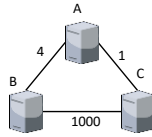
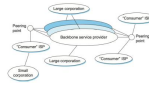


Computer Networks X_400487

Lecture 5

Chapter 5: The Network Layer—Part 1



Lecturer: Jesse Donkervliet



Vrije Universiteit Amsterdam

Roadmap of the Computer Networks Course

Lets distributed applications communicate

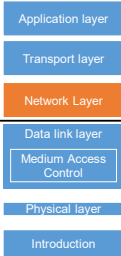
Sends segments from one **process** to another within and across networks

Sends packets from one **machine** to another within and across networks

Sends frames from one machine to another over a single link / local network

Sends bits over a physical medium

Basic principles and course overview



You are here

Midterm

2

Recap Data Link Layer

Data link layer (partially) answers the following questions:

1. How create frames from bits/bytes?
2. How to detect/correct transmission errors?
3. How to efficiently multiplex frames from multiple stations over a single channel? MAC sublayer Q: What kind of efficiency?



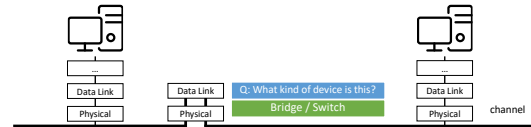
channel

3

Recap Data Link Layer

Data link layer (partially) answers the following questions:

1. How create frames from bits/bytes?
2. How to detect/correct transmission errors?
3. How to efficiently multiplex frames from multiple stations over a single channel? MAC sublayer Q: What kind of efficiency?



channel

4



Image source: NASA

5

What Else Do We Need?

Data link layer not enough for a world-wide *internet* (=network of networks)

1. Switches not built for large networks (e.g., hash table size) Hashmap of all addresses requires very large memory. Searching memory reduces performance
2. Protocols tailored to physical medium: bad idea to use one such protocol for all types of networks

Q: How to solve this?

Add new layer of abstraction: the Network Layer

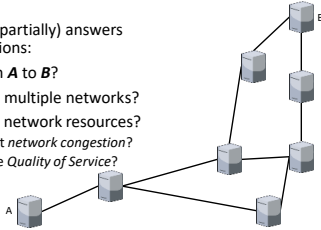
6

The Network Layer

Lowest layer concerned with "end-to-end" delivery

The network layer (partially) answers the following questions:

1. How to get from **A** to **B**?
2. How to connect multiple networks?
3. How to manage network resources?
 1. How to prevent *network congestion*?
 2. How to provide *Quality of Service*?

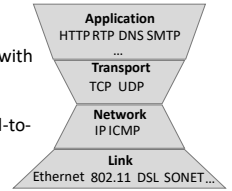


The Network Layer

TCP/IP form the "narrow waist" of the Internet

Heart of the networking model, together with the transport layer (next week)

1. Layers below it do not know about end-to-end delivery
2. Layers above it do not know about the topology of the network
3. Both layers above and below do not know about routing

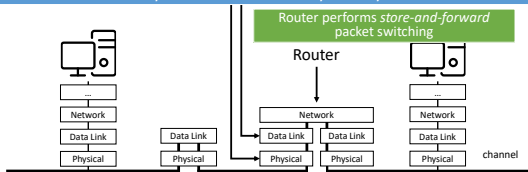


*Although switching is similar to routing...

The Network Layer

Network layer provides new features through *new protocols* and a *new device* (the router)

Q: Why have Data Link and Physical Layer twice?



The Network Layer

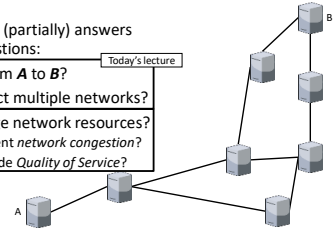
Lowest layer concerned with "end-to-end" delivery

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 1. How to prevent *network congestion*?
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Next lecture

Today's lecture



Today's Lecture

1. Routing Algorithms
2. Internetworking

Routing

Finding a path through a network



Important Properties for Routing

1. Correctness
2. Simplicity
3. Robustness
4. Stability
5. Fairness
6. Efficiency

These properties can (and often do) conflict with each other.



