Electrical Engineering E6761
Computer Communication Networks
Lecture 11
Security

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Tues 4:10-6:40, Mudd 1127
Course URL:
http://www.cs.columbia.edu/~danr/EE6761

Reminders

- Fill out course evaluation (http://oracle.seas.columbia.edu)
  - chance to win a Palm Pilot
- Course project
  - 50% of grade!
  - Due 12/15
  - Include:
    - ~10 pg report
    - list of individual contributions
    - include source code written
    - preferred method of delivery: e-mail

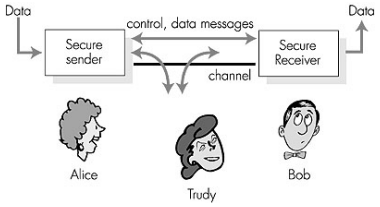
Overview

Foundations:
- what is security?
- cryptography
- authentication
- message integrity
- key distribution and certification

Security in practice:
- application layer: secure e-mail
- transport layer: Internet commerce, SSL, SET
- network layer: IP security

Denial of Service Attacks:
- Common attacks
- solutions

Friends and enemies: Alice, Bob, Trudy



- well-known in network security world
- Bob, Alice (lovers!) want to communicate "securely"
- Trudy, the "intruder" may intercept, delete, add messages

What is network security?

Secrecy: only sender, intended receiver should "understand" msg contents
- sender encrypts msg
- receiver decrypts msg

Authentication: sender, receiver want to confirm identity of each other

Message Integrity: sender, receiver want to ensure message not altered (in transit, or afterwards)

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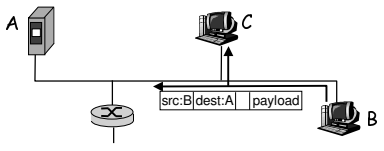
Internet security threats

Packet sniffing:
- broadcast media
- promiscuous NIC (network interface card) reads all packets passing by
- can read all unencrypted data (e.g. passwords)
- e.g.: C sniffs B's packets



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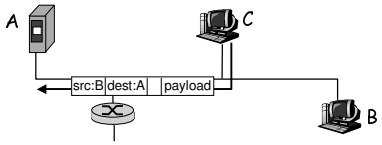
Internet security threats

IP Spoofing:
- can generate "raw" IP packets directly from application, putting any value into IP source address field
- receiver can't tell if source is spoofed
- e.g.: C pretends to be B



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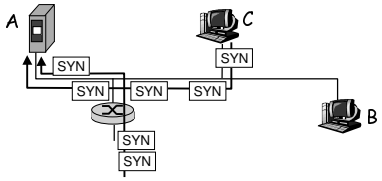
Internet security threats

Denial of service (DOS):
- flood of maliciously generated packets "swamp" receiver
- Distributed DOS (DDOS): multiple coordinated sources swamp receiver
- e.g., C and remote host SYN-attack A
- More opn this at end of lecture…



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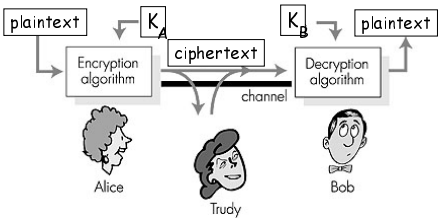
The language of cryptography



symmetric key crypto: sender, receiver keys identical

public-key crypto: encrypt key *public*, decrypt key *secret*

Symmetric key cryptography

substitution cipher: substituting one thing for another

- monoalphabetic cipher: substitute one letter for another

```
plaintext:   abcdefghijklmnopqrstuvwxyz
             |                        |
ciphertext:  mnbvcxzasdfghjklpoiuytrewq
```

E.g.: `Plaintext: bob. i love you. alice`

`ciphertext: nkn. s gktc wky. mgsbc`

Q: How hard to break this simple cipher?:

- brute force (how hard?)
- other?

