Lecture 27
December 4, 2023

Attack Graphs

- Describe attacks in terms of a general graph
  - Generalization of attack trees
- Used to represent attacks, detect attacks, guide penetration testing

Attack Graph and Penetration Testing

Here attack graph is a Petri net

- Nodes $P = \{ p_1, ..., p_n \}$ states of entities relevant to system under attack
- Edges $T = \{ t_1, ..., t_m \}$ transitions between states
- Token on a node means attacker has appropriate control of that entity
- Tokens move to indicate progress of attack
- If node p_i precedes node p_j, attacker must get control of p_i before it can get control of p_j

Attack Graph and Penetration Testing

- McDermott: hypothesize individual flaws as 2 nodes connected by transition; then examine nodes for relationships that allow them to be linked

Attack Graph and *rsh* Attack

- First steps in attack:

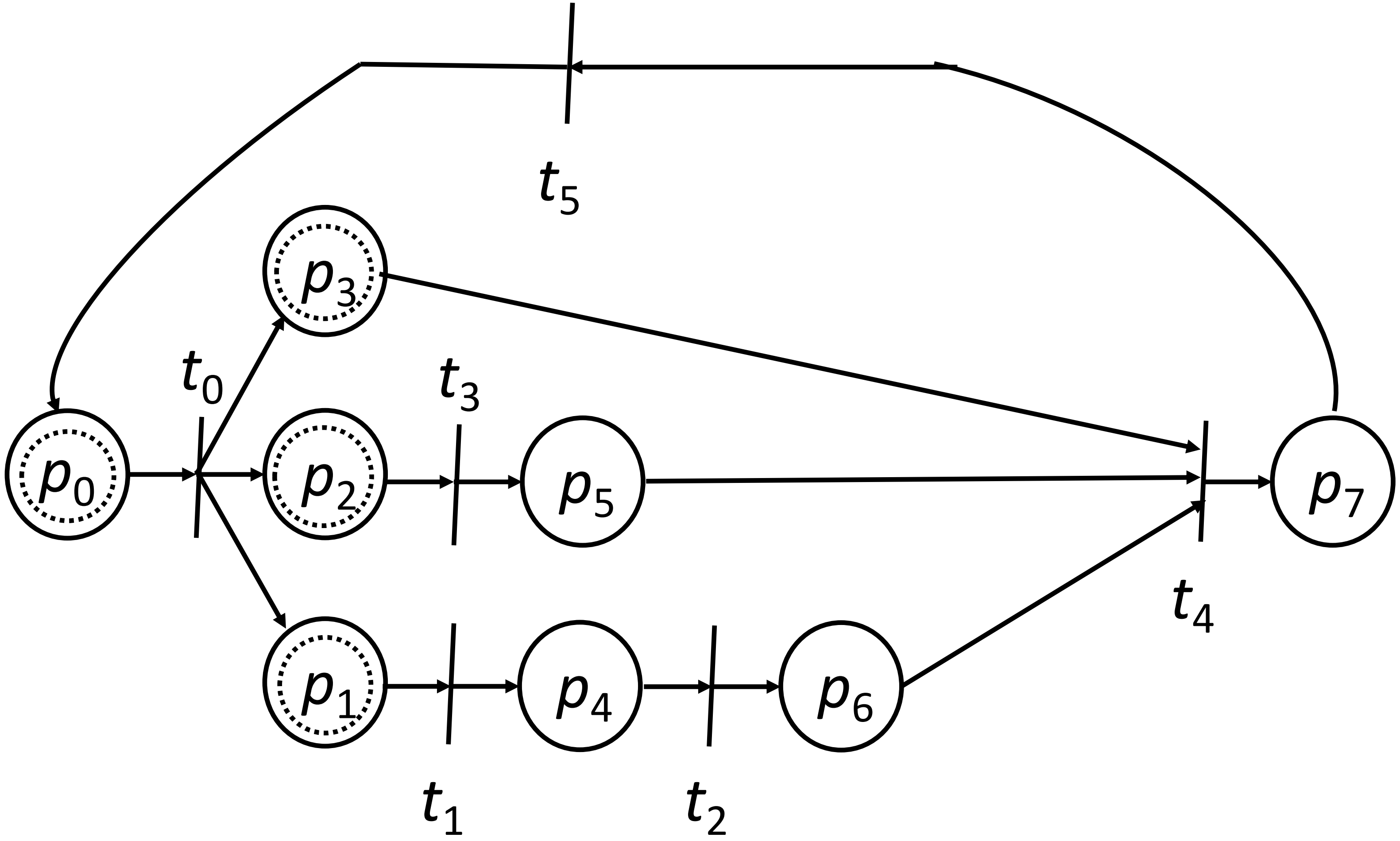
$p_0 \rightarrow p_1$ Initial scan of target