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How to find a route?

We will look at three key ideas:

1. Distance vector routing
2. Link state routing
3. Hierarchical routing

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Routing tables

For each packet, we need to know on which link to forward it.
For this we use a routing table

We are directly connected to A
station C

Routing table for C.			
To	Distance	Line	
A	7	A	
B	59	A	
C	0	-	
D	75	E	

If packet should go to D, minimum distance is 75. Forward to E

17

Routing tables

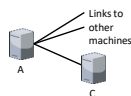
For each packet, we need to know on which link to forward it.
For this we use a routing table

We are indirectly connected to B

Routing table for C.			
To	Distance	Line	
A	7	A	
B	59	A	
C	0	-	
D	75	E	
E	1	E	
F	103	E	

18

Distance Vector Routing



1. Send your *distance vector* to your neighbors
2. Update your *routing table* based on incoming *distance vectors*

Distance from A to B is 1

Distance from C to A is 7

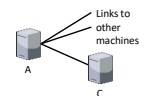
To	Distance	Line
A	7	A
B	59	A
C	0	-
D	75	E
E	1	E
F	103	E

Distance vector A: A, 0; B, 1; C, 7; D, 152; E, 8; F, 110

Q: How to update our routing table?

19

Distance Vector Routing



1. Send your *distance vector* to your neighbors
2. Update your *routing table* based on incoming *distance vectors*

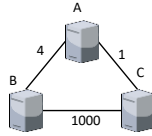
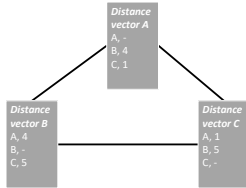
Distance vector A: A, 0; B, 1; C, 7; D, 152; E, 8; F, 110

Routing table for C.			
To	Distance	Line	
A	7	A	
B	59 → 8	A	
C	0	-	
D			
E			
F			

Q: What can go wrong when using this algorithm?

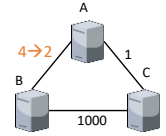
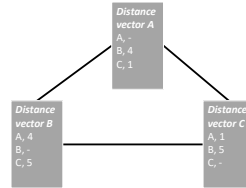
20

Distance Vector Routing Good News Propagation



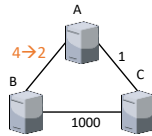
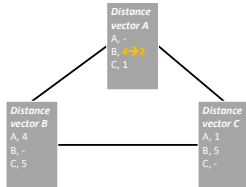
21

Distance Vector Routing Good News Propagation



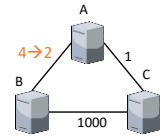
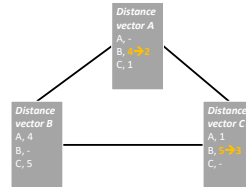
22

Distance Vector Routing Good News Propagation



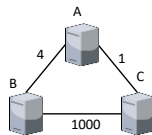
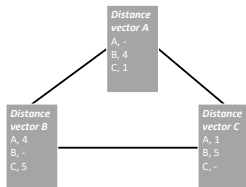
23

Distance Vector Routing Good News Propagation



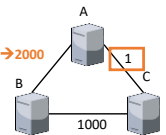
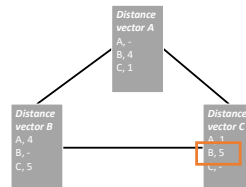
24

