Chapter 23: Vulnerability Analysis

- Background
- Penetration Studies
- Example Vulnerabilities
- Classification Frameworks
- Theory of Penetration Analysis

Overview

- What is a vulnerability?
- Penetration studies
  - Flaw Hypothesis Methodology
  - Examples
- Vulnerability examples
- Classification schemes
  - RISOS, PA, NRL Taxonomy, Aslam's Model
- Theory of penetration analysis
  - Examples

Definitions

- *Vulnerability*, *security flaw*: failure of security policies, procedures, and controls that allow a subject to commit an action that violates the security policy
  - Subject is called an *attacker*
  - Using the failure to violate the policy is *exploiting the vulnerability* or *breaking in*

Formal Verification

- Mathematically verifying that a system satisfies certain constraints
- *Preconditions* state assumptions about the system
- *Postconditions* are result of applying system operations to preconditions, inputs
- Required: postconditions satisfy constraints

Penetration Testing

- Testing to verify that a system satisfies certain constraints
- Hypothesis stating system characteristics, environment, and state relevant to vulnerability
- Result is compromised system state
- Apply tests to try to move system from state in hypothesis to compromised system state

Notes

- Penetration testing is a *testing* technique, not a verification technique
  - It can prove the *presence* of vulnerabilities, but not the *absence* of vulnerabilities
- For formal verification to prove absence, proof and preconditions must include *all* external factors
  - Realistically, formal verification proves absence of flaws within a particular program, design, or environment and not the absence of flaws in a computer system (think incorrect configurations, etc.)

Penetration Studies

- Test for evaluating the strengths and effectiveness of all security controls on system
  - Also called *tiger team attack* or *red team attack*
  - Goal: violate site security policy
  - Not a replacement for careful design, implementation, and structured testing
  - Tests system *in toto*, once it is in place
    - Includes procedural, operational controls as well as technological ones

Goals

- Attempt to violate specific constraints in security and/or integrity policy
  - Implies metric for determining success
  - Must be well-defined
- Example: subsystem designed to allow owner to require others to give password before accessing file (i.e., password protect files)
  - Goal: test this control
  - Metric: did testers get access either without a password or by gaining unauthorized access to a password?

Goals

- Find some number of vulnerabilities, or vulnerabilities within a period of time
  - If vulnerabilities categorized and studied, can draw conclusions about care taken in design, implementation, and operation
  - Otherwise, list helpful in closing holes but not more
- Example: vendor gets confidential documents, 30 days later publishes them on web
  - Goal: obtain access to such a file; you have 30 days
  - Alternate goal: gain access to files; no time limit (a Trojan horse would give access for over 30 days)

Layering of Tests

1. External attacker with no knowledge of system
   - Locate system, learn enough to be able to access it
2. External attacker with access to system
   - Can log in, or access network servers
   - Often try to expand level of access
3. Internal attacker with access to system
   - Testers are authorized users with restricted accounts (like ordinary users)
   - Typical goal is to gain unauthorized privileges or information

Layering of Tests (con't)

- Studies conducted from attacker's point of view
- Environment is that in which attacker would function
- If information about a particular layer irrelevant, layer can be skipped
  - Example: penetration testing during design, development skips layer 1
  - Example: penetration test on system with guest account usually skips layer 2

Methodology

- Usefulness of penetration study comes from documentation, conclusions
  - Indicates whether flaws are endemic or not
  - It does not come from success or failure of attempted penetration
- Degree of penetration's success also a factor
  - In some situations, obtaining access to unprivileged account may be less successful than obtaining access to privileged account

Flaw Hypothesis Methodology

1. Information gathering
   - Become familiar with system's functioning
2. Flaw hypothesis
   - Draw on knowledge to hypothesize vulnerabilities
3. Flaw testing
   - Test them out
4. Flaw generalization
   - Generalize vulnerability to find others like it
5. (*maybe*) Flaw elimination
   - Testers eliminate the flaw (usually *not* included)

Information Gathering

- Devise model of system and/or components
  - Look for discrepancies in components
  - Consider interfaces among components
- Need to know system well (or learn quickly!)
  - Design documents, manuals help
    - Unclear specifications often misinterpreted, or interpreted differently by different people
  - Look at how system manages privileged users

Flaw Hypothesizing

- Examine policies, procedures
  - May be inconsistencies to exploit
  - May be consistent, but inconsistent with design or implementation
  - May not be followed
- Examine implementations
  - Use models of vulnerabilities to help locate potential problems
  - Use manuals; try exceeding limits and restrictions; try omitting steps in procedures

Flaw Hypothesizing (*con't*)

- Identify structures, mechanisms controlling system
  - These are what attackers will use
  - Environment in which they work, and were built, may have introduced errors
- Throughout, draw on knowledge of other systems with similarities
  - Which means they may have similar vulnerabilities
- Result is list of possible flaws

Flaw Testing

- Figure out order to test potential flaws
  - Priority is function of goals
    - Example: to find major design or implementation problems, focus on potential system critical flaws
    - Example: to find vulnerability to outside attackers, focus on external access protocols and programs
- Figure out how to test potential flaws
  - Best way: demonstrate from the analysis
    - Common when flaw arises from faulty spec, design, or operation
  - Otherwise, must try to exploit it

Flaw Testing (*con't*)

- Design test to be least intrusive as possible
  - Must understand exactly why flaw might arise
- Procedure
  - Back up system
  - Verify system configured to allow exploit
    - Take notes of requirements for detecting flaw
  - Verify existence of flaw
    - May or may not require exploiting the flaw
    - Make test as simple as possible, but success must be convincing
  - Must be able to repeat test successfully

Flaw Generalization

- As tests succeed, classes of flaws emerge
  - Example: programs read input into buffer on stack, leading to buffer overflow attack; others copy command line arguments into buffer on stack $\Rightarrow$ these are vulnerable too
- Sometimes two different flaws may combine for devastating attack
  - Example: flaw 1 gives external attacker access to unprivileged account on system; second flaw allows any user on that system to gain full privileges $\Rightarrow$ any external attacker can get full privileges

Flaw Elimination

- Usually not included as testers are not best folks to fix this
  - Designers and implementers are
- Requires understanding of context, details of flaw including environment, and possibly exploit
  - Design flaw uncovered during development can be corrected and parts of implementation redone
    - Don't need to know how exploit works
  - Design flaw uncovered at production site may not be corrected fast enough to prevent exploitation
    - So need to know how exploit works

Michigan Terminal System

- General-purpose OS running on IBM 360, 370 systems
- Class exercise: gain access to terminal control structures
  - Had approval and support of center staff
  - Began with authorized account (level 3)

