Announcement

- Assignment #3 Due today
- Quizzes
  - Will be released between Dec.5 and the final (Dec.14)
- Lecture schedule
  - System security starts next Tuesday

Intrusion Detection

Today: Intrusion Detection

- Path traversal attacks
- Types of detectors
  - Network intrusion detection system (NIDS)
  - Host-based intrusion detection system (HIDS)
- Detection accuracy
  - False positives and false negatives
  - Base rate fallacy
  - Combining detectors
- Styles of detection
  - Signature-based detection
  - Specification-based detection
  - Anomaly-based detection
  - Behavioral detection

Today: Intrusion Detection

- We’ve talked about many ways to prevent attacks
- However, some not all methods are perfect: attacks will slip through our defenses
- Recall: “Detect if you can’t prevent”
- How can we detect network attacks when they happen?

Path Traversal Attacks

Top 25 Most Dangerous Software Weaknesses (2020)

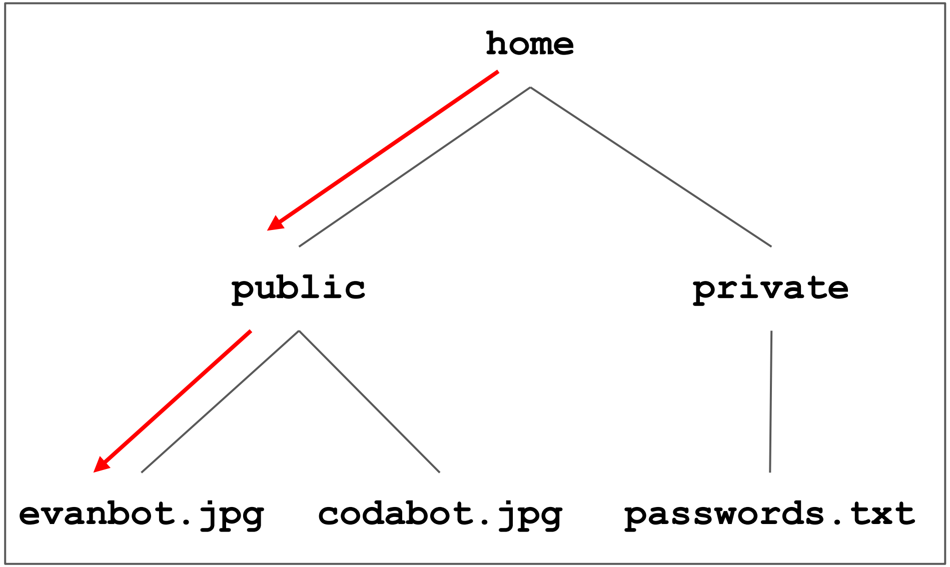
Rank	ID	Name	Score
[1]	CWE-79	Improper Neutralization of Input During Web Page Generation ('Cross-site Scripting')	46.82
[2]	CWE-787	Out-of-bounds Write	46.17
[3]	CWE-20	Improper Input Validation	33.47
[4]	CWE-125	Out-of-bounds Read	26.50
[5]	CWE-119	Improper Restriction of Operations within the Bounds of a Memory Buffer	23.73
[6]	CWE-89	Improper Neutralization of Special Elements used in an SQL Command ('SQL Injection')	20.69
[7]	CWE-200	Exposure of Sensitive Information to an Unauthorized Actor	19.16
[8]	CWE-416	Use After Free	18.87
[9]	CWE-352	Cross-Site Request Forgery (CSRF)	17.29
[10]	CWE-78	Improper Neutralization of Special Elements used in an OS Command ('OS Command Injection')	16.44
[11]	CWE-190	Integer Overflow or Wraparound	15.81
[12]	CWE-22	Improper Limitation of a Pathname to a Restricted Directory ('Path Traversal')	13.67
[13]	CWE-476	NULL Pointer Dereference	8.35
[14]	CWE-287	Improper Authentication	8.17
[15]	CWE-434	Unrestricted Upload of File with Dangerous Type	7.38
[16]	CWE-732	Incorrect Permission Assignment for Critical Resource	6.95
[17]	CWE-94	Improper Control of Generation of Code ('Code Injection')	6.53

Unix File Paths

- A file path points to a file or a directory (folder) on a Unix system
- File paths have special characters
    - `/` (slash): Separates directories
    - `.` (one period): Shorthand for the current directory
    - `..` (two periods): Shorthand for the parent directory

