Final Review

Final Exam

- Time: see syllabus in Canvas
- Location: Canvas + Honorlock
- Scope
  - Chapters 4, 5: Network layer
  - Chapter 6: Link layer
  - Chapter 8: Network security

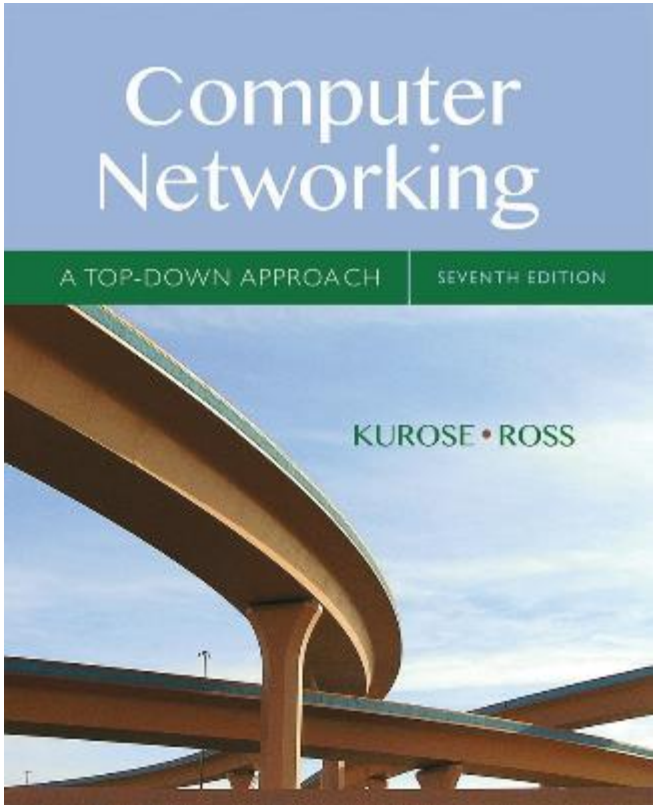
Final Exam

- Format
  - 20 questions (4 pts each), similar to those in weekly quizzes
  - 4 problems (5 pts each), similar to those in homework

- How to prepare
  - Review slides
  - Quiz questions
  - Homework problems

Chapter 4
Network Layer: The Data Plane

Slides adopted from original ones provided by the textbook authors.



Computer Networking: A Top Down Approach

7^{th} edition
Jim Kurose, Keith Ross
Pearson/Addison Wesley
April 2016

Chapter 4: outline

4.1 Overview of Network layer
- data plane
- control plane

4.2 What's inside a router

4.3 IP: Internet Protocol
- datagram format
- fragmentation
- IPv4 addressing
- network address translation
- IPv6

4.4 Generalized Forward and SDN
- match
- action
- OpenFlow examples of match-plus-action in action

Key Network-Layer Functions

- *forwarding – data plane:* move packets from router's input to appropriate router output
- *routing – control plane:* determine route taken by packets from source to dest.

Chapter 4: outline

4.1 Overview of Network layer
- data plane
- control plane

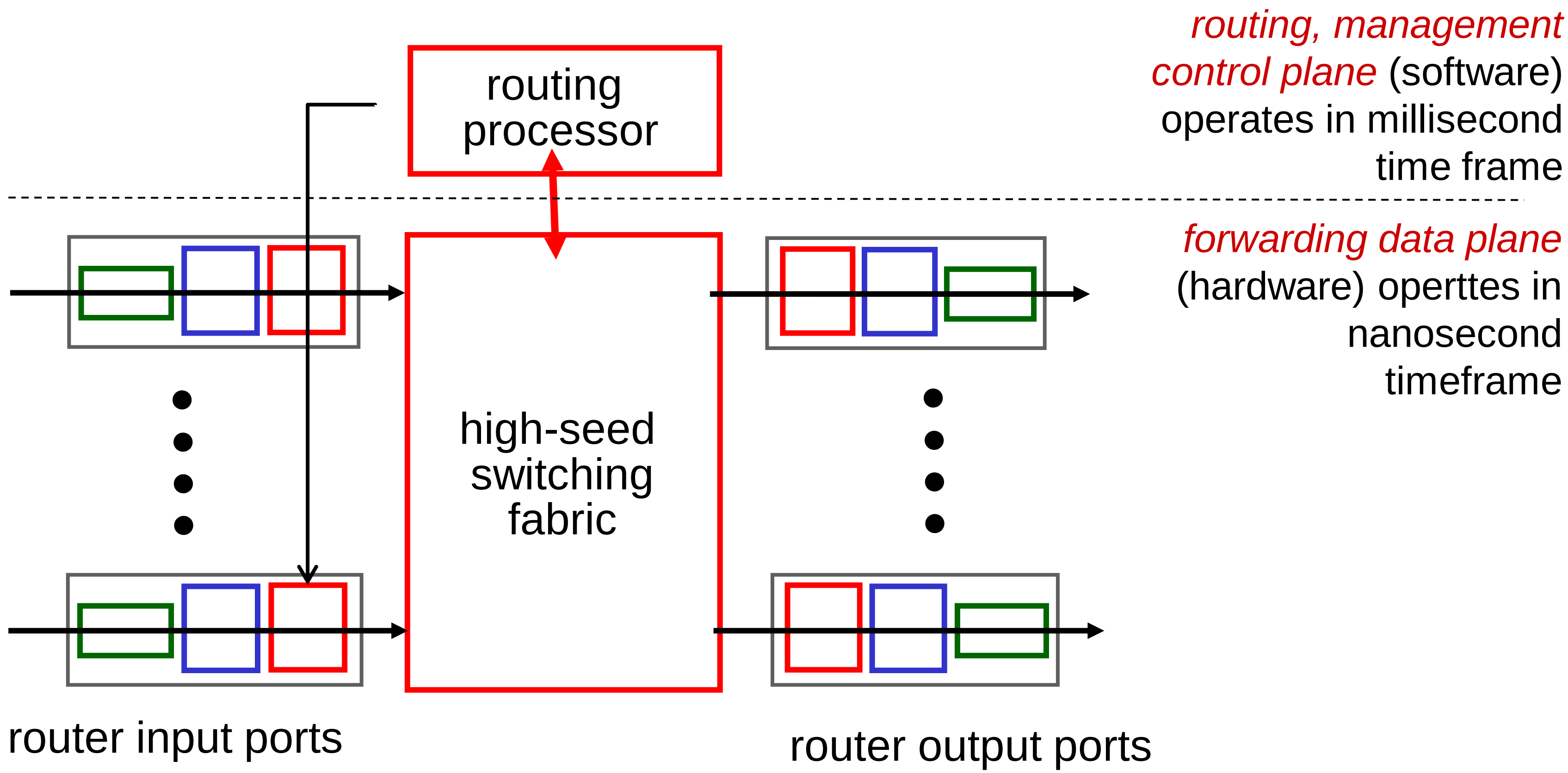
4.2 What's inside a router

4.3 IP: Internet Protocol
- datagram format
- fragmentation
- IPv4 addressing
- network address translation
- IPv6

4.4 Generalized Forward and SDN
- match
- action
- OpenFlow examples of match-plus-action in action

Router architecture overview

- high-level view of generic router architecture:



Longest prefix matching

- forwarding table lookup: destination based matching
- a destination may match multiple prefixes
- *longest* matching prefix is selected

Scheduling mechanisms

- *scheduling:* choose next packet to send on link
- different scheduling mechanisms:
  - FIFO (first in first out)
  - priority scheduling
  - round robin
  - WFQ (weighted fair queuing)