$p_0 \rightarrow p_2$ Identify an unused address

$p_0 \rightarrow p_3$ Establish that target trusts another host

$p_1 \rightarrow p_4$ Forge SYN packet

Attack Graph and *rsh* Attack



Petri net represents *rsh* attack

1. Before attack
2. After attack

Attack Graph and *rsh* Attack

States

- p_0: starting state
- p_1: found unused address on target network
- p_2: found trusted host
- p_3: found target that trusts the trusted host
- p_4: forged SYN packet created
- p_5: able to predict TCP sequence numbers of target host
- p_6: saturated state of network connections of trusted host
- p_7: final (compromised) state

Transitions

- t_0: attacker scanning system (splits into 3 transitions)
- t_1: attacker creating forged SYN packet
- t_2: attacker launching SYN flood against trusted host
- t_3: attacker figuring out how to predict victim's TCP sequence numbers
- t_4: forged SYN packet created
- t_5: attacker modifying trusted host file on victim
  - Attacker can now get *root* access on victim

Attack Graph and *rsh* Attack

- Attack starts at p_0
- t_0 splits into 3 transitions, as on success, 3 states of interest
- Need to instantiate all 3 states:
  - p_1: find unused address on target
  - p_2: find trusted host
  - p_3: find target that trusts trusted host
- t_1 is creating forged SYN packet
  - Transition from p_1 to p_4
- t_2 is attacker launching SYN flood (DoS) against trusted host
  - Transition from p_4 to p_6

Attack Graph and *rsh* Attack

- t_3: attacker figuring out how to predict victim's TCP sequence numbers
  - Transition from p_2 to p_4
- t_4: attacker launches attack using entities above
  - Transition from p_3, p_5, and p_6 to p_7
- t_5: attacker executes command
  - Example: modifying trusted hosts file to be able to get *root*

Intrusion Response

- Incident prevention
- Intrusion handling
  - Containment phase
  - Eradication phase
  - Follow-up phase
- Incident response groups

Incident Prevention

- Identify attack *before* it completes
- Prevent it from completing
- Jails useful for this
- IDS-based methods detect beginning of incidents and block their completion
- Diversity increases difficulty of attacks succeeding

Jailing

- Attacker placed in a confined environment that looks like a full, unrestricted environment
- Attacker may download files, but gets bogus ones
- Can imitate a slow system, or an unreliable one
- Useful to figure out what attacker wants
- MLS systems provide natural jails

Example Jail

- Cheswick recorded a break-in attempt using the SMTP server
- He created a very restrictive account, put the attacker in it
  - Monitored actions, including who the intruder was attacked
    - None succeeded and Cheswick notified the sysadmins of those systems
  - File system visible to attacker resembled UNIX file system
    - Lacked some programs that provided system information, or could reveal deception
    - Access times to critical files masked
- At request of management, finally shut down jail

IDS-Based Method

- Based on IDS that monitored system calls
- IDS records anomalous system calls in locality frame buffer
  - When number of calls in buffer exceeded user-defined threshold, system delayed evaluation of system calls
  - If second threshold exceeded, process cannot spawn child
- Performance impact should be minimal on legitimate programs
  - System calls small part of runtime of most programs

Example Implementation

- Implemented in kernel of Linux system
- Test #1: *ssh* daemon
  - Detected attempt to use global password installed as back door in daemon
  - Connection slowed down significantly
  - When second threshold set to 1, attacker could not obtain login shell
- Test #2: *sendmail* daemon
  - Detected attempts to break in
  - Delays grew quickly to 2 hours per system call

Diversity

- Monoculture: an attack that works against one system works against all
- Diverse culture: one attack will not compromise all systems
  - Many different types of systems
  - Also can vary system configurations

Attack Surface and Moving Target Defense

- *Attack surface*: set of entry points, data that attackers can use to compromise system
- Usual approach: harden system to reduce attack surface, so more difficult for attackers to succeed
- *Defender's dilemma*: asymmetry between attacker, defender introduced by attack surface being non-empty
- *Moving target defense* (*MTD*): change attack surface while system runs
  - Attacks that work one time may not work another time
  - Reconnaissance data gathered as a prelude to attack no longer accurate after changes