Step 1: Information Gathering

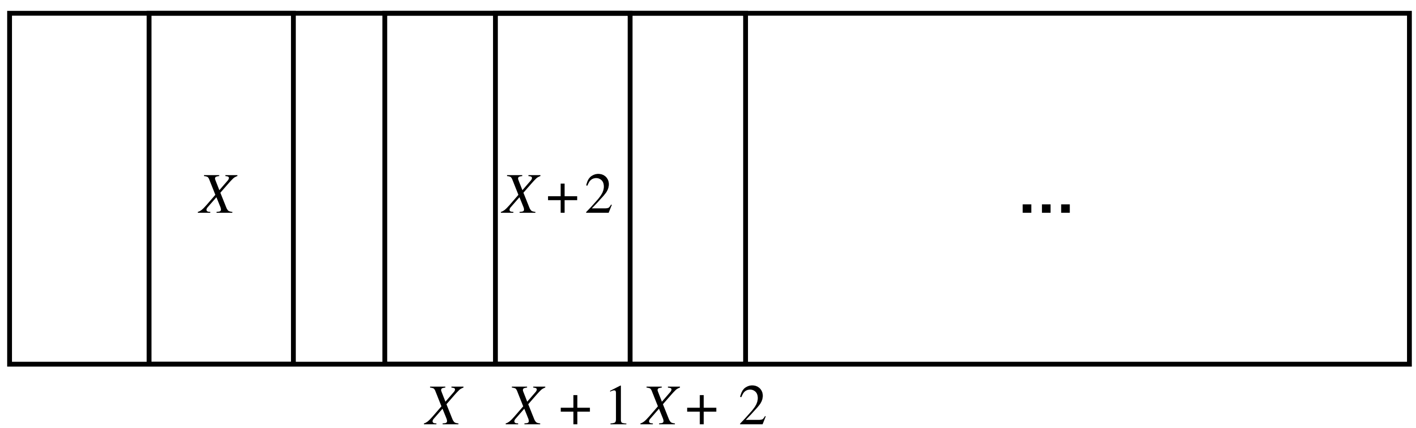
- Learn details of system's control flow and supervisor
  - When program ran, memory split into segments
  - 0-4: supervisor, system programs, system state
    - Protected by hardware mechanisms
  - 5: system work area, process-specific information including privilege level
    - Process should not be able to alter this
  - 6 on: user process information
    - Process can alter these
- Focus on segment 5

Step 2: Information Gathering

- Segment 5 protected by virtual memory protection system
  - System mode: process can access, alter data in segment 5, and issue calls to supervisor
  - User mode: segment 5 not present in process address space (and so can't be modified)
- Run in user mode when user code being executed
- User code issues system call, which in turn issues supervisor call

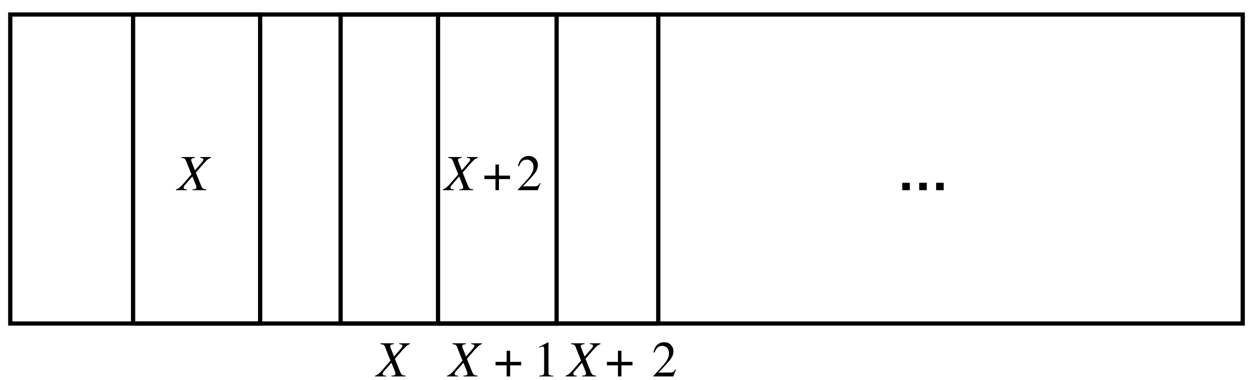
How to Make a Supervisor Call

- System code checks parameters to ensure supervisor accesses authorized locations only
  - Parameters passed as list of addresses (*X*, *X*+1, *X*+2) constructed in user segment
  - Address of list (*X*) passed via register



Step 3: Flaw Hypothesis

- Consider switch from user to system mode
  - System mode requires supervisor privileges
- Found: a parameter could point to another element in parameter list
  - Below: address in location *X*+1 is that of parameter at *X*+2
  - Means: system or supervisor procedure could alter parameter's address *after* checking validity of old address



Step 4: Flaw Testing

- Find a system routine that:
  - Used this calling convention;
  - Took at least 2 parameters and altered 1
  - Could be made to change parameter to any value (such as an address in segment 5)
- Chose line input routine
  - Returns line number, length of line, line read
- Setup:
  - Set address for storing line number to be address of line length

Step 5: Execution

- System routine validated all parameter addresses
  - All were indeed in user segment
- Supervisor read input line
  - Line length set to value to be written into segment 5
- Line number stored in parameter list
  - Line number was set to be address in segment 5
- When line read, line length written into location address of which was in parameter list
  - So it overwrote value in segment 5

Step 6: Flaw Generalization

- Could not overwrite anything in segments 0-4
  - Protected by hardware
- Testers realized that privilege level in segment 5 controlled ability to issue supervisor calls (as opposed to system calls)
  - And one such call turned off hardware protection for segments 0-4 …
- Effect: this flaw allowed attackers to alter anything in memory, thereby completely controlling computer

Burroughs B6700

- System architecture: based on strict file typing
  - Entities: ordinary users, privileged users, privileged programs, OS tasks
    - Ordinary users tightly restricted
    - Other 3 can access file data without restriction but constrained from compromising integrity of system
  - No assemblers; compilers output executable code
  - Data files, executable files have different types
    - Only compilers can produce executables
    - Writing to executable or its attributes changes its type to data
- Class exercise: obtain status of privileged user

Step 1: Information Gathering

- System had tape drives
  - Writing file to tape preserved file contents
  - Header record indicates file attributes including type
- Data could be copied from one tape to another
  - If you change data, it's still data

Step 2: Flaw Hypothesis

- System cannot detect change to executable file if that file is altered off-line

Step 3: Flaw Testing

- Write small program to change type of any file from data to executable
  - Compiled, but could not be used yet as it would alter file attributes, making target a data file
  - Write this to tape
- Write a small utility to copy contents of tape 1 to tape 2
  - Utility also changes header record of contents to indicate file was a compiler (and so could output executables)

Creating the Compiler

- Run copy program
  - As header record copied, type becomes "compiler"
- Reinstall program as a new compiler
- Write new subroutine, compile it normally, and change machine code to give privileges to anyone calling it (this makes it data, of course)
  - Now use new compiler to change its type from data to executable
- Write third program to call this
  - Now you have privileges