Unix File Paths

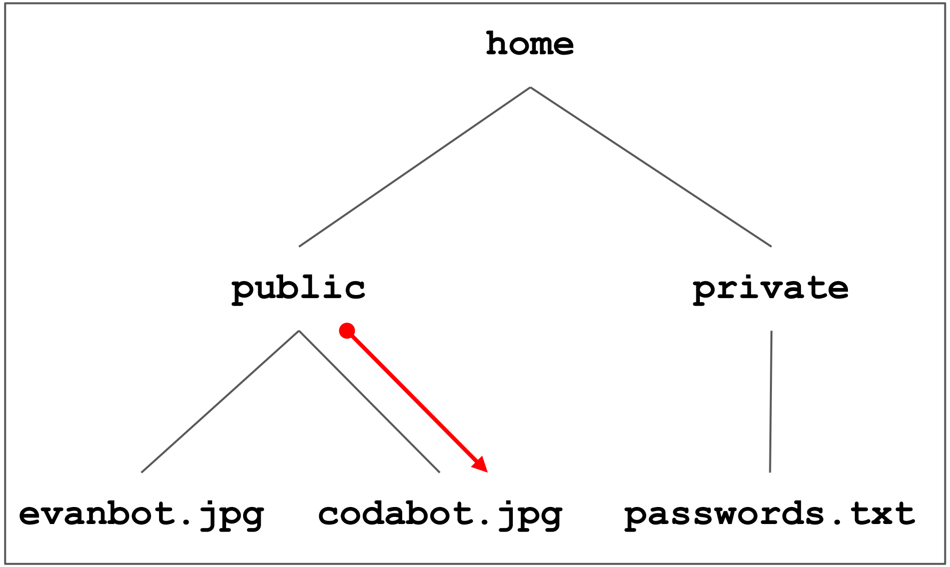
`/home/public/evanbot.jpg`



Unix File Paths

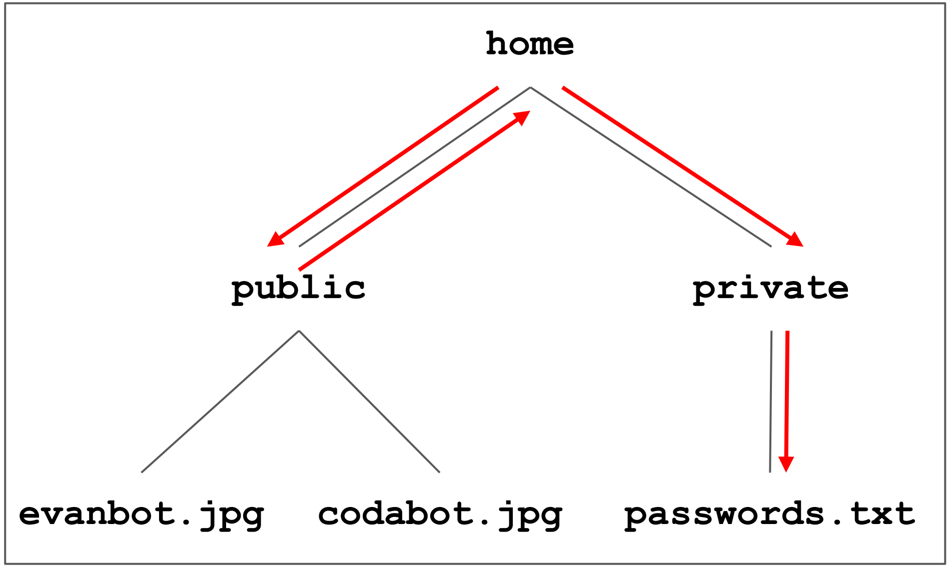
ITIS 6200 / 8200

`./codabot.jpg` (Assume we're currently in **`public`**)



Unix File Paths

`/home/public/../private/passwords.txt`



Path Traversal Intuition

Frontend

Enter file name:

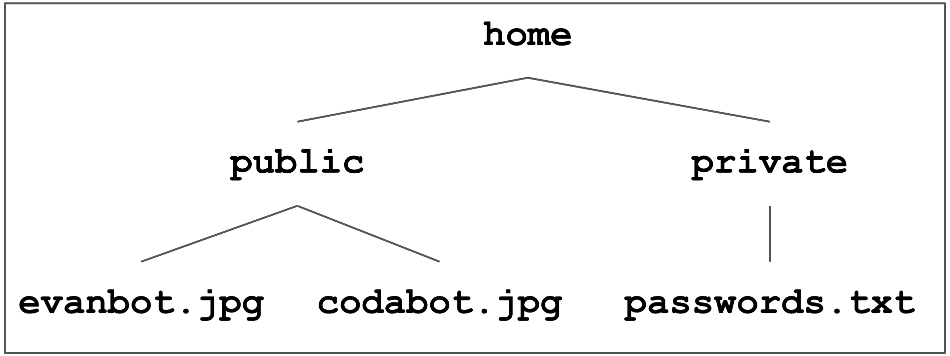
`evanbot.jpg`

Submit

Backend

Send this file to the user:
`/home/public/evanbot.jpg`

Backend Filesystem



Path Traversal Intuition

Frontend

Enter file name:

`../private/passwords.txt`

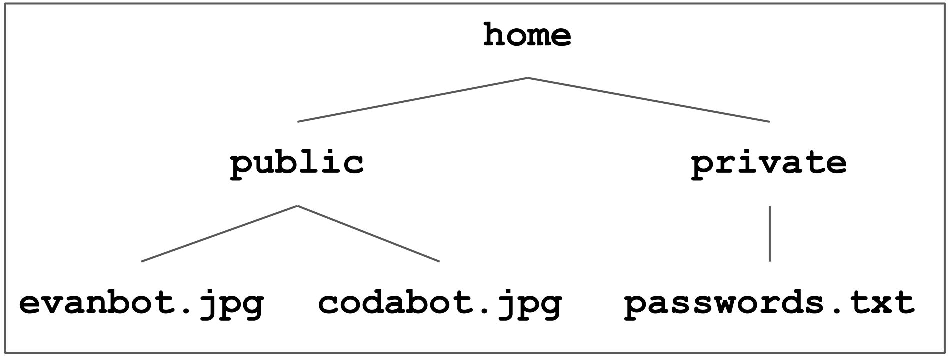
Submit

Backend

Send this file to the user:

`/home/public/../private/passwords.txt`

Backend Filesystem



Path Traversal Attacks

- **Path traversal attack**: Accessing unauthorized files on a remote server by exploiting Unix file path semantics
  - Often makes use of `../` to enter other directories
  - Vulnerability: User input is interpreted as a file path by the Unix file system
- Defense: Check that user input is not interpreted as a file path

Types of Detectors

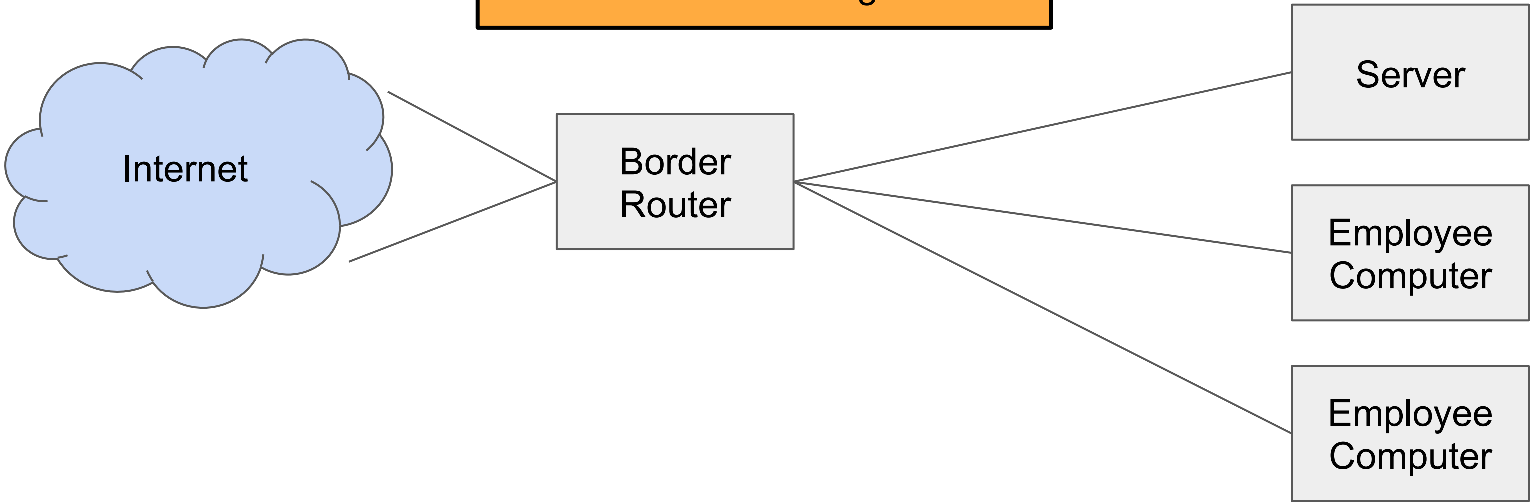
Types of Detectors

- Three types of detectors
  - Network Intrusion Detection System (NIDS)
  - Host-based Instruction Detection System (HIDS)
  - Logging
- The main difference is where the detector is deployed