Distance Vector Routing Bad News Propagation



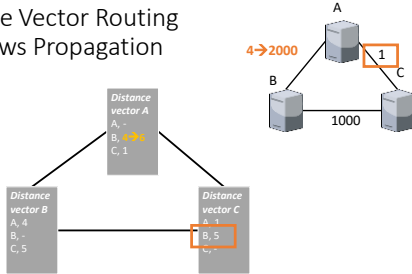
25

Distance Vector Routing Bad News Propagation



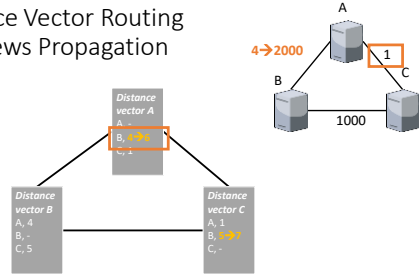
26

Distance Vector Routing
Bad News Propagation



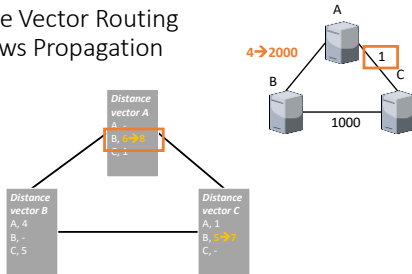
27

Distance Vector Routing
Bad News Propagation



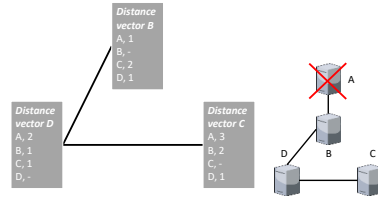
28

Distance Vector Routing
Bad News Propagation



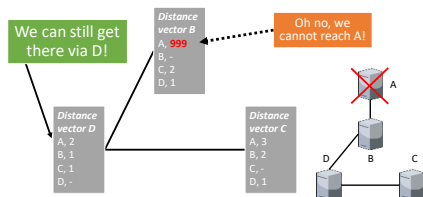
29

Count to infinity problem
When machine fails



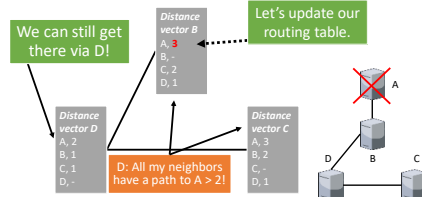
30

Count to infinity problem
When machine fails



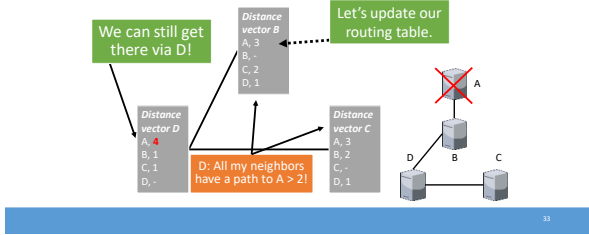
31

Count to infinity problem
When machine fails

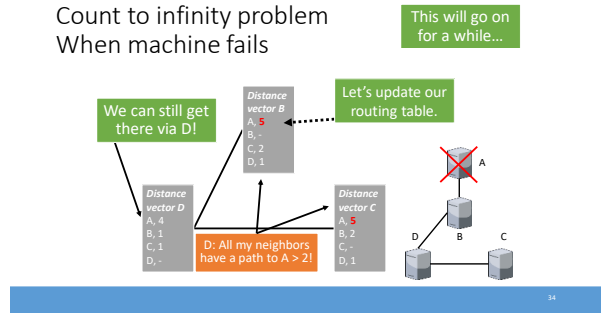


32

Count to infinity problem
When machine fails



Count to infinity problem
When machine fails



Link state routing

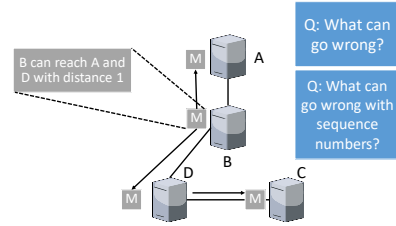
Replaced distance vector routing in ARPANET in 1979

Does not suffer from the *count to infinity problem*, but is more complex

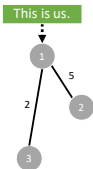
Uses a *shortest path algorithm*

1. Routers only send packets with information about their direct neighbors
2. These packets are *flooded* over the network
3. Routers built an overview of the network using these packets and run a shortest path algorithm

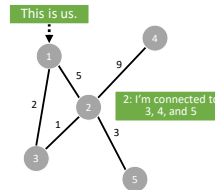
Flooding link state packets



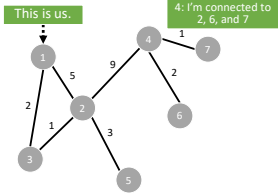
Link state routing
Building a map of the network