Corporate Computer System

- Goal: determine whether corporate security measures were effective in keeping external attackers from accessing system
- Testers focused on policies and procedures
  - Both technical and non-technical

Step 1: Information Gathering

- Searched Internet
  - Got names of employees, officials
  - Got telephone number of local branch, and from them got copy of annual report
- Constructed much of the company's organization from this data
  - Including list of some projects on which individuals were working

Step 2: Get Telephone Directory

- Corporate directory would give more needed information about structure
  - Tester impersonated new employee
    - Learned two numbers needed to have something delivered off-site: employee number of person requesting shipment, and employee's Cost Center number
  - Testers called secretary of executive they knew most about
    - One impersonated an employee, got executive's employee number
    - Another impersonated auditor, got Cost Center number
  - Had corporate directory sent to off-site "subcontractor"

Step 3: Flaw Hypothesis

- Controls blocking people giving passwords away not fully communicated to new employees
  – Testers impersonated secretary of senior executive
    - Called appropriate office
    - Claimed senior executive upset he had not been given names of employees hired that week
    - Got the names

Step 4: Flaw Testing

- Testers called newly hired people
  - Claimed to be with computer center
  - Provided "Computer Security Awareness Briefing" over phone
  - During this, learned:
    - Types of computer systems used
    - Employees' numbers, logins, and passwords
- Called computer center to get modem numbers
  - These bypassed corporate firewalls
- Success

Penetrating a System

- Goal: gain access to system
- We know its network address and nothing else
- First step: scan network ports of system
  - Protocols on ports 79, 111, 512, 513, 514, and 540 are typically run on UNIX systems
- Assume UNIX system; SMTP agent probably *sendmail*
  - This program has had lots of security problems
  - Maybe system running one such version …
- Next step: connect to *sendmail* on port 25

Output of Network Scan

```
ftp             21/tcp File Transfer
telnet          23/tcp Telnet
smtp            25/tcp Simple Mail Transfer
finger          79/tcp Finger
sunrpc         111/tcp SUN Remote Procedure Call
exec           512/tcp remote process execution (rexecd)
login          513/tcp remote login (rlogind)
shell          514/tcp rlogin style exec (rshd)
printer        515/tcp spooler (lpd)
uucp           540/tcp uucpd
nfs           2049/tcp networked file system
xterm         6000/tcp x-windows server
```

Output of *sendmail*

```
220 zzz.com sendmail 3.1/zzz.3.9, Dallas, Texas, ready
   at Wed, 2 Apr 97 22:07:31 CST
```

Version 3.1 has the "wiz" vulnerability that recognizes the "shell" command … so let's try it
Start off by identifying yourself

```
helo xxx.org
250 zzz.com Hello xxx.org, pleased to meet you
```

Now see if the "wiz" command works … if it says "command unrecognized", we're out of luck

```
wiz
250 Enter, O mighty wizard!
```

It does! And we didn't need a password … so get a shell

```
shell
#
```

And we have full privileges as the superuser, root

Penetrating a System (Revisited)

- Goal: from an unprivileged account on system, gain privileged access
- First step: examine system
  - See it has dynamically loaded kernel
  - Program used to add modules is *loadmodule* and must be privileged
  - So an unprivileged user can run a privileged program … this suggests an interface that controls this
  - Question: how does *loadmodule* work?

loadmodule

- Validates module ad being a dynamic load module
- Invokes dynamic loader *ld.so* to do actual load; also calls *arch* to determine system architecture (chip set)
  – Check, but only privileged user can call *ld.so*
- How does *loadmodule* execute these programs?
  – Easiest way: invoke them directly using *system*(3), which does not reset environment when it spawns subprogram

First Try

- Set environment to look in local directory, write own version of *ld.so*, and put it in local directory
  - This version will print effective UID, to demonstrate we succeeded
- Set search path to look in current working directory *before* system directories
- Then run *loadmodule*
  - Nothing is printed—darn!
  - Somehow changing environment did not affect execution of subprograms—why not?

What Happened

- Look in executable to see how *ld.so*, *arch* invoked
  - Invocations are "/bin/ld.so", "/bin/arch"
  - Changing search path didn't matter as never used
- Reread *system*(3) manual page
  - It invokes command interpreter *sh* to run subcommands
- Read *sh*(1) manual page
  - Uses **IFS** environment variable to separate words
  - These are by default blanks … can we make it include a "/"?
    - If so, *sh* would see "/bin/ld.so" as "bin" followed by "ld.so", so it would look for command "bin"

Second Try

- Change value of **IFS** to include "/"
- Change name of our version of *ld.so* to *bin*
  - Search path still has current directory as first place to look for commands
- Run *loadmodule*
  - Prints that its effective UID is 0 (root)
- Success!

Generalization

- Process did not clean out environment before invoking subprocess, which inherited environment
  – So, trusted program working with untrusted environment (input) … result should be untrusted, but is trusted!
- Look for other privileged programs that spawn subcommands
  – Especially if they do so by calling *system*(3) …

Penetrating a System *redux*

- Goal: gain access to system
- We know its network address and nothing else
- First step: scan network ports of system
  - Protocols on ports 17, 135, and 139 are typically run on Windows NT server systems

Output of Network Scan

```
qotd            17/tcp  Quote of the Day
ftp             21/tcp  File Transfer [Control]
loc-srv        135/tcp  Location Service
netbios-ssn    139/tcp  NETBIOS Session Service [JBP]
```

First Try

- Probe for easy-to-guess passwords
  - Find system administrator has password "Admin"
  - Now have administrator (full) privileges on local system
- Now, go for rights to other systems in domain

Next Step

- Domain administrator installed service running with domain admin privileges on local system
- Get program that dumps local security authority database
  - This gives us service account password
  - We use it to get domain admin privileges, and can access any system in domain

Generalization

- Sensitive account had an easy-to-guess password
  - Possible procedural problem
- Look for weak passwords on other systems, accounts
- Review company security policies, as well as education of system administrators and mechanisms for publicizing the policies

Debate

- How valid are these tests?
  - Not a substitute for good, thorough specification, rigorous design, careful and correct implementation, meticulous testing
  - Very valuable *a posteriori* testing technique
    - Ideally unnecessary, but in practice very necessary
- Finds errors introduced due to interactions with users, environment
  - Especially errors from incorrect maintenance and operation
  - Examines system, site through eyes of attacker

Problems

- Flaw Hypothesis Methodology depends on caliber of testers to hypothesize and generalize flaws
- Flaw Hypothesis Methodology does not provide a way to examine system systematically
  - Vulnerability classification schemes help here