Symmetric key crypto: DES

DES: Data Encryption Standard

- US encryption standard [NIST 1993]
- 56-bit symmetric key, 64 bit plaintext input
- How secure is DES?
  - DES Challenge: 56-bit-key-encrypted phrase ("Strong cryptography makes the world a safer place") decrypted (brute force) in 4 months
  - no known "backdoor" decryption approach
- making DES more secure
  - use three keys sequentially (3-DES) on each datum
  - use cipher-block chaining

Symmetric key crypto: DES

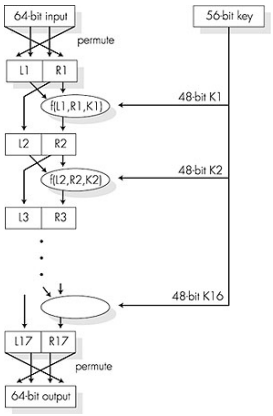
DES operation

initial permutation

16 identical "rounds" of function application, each using different 48 bits of key

final permutation

DES uses a series of shifting and XOR operations



Public Key Cryptography

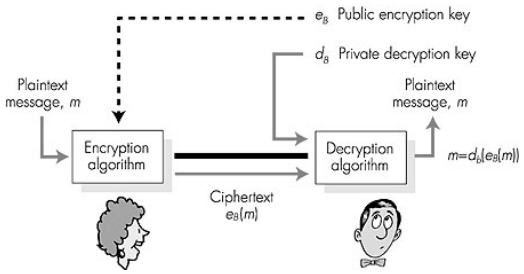
symmetric key crypto

- requires sender, receiver know shared secret key
- Q: how to agree on key in first place (particularly if never "met")?

public key cryptography

- radically different approach [Diffie-Hellman76, RSA78]
- sender, receiver do *not* share secret key
- encryption key *public* (known to *all*)
- decryption key private (known only to receiver)

Public key cryptography



Public key encryption algorithms

Two inter-related requirements:

1. need $d_B(\cdot)$ and $e_B(\cdot)$ such that
   $d_B(e_B(m)) = m$
2. need public and private keys for $d_B(\cdot)$ and $e_B(\cdot)$.

RSA: Rivest, Shamir, Adelson algorithm

RSA: Choosing keys

1. Choose two large prime numbers *p, q*. (e.g., 1024 bits each)
2. Compute $n = pq$, $z = (p-1)(q-1)$
3. Choose e (with $e<n$) that has no common factors with z. (e, z are "relatively prime").
4. Choose d such that $ed-1$ is exactly divisible by z.
   (in other words: $ed \bmod z = 1$).
5. *Public* key is (n,e). *Private* key is (n,d).

Note: d and e have similar properties (i.e., d, z rel. prime)
Hence, either one can be used in public / private key

- Why can't Trudy compute d?
  - p or q (because it's hard to factor #'s)
  - hence, doesn't know z
  - so even when Trudy has e, can't compute d

Why are these steps easy (given knowledge of z)?

RSA: Encryption, decryption

0. Given (n,e) and (n,d) as computed above

1. To encrypt bit pattern, m, compute
   $c = m^e \bmod n$ (i.e., remainder when m^e is divided by n)

2. To decrypt received bit pattern, c, compute
   $m = c^d \bmod n$ (i.e., remainder when c^d is divided by n)

Magic happens! $m = (m^e \bmod n)^d \bmod n$

- Since e can be public or private, then
  - can encrypt w/ public, decrypt w/ private or
  - can encrypt w/ private, decrypt w/ public

RSA: Why:

$m = (m^e \bmod n)^d \bmod n$

Number theory result: If p,q prime, $n = pq$, then

$$x^y \bmod n = x^{y \bmod (p-1)(q-1)} \bmod n$$

$$(m^e \bmod n)^d \bmod n = m^{ed} \bmod n$$

$= m^{ed \bmod (p-1)(q-1)} \bmod n$
(using number theory result above)

$= m^1 \bmod n$
(since we chose ed to be divisible by $(p-1)(q-1)$ with remainder 1)

$= m$

RSA example:

Bob chooses $p=5$, $q=7$. Then $n=35$, $z=24$.
$e=5$ (so e, z relatively prime).
$d=29$ (so $ed-1$ = 144 exactly divisible by z).