Structure of a Network

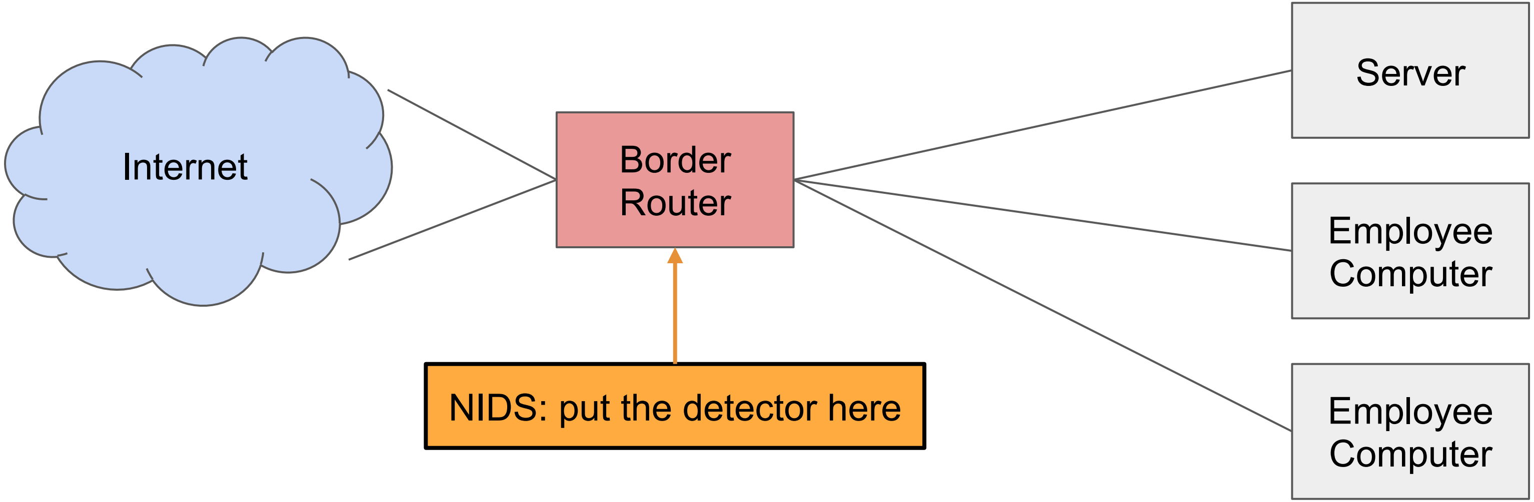
ITIS 6200 / 8200

End hosts in the local network send packets to the Internet by sending it to the border router for forwarding



Network Intrusion Detection System (NIDS)

- **Network intrusion detection system** (**NIDS**): A detector installed on the network, between the local network and the rest of the Internet
  - Monitors network traffic to detect attacks



Network Intrusion Detection System (NIDS)

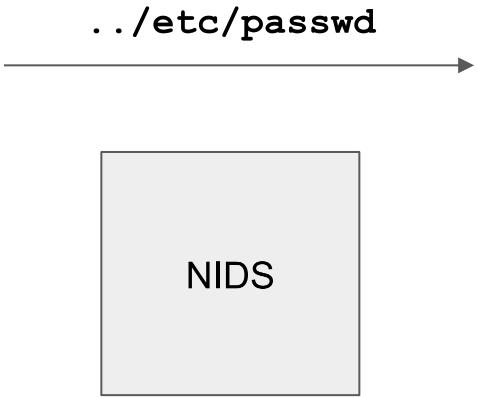
- Operation:
  - NIDS has a **table** of all active connections and maintains state for each connection
  - If the NIDS sees a packet not associated with any known connection, create a new entry in the table
    - Example: A connection that started before the NIDS started running
  - NIDS can be used for more sophisticated network monitoring: not only detect attacks, but analyze and understand all the network traffic

NIDS: Benefits

- Cheap: A single detector can cover a lot of systems
- Easy to scale: As the network gets larger, add computing power to the NIDS
- Simple management: Easy to install and manage a single detector
- End systems are unaffected
  - Doesn't consume any resources on end systems
  - Useful for adding security on an existing system
- Smaller trusted computing base (TCB)
  - Only the detector needs to be trusted