Vulnerability Classification

- Describe flaws from differing perspectives
  - Exploit-oriented
  - Hardware, software, interface-oriented
- Goals vary; common ones are:
  - Specify, design, implement computer system without vulnerabilities
  - Analyze computer system to detect vulnerabilities
  - Address any vulnerabilities introduced during system operation
  - Detect attempted exploitations of vulnerabilities

Example Flaws

- Use these to compare classification schemes
- First one: race condition (*xterm*)
- Second one: buffer overflow on stack leading to execution of injected code (*fingerd*)
- Both are very well known, and fixes available!
  – And should be installed everywhere …

Flaw #1: xterm

- *xterm* emulates terminal under X11 window system
  - Must run as *root* user on UNIX systems
    - No longer universally true; reason irrelevant here
- Log feature: user can log all input, output to file
  - User names file
  - If file does not exist, *xterm* creates it, makes owner the user
  - If file exists, *xterm* checks user can write to it, and if so opens file to append log to it

File Exists

- Check that user can write to file requires special system call
  - Because *root* can append to any file, check in *open* will always succeed

Check that user can write to file "/usr/tom/X"

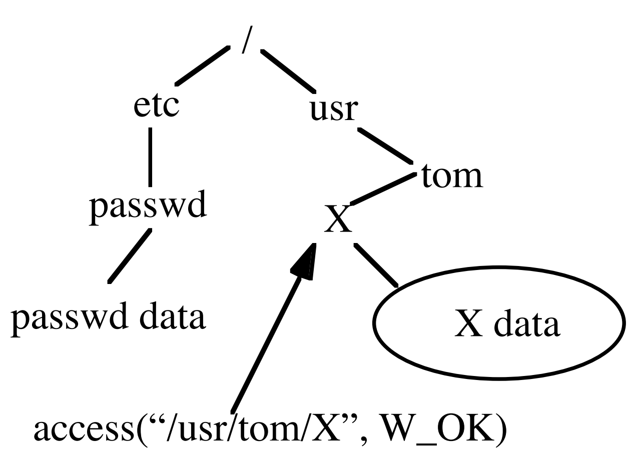
```
if (access("/usr/tom/X", W_OK) == 0){
```

Open "/usr/tom/X" to append log entries

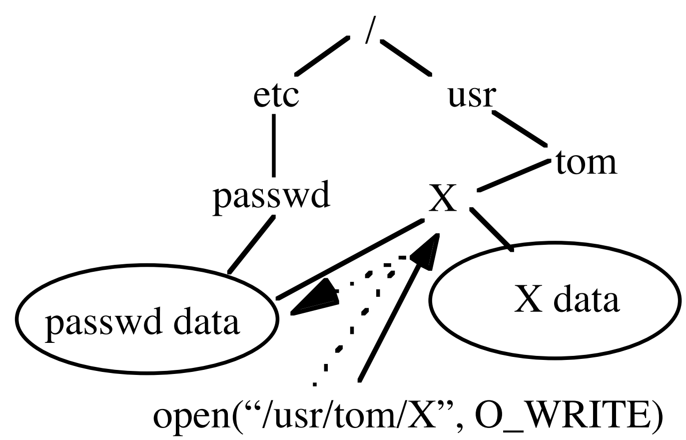
```
   if ((fd = open("/usr/tom/X", O_WRONLY|O_APPEND))< 0){
               /* handle error: cannot open file */
   }
}
```

Problem

- Binding of file name "/usr/tom/X" to file object can change between first and second lines
  - (a) is at *access*; (b) is at *open*
  - Note file opened is *not* file checked



(a)



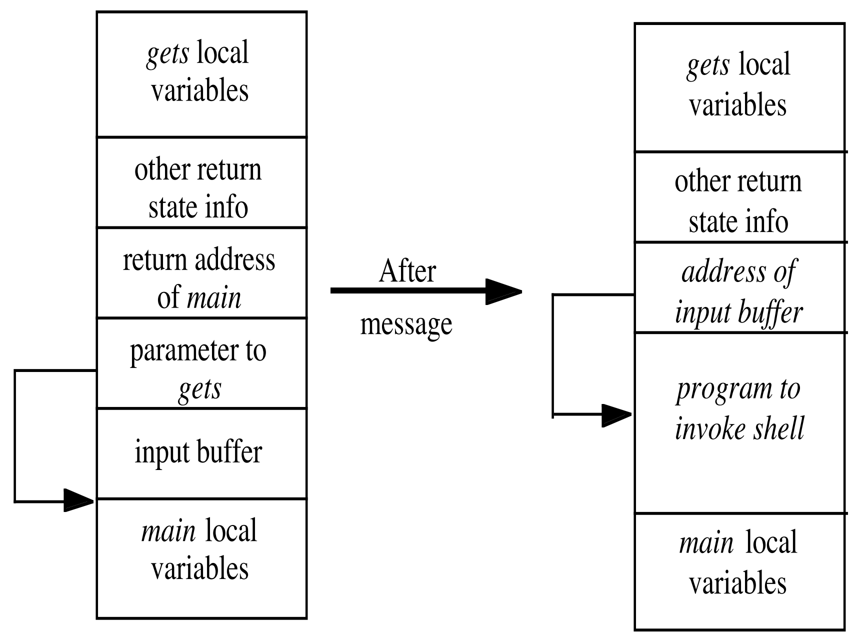
(b)

Flaw #2: *fingerd*

- Exploited by Internet Worm of 1988
  - Recurs in many places, even now
- *finger* client send request for information to server *fingerd* (*finger* daemon)
  - Request is name of at most 512 chars
  - What happens if you send more?

Buffer Overflow

- Extra chars overwrite rest of stack, as shown
- Can make those chars change return address to point to beginning of buffer
- If buffer contains small program to spawn shell, attacker gets shell on target system



Frameworks

- Goals dictate structure of classification scheme
  - Guide development of attack tool ⇒ focus is on steps needed to exploit vulnerability
  - Aid software development process ⇒ focus is on design and programming errors causing vulnerabilities
- Following schemes classify vulnerability as n-tuple, each element of n-tuple being classes into which vulnerability falls
  - Some have 1 axis; others have multiple axes

Research Into Secure Operating Systems (RISOS)

- Goal: aid computer, system managers in understanding security issues in OSes, and help determine how much effort required to enhance system security
- Attempted to develop methodologies and software for detecting some problems, and techniques for avoiding and ameliorating other problems
- Examined Multics, TENEX, TOPS-10, GECOS, OS/MVT, SDS-940, EXEC-8

Classification Scheme

- Incomplete parameter validation
- Inconsistent parameter validation
- Implicit sharing of privileged/confidential data
- Asynchronous validation/inadequate serialization
- Inadequate identification/authentication/authorization
- Violable prohibition/limit
- Exploitable logic error

