Computer Security

12. Network Security:
Conversation Isolation VPNs & TLS
Firewalls

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Network Layer Conversation Isolation:

Virtual Private Networks (VPNs)

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Fundamental Layer 2 & 3 Problems

- IP relies on store-and-forward networking
  - Network data passes through untrusted hosts
  - Routes may be altered to pass data through malicious hosts
- Packets can be sniffed (and new forged packets injected)
- Ethernet, IP, TCP & UDP
  - All designed with no authentication or integrity mechanisms
  - No source authentication on IP packets – they might be forged
  - TCP session state can be examined or guessed … … and then TCP sessions can be hijacked
  - Man-in-the-middle attacks are possible
- ARP, DHCP, DNS protocols
  - Can be spoofed to redirect traffic to malicious hosts
- Internet route advertisement protocols are not secure
  - Can redirect traffic to malicious routers/hosts

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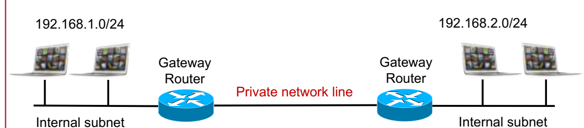
Solution: Use private networks

Connect multiple geographically-separated private subnetworks together



But this is expensive … and not feasible in many cases (e.g., cloud servers)

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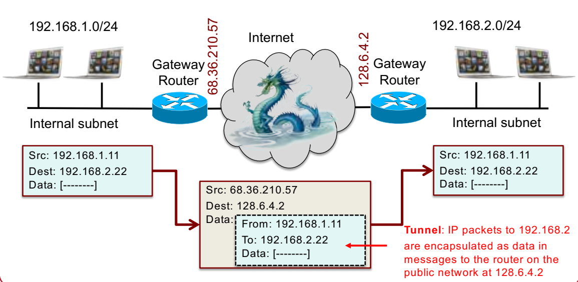
What's a tunnel?

Tunnel = Packet encapsulation

Treat an entire IP datagram as payload on the public network



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Virtual Private Networks

Take the concept of tunneling

… and safeguard the encapsulated data

- **Add a MAC (message authentication code)**
  - Ensure that outsiders don't modify the data
- **Encrypt the contents**
  - Ensure that outsiders can't read the data

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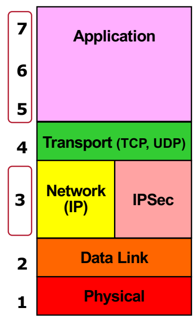
IPsec

Internet Protocol Security

End-to-end solution at the IP layer

Two protocols:

- **IP Authentication Header** Protocol (AH)
  - Authentication & integrity of payload and header
  - ***Provides integrity***
- **Encapsulating Security Payload** (ESP)
  - AH + Confidentiality of payload
  - ***Adds content encryption***



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Tunnel mode vs. transport mode

Tunnel mode VPN

- Communication between gateways: *network-to-network*
- Or *host-to-network*
- Entire IP datagram is encapsulated
  - The system sends IP packets to various addresses on subnet
  - A router (tunnel endpoint) on the remote side extracts the datagram and routes it on the internal network

Transport mode VPN

- Communication between hosts
- IP header is not modified
  - The system communicates directly with only one other system

Note: this does not operate at the transport layer – IP datagrams can be sent to various services on the host

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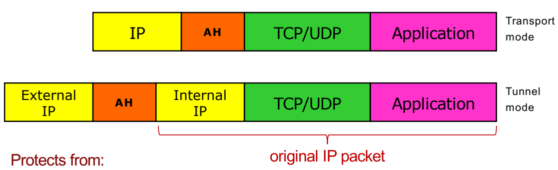
IPsec Authentication Header (AH)

Guarantees integrity & authenticity of IP packets

- MAC for the contents of the entire IP packet
- Computed over unchangeable IP datagram fields (e.g., not TTL or fragmentation fields)



Protects from:

- Tampering
- Forging addresses
- Replay attacks (sequence number in MAC-protected AH)