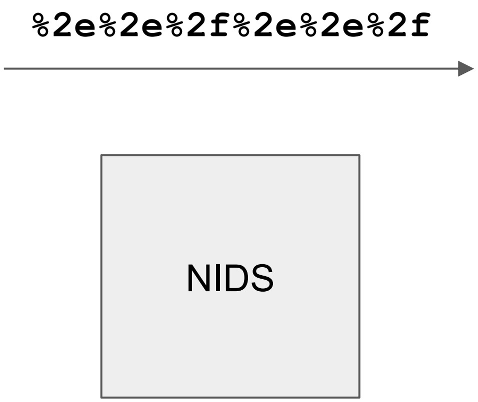
Drawback: Inconsistent Interpretation

- What should the NIDS do if it sees this packet?
- This looks like a path traversal attack… Maybe it should alert
- What if the packet's TTL expires before it reaches any end host?
- Problem: What the NIDS sees doesn't exactly match what arrives at the end system



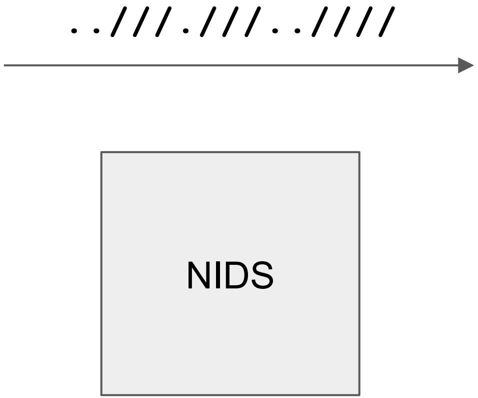
Drawback: Inconsistent Interpretation

- What should the NIDS do if it sees this packet?
- This doesn't look like a path traversal attack...maybe it shouldn't alert
- This input is using URL percent encoding. If you decode it, you get `../etc/passwd`!
- Problem: Inputs are interpreted differently between the NIDS and the end system



Drawback: Inconsistent Interpretation

- What should the NIDS do if it sees this packet?
- What file on the file system does this file path refer to? It's hard for the NIDS to know
- Problem: Information needed to interpret correctly is missing



Evasion Attacks

- Problem: Imperfect observability
  - What the NIDS sees doesn't match what the end system sees
  - Example: The packet's time-to-live (TTL) might expire before reaching the end host
- Problem: Incomplete analysis (double parsing)
  - Inconsistency: Inputs are interpreted and parsed differently between the NIDS and the end system
  - Ambiguity: Information needed to interpret correctly is missing
- **Evasion attack**: Exploit inconsistency and ambiguity to provide malicious inputs that are not detected by the NIDS

Evasion Attacks: Defenses

- Make sure that the NIDS and the end host are using the same interpretations
  - This can be very challenging
  - How do we detect the URL-encoded attack `%2e%2e%2f%2e%2e%2f`?
    Now the NIDS has to parse URL encodings!
  - How do we detect a more complicated path traversal attack `..///.///..////`?
    Now the NIDS has to parse Unix file paths!

- Impose a canonical (“normalized”) form for all inputs
  - Example: Force all URLs to expand all URL encodings or not expand all URL encodings

- Analyze all possible interpretations instead of assuming one

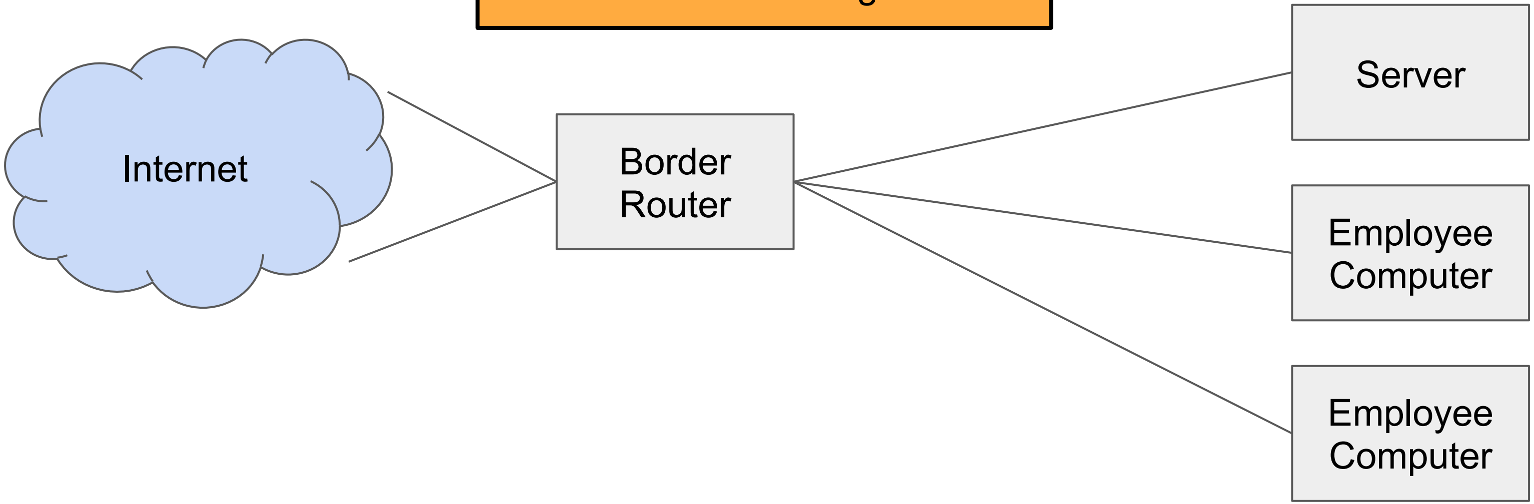
- Flag potential evasions so they can be investigated further