Incomplete Parameter Validation

- Parameter not checked before use
- Example: emulating integer division in kernel (RISC chip involved)
  - Caller provided addresses for quotient, remainder
  - Quotient address checked to be sure it was in user's protection domain
  - Remainder address *not* checked
    - Set remainder address to address of process' level of privilege
    - Compute 25/5 and you have level 0 (kernel) privileges
- Check for type, format, range of values, access rights, presence (or absence)

Inconsistent Parameter Validation

- Each routine checks parameter is in proper format for that routine but the routines require different formats
- Example: each database record 1 line, colons separating fields
  - One program accepts colons, newlines as pat of data within fields
  - Another program reads them as field and record separators
  - This allows bogus records to be entered

Implicit Sharing of Privileged / Confidential Data

- OS does not isolate users, processes properly
- Example: file password protection
  - OS allows user to determine when paging occurs
  - Files protected by passwords
    - Passwords checked char by char; stops at first incorrect char
  - Position guess for password so page fault occurred between 1st, 2nd char
    - If no page fault, 1st char was wrong; if page fault, it was right
  - Continue until password discovered

Asynchronous Validation / Inadequate Serialization

- Time of check to time of use flaws, intermixing reads and writes to create inconsistencies
- Example: *xterm* flaw discussed earlier

Inadequate Identification / Authorization / Authentication

- Erroneously identifying user, assuming another's privilege, or tricking someone into executing program without authorization
- Example: OS on which access to file named "SYS$*DLOC$" meant process privileged
  - Check: can process access any file with qualifier name beginning with "SYS" and file name beginning with "DLO"?
  - If your process can access file "SYSA*DLOC$", which is ordinary file, your process is privileged

Violable Prohibition / Limit

- Boundary conditions not handled properly
- Example: OS kept in low memory, user process in high memory
  - Boundary was highest address of OS
  - All memory accesses checked against this
  - Memory accesses not checked beyond end of high memory
    - Such addresses reduced modulo memory size
  - So, process could access (memory size)+1, or word 1, which is part of OS …

Exploitable Logic Error

- Problems not falling into other classes
  - Incorrect error handling, unexpected side effects, incorrect resource allocation, etc.
- Example: unchecked return from monitor
  - Monitor adds 1 to address in user's PC, returns
    - Index bit (indicating indirection) is a bit in word
    - Attack: set address to be –1; adding 1 overflows, changes index bit, so return is to location stored in register 1
  - Arrange for this to point to bootstrap program stored in other registers
    - On return, program executes with system privileges

Legacy of RISOS

- First funded project examining vulnerabilities
- Valuable insight into nature of flaws
  - Security is a function of site requirements and threats
  - Small number of fundamental flaws recurring in many contexts
  - OS security not critical factor in design of OSes
- Spurred additional research efforts into detection, repair of vulnerabilities

Program Analysis (PA)

- Goal: develop techniques to find vulnerabilities
- Tried to break problem into smaller, more manageable pieces
- Developed general strategy, applied it to several OSes
  - Found previously unknown vulnerabilities

Classification Scheme

- Improper protection domain initialization and enforcement
  - Improper choice of initial protection domain
  - Improper isolation of implementation detail
  - Improper change
  - Improper naming
  - Improper deallocation or deletion
- Improper validation
- Improper synchronization
  - Improper indivisibility
  - Improper sequencing
- Improper choice of operand or operation

Improper Choice of Initial Protection Domain

- Initial incorrect assignment of privileges, security and integrity classes
- Example: on boot, protection mode of file containing identifiers of all users can be altered by any user
  - Under most policies, should not be allowed

Improper Isolation of Implementation Detail

- Mapping an abstraction into an implementation in such a way that the abstraction can be bypassed
- Example: virtual machines modulate length of time CPU is used by each to send bits to each other
- Example: Having raw disk accessible to system as ordinary file, enabling users to bypass file system abstraction and write directly to raw disk blocks

Improper Change

- Data is inconsistent over a period of time
- Example: *xterm* flaw
  - Meaning of "/usr/tom/X" changes between *access* and *open*
- Example: parameter is validated, then accessed; but parameter is changed between validation and access
  - Burroughs B6700 allowed allowed this

Improper Naming

- Multiple objects with same name
- Example: Trojan horse
  - *loadmodule* attack discussed earlier; "bin" could be a directory or a program
- Example: multiple hosts with same IP address
  - Messages may be erroneously routed

Improper Deallocation or Deletion

- Failing to clear memory or disk blocks (or other storage) after it is freed for use by others
- Example: program that contains passwords that a user typed dumps core
  - Passwords plainly visible in core dump

Improper Validation

- Inadequate checking of bounds, type, or other attributes or values
- Example: *fingerd*'s failure to check input length

Improper Indivisibility

- Interrupting operations that should be uninterruptable
  - Often: “interrupting atomic operations”
- Example: *mkdir* flaw (UNIX Version 7)
  - Created directories by executing privileged operation to create file node of type directory, then changed ownership to user
  - On loaded system, could change binding of name of directory to be that of password file after directory created but before change of ownership
  - Attacker can change administrator’s password

Improper Sequencing

- Required order of operations not enforced
- Example: one-time password scheme
  - System runs multiple copies of its server
  - Two users try to access same account
    - Server 1 reads password from file
    - Server 2 reads password from file
    - Both validate typed password, allow user to log in
    - Server 1 writes new password to file
    - Server 2 writes new password to file
  - Should have every read to file followed by a write, and vice versa; not two reads or two writes to file in a row

Improper Choice of Operand or Operation

- Calling inappropriate or erroneous instructions
- Example: cryptographic key generation software calling pseudorandom number generators that produce predictable sequences of numbers

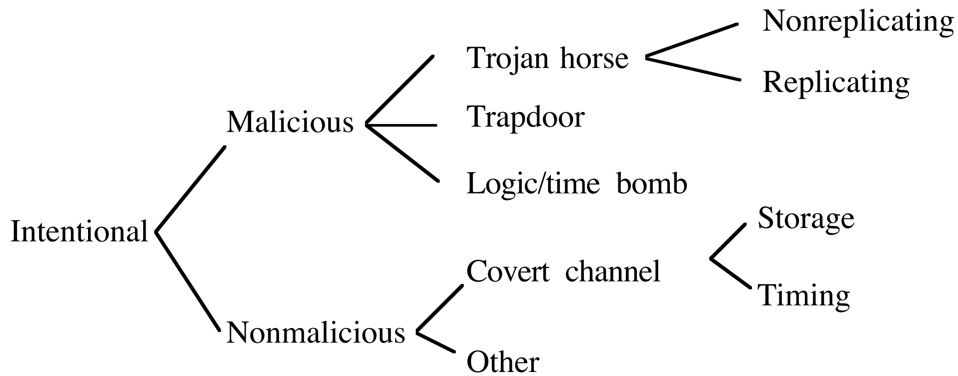
Legacy

- First to explore automatic detection of security flaws in programs and systems
- Methods developed but not widely used
  - Parts of procedure could not be automated
  - Complexity
  - Procedures for obtaining system-independent patterns describing flaws not complete