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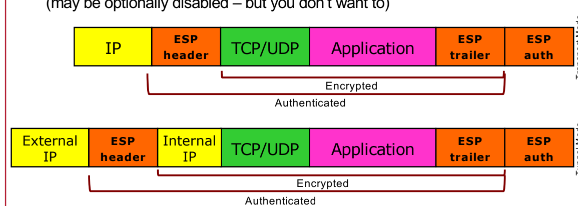
IPsec Encapsulating Security Payload (ESP)

Encrypts entire payload

- Plus authentication of payload and IP header (everything AH does) (may be optionally disabled – but you don't want to)



IPsec is a separate protocol from UDP or TCP – protocol 51 in the IP header
Layer 3 protocol – gateway routers are responsible for encapsulating/decapsulating

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IPSec algorithms

Authentication

- Certificates, or pre-shared key authentication
  - Public keys in certificates (RSA or ECC) used for authenticating users (prove you have a private key by decrypting data encrypted with the public key in your certificate)
  - Pre-shared = configure a shared key ahead of time

Key exchange – *Diffie-Hellman*

- Diffie-Hellman to exchange public keys for key generation
- Key lifetimes determine when new keys are regenerated
- Random key generation ensures Forward Secrecy

Confidentiality – *symmetric algorithm*

- 3DES-CBC
- AES-CBC

Integrity protection & authenticity – *MACs*

- HMAC-SHA1
- HMAC-SHA2

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Transport Layer Conversation Isolation:

Transport Layer Security (TLS)

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Network vs. Transport Layer

VPNs were designed to operate at the **network layer**
- Connect networks together
- They establish a secure communication channel that can then be shared by multiple applications
- Applications are not aware that the VPN is there

What if we want to talk to a network service, such as a web server … but securely?
- VPNs aren't an easy answer
- We want to do this at the **transport layer** – for a single application talking to a service on a socket

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Transport Layer Security

Goal: provide a *transport layer* security protocol

After setup, applications feel like they are using TCP sockets

SSL: Secure Socket Layer

Created with HTTP in mind
- Web sessions should be secure
  - Encrypted, tamperproof, resilient to man-in-the-middle attacks
- Mutual authentication is usually not needed
  - Client needs to identify the server but the server isn't expected to know all clients
  - Rely on password authentication after the secure channel is set up

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TLS vs. SSL – versions

SSL evolved to TLS (Transport Layer Security)

SSL 3.0 was the last version of SSL
… and is considered insecure

We now use TLS (but is often still called SSL)
- TLS 1.0 = SSL 3.1, TLS 1.1 = SSL 3.2, TLS 1.2 = SSL 3.3
- Latest version = TLS 1.3 = SSL 3.4

- Retired versions
  - TLS 1.0/SSL 3 are not considered strong anymore and their use is not recommended
  - As of 2019, Google Chrome deprecates support for TLS 1.1

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TLS Protocol

Goal

Provide authentication (usually one-way), privacy, & data integrity between two applications

Principles
- **Data encryption**
  - Use symmetric cryptography to encrypt data
  - **Key exchange**: keys generated uniquely at the start of each session
- **Data integrity**
  - Include a MAC with transmitted data to ensure message integrity
- **Authentication**
  - Use public key cryptography & X.509 certificates for authentication
  - Optional – can authenticate 0, 1, or both parties
- **Interoperability & evolution**
  - Support many different key exchange, encryption, integrity, & authentication protocols – negotiate what to use at the start of a session

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TLS Protocol & Ciphers

Two sub-protocols

1. Authenticate & establish keys
- Authentication
  - Public keys (X.509 certificates and – usually – RSA cryptography)
- Key exchange options
  - Ephemeral Diffie-Hellman keys (generated for each session)
  - Pre-shared key

2. Communicate
- Data encryption options – *symmetric cryptography*
  - AES GCM, AES CBC, ARIA (GCM/CBC), ChaCha20-Poly1305, …
- Data integrity options – *message authentication codes*
  - HMAC-MD5, HMAC-SHA1, HMAC-SHA256/384, …