Drawback: Encrypted Traffic

- TLS is end-to-end secure, so a NIDS can’t read any encrypted traffic
- One possible solution: Give the NIDS access to all the network’s private keys
  - Now the NIDS can decrypt messages to inspect them for attacks
  - Problem: Users have to share their private key with someone else

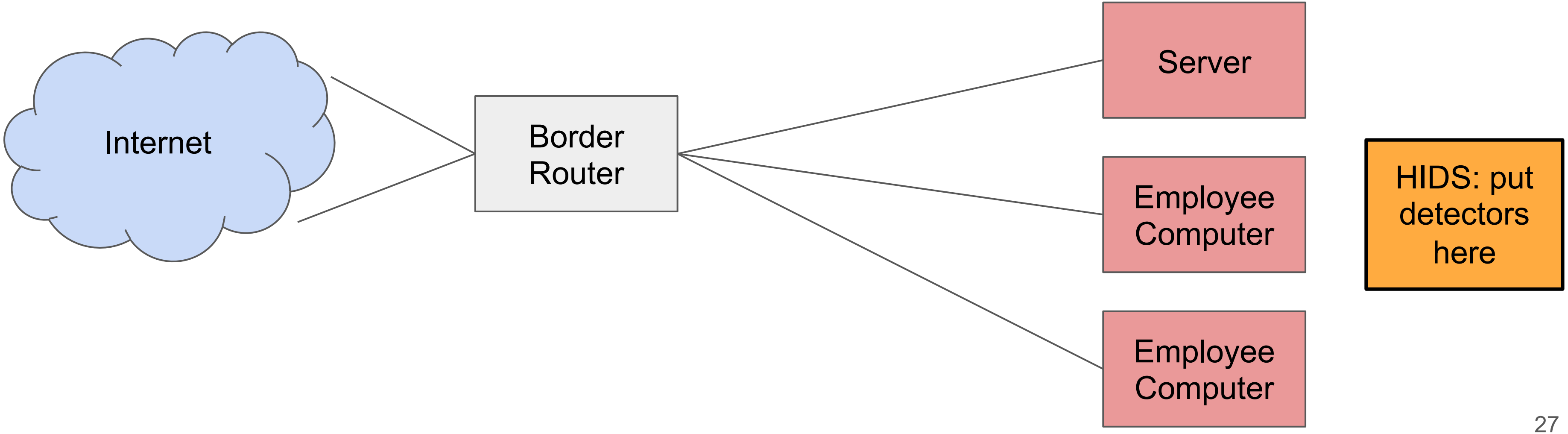
Recall: Structure of a Network

End hosts in the local network send packets to the Internet by sending it to the border router for forwarding



Host-Based Intrusion Detection System (HIDS)

- **Host-based intrusion detection system (HIDS)**: A detector installed on each end system



Host-Based Intrusion Detection System (HIDS)

- Benefits
  - Fewer problems with inconsistencies or ambiguities: The HIDS is on the end host, so it will interpret packets exactly the same as the end host!
  - Works for encrypted messages
  - Can protect against non-network threats too (e.g. malicious user inside the network)
  - Performance scales better than NIDS: one NIDS is more vulnerable to being overwhelmed than many HIDS
- Drawbacks
  - Expensive: Need to install one detector for every end host
  - Evasion attacks are still possible (consider Unix file name parsing)

Logging

- **Logging**: Analyze log files generated by end systems
    - Example: Each night, run a script on the log files to analyze them for attacks
- Benefits
    - Cheap: Modern web servers often already have built-in logging systems
    - Fewer problems with inconsistencies or ambiguities: The logging system works on the end host, so it will interpret packets exactly the same as the end host!
- Drawbacks
    - Unlike NIDS and HIDS, there is no real-time detection: attacks are only detected **after the attack has happened**
    - Some evasion attacks are still possible (again, consider Unix file name parsing)
    - The attacker could change the logs to erase evidence of the attack

