Special Topics in Security
ECE 5698

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Race Conditions

Overview

- Parallel execution of tasks
  - multi-process or multi-threaded environment
  - tasks can interact with each other

- Interaction
  - shared memory (or address space)
  - file system
  - signals

- Results of tasks depends on relative timing of events

$\rightarrow$ Indeterministic behavior

Race Conditions

- Race conditions
  - alternative term for indeterministic behavior
  - often a robustness issue
  - but also many important security implications

- Assumption needs to hold for some time for correct behavior, but assumption can be violated

- Time window when assumption can be violated
  → window of vulnerability

Race Conditions

- Window of vulnerability can be very short
  - race condition problems are difficult to find with testing and difficult to reproduce
  - attacker can slow down victim process/machine to extend window and can often launch many attempts

- Deadlock
  - special form of race condition
  - two processes are preventing each other from accessing a shared resource, resulting in both processes ceasing to function

Race Conditions

- General assumption
  - sequence of operations
    - is not atomic
    - can be interrupted at any time for arbitrary lengths
  - use proper countermeasures to ensure deterministic results

  $\rightarrow$ Synchronization primitives

- Locking
  - can impose performance penalty
  - critical section has to be as small as possible

Race Conditions

- Case study

```
public class Counter extends HttpServlet {
    int count = 0;
    public void doGet(HttpServletRequest in,
                      HttpServletResponse out)
    {
        out.setContentType("text/plain");
        Printwriter p = out.getWriter();
        count++;
        p.println(count + " hits so far!");
    }
}
```

Race Conditions

- Time-of-Check, Time-of-Use (TOCTOU)
  - common race condition problem
  - problem:

    Time-**O**f-**C**heck (t_1): validity of assumption *A* on entity *E* is checked

    Time-**O**f-**U**se (t_2): assuming *A* is still valid, E is used

    Time-Of-Attack (t_3): assumption *A* is invalidated

    $t_1 < t_3 < t_2$

- Program has to execute with elevated privilege
  - otherwise, attacker races for his own privileges

TOCTOU

- Steps to access a resource
  1. obtain reference to resource
  2. query resource to obtain characteristics
  3. analyze query results
  4. if resource is fit, access it

- Often occurs in Unix file system accesses
  - check permissions for a certain file name (e.g., using **`access(2)`**)
  - open the file, using the file name (e.g., using **`fopen(3)`**)
  - four levels of indirection (symbolic link - hard link - inode - file descriptor)

- Windows uses file handles and includes checks in API open call

Overview

- Case study

```
/* access returns 0 on success */
if(!access(file, W_OK)) {
        …
        f = fopen(file, "wb+");
        write_to_file(f);
        …
} else {
        fprintf(stderr, "Permission denied when trying to open %s.\n", file);
}
```

- Attack

```
$ touch dummy; ln –s dummy pointer
$ rm pointer; ln –s /etc/passwd pointer
```

Examples

- TOCTOU Examples
  - Filename Redirection
  - Setuid Scripts
    1. exec() system call invokes seteuid() call prior to executing program
    2. program is a script, so command interpreter is loaded first
    3. program interpreted (with root privileges) is invoked on script name
    4. attacker can replace script content between step 2 and 3

Examples

- “Vulnerability” in certain browsers (Firefox, Opera)
  – user is registering for something and is asked to type “ONLY”
  – when “L“ is pressed, security relevant application is started, user then presses “Y”…

- User is tricked into double-clicking a certain area in the browser
  – What happens? User is tricked into clicking on “Y” and a malicious application (plug-in) is installed…

- Such vulnerabilities are difficult to discover and fix
  – one way of fixing could be to build in delays and randomly place dialogs on the screen

Examples

- TOCTOU Examples
  - Directory operations
    - **rm** can remove directory trees, traverses directories depth-first
    - issues **chdir("..")** to go one level up after removing a directory branch
    - by relocating subdirectory to another directory,
      arbitrary files can be deleted
  - SQL **select** before **insert**
    - when select returns no results, insert a (unique) element
    - when DB does not check, possible to insert two
      elements with same key

Examples

- TOCTOU Examples
  - LOMAC
    - Linux kernel level monitor
    - checks system calls
    - arguments copied to module and checked
    - then, arguments are copied again to invoke actual system call