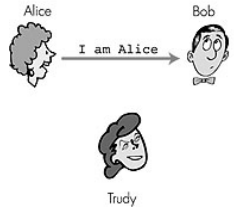
	letter	m	m^e	$c = m^e \bmod n$
encrypt:	l	12	1524832	17

	c	c^d	$m = c^d \bmod n$	letter
decrypt:	17	481968572106750915091411825223071697	12	l

Authentication

Goal: Bob wants Alice to "prove" her identity to him

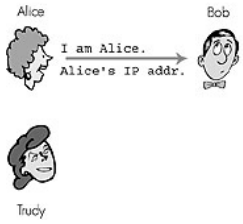
Protocol ap1.0: Alice says "I am Alice"



Failure scenario??

Authentication: another try

Protocol ap2.0: Alice says "I am Alice" and sends her IP address along to "prove" it.



Failure scenario??

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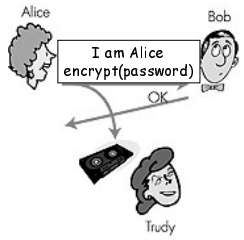
Authentication: yet another try

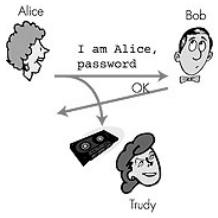
Protocol ap3.1: Alice says "I am Alice" and sends her *encrypted* secret password to "prove" it.



Failure scenario?

Authentication: another try

Protocol ap3.0: Alice says "I am Alice" and sends her secret password to "prove" it.



Failure scenario?

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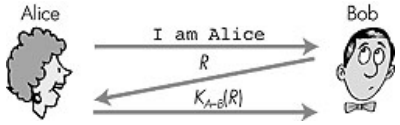
Authentication: yet another try

Goal: avoid playback attack

Nonce: number (R) used only once in a lifetime

ap4.0: to prove Alice "live", Bob sends Alice nonce, R. Alice must return R, encrypted with **shared** secret key



Failures, drawbacks?

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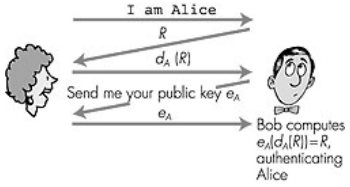
Authentication: ap5.0

ap4.0 requires shared symmetric key
- problem: how do Bob, Alice agree on key
- can we authenticate using public key techniques?

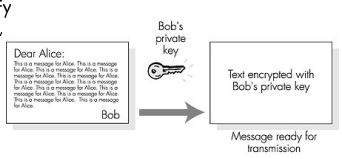
ap5.0: use nonce, public key cryptography



Digital Signatures

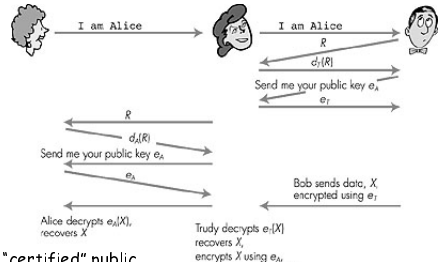
Cryptographic technique analogous to hand-written signatures.
- Sender (Bob) digitally signs document, establishing he is document owner/creator.
- Verifiable, nonforgeable: recipient (Alice) can verify that Bob, and no one else, signed document.

Simple digital signature for message m:
- Bob encrypts m with his private key d_B, creating signed message, $d_B(m)$.
- Bob sends m and $d_B(m)$ to Alice.



ap5.0: security hole

Man (woman) in the middle attack: Trudy poses as Alice (to Bob) and as Bob (to Alice)



Need "certified" public keys (more later …)

Digital Signatures (more)

- Suppose Alice receives msg *m*, and digital signature $d_B(m)$
- Alice verifies *m* signed by Bob by applying Bob's public key e_B to $d_B(m)$ *then* checks $e_B(d_B(m)) = m$.
- If $e_B(d_B(m)) = m$, whoever signed *m* must have used Bob's private key.

Alice thus verifies that:
- Bob signed *m*.
- No one else signed *m*.
- Bob signed m and not *m'*.

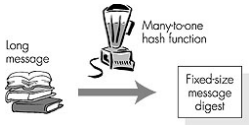
Non-repudiation:
- Alice can take *m*, and signature $d_B(m)$ to court and prove that Bob signed *m*.