Chapter 4: outline

4.1 Overview of Network layer
- data plane
- control plane

4.2 What's inside a router

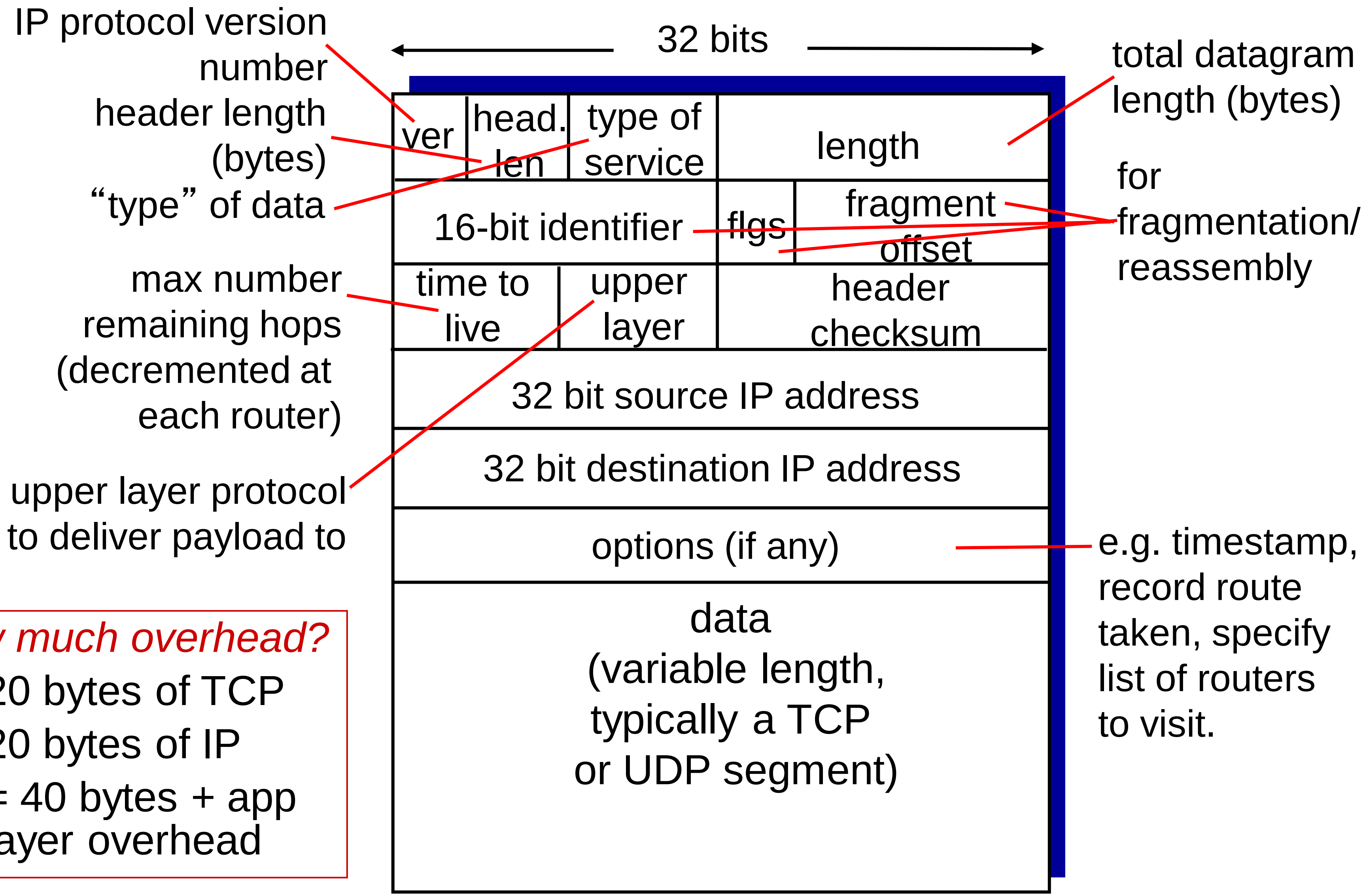
4.3 IP: Internet Protocol
- datagram format
- fragmentation
- IPv4 addressing
- network address translation
- IPv6

4.4 Generalized Forward and SDN
- match
- action
- OpenFlow examples of match-plus-action in action

Transmission modes

- Unicast: one to one transmission
  - Most traffic
- Multicast: one to many transmission
  - Video conferencing, online games
- Broadcast: one to all transmission
  - DHCP, ARP

IPv4 datagram format



how much overhead?

- 20 bytes of TCP
- 20 bytes of IP
- = 40 bytes + app layer overhead

IP addressing: CIDR

CIDR: Classless InterDomain Routing

- subnet portion of address of arbitrary length
- address format: a.b.c.d/x, where x is # bits in subnet portion of address

DHCP: Dynamic Host Configuration Protocol

goal: allow host to *dynamically* obtain its IP address from network server when it joins network

- can renew its lease on address in use
- allows reuse of addresses (only hold address while connected/"on")
- support for mobile users who want to join network (more shortly)

DHCP overview:

- host broadcasts "DHCP discover" msg [optional]
- DHCP server responds with "DHCP offer" msg [optional]
- host requests IP address: "DHCP request" msg
- DHCP server sends address: "DHCP ack" msg

NAT: network address translation

implementation: NAT router must:

- *outgoing datagrams: replace* (source IP address, port #) of every outgoing datagram to (NAT IP address, new port #)

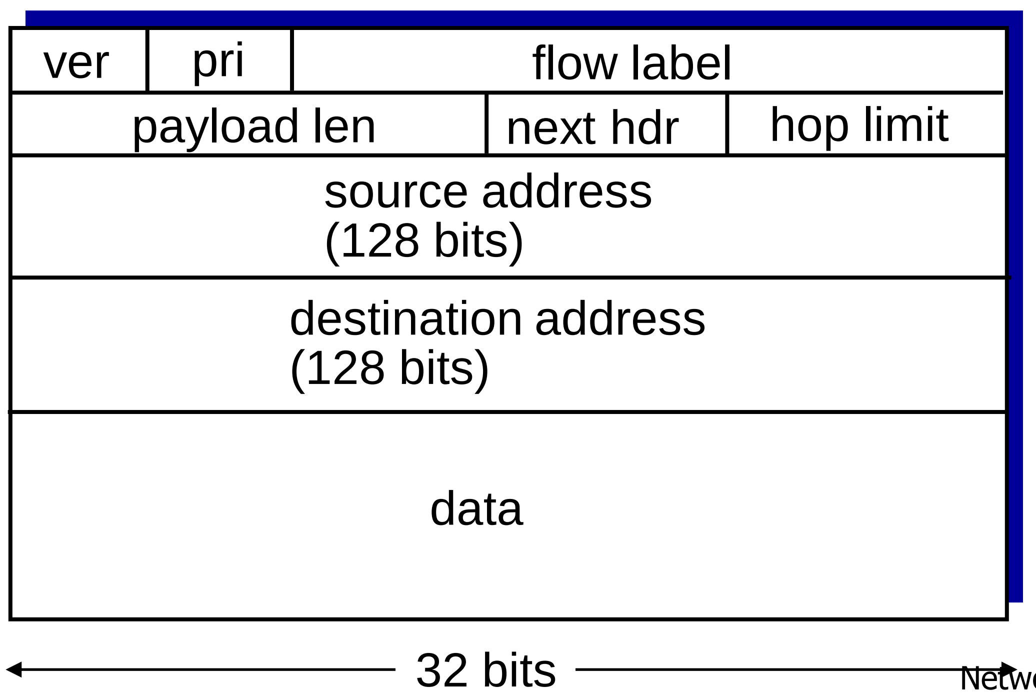
  . . . remote clients/servers will respond using (NAT IP address, new port #) as destination addr

- *remember (in NAT translation table)* every (source IP address, port #) to (NAT IP address, new port #) translation pair

- *incoming datagrams: replace* (NAT IP address, new port #) in dest fields of every incoming datagram with corresponding (source IP address, port #) stored in NAT table

IPv6 datagram format

- *motivations*
  - more IP addresses: 128-bit
  - speed processing/forwarding: fixed-length header, no fragmentation allowed, checksum removed
  - facilitate QoS