Examples

- TOCTOU Examples
  - File meta-information
    - **chown(2)** and **chmod(2)** are unsafe
    - operate on file names
    - use **fchown(2)** and **fchmod(2)** that use file descriptors
  - Joe Editor
    - when joe crashes (e.g., segmentation fault, xterm crashes)
    - unconditionally append open buffers to local DEADJOE file
    - DEADJOE could be symbolic link to security-relevant file

Temporary Files

- Similar issues as with regular files
  - commonly opened in **/tmp** or **/var/tmp**
  - often guessable file names

- “Secure” procedure
  1. pick a prefix for your filename
  2. generate at least 64 bits of high-quality randomness
  3. base64 encode the random bits
  4. concatenate the prefix with the encoded random data
  5. set umask appropriately (0066 is usually good)
  6. use **fopen(3)** to create the file, opening it in the proper mode
  7. delete the file immediately using **unlink(2)**
  8. perform reads, writes, and seeks on the file as necessary
  9. finally, close the file

Temporary Files

- Library functions to create temporary files can be insecure
  - **mktemp(3)** is not secure, use **mkstemp(3)** instead
  - old versions of **mkstemp(3)** did not set umask correctly

- Temp Cleaners
  - programs that clean “old” temporary files from **temp** directories
  - first **lstat(2)** file, then use **unlink(2)** to remove files
  - vulnerable to race condition when attacker replaces file between **lstat(2)** and **unlink(2)**
  - arbitrary files can be removed
  - delay program long enough until temp cleaner removes active file

Prevention

- “Handbook of Information Security Management” suggests
  1. increase number of checks
  2. move checks closer to point of use
  3. immutable bindings
- Only number 3 is acceptable!
- Immutable bindings
  - operate on file descriptors
  - do not check access by yourself (i.e., no use of **access(2)**)
    drop privileges instead and let the file system do the job
- Use the **O_CREAT | O_EXCL** flags to create a new file with **open(2)** and be prepared to have the open call fail

Prevention

- Some calls require file names

  link(), mkdir(), mknod(), rmdir(), symlink(), unlink()

  - especially **unlink(2)** is troublesome

- Secure File Access
  - create “secure” directory
  - directory only write and executable by UID of process
  - check that no parent directory can be modified by attacker
    - walk up directory tree checking for permissions and links at each step

Locking

- Ensures exclusive access to a certain resource
- Used to circumvent accidental race conditions
  - advisory locking (processes need to cooperate)
  - not mandatory, therefore not secure
- Often, files are used for locking
  - portable (files can be created nearly everywhere)
  - “stuck” locks can be easily removed
- Simple method
  - open file using the `O_EXCL` flag

Non-FS Race Conditions

- Linux / BSD kernel ptrace(2) / execve(2) race condition
- ptrace(2)
  - debugging facility
  - used to access other process' registers and memory address space
  - can only attach to processes of same UID, except being run by root
- execve(2)
  - execute program image

Non-FS Race Conditions

- Problem with **execve(2)**

  1. first checks whether process is being traced
  2. open image (may block)
  3. allocate memory (may block)
  4. set process EUID according to setuid flags

- Window of vulnerability between step 1 and step 4
  - attacker can attach via ptrace
  - blocking kernel operations allow other user processes to run

Non-FS Race Conditions

- Signaler handler race conditions

- Signals
  - used for asynchronous communication between processes
  - signal handler can be called in response to multiple signals
  - signal handler must be written re-entrant
    or block other signals

- Example
  - sendmail up to 8.11.3 and 8.12.0.Beta7
    - syslog(3) is called inside the signal handler
    - race condition can cause heap corruption because of double free vulnerability

Non-FS Race Conditions

- Windows DCOM / RPC vulnerability
  - RPCSS service
  - multiple threads process single packet
  - one thread frees memory,
    while other process still works on it
  - can result in memory corruption
  - and thus denial of service

Detection

- Static code analysis

  1. specify potentially unsafe patterns
     and perform pattern matching on source code

  2. source code analysis and model checking
     - MOPS (MOdel-checking Programs for Security properties)

Detection

- Static code analysis

  3. Source code analysis and annotations / rules
     - RacerX (found problems in Linux and commercial software)
     - rccjava (found problems in java.io and java.util)

- Dynamic analysis

  1. inferring data races during runtime
     - "Eraser: A Dynamic Data Race Detector for Multithreaded Programs" , ACM Transactions on CS, 1997

…and to complete…

Testing

Overview

- When system is designed and implemented
  - correctness has to be tested
- Different types of tests are necessary
  - validation
    - is the system designed correctly?
    - does the design meet the problem requirements?
  - verification
    - is the system implemented correctly?
    - does the implementation meet the design requirements?
- Different features can be tested
  - functionality, performance, *security*

Testing

- Edsger Dijkstra

  Program testing can be quite effective for showing the presence of bugs, but is hopelessly inadequate for showing their absence.