Message Digests

Computationally expensive to public-key-encrypt long messages

Goal: fixed-length, easy to compute digital signature, "fingerprint"

- apply hash function H to *m*, get fixed size message digest, *H(m)*.



Hash function properties:

- Many-to-1
- Produces fixed-size msg digest (fingerprint)
- Given message digest x, computationally infeasible to find m such that x = H(m)
- computationally infeasible to find any two messages m and m' such that H(m) = H(m').

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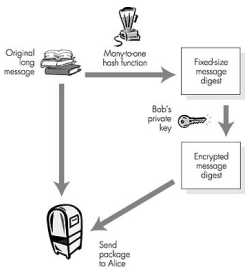
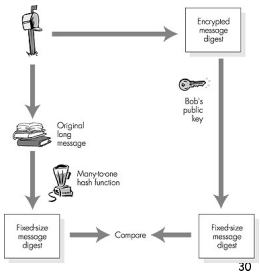
Digital signature = Signed message digest

Bob sends digitally signed message:



Alice verifies signature and integrity of digitally signed message:



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Hash Function Algorithms

- Internet checksum would make a poor message digest.
  - Too easy to find two messages with same checksum.
- MD5 hash function widely used.
  - Computes 128-bit message digest in 4-step process.
  - arbitrary 128-bit string x, appears difficult to construct msg m whose MD5 hash is equal to x.
- SHA-1 is also used.
  - US standard
  - 160-bit message digest

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Encrypting long-lived sessions

- Session may be transmitted using numerous packets
- Problem: Public/Private key encryption/decryption a slow expensive process, DES encryption takes much less time
- Q: How can a session be encrypted efficiently (e.g., via DES) without forcing participants to find trusted medium to exchange a shared session key?

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Combining Public Key Crypto & DES

- Solution: use public key crypto to deliver the DES key, then use the DES key for the remainder of the session
- Assume: Session A transmitting packets to B
  - Step 1: A randomly chooses a DES key, K, at random
  - Step 2: A encrypts K using B's public key, P_B, and sends $P_B(K)$ to B
  - Step 3: B decrypts K using it's private key, p_B
- A & B now both have the DES key, K, and can use it for the remainder of the session

Trusted Intermediaries

Problem:

- How do two entities establish shared secret key over network?

Solution:

- trusted key distribution center (KDC) acting as intermediary between entities

Problem:

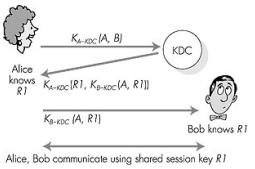
- When Alice obtains Bob's public key (from web site, e-mail, diskette), how does she know it is Bob's public key, not Trudy's?

Solution:

- trusted certification authority (CA)

Key Distribution Center (KDC)

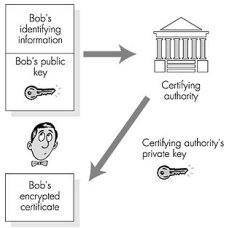
- Alice,Bob need shared symmetric key.
- KDC: server shares different secret key with each registered user.
- Alice, Bob know own symmetric keys, $K_{A\text{-}KDC}$ $K_{B\text{-}KDC}$, for communicating with KDC.



- Alice communicates with KDC, gets session key R1, and $K_{B\text{-}KDC}(A,R1)$
- Alice sends Bob $K_{B\text{-}KDC}(A,R1)$, Bob extracts R1
- Alice, Bob now share the symmetric key R1.

Certification Authorities

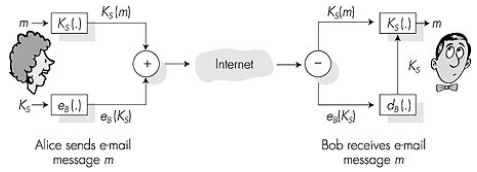
- Certification authority (CA) binds public key to particular entity.
- Entity (person, router, etc.) can register its public key with CA.
  - Entity provides "proof of identity" to CA.
  - CA creates certificate binding entity to public key.
  - Certificate digitally signed by CA.