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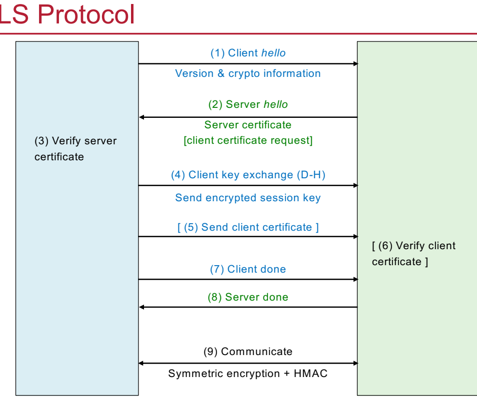
TLS Protocol



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Benefits of TLS

Benefits

- Protects integrity of communications
- Protects the privacy of communications
- Validates the authenticity of the server (if you trust the CA)

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Some past attacks on TLS

- Man-in-the-middle: BEAST attack in TLS 1.0
  - Attacker was able to see Initialization Vector (IV) for CBC and deduce plaintext (because of known HTML headers & cookies)
    - An IV doesn't have to be secret – but it turned out this wasn't a good idea
  - **Attacker was able to send chosen plaintext & get it encrypted with a known IV**
  - Fixed by using fresh IVs for each new 16K block
- Man-in-the-middle: crypto renegotiation
  - Attacker can renegotiate the handshake protocol during the session to disable encryption
  - Proposed fix: have client & server verify info about previous handshakes
- THC-SSL-DoS attack
  - Attacker initiates a TLS handshake & requests a renegotiation of the encryption key – repeat over & over, using up server resources

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Some past attacks on TLS

- Man-in-the-middle: 3SHAKE
  - Malicious server gets client credentials and forwards them to another server
  - Malicious server impersonates the client
- FREAK
  - Tricks server into renegotiating a connection with weak RSA encryption keys
- Heartbleed: vulnerability in popular extension to OpenSSL library
  - Extension was used to keep the connection alive
    - Client sends payload containing data & the size of the data
    - Server responds with the same message
  - If the client sent false data length, the server would respond with random data
    - That data was memory contents which could include the private key of the server

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Client authentication Problem

- SSL supports mutual authentication
  - Clients can authenticate servers & servers can authenticate clients
- Client authentication is almost never used
  - Generating keys & obtaining certificates is not an easy process for users
  - Any site can request the user's certificate
    - User will be unaware their anonymity is lost
  - Moving private keys around can be difficult
    - What about users on shared or public computers?
- We usually rely on other authentication mechanisms
  - Usually user name and password
  - But there no danger of eavesdropping since the session is encrypted
  - May use one-time passwords or two-factor authentication if worried about eavesdroppers at physical premises

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Firewalls

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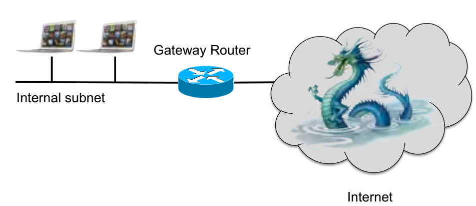
Network Security Goals

- **Confidentiality**: sensitive data & systems not accessible
- **Integrity**: data not modified during transmission
- **Availability**: systems should remain accessible



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Firewall

- Separate your local network from the Internet
  - Protect the border between trusted internal networks and the untrusted Internet
- Approaches
  - Packet filters
  - Application proxies
  - Intrusion detection / intrusion protection systems

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Packet Filters

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Screening router

- Border router (gateway router)
  - Router between the internal network(s) and external network(s)
  - Any traffic between internal & external networks passes through the border router

Instead of just routing the packet, decide *whether* to route it

- Screening router = Packet filter
  Allow or deny packets based on
  - Incoming & outgoing interfaces
  - Source & destination IP addresses
  - Source & destination TCP/UDP ports, ICMP command
  - Protocol (e.g., TCP, UDP, ICMP, IGMP, RSVP, etc.)