Example: IP Address Hopping

- Client needs to contact server
- Component maps destination IP address, port number to different IP address, port number
  - These are chosen (pseudo)randomly
- When packet reaches network, another component remaps IP destination IP address, port number to real IP address, port number
  - If client, server on different networks, changed IP address must be on the same network as server
  - Mapping changes frequently (e.g., every minute)
- Attacker monitoring network cannot obtain real IP address, port number of server

Example: Mapping for Port Hopping

1. Divide time into discrete intervals of length τ at times $t_0, \ldots, t_i, \ldots$
   - At time *k*, port $p_k = f(k, s)$, where *s* is seed and *f* a pseudorandom number generator
   - Ports overlap at interval boundaries
   - So if *L* amount of overlap, p_k valid over interval $[t_k - L_\tau, t_k + L_\tau]$
2. Use encryption algorithm for mapping
   - Low-order octet of IP address and port number enciphered
   - High octet of result is low-order octet of IP address, rest is port number
   - Remapping just reverses encryption to get real IP address, port number

Notes on Moving Target Defenses

- Network-based MTDs
  - Must rely on randomness to prevent attacker from predicting changes to attack surface
  - Defender must distinguish between clients authorized to connect and clients not authorized to connect
- Host-based MTDs
  - Also must rely on randomness to prevent attacker from predicting changes to attack surface
  - Here, attacker is typically authorized to have access to some account in some way
  - Attack surface is within host

Address Space Layout Randomization

- Executables have several segments
  - Exact number, layout depends on compiler and systems
- When loaded into memory, segments arranged in particular order
  - That way, positions of variables, functions fixed in virtual memory
  - Attack tools exploit knowing where these are
- *Address space layout randomization* (ASLR) perturb the placement of segments, variables, functions
  - Then attack tools exploiting knowing where segments, variables, functions won't work

Address Space Layout Randomization

- Key question: how is perturbation done?
- Simplest: randomize placement of segments in virtual memory
- Others
  - Randomize order and/or locations of variables, functions within segments
  - Add rando amount of space between variables, between functions
- Effectiveness depends on entropy introduced into address space
  - 32-bit Linux: uncertainty of segment base typically 16 bits, so easy to use brute force attack
  - 64-bit Linux: uncertainty of segment base typically 40 bits, so a search takes long enough that it is likely to be detected

Intrusion Handling

- Restoring system to satisfying site security policy
- Six phases
    - *Preparation* for attack (before attack detected)
    - *Identification* of attack
    - *Containment* of attack (confinement)
    - *Eradication* of attack (stop attack)
    - *Recovery* from attack (restore system to secure state)
    - *Follow-up* to attack (analysis and other actions)
- Discussed in what follows

Containment Phase

- Goal: limit access of attacker to system resources
- Two methods
  - Passive monitoring
  - Constraining access

Passive Monitoring

- Records attacker's actions; does *not* interfere with attack
  - Idea is to find out what the attacker is after and/or methods the attacker is using
- Problem: attacked system is vulnerable throughout
  - Attacker can also attack other systems
- Example: type of operating system can be derived from settings of TCP and IP packets of incoming connections
  - Analyst draws conclusions about source of attack
  - *nmap* does this; usually successful

Constraining Actions

- Reduce protection domain of attacker
- Problem: if defenders do not know what attacker is after, reduced protection domain may contain what the attacker is after
  - Stoll created document that attacker downloaded
  - Download took several hours, during which the phone call was traced to Germany

Example: Honeypots

- Entities designed to entice attacker to do something
- *Honeyfiles*, *honeydocuments*: designed to entice attackers to read or download it
  - Stoll used this to keep intruder on line long enough to be traced (internationally)
- *Honeypots*, *decoy servers*: servers offering many targets for attackers
  - Idea is attackers will take actions on them that reveal goals
  - These are instrumented, monitored closely
- *Honeynets*: like honeypots, but a full network
  - Treated like honeypots

Deception

- Cohen's Deception Tool Kit
  - Creates false network interface
  - Can present any network configuration to attackers
  - When probed, can return wide range of vulnerabilities
  - Attacker wastes time attacking non-existent systems while analyst collects and analyzes attacks to determine goals and abilities of attacker
  - Experiments showed deception is effective response to keep attackers from targeting real systems