Chapter 4: outline

4.1 Overview of Network layer
- data plane
- control plane

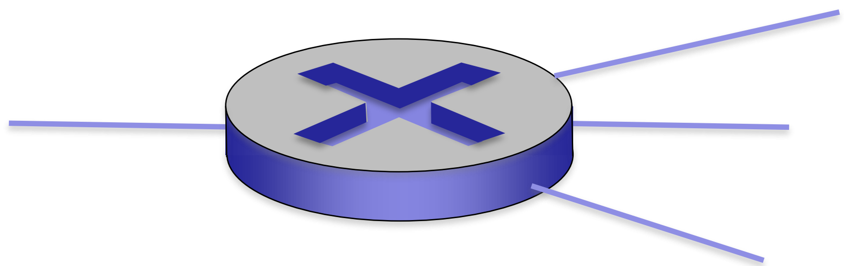
4.2 What's inside a router

4.3 IP: Internet Protocol
- datagram format
- fragmentation
- IPv4 addressing
- network address translation
- IPv6

4.4 Generalized Forward and SDN
- match
- action
- OpenFlow examples of match-plus-action in action

OpenFlow data plane abstraction

- *flow*: defined by header fields
- generalized forwarding: simple packet-handling rules
  - *Pattern:* match values in packet header fields
  - *Actions: for matched packet:* drop, forward, modify, matched packet or send matched packet to controller
  - *Priority*: disambiguate overlapping patterns
  - *Counters:* #bytes and #packets



* : wildcard

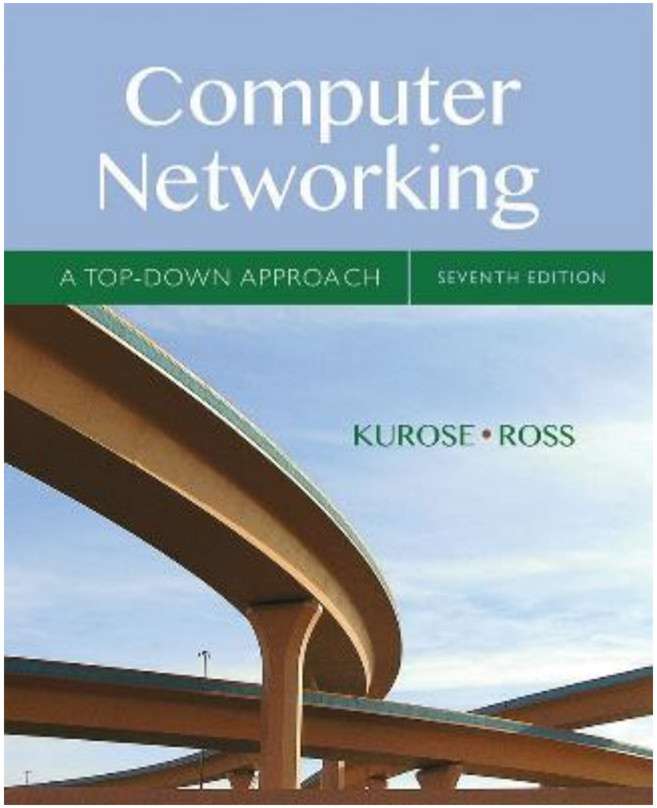
1. src=1.2.*.*, dest=3.4.5.* → drop
2. src = *.*.*.*, dest=3.4.*.* → forward(2)
3. src=10.1.2.3, dest=*.*.*.* → send to controller

OpenFlow abstraction

- *match+action:* unifies different kinds of devices

- Router
  - *match:* longest destination IP prefix
  - *action:* forward out a link
- Switch
  - *match:* destination MAC address
  - *action:* forward or flood
- Firewall
  - *match*: IP addresses and TCP/UDP port numbers
  - *action:* permit or deny
- NAT
  - *match:* IP address and port
  - *action:* rewrite address and port

Chapter 5
Network Layer:
The Control Plane



Computer Networking: A Top Down Approach

7th edition
Jim Kurose, Keith Ross
Pearson/Addison Wesley
April 2016

Slides adopted from original ones provided by the textbook authors.

Chapter 5: outline

5.1 introduction

5.2 routing protocols

- link state
- distance vector

5.3 intra-AS routing in the Internet: OSPF

5.4 routing among the ISPs: BGP

5.5 The SDN control plane

5.6 ICMP: The Internet Control Message Protocol

5.7 Network management and SNMP

Network-layer functions

Two approaches to structuring network control plane:

- per-router control (traditional)
- logically centralized control (software defined networking)

Chapter 5: outline

5.1 introduction

5.2 routing protocols

- link state
- distance vector

5.3 intra-AS routing in the Internet: OSPF

5.4 routing among the ISPs: BGP

5.5 The SDN control plane

5.6 ICMP: The Internet Control Message Protocol

5.7 Network management and SNMP

Dijsktra's algorithm

```
Initialization:
  N' = {u}
  for all nodes v
    if v adjacent to u
        then D(v) = c(u,v)
    else D(v) = ∞

Loop
   find w not in N' such that D(w) is a minimum
   add w to N'
   update D(v) for all v adjacent to w and not in N' :
      D(v) = min( D(v), D(w) + c(w,v) )
   /* new cost to v is either old cost to v or known
    shortest path cost to w plus cost from w to v */
until all nodes in N'
```

Distance vector algorithm

Bellman-Ford equation

$$d_x(y) = \min_v \{c(x,v) + d_v(y)\}$$

iterative, asynchronous: each local iteration caused by:

- local link cost change
- DV update message from neighbor

distributed:

- each node notifies neighbors *only* when its DV changes
  - neighbors then notify their neighbors if necessary

each node:

wait for (change in local link cost or msg from neighbor)

recompute estimates

if DV to any dest has changed, *notify* neighbors

Chapter 5: outline

5.1 introduction

5.2 routing protocols
- link state
- distance vector

5.3 intra-AS routing in the Internet: OSPF

5.4 routing among the ISPs: BGP

5.5 The SDN control plane

5.6 ICMP: The Internet Control Message Protocol

5.7 Network management and SNMP

Hierarchical routing

aggregate routers into regions known as "autonomous systems" (AS) (a.k.a. "domains")

intra-AS routing

- routing among hosts, routers in same AS ("network")
- all routers in AS must run *same* intra-domain protocol
- routers in *different* AS can run *different* intra-domain routing protocol
- gateway router: at "edge" of its own AS, has link(s) to router(s) in other AS'es

inter-AS routing

- routing among AS'es
- gateways perform inter-domain routing (as well as intra-domain routing)

OSPF (Open Shortest Path First)

- open protocol, based on Link State algorithm
- router floods OSPF link-state advertisements to all other routers in *entire* AS
- *security:* all OSPF messages authenticated
- ECMP: equal-cost multiple paths
- *two-level hierarchy:* local area, backbone

Chapter 5: outline

5.1 introduction

5.2 routing protocols

- link state
- distance vector

5.3 intra-AS routing in the Internet: OSPF

5.4 routing among the ISPs: BGP

5.5 The SDN control plane

5.6 ICMP: The Internet Control Message Protocol

5.7 Network management and SNMP

BGP (Border Gateway Protocol)

- two types of BGP (TCP) sessions
  - eBGP: between neighboring ASs
  - iBGP: inside same AS

- router may learn about more than 1 route to destination AS, selects route based on:
  1. local preference value attribute: policy decision
  2. shortest AS-PATH
  3. closest NEXT-HOP router: hot potato routing
  4. additional criteria

Chapter 5: outline

5.1 introduction

5.2 routing protocols

- link state
- distance vector

5.3 intra-AS routing in the Internet: OSPF

5.4 routing among the ISPs: BGP

5.5 The SDN control plane

5.6 ICMP: The Internet Control Message Protocol

5.7 Network management and SNMP

Software defined networking (SDN)

SDN: logically centralized control plane

- easier network management
- ability to program routers
- open implementation of control plane