- When Alice wants Bob's public key:
- gets Bob's certificate (Bob or elsewhere).
- Apply CA's public key to Bob's certificate, get Bob's public key

Secure e-mail

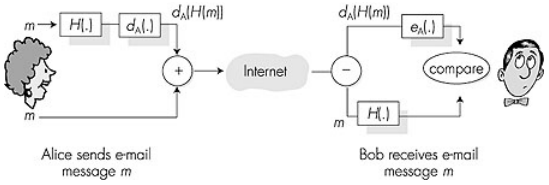
- Alice wants to send secret e-mail message, m, to Bob.



- generates random symmetric private key, K_S.
- encrypts message with K_S
- also encrypts K_S with Bob's public key.
- sends both $K_S(m)$ and $e_B(K_S)$ to Bob.

Secure e-mail (continued)

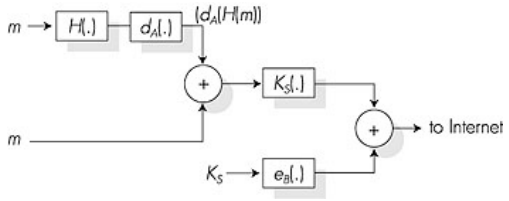
- Alice wants to provide sender authentication message integrity.



- Alice digitally signs message.
- sends both message (in the clear) and digital signature.

Secure e-mail (continued)

- Alice wants to provide secrecy, sender authentication, message integrity.



Note: Alice uses both her private key, Bob's public key.

Pretty good privacy (PGP)

- Internet e-mail encryption scheme, a de-facto standard.
- Uses symmetric key cryptography, public key cryptography, hash function, and digital signature as described.
- Provides secrecy, sender authentication, integrity.
- Inventor, Phil Zimmerman, was target of 3-year federal investigation.

A PGP signed message:

```
---BEGIN PGP SIGNED MESSAGE---
Hash: SHA1

Bob:My husband is out of town
    tonight.Passionately yours, Alice

---BEGIN PGP SIGNATURE---
Version: PGP 5.0
Charset: noconv
yhHJRHhGJGhgg/12EpJ+lo8gE4vB3mqJhFEvZ
    P9t6n7G6m5Gw2
---END PGP SIGNATURE---
```

Secure sockets layer (SSL)

- PGP provides security for a specific network app.
- SSL works at transport layer. Provides security to any TCP-based app using SSL services.
- SSL: used between WWW browsers, servers for I-commerce (https).
- SSL security services:
  - server authentication
  - data encryption
  - client authentication (optional)
- Server authentication:
  - SSL-enabled browser includes public keys for trusted CAs.
  - Browser requests server certificate, issued by trusted CA.
  - Browser uses CA's public key to extract server's public key from certificate.
- Visit your browser's security menu to see its trusted CAs.

SSL (continued)

Encrypted SSL session:

- Browser generates symmetric session key, encrypts it with server's public key, sends encrypted key to server.
- Using its private key, server decrypts session key.
- Browser, server agree that future msgs will be encrypted.
- All data sent into TCP socket (by client or server) is encrypted with session key.
- SSL: basis of IETF Transport Layer Security (TLS).
- SSL can be used for non-Web applications, e.g., IMAP.
- Client authentication can be done with client certificates.

Secure electronic transactions (SET)

- designed for payment-card transactions over Internet.
- provides security services among 3 players:
  - customer
  - merchant
  - merchant's bank

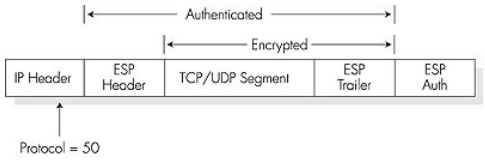
  All must have certificates.
- SET specifies legal meanings of certificates.
  - apportionment of liabilities for transactions
- Customer's card number passed to merchant's bank without merchant ever seeing number in plain text.
  - Prevents merchants from stealing, leaking payment card numbers.
- Three software components:
  - Browser wallet
  - Merchant server
  - Acquirer gateway
- See text for description of SET transaction.