- Testing
  - analysis that discovers what *is* and compares it to what *should be*
  - should be done throughout the development cycle
  - necessary process
  - but not a substitute for sound design and implementation
  - for example, running public attack tools against a server cannot prove that server is implemented securely

Testing

- Classification of testing techniques
  - white-box testing
    - testing all the implementation
    - path coverage considerations
    - faults of commission
    - find implementation flaws
    - but cannot guarantee that specifications are fulfilled
  - black-box testing
    - testing against specification
    - only concerned with input and output
    - faults of omissions
    - specification flaws are detected
    - but cannot guarantee that implementation is correct

Testing

- Classification of testing techniques
  - static testing
    - check requirements and design documents
    - perform source code auditing
    - theoretically reason about (program) properties
    - cover a possible infinite amount of input (e.g., use ranges)
    - no actual code is executed
  - dynamic testing
    - feed program with input and observe behavior
    - check a certain number of input and output values
    - code is executed (and must be available)

Testing

- Automatic testing
  - testing should be done continuously
  - involves a lot of input, output comparisons, and test runs
  - therefore, ideally suitable for automation
  - testing hooks are required, at least at module level
  - nightly builds with tests for complete system are advantageous
- Regression tests
  - test designed to check that a program has not "regressed”, that is, that previous capabilities have not been compromised by introducing new ones

Testing

- Software fault injection
  - go after effects of bugs instead of bugs
  - reason is that bugs cannot be completely removed
  - thus, make program fault-tolerant
  - failures are deliberately injected into code
  - effects are observed and program is made more robust

- Most testing techniques can be used to identify security problems

Security Testing

- Design level
  - not much tool support available
  - manual design reviews
  - formal methods
  - attack graphs
- Formal methods
  - formal specification that can be mathematically described and verified
  - often used for small, *safety*-critical programs

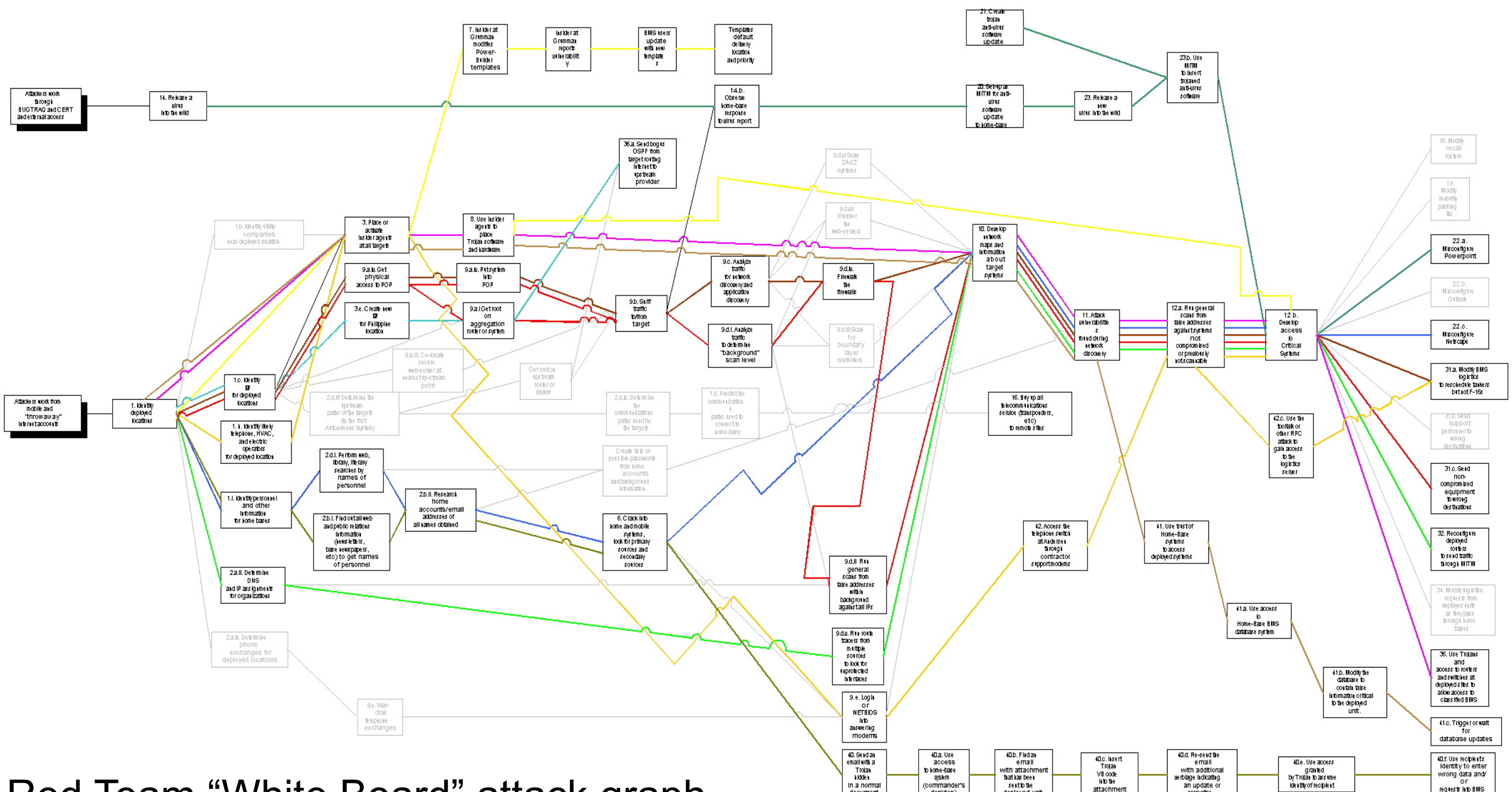
    e.g., control program for nuclear power plant
  - state and state transitions must be formalized and