Chapter 5: outline

5.1 introduction

5.2 routing protocols

- link state
- distance vector

5.3 intra-AS routing in the Internet: OSPF

5.4 routing among the ISPs: BGP

5.5 The SDN control plane

5.6 ICMP: The Internet Control Message Protocol

5.7 Network management and SNMP

ICMP: internet control message protocol

- used by hosts & routers to communicate network-level information
  - error reporting: unreachable host, network, port, protocol
  - echo request/reply (used by ping)
- network-layer "above" IP:
  - ICMP msgs carried in IP datagrams
- ICMP message: type, code plus first 8 bytes of IP datagram causing error

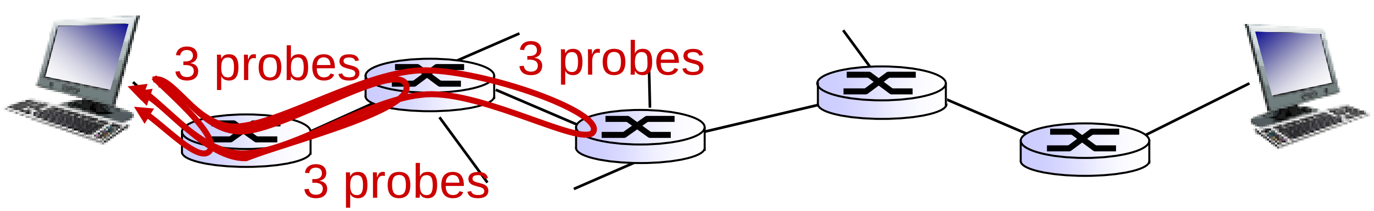
Type	Code	description
0	0	echo reply (ping)
3	0	dest. network unreachable
3	1	dest host unreachable
3	2	dest protocol unreachable
3	3	dest port unreachable
3	6	dest network unknown
3	7	dest host unknown
4	0	source quench (congestion control - not used)
8	0	echo request (ping)
9	0	route advertisement
10	0	router discovery
11	0	TTL expired
12	0	bad IP header

Traceroute and ICMP

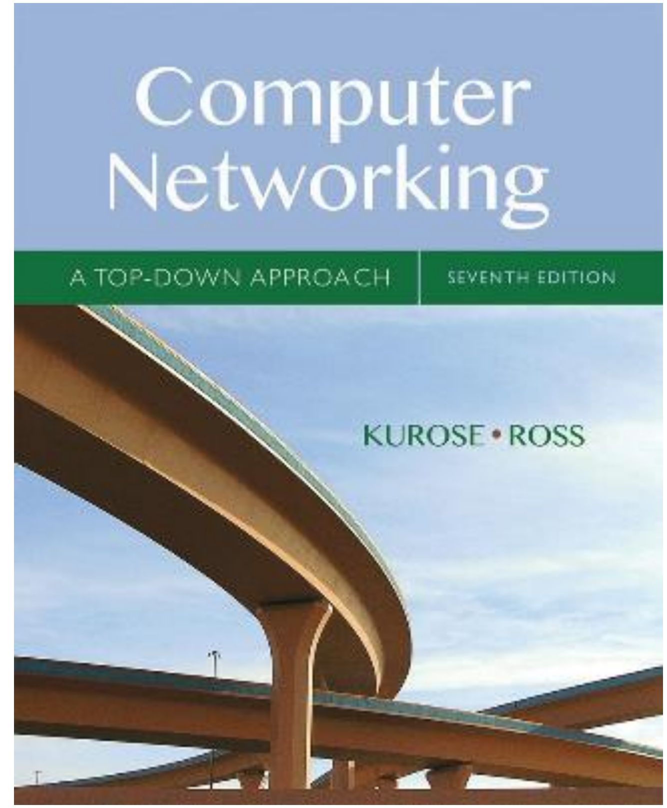
- source sends series of UDP segments to destination
  - first set has TTL =1
  - second set has TTL=2, etc.
  - unlikely port number
- when datagram in *n*th set arrives to nth router:
  - router discards datagram and sends source ICMP message (type 11, code 0)
  - ICMP message include name of router & IP address
- when ICMP message arrives, source records RTTs

stopping criteria:

- UDP segment eventually arrives at destination host
- destination returns ICMP "port unreachable" message (type 3, code 3)
- source stops



Chapter 6 The Link Layer and LANs



Computer Networking: A Top Down Approach

7th edition
Jim Kurose, Keith Ross
Pearson/Addison Wesley
April 2016

Slides adopted from original ones provided by the textbook authors.

Link layer, LANs: outline

6.1 introduction, services

6.2 error detection, correction

6.3 multiple access protocols

6.4 LANs
- addressing, ARP
- Ethernet
- switches
- VLANS

6.5 link virtualization: MPLS

6.6 data center networking

6.7 a day in the life of a web request

Link layer services

- *framing*
- *link access*
- *error detection and correction*

Link layer, LANs: outline

6.1 introduction, services

6.2 error detection, correction

6.3 multiple access protocols

6.4 LANs
- addressing, ARP
- Ethernet
- switches
- VLANS

6.5 link virtualization: MPLS

6.6 data center networking

6.7 a day in the life of a web request

CRC example

want:

$D \cdot 2^r$ XOR R = nG

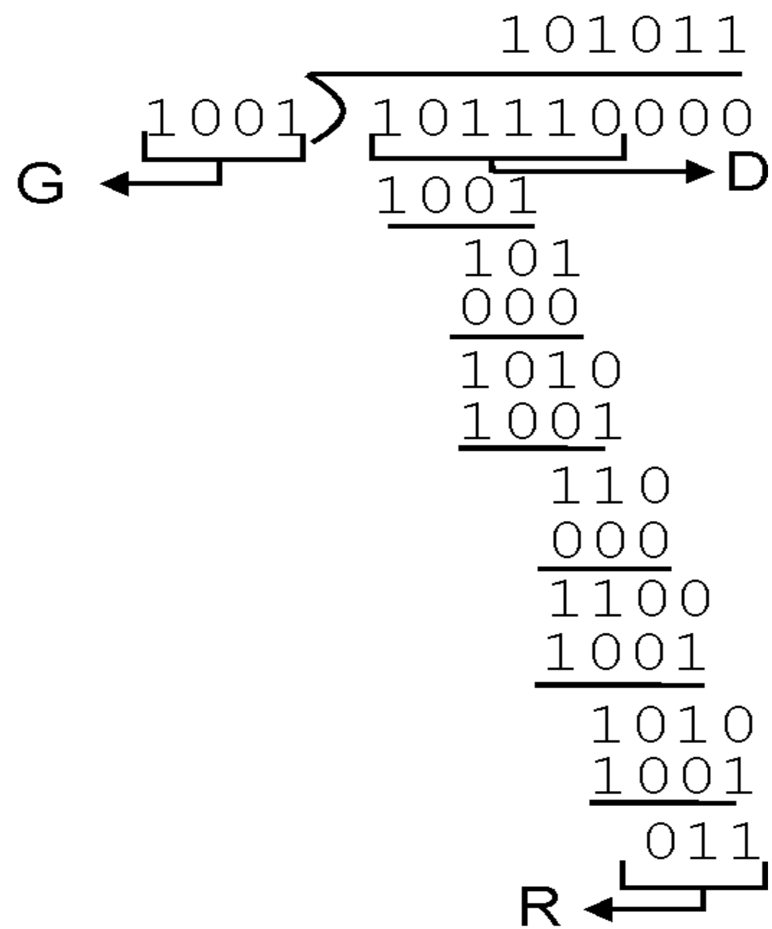
equivalently:

$D \cdot 2^r$ = nG XOR R

equivalently:

if we divide $D \cdot 2^r$ by G, want remainder R to satisfy:

$$R = remainder\left[\frac{D \cdot 2^r}{G}\right]$$



Link layer, LANs: outline

6.1 introduction, services

6.2 error detection, correction

6.3 multiple access protocols

6.4 LANs
- addressing, ARP
- Ethernet
- switches
- VLANS

6.5 link virtualization: MPLS

6.6 data center networking

6.7 a day in the life of a web request

Summary of MAC protocols

- *channel partitioning,* by time, frequency or code
  - Time Division
  - Frequency Division
  - Code Division
- *random access* (dynamic),
  - ALOHA, S-ALOHA
  - CSMA (carrier sensing): easy in some technologies (wire), hard in others (wireless)
  - CSMA/CD used in Ethernet
  - CSMA/CA used in Wi-Fi
- *taking turns*
  - polling from central site used in Bluetooth
  - token passing used in fiber optical, token ring