NRL Taxonomy

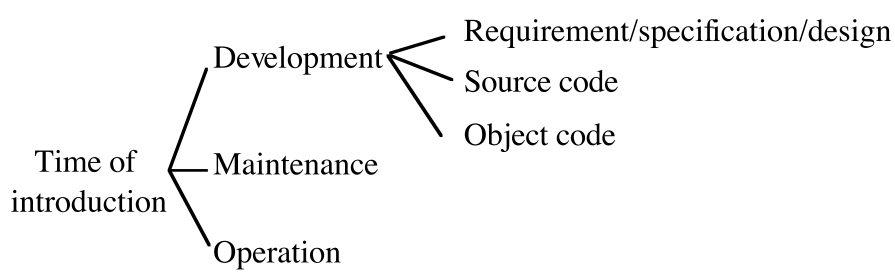
- Goals:
  - Determine how flaws entered system
  - Determine when flaws entered system
  - Determine where flaws are manifested in system
- 3 different schemes used:
  - Genesis of flaws
  - Time of flaws
  - Location of flaws

Genesis of Flaws



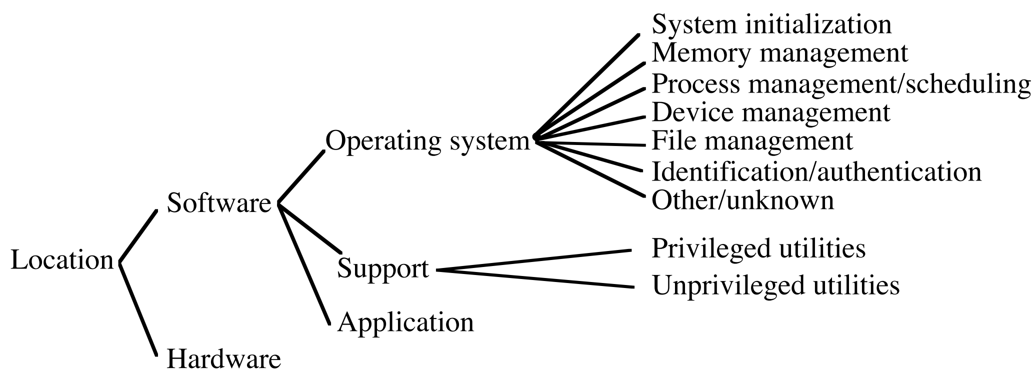
- Inadvertent (unintentional) flaws classified using RISOS categories; not shown above
  - If most inadvertent, better design/coding reviews needed
  - If most intentional, need to hire more trustworthy developers and do more security-related testing

Time of Flaws



- Development phase: all activities up to release of initial version of software
- Maintenance phase: all activities leading to changes in software performed under configuration control
- Operation phase: all activities involving patching and not under configuration control

Location of Flaw



- Focus effort on locations where most flaws occur, or where most serious flaws occur

Legacy

- Analyzed 50 flaws
- Concluded that, with a large enough sample size, an analyst could study relationships between pairs of classes
  - This would help developers focus on most likely places, times, and causes of flaws
- Focused on social processes as well as technical details
  - But much information required for classification not available for the 50 flaws

Aslam's Model

- Goal: treat vulnerabilities as faults and develop scheme based on fault trees
- Focuses specifically on UNIX flaws
- Classifications unique and unambiguous
  - Organized as a binary tree, with a question at each node. Answer determines branch you take
  - Leaf node gives you classification
- Suited for organizing flaws in a database

Top Level

- Coding faults: introduced during software development
  - Example: *fingerd*'s failure to check length of input string before storing it in buffer
- Emergent faults: result from incorrect initialization, use, or application
  - Example: allowing message transfer agent to forward mail to arbitrary file on system (it performs according to specification, but results create a vulnerability)

Coding Faults

- Synchronization errors: improper serialization of operations, timing window between two operations creates flaw
  - Example: *xterm* flaw
- Condition validation errors: bounds not checked, access rights ignored, input not validated, authentication and identification fails
  - Example: *fingerd* flaw

Emergent Faults

- Configuration errors: program installed incorrectly
  - Example: *tftp* daemon installed so it can access any file; then anyone can copy any file
- Environmental faults: faults introduced by environment
  - Example: on some UNIX systems, any shell with "-" as first char of name is interactive, so find a setuid shell script, create a link to name "-gotcha", run it, and you has a privileged interactive shell

Legacy

- Tied security flaws to software faults
- Introduced a precise classification scheme
  - Each vulnerability belongs to exactly 1 class of security flaws
  - Decision procedure well-defined, unambiguous

Comparison and Analysis

- Point of view
  - If multiple processes involved in exploiting the flaw, how does that affect classification?
    - *xterm*, *fingerd* flaws depend on interaction of two processes (*xterm* and process to switch file objects; *fingerd* and its client)
- Levels of abstraction
  - How does flaw appear at different levels?
    - Levels are abstract, design, implementation, etc.

xterm and PA Classification

- Implementation level
  - *xterm*: improper change
  - attacker's program: improper deallocation or deletion
  - operating system: improper indivisibility

xterm and PA Classification

- Consider higher level of abstraction, where directory is simply an object
  - create, delete files maps to writing; read file status, open file maps to reading
  - operating system: improper sequencing
    - During read, a write occurs, violating Bernstein conditions
- Consider even higher level of abstraction
  - attacker's process: improper choice of initial protection domain
    - Should not be able to write to directory containing log file
    - Semantics of UNIX users require this at lower levels

xterm and RISOS Classification

- Implementation level
  - *xterm*: asynchronous validation/inadequate serialization
  - attacker's process: exploitable logic error and violable prohibition/limit
  - operating system: inconsistent parameter validation

xterm and RISOS Classification

- Consider higher level of abstraction, where directory is simply an object (as before)
  - all: asynchronous validation/inadequate serialization
- Consider even higher level of abstraction
  - attacker’s process: inadequate identification/authentication/authorization
    - Directory with log file not protected adequately
    - Semantics of UNIX require this at lower levels

xterm and NRL Classification

- Time, location unambiguous
  - Time: during development
  - Location: Support:privileged utilities
- Genesis: ambiguous
  - If intentional:
    - Lowest level: inadvertent flaw of serialization/aliasing
  - If unintentional:
    - Lowest level: nonmalicious: other
  - At higher levels, parallels that of RISOS

xterm and Aslam's Classification

- Implementation level
  - attacker's process: object installed with incorrect permissions
    - attacker's process can delete file
  - *xterm*: access rights validation error
    - *xterm* doesn't properly validate file at time of access
  - operating system: improper or inadequate serialization error
    - deletion, creation should not have been interspersed with access, open
  - Note: in absence of explicit decision procedure, all could go into class race condition