    unsafe states must be described
  - “model checker” can ensure that no unsafe state is reached

Security Testing

- Attack graph
  - given
    - a finite state model, M, of a network
    - a security property P
  - an attack is an execution of M that violates P
  - an attack graph is a set of attacks of M
- Attack graph generation
  - done by hand
    - error prone and tedious
    - impractical for large systems
  - automatic generation
    - provide state description
    - transition rules

Security Testing

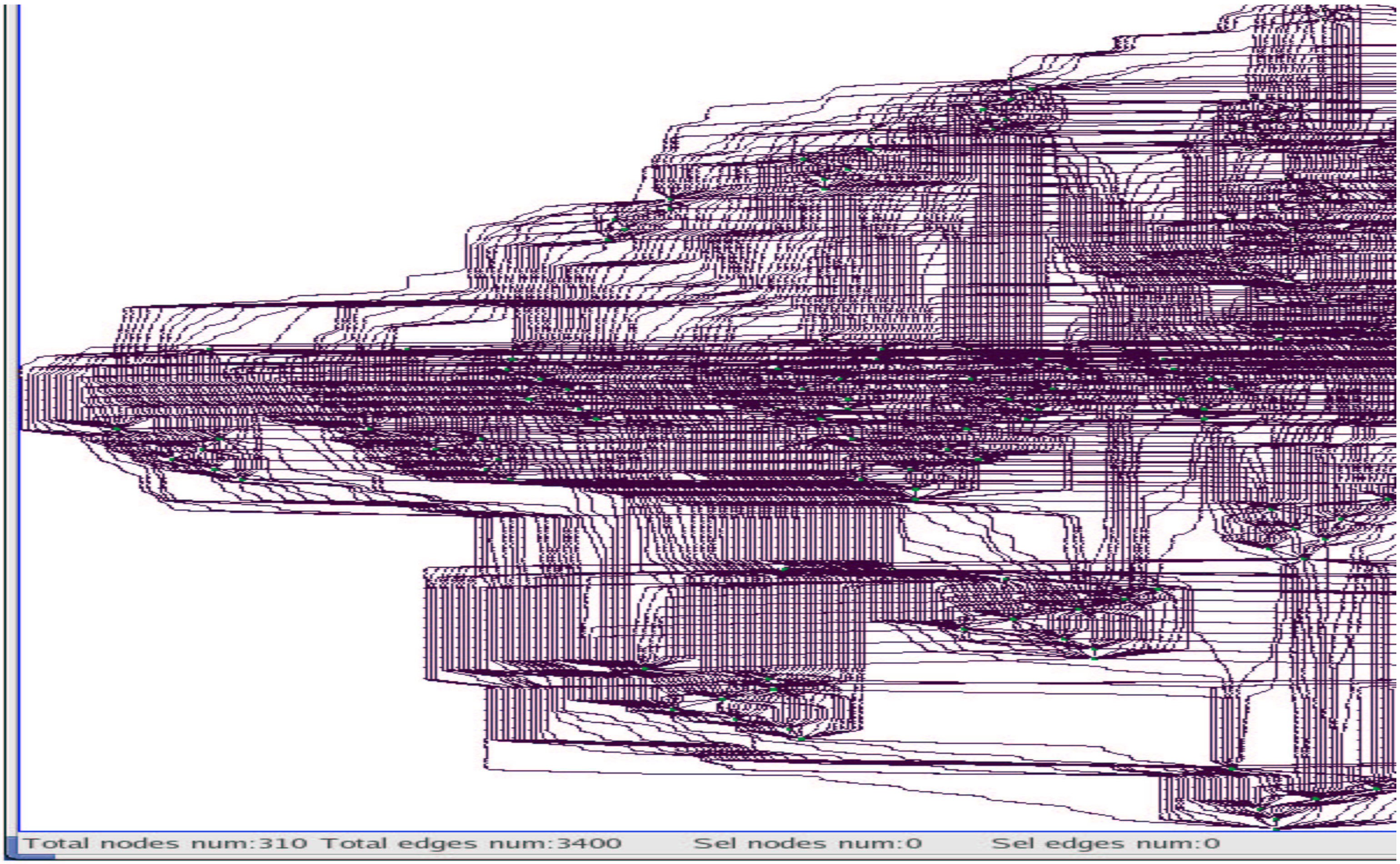


Sandia Red Team “White Board” attack graph from DARPA CC20008 Information battle space preparation experiment

Security Testing

P = Attacker gains root access to Host 1.

4 hosts
30 actions
310 nodes
3400 edges



Security Testing

- Implementation Level
  - detect known set of problems and security bugs
  - more automatic tool support available
  - target particular flaws
  - reviewing (auditing) software for flaws is reasonably well-known and well-documented
  - support for static and dynamic analysis
  - ranges from “how-to” for manual code reviewing to elaborate model checkers or compiler extensions

Static Security Testing

- Manual auditing
  - code has to support auditing
    - architectural overview
    - comments
    - functional summary for each method
  - OpenBSD is well know for good auditing process
    - 6 -12 members since 1996
    - comprehensive file-by-file analysis
    - multiple reviews by different people
    - search for bugs in general
    - proactive fixes
  - Microsoft also has intensive auditing processes
    - Every piece of written code has to be reviewed by another developer

Static Security Testing

- Manual auditing
  - tedious and difficult task