Detection Accuracy

Detection Errors

- Two main types of detector errors
  - **False positive**: Detector alerts when there is no attack
  - **False negative**: Detector fails to alert when there is an attack

- Detector accuracy is often assessed in terms of the rates at which these errors occur
  - **False positive rate** (**FPR**): The probability the detector alerts, given there is no attack
  - **False negative rate** (**FNR**): The probability the detector does not alert, given there is an attack

Perfect Detectors

- Can we build a detector with a false positive rate of 0%? How about a detector with a false negative rate of 0%?
  - false positive rate: The probability the detector alerts, given there is no attack
  - false negative rate: The probability the detector does not alert, given there is an attack

```
void detector_with_no_false_positives(char *input) {
    printf("Nope, not an attack!");
}
```

```
void detector_with_no_false_negatives(char *input) {
    printf("Yep, it's an attack!");
}
```

Detection Tradeoffs

- The art of a good detector is achieving an effective balance between false positives and false negatives
- The quality of the detector depends on the system you’re using it on
  - What is the rate of attacks on your system?
  - How much does a false positive cost in your system?
  - How much does a false negative cost in your system?
- Example of cost analysis: Fire alarms
  - Which is better: a very low false positive rate or a very low false negative rate?
  - Cost of a false positive: The fire department needs to inspect the building
  - Cost of a false negative: The building burns down
  - In this situation, false negatives are much more expensive!
  - We want a detector with a low false negative rate

Combining Detectors

- Can you combine two independent detectors to create a better detector?
- Parallel composition
  - Alert if either detector alerts
  - Intuition: The combination generates more alerts
  - Reduces false negative rate
  - Increases false positive rate
- Series composition
  - Alert only if both detectors alert
  - Intuition: The combination generates fewer alerts
  - Reduces false positive rate
  - Increases false negative rate
- There is no free lunch: reducing one rate usually increases the other

Styles of Detection

Styles of Detection

- So far we’ve talked about types of detectors: *what* the detector is scanning
- Now we’ll talk about styles of detection: *how* the detector scans data to find attacks
- Four main styles of detection
  - Signature-based detection
  - Specification-based detection
  - Anomaly-based detection
  - Behavioral detection

Signature-based Detection

- **Signature-based detection**: Flag any activity that matches the structure of a known attack
- Signature-based detection is **blacklisting**: Keep a list of patterns that are not allowed, and alert if we see something on the list
- Signatures can be at different network layers
  - Example: TCP/IP header fields
  - Example: URLs
  - Example: Payload of the HTTP request

Signature-based Detection: Examples

- Example: Path traversal attacks
  - We know that `../` is often part of a path traversal attack
  - Strategy: Alert if any request contains `../`

Signature-based Detection: Tradeoffs

- Benefits
  - Conceptually simple
  - Very good at detecting known attacks
  - Easy to share signatures and build up shared libraries of attacks
- Drawbacks
  - Won’t catch new attacks without a known signature
  - Might not catch variants of known attacks if the variant doesn’t match the signature
  - The attacker can modify their attack to avoid matching a signature
  - Simpler versions only look at raw bytes, without parsing them in context
    - May miss variants
    - May generate lots of false positives

Specification-based Detection

- **Specification-based detection**: Specify allowed behavior and flag any behavior that isn't allowed behavior

- Specification-based detection is **whitelisting**: Keep a list of allowed patterns, and alert if we see something that is not on the list

Specification-based Detection: Examples

- Example: Path traversal attacks
    - We have a folder where all filenames are alphanumeric (a-z, A-Z, 0-9)
    - We specify that only alphanumeric characters are allowed as input
    - Strategy: Alert if any request contains something other than alphanumeric characters
    - If an attacker tries a path traversal attack (`../`), the detector will flag it

Specification-based Detection: Tradeoffs

- Benefits
  - Can detect new attacks we’ve never seen before
  - If we properly specify all allowed behavior, can have low false positive rate
- Drawbacks
  - Takes a lot of time and effort to manually specify all allowed behavior
  - May need to update specifications as things change

Anomaly-based Detection

- Idea: Attacks look unusual

- **Anomaly-based detection**: Develop a model of what normal activity looks like. Alert on any activity that deviates from normal activity.
  - Example: Analyze historical logs to develop the model

- Similar to specification-based detection, but learn a model of normal behavior instead of manually specifying normal behavior

Anomaly-based Detection: Examples

- Example: Path traversal attacks
  - Analyze characters in requests and learn that `..` only appears in attacks
  - Strategy: Alert if any request contains `..`