The Point

- The schemes lead to ambiguity
  - Different researchers may classify the same vulnerability differently for the same classification scheme
- Not true for Aslam's, but that misses connections between different classifications
  - *xterm* is race condition as well as others; Aslam does not show this

fingerd and PA Classification

- Implementation level
  - *fingerd*: improper validation
  - attacker's process: improper choice of operand or operation
  - operating system: improper isolation of implementation detail

fingerd and PA Classification

- Consider higher level of abstraction, where storage space of return address is object
  - operating system: improper change
  - *fingerd*: improper validation
    - Because it doesn't validate the type of instructions to be executed, mistaking data for valid ones
- Consider even higher level of abstraction, where security-related value in memory is changing and data executed that should not be executable
  - operating system: improper choice of initial protection domain

fingerd and RISOS Classification

- Implementation level
  - *fingerd*: incomplete parameter validation
  - attacker's process: violable prohibition/limit
  - operating system: inadequate identification/authentication/authorization

fingerd and RISOS Classification

- Consider higher level of abstraction, where storage space of return address is object
  - operating system: asynchronous validation/inadequate serialization
  - *fingerd*: inadequate identification/authentication/authorization
- Consider even higher level of abstraction, where security-related value in memory is changing and data executed that should not be executable
  - operating system: inadequate identification/authentication/authorization

fingerd and NRL Classification

- Time, location unambiguous
  - Time: during development
  - Location: support: privileged utilities
- Genesis: ambiguous
  - Known to be inadvertent flaw
  - Parallels that of RISOS

fingerd and Aslam Classification

- Implementation level
  - *fingerd*: boundary condition error
  - attacker's process: boundary condition error
    - operating system: environmental fault
      - If decision procedure not present, could also have been access rights validation errors

Theory of Penetration

- Goal: detect previously undetected flaws
- Based on two hypotheses:
  - Hypothesis of Penetration Patterns
  - Hypothesis of Penetration-Resistent Systems
- Idea: formulate principles consistent with these hypotheses and check system for inconsistencies

Hypothesis of Penetration Patterns

System flaws that cause a large class of penetration patterns can be identified in system (i.e., TCB) source code as incorrect/absent condition checks or integrated flows that violate the intentions of the system designers.

- Meaning: an appropriate set of design, implementation principles will prevent vulnerabilities

Hypothesis of Penetration-Resistent Systems

A system (i.e., TCB) is largely resistant to penetration if it adheres to a specific set of design properties.

Example properties:

- Users must not be able to tamper with system
- System must check all references to objects
- Global objects belonging to the system must be consistent with respect to both timing and storage
- Undesirable system and user dependencies must be eliminated

Flow-Based Model

- Focus on flow of control during parameter validation
- Consider *rmdir*(*fname*)
  - Allocates space for copy of parameter on stack
  - Copies parameter into allocated storage
- Control flows through 3 steps:
  - Allocation of storage
  - Binding of parameter with formal argument
  - Copying formal argument (parameter) to storage
- Problem: length of parameter not checked

Model

- System is sequence of states, transitions
- Abstract cell set $C = \{ c_i \}$
  - Set of system entities that hold information
- System function set $F = \{ f_i \}$
  - All system functions user may invoke
  - $Z \subseteq F$ contains those involving time delays
- System condition set $R = \{ r_i \}$
  - Set of all parameter checks

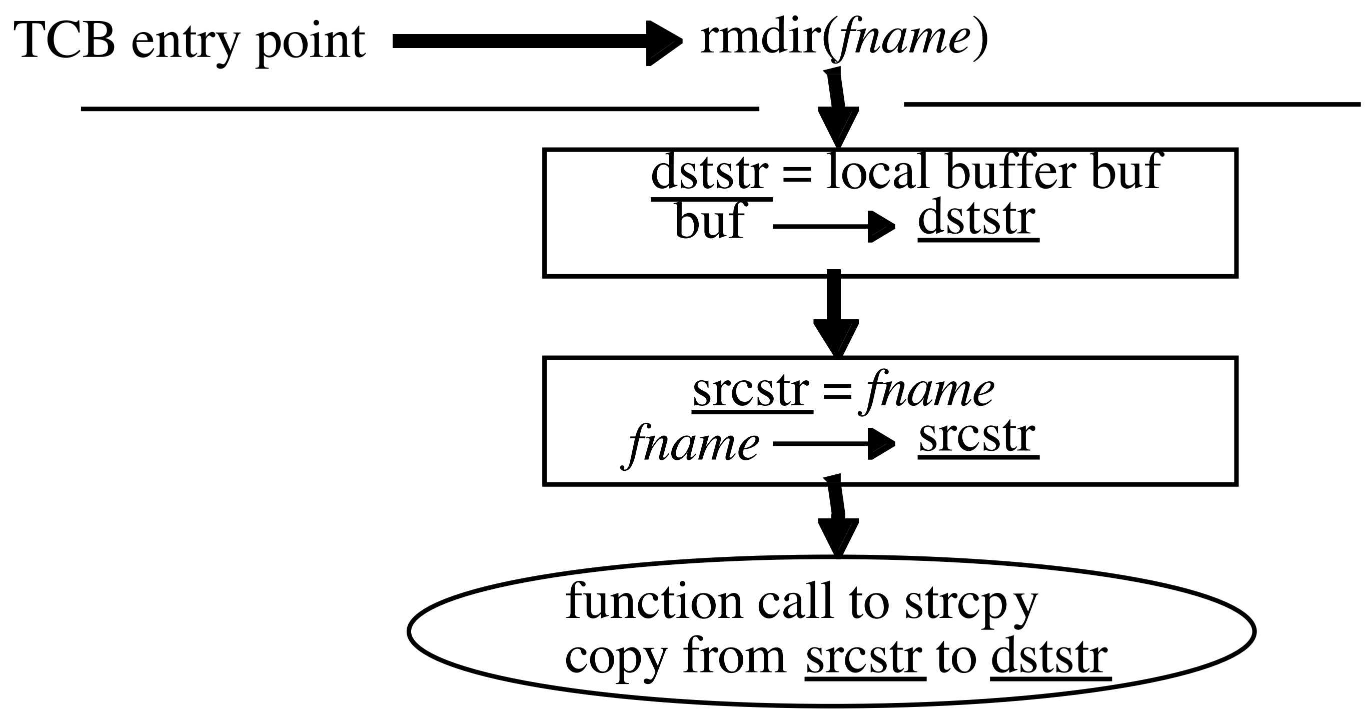
More Model

- Information flow set $IF = C \times C$
  - Set of all possible information flows between pairs of abstract cells
  - (c_i, c_j) means information flows from c_i to c_j
- Call relationship set $SF = F \times F$
  - Set of all possible information flows between pairs of system functions
  - (f_i, f_j) means f_i calls f_j or f_i returns to f_j
- These capture flow of information, control throughout system