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Filter chaining

An IP packet entering a router is matched against a set of rules: access control list (ACL) or chain

Each rule contains criteria and an action

- Criteria: packet screening rule
- Actions
  - ***Accept*** – and stop processing additional rules
  - ***Drop*** – discard the packet and stop processing additional rules
  - ***Reject*** – and send an error to the sender (ICMP Destination Unreachable)
- Also
  - ***Route*** – reroute packets
  - ***Nat*** – perform network address translation
  - ***Log*** – record the activity

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Filter structure is vendor specific

Examples

- Windows
  - ***Allow***, ***Block***
  - Options such as
    - Discard all traffic except packets allowed by filters *(default deny)*
    - Pass through all traffic except packets prohibited by filters *(default allow)*
- OpenBSD
  - ***Pass*** (allow), ***Block***
- Linux nftables (netfilter)
  - Chain types: ***filter***, ***route***, ***nat***
  - Chain control
    - ***Return*** – stop traversing a chain
    - ***Jump*** – jump to another chain (*goto* = same but no return)

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Network Ingress Filtering: incoming packets

Basic firewalling principle

No direct inbound connections external systems (Internet) to any internal host – all traffic must flow through a firewall and be inspected

- Determine which services you want to expose to the Internet
  - e.g., HTTP & HTTPS: TCP ports 80 and 443
- Create a list of services and allow only those inbound ports and protocols to the machines hosting the services.
- Default Deny model - by default, "**deny all**"
  - Anything not specifically permitted is dropped
  - May want to log denies to identify who is attempting access

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Network Ingress Filtering (inbound)

- Disallow IP source address spoofing
  - Restrict forged traffic (RFC 2827)
- At the ISP
  - Filter upstream traffic - prohibit an attacker from sending traffic from forged IP addresses
  - Attacker must use a valid, reachable source address
- Disallow incoming/outgoing traffic from private, non-routable IP addresses
  - Helps with DDoS attacks such as SYN flooding from lots of invalid addresses

```
access-list 199 deny ip 192.168.0.0 0.0.255.255 any log
access-list 199 deny ip 224.0.0.0 0.0.0.255 any log
               ....
access-list 199 permit ip any any
```


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Network Egress Filtering (outbound)

- Usually we don't worry about outbound traffic
  - *Communication from a higher security network (internal) to a lower security network (Internet) is usually fine*
- Why might we want to restrict it?
  - Consider: if a web server is compromised & all outbound traffic is allowed, it can connect to an external server and download more malicious code ... or launch a DoS attack on the internal network
  - Also, log which servers are trying to access external addresses

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Stateful Inspection – 2nd generation firewalls

- Retain state information about a stream of related packets
- Examples
  - TCP connection tracking
    - Disallow TCP data packets unless a connection is set up
  - ICMP echo-reply
    - Allow ICMP echo-reply only if a corresponding echo request was sent.
  - Related traffic
    - Identify & allow traffic that is related to a connection
    - Example: related ports in FTP
      - Client connects to server on port 21 to send commands
      - Server connects back to client on port 20 to send data

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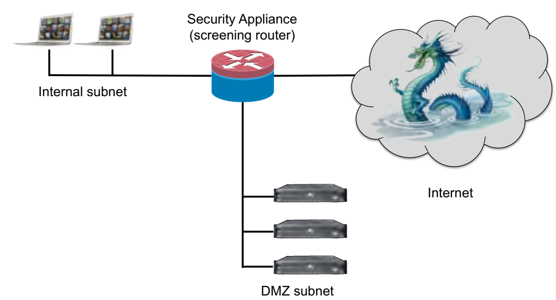
Network Design: DMZ



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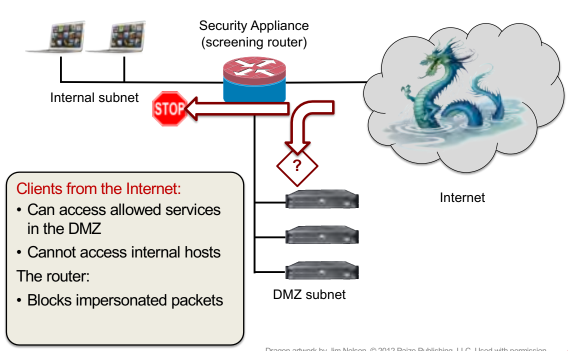