Link layer, LANs: outline

6.1 introduction, services

6.2 error detection, correction

6.3 multiple access protocols

6.4 LANs
- addressing, ARP
- Ethernet
- switches
- VLANS

6.5 link virtualization: MPLS

6.6 data center networking

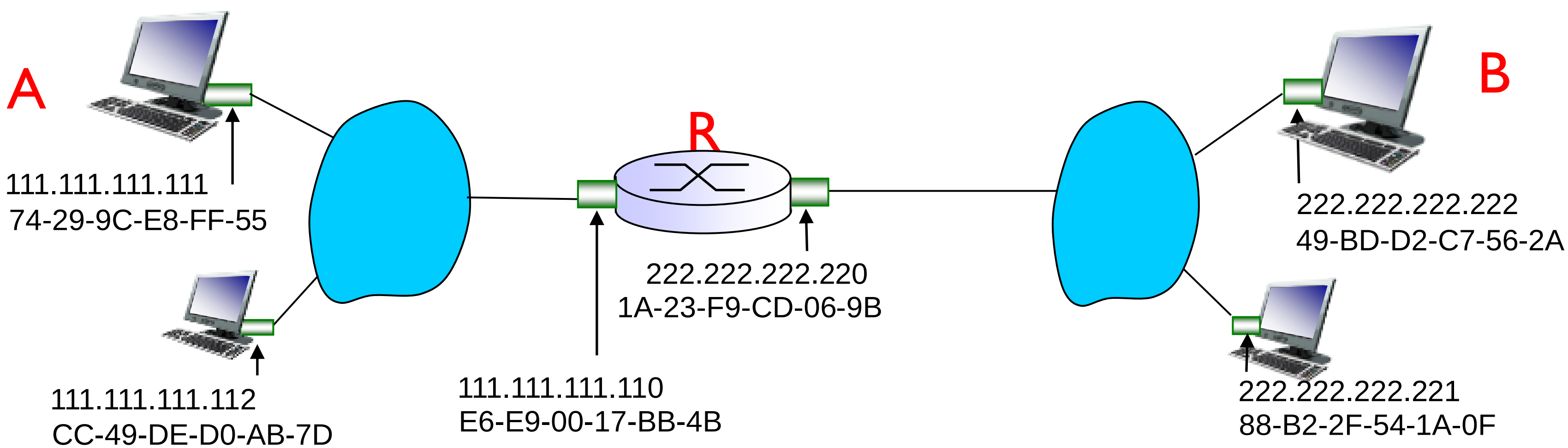
6.7 a day in the life of a web request

ARP: mapping IP to MAC

- A wants to send datagram to B
  - B's MAC address not in A's ARP table.
- A broadcasts ARP query packet, containing B's IP address
  - dest MAC address = FF-FF-FF-FF-FF-FF
  - all nodes on LAN receive ARP query
- B receives ARP packet, replies to A with its (B's) MAC address
  - frame sent to A's MAC address (unicast)
- A caches (saves) IP-to-MAC address pair in its ARP table until information becomes old (times out)
  - soft state: information that times out (goes away) unless refreshed
- ARP is "plug-and-play":
  - nodes create their ARP tables *without intervention from net administrator*

Addressing: routing to another LAN

- Destination IP in another LAN
  - Destination MAC is that of first hop router interface (aka default gateway)
- Destination IP in same LAN
  - Destination MAC is that of destination host



Link layer, LANs: outline

6.1 introduction, services

6.2 error detection, correction

6.3 multiple access protocols

6.4 LANs

- addressing, ARP
- Ethernet
- switches
- VLANS

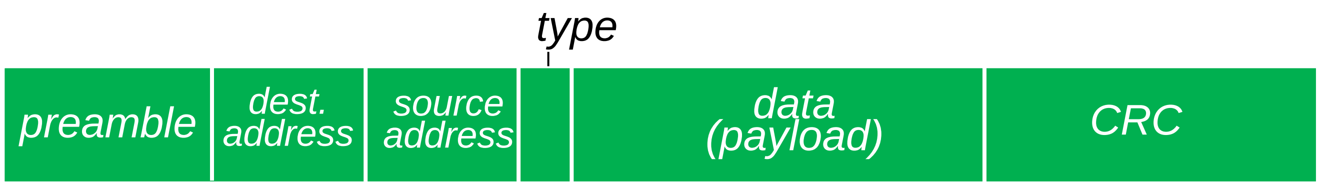
6.5 link virtualization: MPLS

6.6 data center networking

6.7 a day in the life of a web request

Ethernet

- Two topologies: bus, star
- frame structure: sending adapter encapsulates IP datagram (or other network layer protocol packet) in Ethernet frame



- features:
  - *Connectionless, Unreliable*
  - MAC protocol: unslotted *CSMA/CD wth binary backoff*

Link layer, LANs: outline

6.1 introduction, services

6.2 error detection, correction

6.3 multiple access protocols

6.4 LANs

- addressing, ARP
- Ethernet
- switches
- VLANS

6.5 link virtualization: MPLS

6.6 data center networking

6.7 a day in the life of a web request

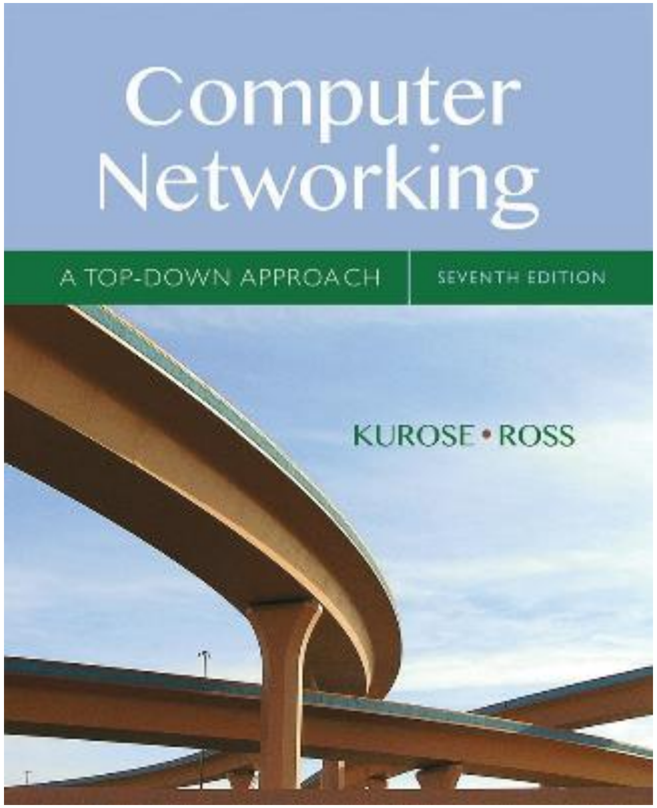
Ethernet switch

- link-layer device: takes an *active* role
  - store, forward Ethernet frames
  - examine incoming frame's MAC address, selectively forward frame to one-or-more outgoing links when frame is to be forwarded on segment, uses CSMA/CD to access segment
- *transparent*
  - hosts are unaware of presence of switches
- *plug-and-play, self-learning*
  - switches do not need to be configured

Switch: self-learning

- switch learns which hosts can be reached through which interfaces
  - when frame received, switch "learns" location of sender
  - records sender/location pair in switch table
- forwarding packet
  - frame destination unknown: flood
  - destination location known: selective send

Chapter 8 Security



Computer Networking: A Top Down Approach

7th edition
Jim Kurose, Keith Ross
Pearson/Addison Wesley
April 2016

Slides adopted from original ones provided by the textbook authors.