System-Critical Functions

- Functions that analysts deem critical with respect to penetration
  - Functions that cause time delays, because they may allow window during which checked parameters are changed
  - Functions that can cause system crash
- System-critical function set *K*
- System entry points *E*
  - Gates through which user processes invoke system functions

rmdir



TCB entry point
rmdir(*fname*)
dststr = local buffer buf
buf
dststr
srcstr = *fname*
fname
srcstr
function call to strcpy
copy from srcstr to dststr

rmdir and Model

- $fname \in C$
  - Points to global entity
- $rmdir \in F$, $rmdir \in E$
  - System function and also entry point
- *fname* cannot be illegal address
  - $islegal(fname) \in R$
- length of *fname* less than that of *buf*
  - $length(fname) < spacefor(buf) \in R$

rmdir and Model

- *strcpy* ∈ *K*
  - Because *strcpy* does not check source, destination bounds
- (*fname*, *buf*) ∈ IF
  - Because information flows from *fname* to *buf*
- (*rmdir*, *strcpy*) ∈ SF
  - Because *rmdir* calls *strcpy*

More Model

- Alter set $AC = \{ (c_i, R_i) \}, R_i \subseteq R$
- View set $VC = \{ (c_i, R_i') \}, R_i \subseteq R$
  – Set of abstract cells that can be altered/viewed and conditions that must be validated first
- $Element(c_i, R_i)$ predicate
  – Conditions in $R_i \subseteq R$ must be checked before c_i viewed or altered
- Critical function set $KF = \{ (k_i, R_i'') \}, R_i \subseteq R$
- Entry point set $EF = \{ (e_i, R_i''') \}, R_i \subseteq R$
  – Analogous to AC

More *rmdir*

- *strcpy* must validate *fname*'s address as legal before viewing *fname*
- *strcpy* must validate that size of *fname* is small enough to fit in *buf* before altering *buf*
- Hence:

$(\mathit{strcpy}, \mathit{islegal}(\mathit{fname}) \wedge \mathit{length}(\mathit{fname}) < \mathit{spacefor}(\mathit{buf})) \in \mathit{KF}$

History of Transitions

- Altered cells set $ACS = \{ (c_i, e_i, pc_i) \}$
- Viewed cells set $VCS = \{ (c_i, e_i, pc_i') \}$
  - c_i has been altered/viewed by invoking entry point e_i, and pc_i, $pc_i' \subseteq IF \cup SF \cup R$ sequence of information flows, function flows, conditions along path
- Critical functions invoked set $KCS = \{ (k_i, e_i, pc_i'') \}$
  - Like ACS, but k_i has been invoked by invoking entry point e_i
- (ACS, VCS, KCS) make up state of system

Penetration-Resistant State: Idea

- If the system function checks all conditions on the global variables to be altered or viewed, and all conditions on the system-critical functions, then system cannot be penetrated using a technique that exploits failure to check conditions
  - Need to check on entry
  - Need to check conditions on memory locations or system-critical functions
  - Need to check changes in previously checked parameters as result of time delay caused by a function

Penetration-Resistant State

State that meets the following requirements:

1. For all states $(c, e, p) \in ACS$:
   a) Conditions associated with $e \in EF$ subset of conditions checked in p
   b) Conditions associated with cell $c \in AC$ subset of conditions checked in p
   c) A subsequence of p contains the last element of p, the conditions in part b, and does not contain any elements (f, g) $\in$ SF with $f \in Z$ or $g \in Z$
2. Requirement 1, but for VCS rather than ACS
3. Requirement 1, but for $(k, e, p) \in KFS$ rather than ACS

State Transition Rules

- Control updating of information as system changes
- τ state transition function
- $\Sigma = (ACS, VCS, KCS)$
- $\tau(\Sigma) = \Sigma' = (ACS', VCS', KCS')$
- Functions are *alter_cell*, *view_cell*, *invoke_crit_func*

Altering Cells

- *alter_cell*(c, e, p)
  - Check:
    - $c \in C$, $e \in E$, $p \subseteq IF \cup SF \cup R$
    - Requirement 1 holds
  - If so:
    - $ACS' = ACS \cup \{ (c, e, p) \}$
    - $VCS' = VCS$
    - $KCS' = KCS$
  - If not, new state is not penetration-resistant

Viewing Cells

- $view\_cell(c, e, p)$
  - Check:
    - $c \in C$, $e \in E$, $p \subseteq IF \cup SF \cup R$
    - Requirement 2 holds
  - If so:
    - $ACS' = ACS$
    - $VCS' = VCS \cup \{ (c, e, p) \}$
    - $KCS' = KCS$
  - If not, new state is not penetration-resistant

Invoking Critical Functions

- *invoke_crit_func*(k, e, p)
  - Check:
    - $k \in K$, $e \in E$, $p \subseteq IF \cup SF \cup R$
    - Requirement 3 holds
  - If so:
    - $ACS' = ACS$
    - $VCS' = VCS$
    - $KCS' = KCS \cup \{ (k, e, p) \}$
  - If not, new state is not penetration-resistant

Penetration Resistance

- ***Theorem***: Let the system be in a state that is penetration-resistant. Then if a state transition function is applied to the current state, the resulting state will also be penetration-resistant.

rmdir Again

- Assume system in penetration-resistant state
- *invoke_crit_func*(*strcpy*, *rmdir*, *p*)
- Requirement 3 must hold
  - No conditions associated with entry point *rmdir*, so 3a holds
  - Conditions for *strcpy* not checked within TCB, so { $islegal(fname) \wedge length(fname) < spacefor(buf)$ } $\not\subseteq p$
  - Requirement 3 does *not* hold
- System no longer in penetration-resistant state

Automated Penetration Analysis Tool

- APA performed this testing automatically
  - *Primitive flow generator* reduces statements to Prolog facts recording needed information
  - *Information flow integrator*, *function flow integrator* integrate execution path derived from primitive flow statements
  - *Condition set consistency prover* analyzes conditions along execution path, reports inconsistencies
  - *Flaw decision module* determines whether conditions for each entry point correspond to penetration-resistant specs (applies Hypothesis of Penetration Patterns)

Questions

- Can this technique be generalized to types of flaws other than consistency checking?
- Can this theory be generalized to classify vulnerabilities?

Summary

- Classification schemes requirements
  - Decision procedure for classifying vulnerability
  - Each vulnerability should have unique classification
- Above schemes do not meet these criteria
  - Inconsistent among different levels of abstraction
  - Point of view affects classification

Key Points

- Given large numbers of non-secure systems in use now, unrealistic to expect less vulnerable systems to replace them
- Penetration studies are effective tests of systems provided the test goals are known and tests are structured well
- Vulnerability classification schemes aid in flaw generalization and hypothesis