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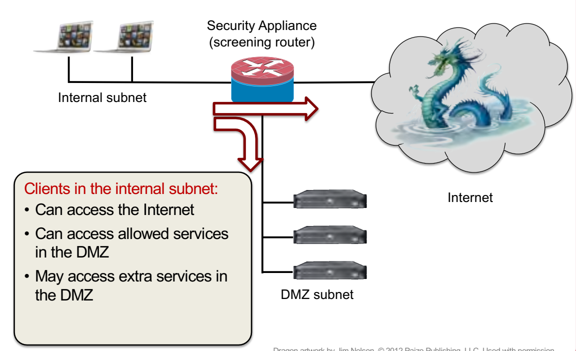

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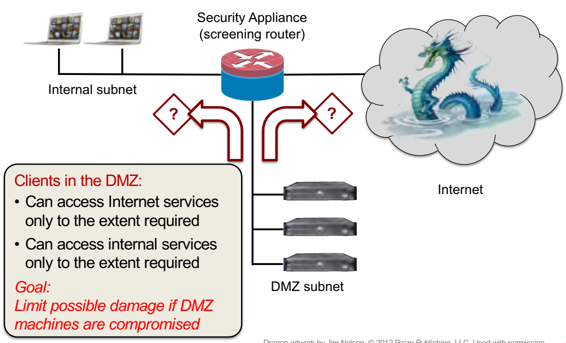
Network Design: DMZ



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Network Address Translation

- Most organizations use private IP addresses
- External traffic goes through a NAT router
  – Network Address Translation
- NAT is an implicit firewall (sort of)
  – Arbitrary hosts and services on them (ports) cannot be accessed unless
    - They are specifically mapped to a specific host/port by the administrator
    - Internal services have initiated outgoing traffic
      – Return traffic from the same address/port will be accepted

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Application-Layer Filtering

Firewalls don't work well when everything is a web service

Deep packet inspection (DPI)

– Look beyond layer 3 & 4 headers
– Need to know something about application protocols & formats

Examples

– **URL filtering**
  - Normal source/destination host/port filtering **+** URL pattern/keywords, rewrite/truncate rules, protocol content filters
  - Detect ActiveX and Java applets; configure specific applets as trusted
    – Remove others from the HTML code

– **Keyword detection**
  - Prevent classified material from leaving the organization
  - Prevent banned content from leaving or entering an organization

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Design Challenges With DPI

- DPI matches IP packet data against known bad patterns
- This must be done at network speeds
  – DPI hardware can only hold a limited number of packets for matching
  – DPI hardware can only store a limited amount of malware patterns

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Deep Content Inspection (DCI)

Deep Packet Inspection evolves to Deep Content Inspection

- Deep Packet Inspection systems
  – Rely on pattern matching and reputation lookup
  – Usually limited to buffering a small set of packets for a stream
- Deep Content Inspection systems
  – Unpacks encoded data
    - Example: base64-encoded MIME data in web and email content
  – Signature matching, compliance analysis (including data loss prevention)
  – Behavior analysis via correlation with previous sessions

The difference is largely marketing on levels of application-layer inspection that take place

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IDS/IPS

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Intrusion Detection/Prevention Systems

IDS/IPS systems are part of Application-layer firewalls

Identify threats and attacks
- IDS: *Intrusion Detection System*
  - Monitor traffic at various points of the network and report problems
- IPS: *Intrusion Prevention System*
  - Sit in between two networks & control traffic between them (like a firewall)
  - Enforce admin-specified policy on detection of problems

Types of Systems
- Protocol-based
- Signature-based
  - We know what is bad; anything else is good
- Anomaly-based
  - We know what is good; anything else is bad

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Protocol-Based IDS

Reject packets that do not follow a prescribed protocol

- Permit return traffic as a function of incoming traffic
- Define traffic of interest (filter), filter on traffic-specific protocol/patterns

Examples
- **DNS inspection**: prevent spoofing DNS replies: make sure they match IDs of sent DNS requests
- **SMTP inspection**: restrict SMTP command set (and command count, arguments, addresses)
- **FTP inspection**: restrict FTP command set (and file sizes and file names)

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Signature-based IDS

Don't search for protocol violations but for possible data attacks

Match patterns of known "bad" behavior
- Viruses
- Malformed URLs
- Buffer overflow code