Chapter 8 roadmap

8.1 What is network security?
8.2 Principles of cryptography
8.3 Message integrity, authentication
8.4 Securing e-mail
8.5 Securing TCP connections: SSL
8.6 Network layer security: IPsec
8.7 Securing wireless LANs
8.8 Operational security: firewalls and IDS

What is network security?

confidentiality: only sender, intended receiver should "understand" message contents

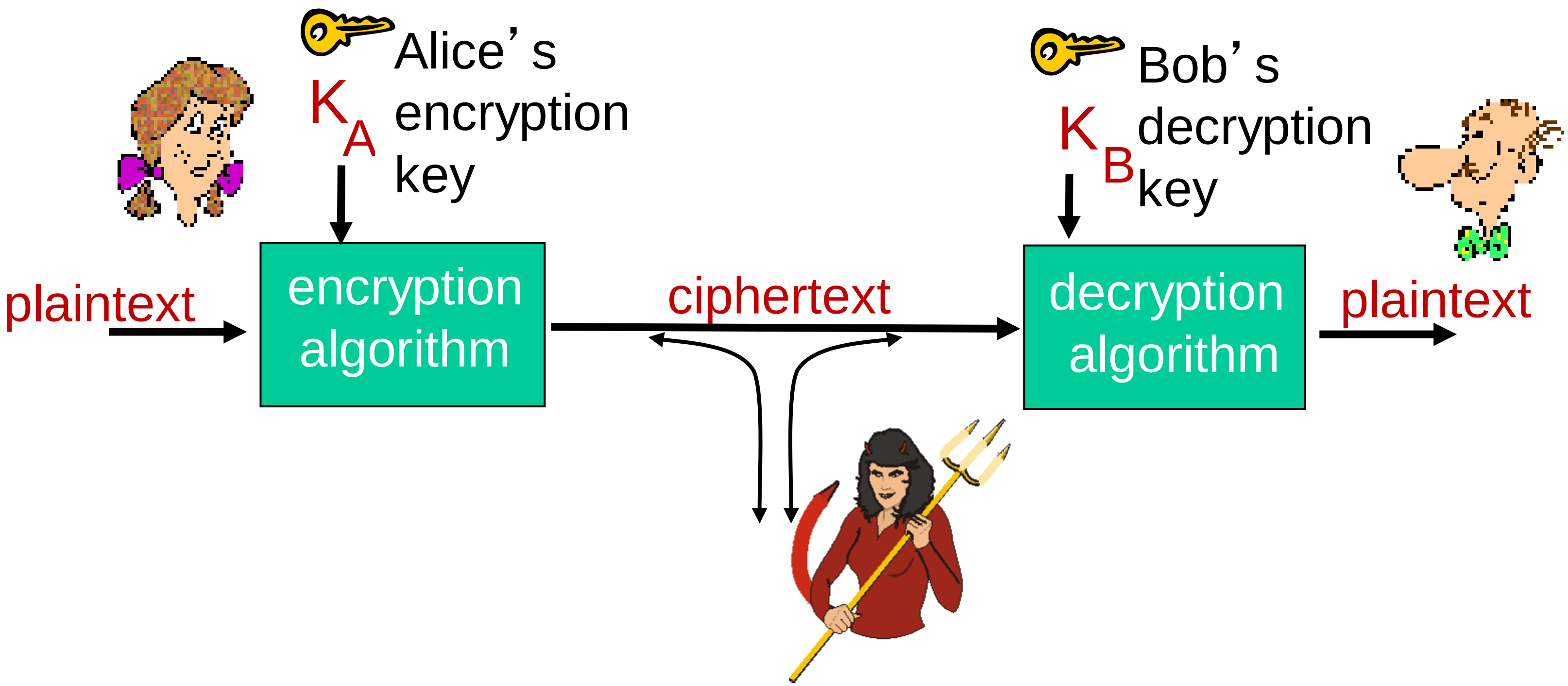
authentication: sender, receiver want to confirm identity of each other

message integrity: sender, receiver want to ensure message not altered (in transit, or afterwards) without detection

access and availability: services must be accessible and available to users

Chapter 8 roadmap

The language of cryptography



m plaintext message

$K_A(m)$ ciphertext, encrypted with key K_A

$m = K_B(K_A(m))$

Breaking an encryption scheme

- cipher-text only attack: Trudy has ciphertext she can analyze
  - brute force: search through all keys
  - statistical analysis
- known-plaintext attack: Trudy has plaintext corresponding to ciphertext
  - e.g., in monoalphabetic cipher, Trudy determines pairings for a,l,i,c,e,b,o,
- chosen-plaintext attack: Trudy can get ciphertext for chosen plaintext

Classical symmetric key cryptography

- symmetric: encryption key = decryption key
- Caesar cipher
  - only 26 keys
  - subject to brute force attack
- Monoalphabetic cipher
  - 26! keys, good enough
  - subject to cryptoanalysis based on language patterns
- Polyalphabetic cipher
  - n monoalphabetic ciphers, $M_1, M_2, \ldots, M_n$, used in cycling pattern
  - hiding language statistics

Modern symmetric key cryptography

- DES: Data Encryption Standard
  - 56-bit key, 64-bit block
  - short key length no longer secure
- AES: Advanced Encryption Standard
  - 128-bit block
  - flexible key length:128, 192, or 256 bits

Public Key Cryptography

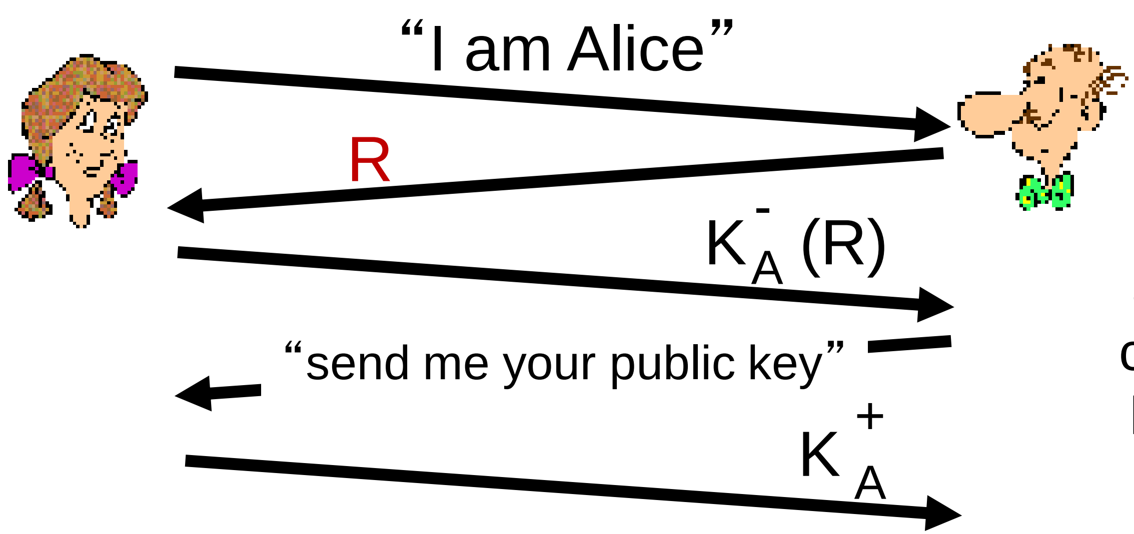
- asymmetric
  - public key known to any one
  - private key known to owner only
  - slow, used to distribute symmetric keys
- RSA
  - can be used for both encryption and signature

Chapter 8 roadmap

8.1 What is network security?
8.2 Principles of cryptography
8.3 Message integrity, *authentication*
8.4 Securing e-mail
8.5 Securing TCP connections: SSL
8.6 Network layer security: IPsec
8.7 Securing wireless LANs
8.8 Operational security: firewalls and IDS