IPsec: Network Layer Security

- Network-layer secrecy:
  - sending host encrypts the data in IP datagram
  - applicable to TCP and UDP segments; ICMP and SNMP messages.
- Network-layer authentication
  - destination host can authenticate source IP address
- Two principle protocols:
  - authentication header (AH) protocol
  - encapsulation security payload (ESP) protocol
- For both AH and ESP, source, destination handshake:
  - create network-layer logical channel called a service agreement (SA)
- Each SA unidirectional.
- Uniquely determined by:
  - security protocol (AH or ESP)
  - source IP address
  - Security Parameter Index (SPI): arbitrary 32-bit connection ID

ESP Protocol

- Provides secrecy, host authentication, data integrity.
- Data, ESP trailer encrypted.
- Next header field is in ESP trailer.
- ESP authentication field is similar to AH authentication field.
- Protocol = 50.



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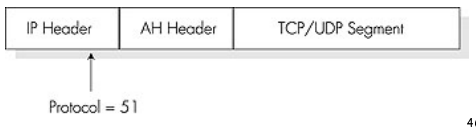
Authentication Header (AH) Protocol

- Provides source host authentication, data integrity, but not secrecy.
- AH header inserted between IP header and IP data field.
- Protocol field = 51.
- Intermediate routers process datagrams as usual.

AH header includes:

- connection identifier
- authentication data: signed message digest, calculated over original IP datagram, providing source authentication, data integrity.
- Next header field: specifies type of data (TCP, UDP, ICMP, etc.)



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Attacks and Attack Prevention

- Problem: there exist users who want to compromise security of a system
  - monetary gain (theft)
  - political gain
  - fun / prestige in the hacker community
- If legitimate users can access a system, so can illegitimate users
  - luck (guess a password)
  - find flaws in system security and crack through
- Fact: As systems become more complex, more loopholes are created that permit break-ins
  - e.g., anonymous ftp to a system w/ relaxed file permission settings

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Denial of Service Attacks

- Def: DoS is prevention of use of a service by legitimate users, e.g., by
  - flooding of traffic on the network, "drowning" legitimate traffic
  - disrupting a connection between 2 machines
  - preventing an individual from accessing a service
- Compared to other attacks:
  - less damaging: user does not try to steal or erase info
  - harder to stop: simply involves sending lots of traffic

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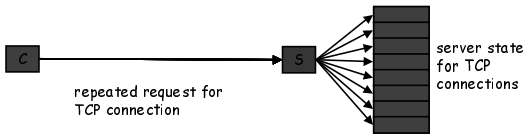
Syn Flood

- Attack takes advantage of TCP handshake
  - TCP receiver sends SYN
  - server creates state and sends SYN back to receiver, waits for receiver to begin connection
- A machine can issue multiple SYNs and use up connection state at the server



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Preventing Syn Floods

- Limit rate of connections from given address
  - Problem: receivers can perform **IP spoofing**: use fake source address
  - no confirmation of source address provided
  - Q: why doesn't IPsec solve the problem?
- Use nonces, e.g.,:
  - step 1: rcvr sends SYN
  - step 2: sender chooses random # n and sends to rcvr
  - step 3: rcvr sends SYN w/ n
  - Problem: sender must keep nonce state - not much help over keeping SYN state
- What may help: Prevent spoofing or identify actual location of spoofers

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Preventing Spoofing

- Goal: if a packet has a fake source address, it should be dropped
- CISCO routers provide "Verify Reverse Path"
  - a packet P with source address S should only be accepted on interface i if a packet P with destination address P is forwarded out on interface i
  - Recall: reverse-path forwarding is what is used by multicast routing protocols
  - Problem:
    - Verify Reverse Path assumes that routing is symmetric
    - Otherwise, likely to block legitimate traffic

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Tracking DoS attacks that use spoofing

- Goal: identify location where the DoS attack is coming from
- Observation: DoS attacks transmit lots of packets
- Assumptions
  - attack mounted from single point (note: in practice, attacks often consist of coordinated transmission from distributed set of hosts)
  - attack packets can be distinguished from regular traffic