  - some initiatives were less successful
    - Sardonix (security portal)

      "Reviewing old code is tedious and boring and no one wants to do it," Crispin Cowan said.

    - Linux Security Audit Project (LSAP)

```
Statistics for All Time
Lifespan |   Rank|Page Views|D/l|Bugs|Support|Patches|Trkr|Tasks
1459 days|0(0.00)|     4,887|  0|0(0)|   0(0)|   0(0)|0(0)| 0(0)
```

Static Security Testing

- Syntax checker
  - parse source code and check for functions that have known vulnerabilities, e.g., `strcpy()`, `strcat()` (as we saw in the buffer overflows lecture)
  - also limited support for arguments (e.g., variable, static string)
  - only suitable as first basic check
  - cannot understand more complex relationships
  - no control flow or data flow analysis

  - Examples
    - flawfinder
    - RATS (Rough Auditing Tool for Security)
    - ITS4

Static Security Testing

- Annotation-based systems
  - programmer uses annotations to specify properties in the source code (e.g., this value must not be NULL)
  - analysis tool checks source code to find possible violations
  - control flow and data flow analysis is performed
  - Examples
    - SPlint
    - Eau-claire
    - UNO (uninitialized vars, out-of-bounds access)

Static Security Testing

- Model-checking
  - programmer specifies security properties that have to hold
  - models realized as state machines
  - statements in the program result in state transitions
  - certain states are considered insecure
  - usually, control flow and data flow analysis is performed
  - example properties
    - drop privileges properly
    - race conditions
    - creating a secure chroot jail
  - examples
    - MOPS (an infrastructure for examining security properties of software)