Example: Honeynet Project

- International project created to learn about attacker community
- Phase 1: identify common threats against specific OSes, configurations
  - Gen-I honeypots crude but very effective
- Phase 2: collect data more efficiently
  - Gen-II honeypots easier to deploy and harder to detect
- Used to gather attack signatures, enable defenders to handle attacks without endangering production systems

Eradication Phase

- Usual approach: deny or remove access to system, or terminate processes involved in attack
- Use wrappers to implement access control
  - Example: wrap system calls
    - On invocation, wrapper takes control of process
    - Wrapper can log call, deny access, do intrusion detection
    - Experiments focusing on intrusion detection used multiple wrappers to terminate suspicious processes
  - Example: network connections
    - Wrapper around servers log, do access control on, incoming connections and control access to Web-based databases

Firewalls

- Mediate access to organization’s network
  - Also mediate access out to the Internet
- Example: Java applets filtered at firewall
  - Use proxy server to rewrite them
    - Change “<applet>” to something else
  - Discard incoming web files with hex sequence CA FE BA BE
    - All Java class files begin with this
  - Block all files with name ending in “.class” or “.zip”
    - Lots of false positives

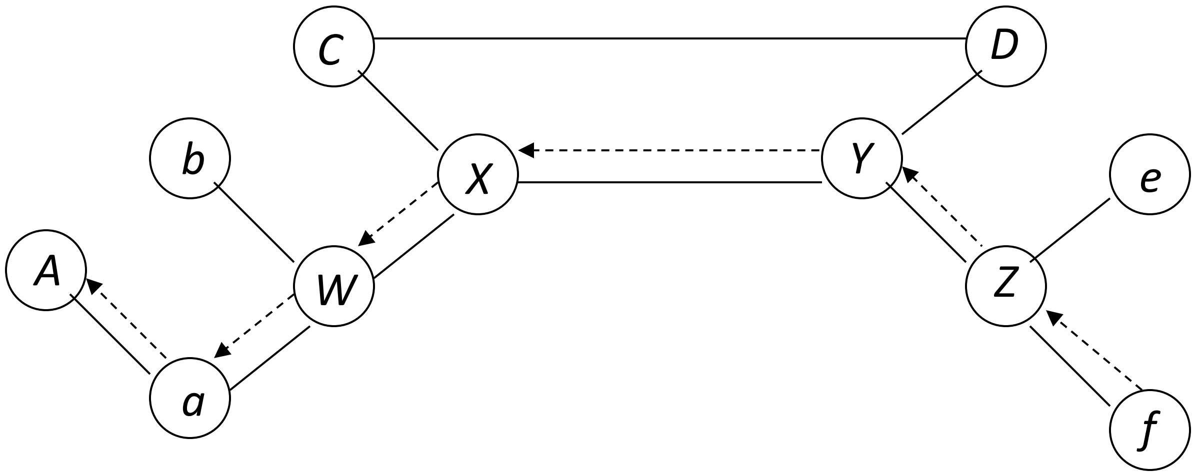
Intrusion Detection and Isolation Protocol

- Coordinates reponse to attacks
- *Boundary controller* is system that can block connection from entering perimeter
  - Typically firewalls or routers
- *Neighbor* is system directly connected
- *IDIP domain* is set of systems that can send messages to one another without messages passing through boundary controller

Protocol

- IDIP protocol engine monitors connection passing through members of IDIP domains
  - If intrusion observed, engine reports it to neighbors
  - Neighbors propagate information about attack
  - Trace connection, datagrams to boundary controllers
  - Boundary controllers coordinate responses
    - Usually, block attack, notify other controllers to block relevant communications

Example



- *C*, *D*, *W*, *X*, *Y*, *Z* boundary controllers
- *f* launches flooding attack on *A*
- Note after *X* suppresses traffic intended for *A*, *W* begins accepting it and *A*, *b*, *a*, and *W* can freely communicate again

Follow-Up Phase

- Take action external to system against attacker
  - Thumbprinting: traceback at the connection level
  - IP header marking: traceback at the packet level
  - Counterattacking

Thumbprinting

- Compares contents of connections to determine which are in a chain of connections
- Characteristic of a good thumbprint
  1. Takes as little space as possible
  2. Low probability of collisions (connections with different contents having same thumbprint)
  3. Minimally affected by common transmission errors
  4. Additive, so two thumbprints over successive intervals can be combined
  5. Cost little to compute, compare