Link state routing
Building a map of the network

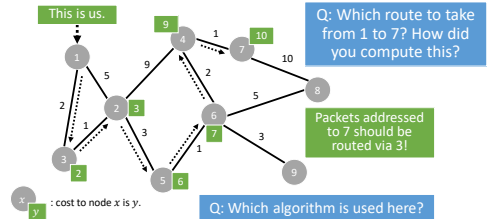


Link state routing
Building a map of the network



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Link state routing
Building a map of the network

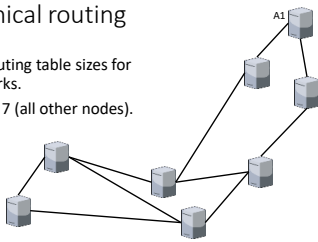


Q: Which algorithm is used here?

40

Hierarchical routing

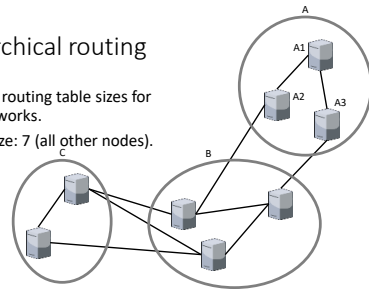
Reducing routing table sizes for large networks.
A1's RT size: 7 (all other nodes).



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Hierarchical routing

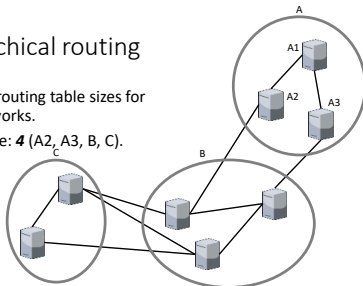
Reducing routing table sizes for large networks.
A1's RT size: 7 (all other nodes).



42

Hierarchical routing

Reducing routing table sizes for large networks.
A1's RT size: 4 (A2, A3, B, C).



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Today's Lecture

1. Routing Algorithms
2. **Internetworking**
 1. Routing in and between Autonomous Systems: OSPF and BGP
 2. Tunneling
 3. Packet fragmentation

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Q: Difference between a single network and a collection of networks?

Internetworking

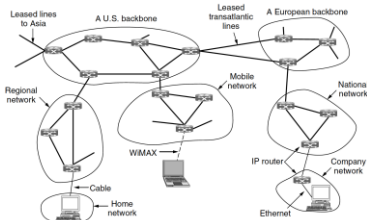
Getting packets to their destination across multiple networks

Internetworking

Challenges for sending packets end-to-end over multiple networks:

1. Technological
 - Different protocols
 - Different maximum packet sizes
 - Different QoS guarantees
2. Political
 - Different costs
 - Privacy concerns
 - Competition/disputes

Structure of the Internet: A Network of Networks

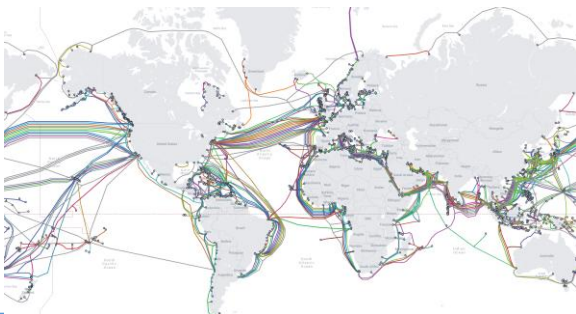


Tanenbaum, Andrew S., and David J. Wetherall. "Computer networks 5th edition." In Pearson Education, Inc. Prentice Hall, 2011.

We've almost come full circle: A Hierarchical Topology

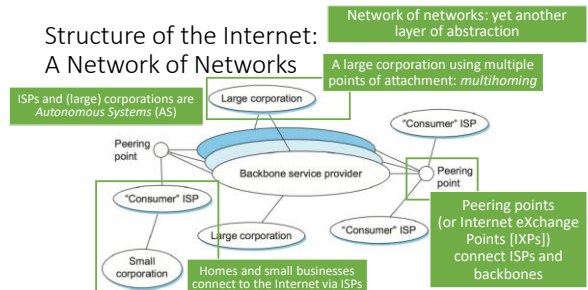


Source: <https://arstechnica.com/information-technology/2014/02/internet-outages-hit-42-dominic-re-efice-dot-tel-and-6-africa-continues/>



Source: <http://www.submarinecables.com/>

Structure of the Internet: A Network of Networks



Peterson, Larry L., and Bruce S. Davie. "Computer networks: a systems approach." Elsevier, 2012.