Authentication: ap5.0

ap5.0: use nonce, public key cryptography



Bob computes

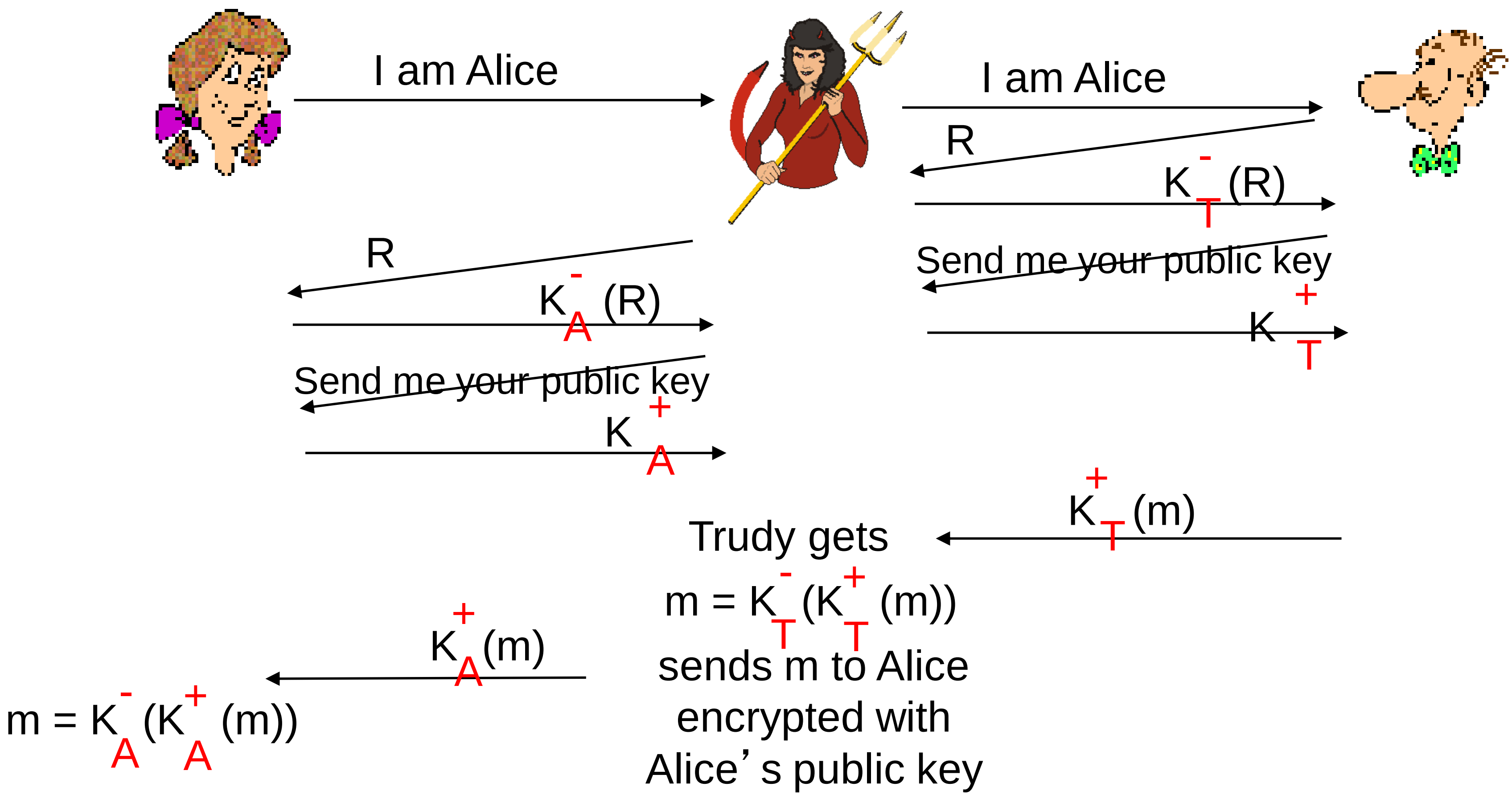
$$K_A^+(K_A^-(R)) = R$$

and knows only Alice could have the private key, that encrypted R such that

$$K_A^+(K_A^-(R)) = R$$

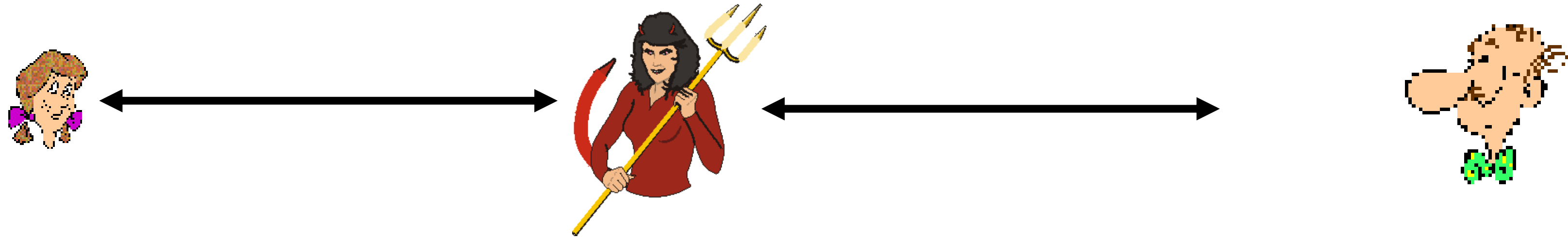
ap5.0: security hole

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



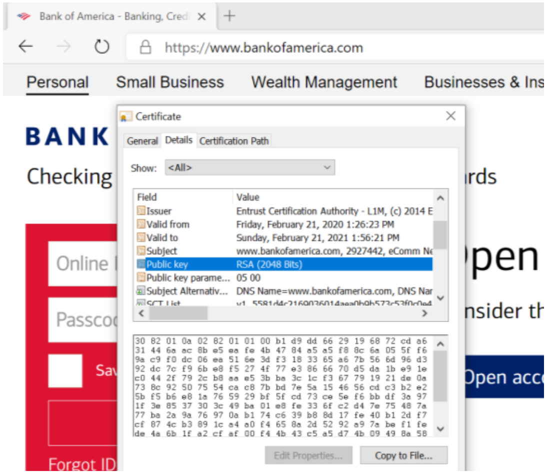
ap5.0: security hole

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

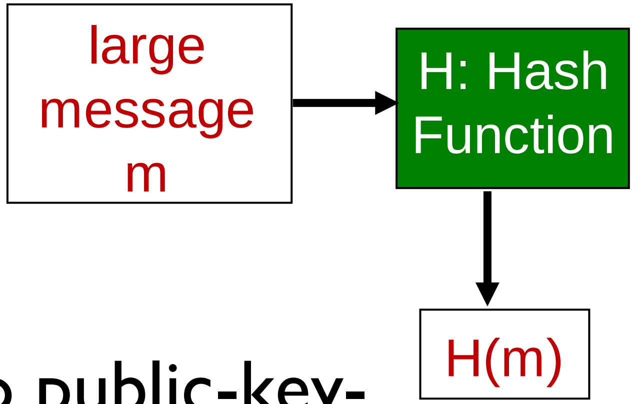


use digital certificate to assure identity

e.g. BoA's certificate proving website authenticity



Message digests



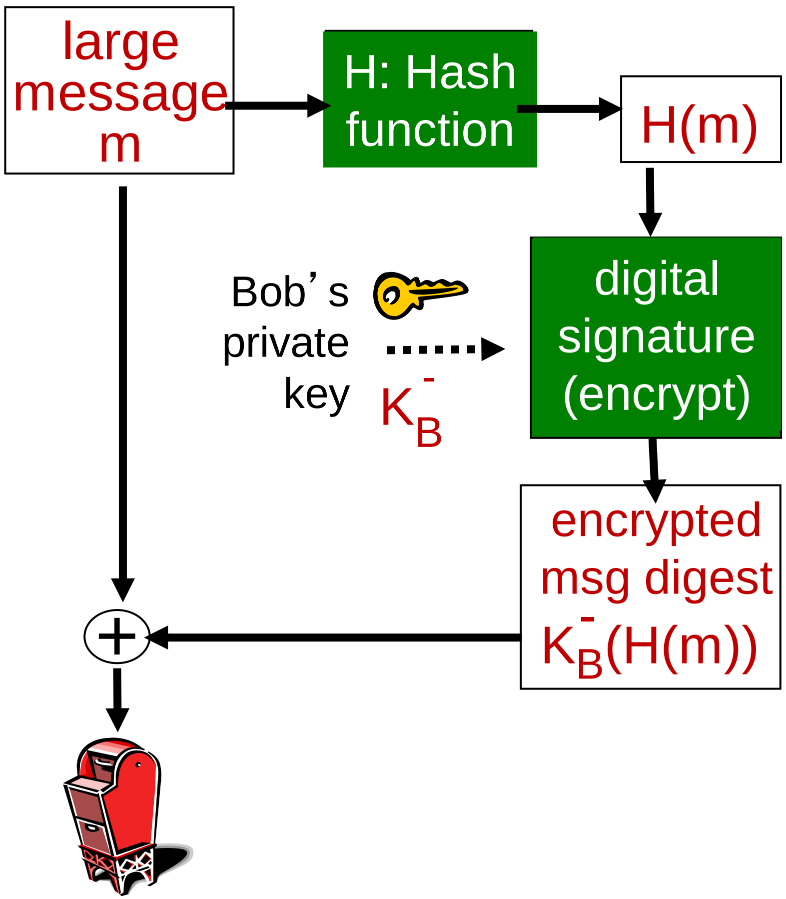
computationally expensive to public-key-encrypt long messages

goal: fixed-length, easy- to-compute digital "fingerprint"

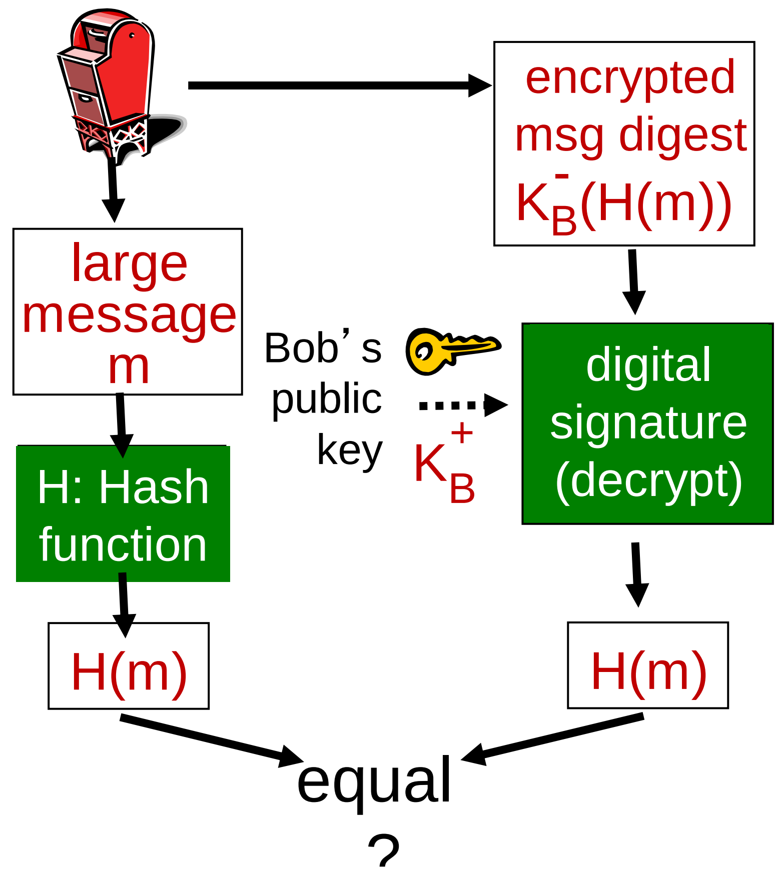
- apply hash function H to *m*, get fixed size message digest, *H(m)*.
- MD5, SHA-1

Digital signature = signed message digest

Bob sends digitally signed message:

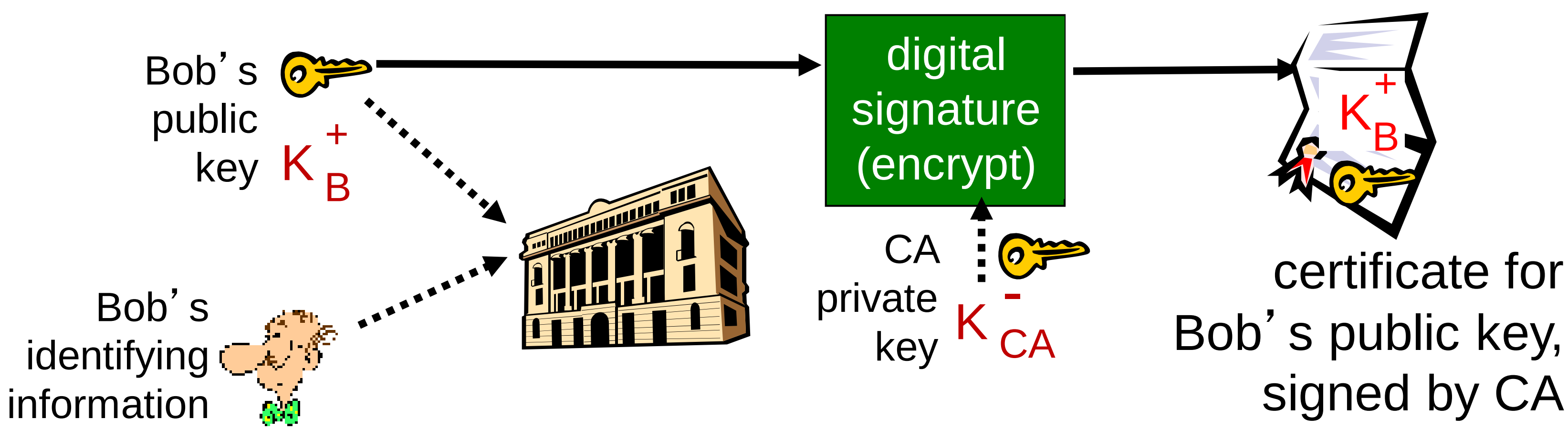


Alice verifies signature, integrity of digitally signed message:



Digital certificate

- *certification authority (CA):* binds public key to particular entity, E.
- E (person, router) registers its public key with CA.
  - E provides "proof of identity" to CA.
  - CA creates certificate binding E to its public key.
  - certificate containing E's public key digitally signed by CA – CA says "this is E's public key"