Example: Foxhound

- Thumbprints are linear combinations of character frequencies
  - Experiment used *telnet*, *rlogin* connections
- Computed over normal network traffic
- Control experiment
  - Out of 4000 pairings, 1 match reported
    - So thumbprints unlikely to match if connections paired randomly
    - Matched pair had identical contents

Experiments

- Compute thumbprints from connections passing through multiple hosts
  - One thumbprint per host
- Injected into a collection of thumbprints made at same time
  - Comparison immediately identified the related ones
- Then experimented on long haul networks
  - Comparison procedure readily found connections correctly

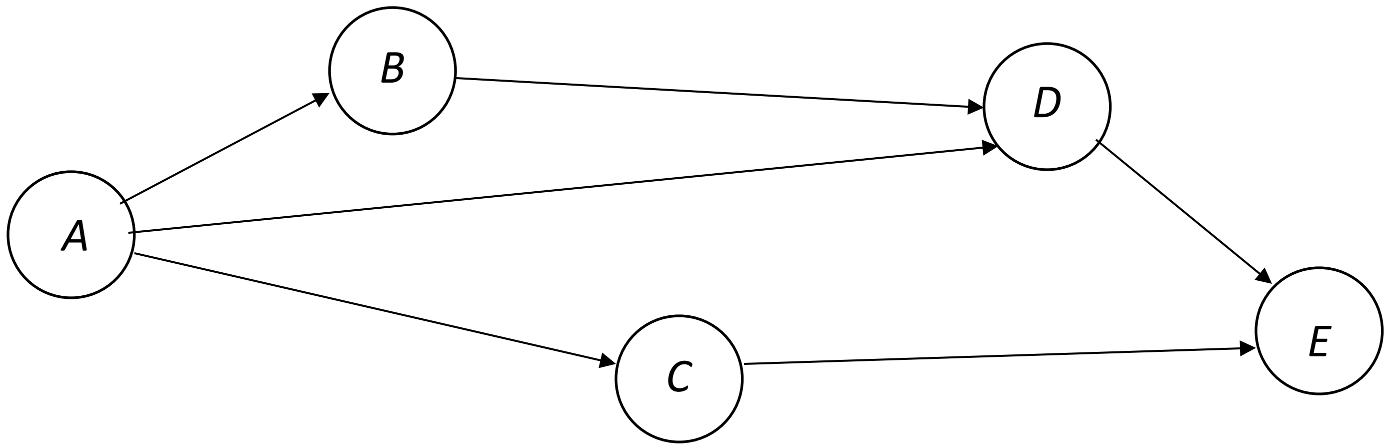
IP Header Marking

- Router places data into each header indicating path taken
- When do you mark it?
  - Deterministic: always marked
  - Probabilistic: marked with some probability
- How do you mark it?
  - Internal: marking placed in existing header
  - Expansive: header expanded to include extra space for marking

Example: Probabilistic Scheme

- Expand header to have *n* slots for router addresses
- Router address placed in slot *s* with probability *sp*
- Use: suppose SYN flood occurs in network

Use



- *E* SYN flooded; 3150 packets could be result of flood
- 600 (*A*, *B*, *D*); 200 (*A*, *D*); 150 (*B*, *D*); 1500 (*D*); 400 (*A*, *C*); 300 (*C*)
  - *A*: 1200; *B*: 750; *C*: 700; *D*: 2450
- Note traffic increases between *B* and *D*
  - *B* probable culprit

Algebraic Technique

- Packets from *A* to *B* along path *P*
- First router labels *j*th packet with x_j
- Routers on *P* have IP addresses $a_0, \ldots, a_n$
- Each router a_i computes $Rx_j + a_i$, R being current mark $a_0x_j^i + \ldots + a_{i-1}$ (Horner's rule)
  - At *B*, marking is $a_0x^n + \ldots + a_n$, evaluated at x_j
- After n+1 packets arrive, can determine route

Alternative

- Alternate approach: at most *l* routers mark packet this way
- *l* set by first router
- Marking routers decrement it
- Experiment analyzed 20,000 packets marked by this scheme; recovered paths of length 25 about 98% of time

Problem

- Who assigns x_j?
  - Infeasible for a router to know it is first on path
  - Can use weighting scheme to determine if router is first
- Attacker can place arbitrary information into marking
  - If router does not select packet for marking, bogus information passed on
  - Destination cannot tell if packet has had bogus information put in it