Internetworking with Autonomous Systems

Involves two key ideas:

1. Routing **inside** an Autonomous System
 - Intradomain routing. Uses an **Interior Gateway Protocol**
We will look at the **Open Shortest Path First (OSPF)** protocol
2. Routing **between** Autonomous Systems
 - Interdomain routing. Uses an **Exterior Gateway Protocol**
We will look at the **Border Gateway Protocol (BGP)**

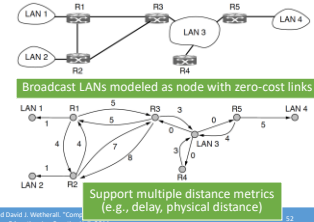
51

Example of an Interior Gateway Protocol Open Shortest Path First (OSPF)

Routing **within** an Autonomous System.

Uses a form of **link state routing**

Builds a graph representation of the network

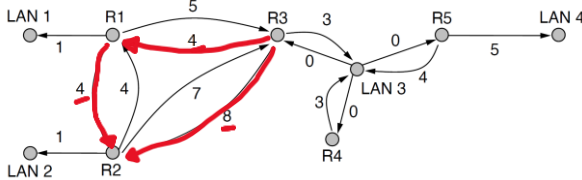


Tanenbaum, Andrew S., and David J. Wetherall. "Computer networks 5th edition." In Pearson Education, Inc. Prentice Hall, 2003.

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Example of an Interior Gateway Protocol Open Shortest Path First (OSPF)

Finds all shortest paths. Uses **Equal Cost MultiPath (ECMP)**: traffic distributed over shortest paths. Example: traffic from R3 to LAN 2



Tanenbaum, Andrew S., and David J. Wetherall. "Computer networks 5th edition." In Pearson Education, Inc. Prentice Hall, 2003.

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OSPF Message Types

Message type	Description
Hello	Used to discover who the neighbors are
Link state update	Provides the sender's costs to its neighbors
Link state ack	Acknowledges link state update
Database description	Announces which updates the sender has
Link state request	Requests information from the partner

OSPF messages are exchanged between routers; are wrapped in IP packets

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Example of an Interior Gateway Protocol Open Shortest Path First (OSPF)

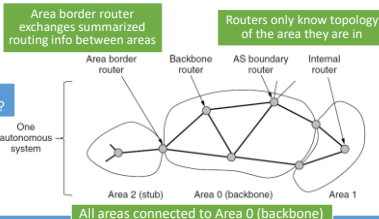
Routing **within** an Autonomous System.

Boundary routers connect to another AS. Uses both an Interior and Exterior Gateway Protocol

Uses a **hierarchy** called "areas" to manage large networks

Q: Why support hierarchical routing?

For destinations not in area: go through backbone



All areas connected to Area 0 (backbone)

Tanenbaum, Andrew S., and David J. Wetherall. "Computer networks 5th edition." In Pearson Education, Inc. Prentice Hall, 2003.

55

Example of an Exterior Gateway Protocol Border Gateway Protocol (BGP)

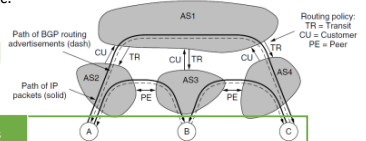
Routing **between** (large) independent networks.

Q: Can you think of examples of such policies?

Supports arbitrary policies put in place by ISPs, companies, organizations, etc.

AS1 provides transit service

Autonomous Systems connect at IXPs



Stub networks do not need BGP: only one way to send outgoing packets

Tanenbaum, Andrew S., and David J. Wetherall. "Computer networks 5th edition." In Pearson Education, Inc. Prentice Hall, 2003.

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Example of an Exterior Gateway Protocol

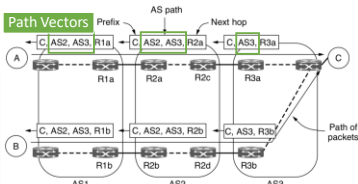
Border Gateway Protocol (BGP)

Routing *between* (large) independent networks.