Anomaly-based Detection: Tradeoffs

- Benefits
  - Can detect attacks we haven't seen before

- Drawbacks
  - Can fail to detect known attacks
  - Can fail to detect new attacks if they don't look unusual to our model
  - What if our model is trained on bad data (e.g. data with a lot of attacks)?
  - The false positive rate might be high (lots of non-attacks look unusual)
  - If we try to reduce false positives by only flagging the most unusual inputs, the false negative rate might be high (we miss slightly unusual attacks)

- Great subject for academic research papers, but not used in practice

Behavioral Detection

- **Behavioral detection**: Look for evidence of compromise

- Unlike the other three styles, we are not scanning the input: We're looking at the actions triggered by the input
  - Instead of looking for the exploit, we're looking for the result of the exploit
  - *Behaviors* can themselves be analyzed using blacklists (signature-based), whitelists (specification-based), or normal behavior (anomaly-based)

Behavioral Detection: Examples

- Example: Path traversal attacks
  - Strategy: See if any unexpected files are being accessed (e.g. the passwords file)

Behavioral Detection: Tradeoffs

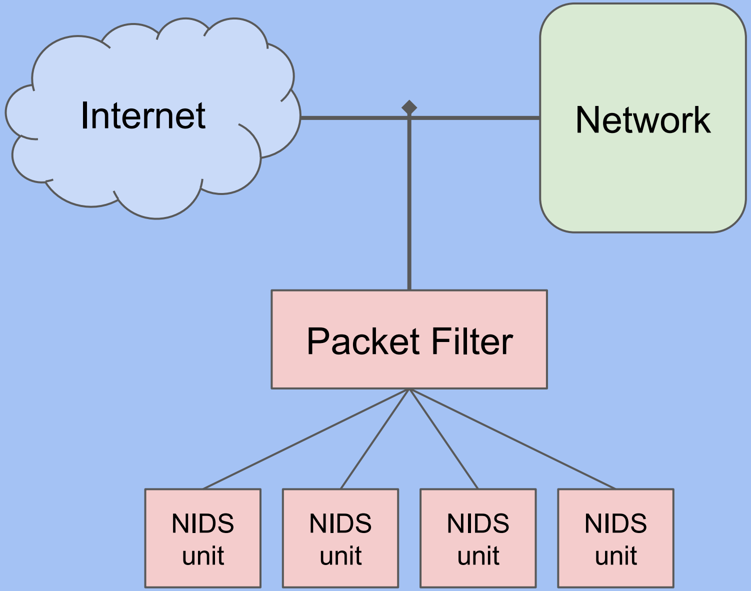
- Benefits
    - Can detect attacks we haven't seen before
    - Can have low false positive rates if we're looking for behavior that rarely occurs in normal programs
    - Can be cheap to implement (e.g. existing tools to monitor system calls for a program)
- Drawbacks
    - Legitimate processes could perform the behavior as well (e.g. accessing a password file)
    - **Only detects attacks after they've already happened**
    - Only detects successful attacks (maybe we want to detect failed attacks as well)
    - The attacker can modify their attack to avoid triggering some behavior

Attacks on Intrusion Detection Systems (IDS)

- The IDS is a system with limited resources, so it is vulnerable to DoS attacks!
  - DoS attack: Exhaust the IDS's memory
    - IDS needs to track all ongoing activity
    - Attacker generates lots of activity to consume all the IDS's memory
    - Example: Spoof TCP SYN packets to force the IDS to keep track of too many connections
  - DoS attack: Exhaust the IDS's processing power
    - Example: If the IDS uses a hash table to keep track of connections, create hash collisions to trigger worst-case complexity (algorithmic complexity attack)
- The IDS analyzes outside input, so it is vulnerable to code injection attacks!
  - Attacker supplies malicious input to exploit the IDS

Inside A Modern IDS

- Employ **defense in depth**
- To cover all devices, use a modern NIDS:
  - Single entry point with a simple packet filter
    - Simple but effective filters can handle 1,000 Gbps
  - Parallel processing using multiple NIDS nodes
    - A single server rack slot can handle 1–5 Gbps, and scales linearly
  - In-depth detection techniques
    - Protocol analysis
    - Signature analysis on content and behavior
    - Shadow execution (execute unknown content found on the network)
    - Extensive logging
    - Automatic updates



Inside A Modern IDS

- Cover individual devices using a HIDS on each device
    - Antivirus software is a kind of HIDS used by many corporations!
    - Block access to blacklisted sites (e.g. malware sites)
    - Detection techniques
        - Protocol analysis
        - Signature analysis on networking traffic
        - Signature analysis on memory and filesystem
        - Query a cloud database to see if a payload has been seen by other devices running the same HIDS
        - Sandboxed execution (execute a payload in a safe, inescapable environment)
            - Analyze the behavior of the program while in the sandbox