Chapter 8 roadmap

Secure e-mail

- Confidentiality and/or signature

- Pretty Good Privacy (PGP), secure email encryption scheme

Chapter 8 roadmap

8.1 What is network security?
8.2 Principles of cryptography
8.3 Message integrity
8.4 Securing e-mail
8.5 Securing TCP connections: SSL
8.6 Network layer security: IPsec
8.7 Securing wireless LANs
8.8 Operational security: firewalls and IDS

SSL: Secure Sockets Layer

- Transport layer security service
- available to all TCP applications
- services provided
  - *confidentiality*
  - *integrity*
  - *authentication*

Chapter 8 roadmap

IPsec

- protect all traffic above IP
  - data integrity
  - origin authentication
  - replay attack prevention
  - confidentiality
- two operation modes
  - transport mode
  - tunnel mode
- two service models:
  - AH
  - ESP

Chapter 8 roadmap

8.1 What is network security?
8.2 Principles of cryptography
8.3 Message integrity
8.4 Securing e-mail
8.5 Securing TCP connections: SSL
8.6 Network layer security: IPsec
8.7 Securing wireless LANs
8.8 Operational security: firewalls and IDS

Wi-Fi security

- WEP
  - Not secure due to use of stream cipher
- 802.11i
  - stronger encryption
  - key distribution
  - separate authentication server

Chapter 8 roadmap

Firewalls types

- stateless packet filters
  - admit/deny packets based on header fields
- stateful packet filters
  - add history information, i.e., previous packets
- application gateways
  - utilize detail in application layer protocols