Uses a **path vector protocol** (form of **distance vector routing**)

Q: A, B, C? How are autonomous systems identified in practice in BGP?

AS identified by address prefix e.g., A is all IP addresses starting with 123



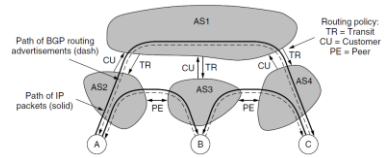
Tanenbaum, Andrew S., and David J. Wetherall. "Computer networks 5th edition." In Pearson Education, Inc. Prentice Hall, 2011.

Border Gateway Protocol (BGP)

Routing based on policies

Examples:

1. Peer above transit
2. Hot potato routing
3. Shortest AS path



Connecting Networks with Different Protocols

If source and destination networks use different protocols, they cannot communicate.

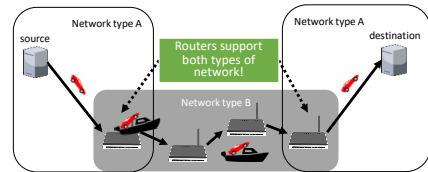


Tunneling

Used to route IPv6 packets over IPv4 networks

Q: Can you name a (dis)advantage?

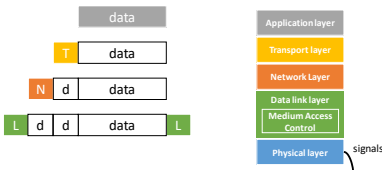
If an intermediate network uses different protocols, they can communicate by tunneling.



Business as usual

Packets in packets in packets in ...

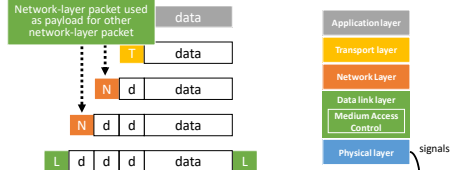
Data wrapped in headers from multiple networking layers.



Tunneling

Packets in packets in packets in ...

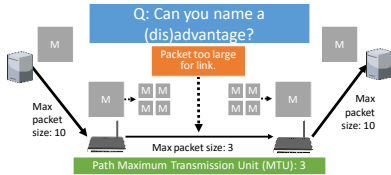
Data wrapped in headers from multiple networking layers.



Packet fragmentation Transparent fragmentation

Q: What can cause packet size limits?

Packet size can be limited by hardware, software, protocols, law, etc.

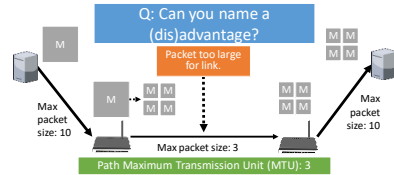


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Packet fragmentation Nontransparent fragmentation

Used in IP!

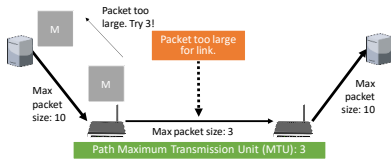
Packet size can be limited by hardware, software, protocols, law, etc.



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Avoiding packet fragmentation MTU discovery

Packet size can be limited by hardware, software, protocols, law, etc.

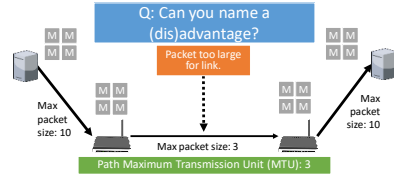


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Avoiding packet fragmentation MTU discovery

Used in IP!

Packet size can be limited by hardware, software, protocols, law, etc.



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Extra Slide(s)

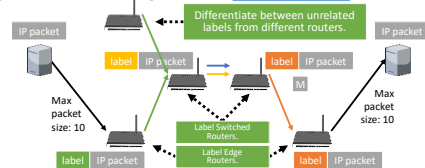
69

MultiProtocol Label Switching (MPLS)

Q: Why replace the labels at each hop?

Supports multiple networks protocols

Simplifies decision making at routers Q: Why useful?



70