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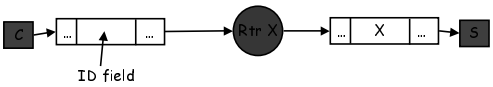
IP Traceback

- Add router ID field to IP packet
- Router stamps a packet with its ID with some probability, p
- Pkt arrives at server: server can identify a router through which the packet passed via the marking
- Probabilistic stamping lets server eventually receive stamps from all routers on path
  (uses observation that DoS attacks involve transmission of many packets)



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Problems with IP traceback

- Have router ID's but don't know the path (i.e., the order in which routers are traversed from client to server)
- Also, what if
  - routers are involved in DoS attack?
  - client sticks in fake router ID?
- Is there still a way to make use of this probabilistic stamping approach?

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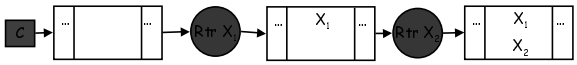
Edge Tracking

- Idea: rather than stamp a packet with a single router ID, have two adjacent routers stamp the pkt



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Edge Tracking

- Add additional bit and additional router tag field
- initially set bit to 0
- At packet arrival to router:
  - Router probabilistically marks packet in first tag field, if marks then sets bit to 1
  - If doesn't mark but bit set to 1, router marks packet in second tag field, sets bit to 0
- packet marked with edge (i.e., 2 routers attached to one another)
- Using edges, server can piece together the order in which routers appear on path
- Q: What about valid vs. invalid markings

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Trusted Suffix

- Given: we deduce a set of edges
  - $(R_1, R_2), (R_2, R_3), \ldots, (R_{n-1}, R_n)$
  - which are valid?
- Some suffix $(R_i, R_{i+1}), (R_{i+1}, R_{i+2}), \ldots, (R_{n-1}, R_n)$ is valid
  - an intruder can make changes at some router on the path, but cannot change the marks downstream

Network Security (summary)

Basic techniques…
- cryptography (symmetric and public)
- authentication
- message integrity

… used in many different security scenarios
- secure email
- secure transport (SSL)
- IP sec

Denial of Service Attacks…
- Prevention
- Detection

See also: firewalls , in network management

Course Summary

What you should now know:
- Protocol Stack (App, Transport, NW, Link, Phys)
- Basic hardware
  - repeaters
  - hubs
  - switches / bridges
  - routers
  - ethernet, LAN
- Addressing
  - MAC (ARP)
  - IP (CIDR, class-based)
  - DNS

Course Summary (cont'd)

- Transport Layer
  - E2E argument
  - Connection Setup/Teardown
  - Reliability (sel-rpt, Go-back-N)
  - Flow control
  - Congestion Control
  - Case studies: TCP, UDP, RTP
  - Multicast group paradigm
- Network Theory
  - Queueing models (M/M/1/K)
  - Fluid models
- Network Layer
  - Router switching (crossbar, fast lookups via tries)
  - Queueing disciplines (FIFO, Round Robin, WFQ, Priority)

Course Summary (cont'd)

- Network Layer (cont'd)
  - Policing (leaky-bucket)
  - Routing (Link-state, distance vector)
  - Multicast routing (Reverse-path flooding, Core-based trees)
- Link Layer
  - MAC protocols
    - CDMA
    - TDMA: Aloha, Slotted Aloha, CSMA
  - Error correction and detection
    - 1D, 2D parity, 1's complement, CRC

Course Summary (cont'd)

- Transport Layer Multimedia Networking
  - Coping with Jitter & Delay
    - buffering
    - interleaving
    - FEC
  - RTP & RTCP, congestion control
  - Multi-rate multicast
    - destination set splitting
    - layering
- Network Layer Multimedia Networking
  - Reservations: Int-Serv, RSVP, MBAC
  - Priority services: DiffServ, Dynamic Packet State
  - MPLS

Course Summary (cont'd)

- Active Queue Management
  - RED
  - ECN (marking)
- Fairness
  - TCP fairness
  - max-min fairness
  - proportional fairness
- Inference
  - bottleneck rate detection
  - multicast tree tomography
  - shared points of congestion
- Security
  - Encryption (DES, public key)
  - Secrecy, authentication, integrity
  - DoS attacks