixed

Violation	Linux Bug	Linux Fixed	BSD Bug	BSD Fixed
Gain control of system	18	15	3	3
Corrupt memory	43	17	2	2
Read arbitrary memory	19	14	7	7
Denial of service	17	5	0	0
Minor	28	1	0	0
Total	125	52	12	12

	Linux	BSD
Local bugs	109	12
Global bugs	16	0
Bugs from inferred ints	12	0
False positives	24	4
Number of checks	~3500	594

Conclusions

- Security takes extra effort
  - Know your security goals
  - Design with security in mind
    - Compartmentalize, least privilege
    - Minimize setuid, root
  - Implement carefully
    - Keep it simple
    - Think about attacks; secure the weakest link
  - Use tools that detect common coding problems
    - There are also tools that can analyze designs, but that's another story (harder to use, current research)