Need a database of known protocol attacks & malware
- Signature = data segments & order of packets that make up the attack
- Only detects known attacks

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Anomaly-based IDS

Search for statistical deviations from normal behavior

Establish baseline behavior first

Examples:
- Port scanning
- Imbalance in protocol distribution
- Imbalance in service access

Challenge
- Distinguish anomalies from legitimate traffic

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Application proxies

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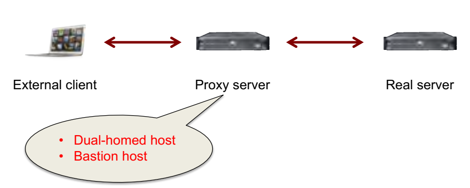
Application proxies

Proxy servers
- Intermediaries between clients and servers
- Stateful inspection and protocol validation



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Firewall Challenges

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Deperimeterization

Boundaries & access between internal & external systems are harder to identify

- Mobile systems
- Cloud-based computing
- USB flash memory
- Web-based applications

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Host-based (personal) firewalls

- Run on the user's systems, not as dedicated firewalls
- Manage network-facing effects of malware
  - Allow only approved applications to send or receive data over the network
- Problem
  - If malware gets elevated privileges, it can reconfigure or disable the firewall
- **Personal IDS**
  - E.g., fail2ban on Linux
    - Scan log files to detect & ban suspicious IP addresses
    - High number of failed logins, probes, URLs that try to target exploits

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Intrusion detection & prevention problems

- There's a lot of stuff going on
  - People visit random websites with varying frequencies
  - Software accesses varying services
  - Buggy software may create bad packets
  - How do you detect what is hostile?
- Attack rates is miniscule … compared to legitimate traffic
  - Even a small % of false positives can be annoying and hide true threats
- Environments are dynamic
  - Content from CDNs or other large server farms has a broad range of IP addresses
  - Malicious actors can coexist with legitimate ones

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Intrusion detection & prevention problems

- Encrypted traffic cannot be easily inspected
  - Just because you visit a web site using HTTPS doesn't mean the site is secure … or hasn't been compromised
- Packet inspection is limiting
  - You may need to extract data from multiple packets
  - You may need to reconstruct sessions
  - Both of these are time consuming and can affect performance
- Threats & services change
  - Rules must be updated

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Summary

Firewall (screening router)	1st generation packet filter that filters packets between networks. Blocks/accepts traffic based on IP addresses, ports, protocols
Stateful inspection firewall	2nd generation packet filter – like a screening router but also considers TCP connection state and information from previous connections (e.g., related ports for services)
Deep Packet Inspection firewall	3rd generation packet filter – examines application-layer protocols
Application proxy	Gateway between two networks for a specific application. Prevents direct connections to the application from outside the network. Responsible for validating the protocol.
IDS/IPS	Can usually do what a stateful inspection firewall does + examine application-layer data for protocol attacks or malicious content. Usually a part of Deep Packet Inspection firewalls
Host-based firewall	Typically screening router with per-application awareness. Sometimes includes anti-virus software for application-layer signature checking
Host-based IPS	Typically allows real-time blocking of remote hosts performing suspicious operations (port scanning, ssh logins)

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DDoS

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DDoS: Distributed Denial of Service

- Compromise machines and create a botnet
  - Systems contact a command & control server for directions
  - Use *amplification* techniques to generate a lot of traffic for targets
    - Exploit services that generate a lot of traffic to a small query
    - **DNS amplification**:
      Small UDP query with forged source address results in large response
- Some targets were too huge to hurt with traffic
  - Amazon, Google, sites using CDNs such as Akamai
- Vast quantities of compromised systems reduce need for amplification
  - Create a botnet of millions of systems

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Dealing with DDoS

Really difficult in general

- Bandwidth management routers
  - Either in data center or ISP
  - Limit outbound or inbound traffic on a per-IP basis
- Detect DNS attack and set null routing
  - Traffic to attacked DNS goes nowhere
- Egress filtering by ISPs
  - Attempt to find malicious hosts participating in DDoS or sending spam
- Identify incoming attackers & block traffic at firewall
  - Difficult with a truly distributed DDoS attack

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The end

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