II. Algorithms of the Internet

1. Routing and Packet Forwarding: Shortest Paths and Autonomous Systems

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Overview

Overview

ARPANET

- Origin of the Internet: ARPANET = **A**dvanced **R**esearch **P**roject **A**gency **Net**work (60s)
  $\Rightarrow$ Barely known in public
- Today: Internet links millions of computers

Overview

Overview over the Layers of the Internet

Application Layer	Peer-to-Peer-networks, e.g. Telnet = Telecommunication Network FTP = File Transfer Protocol HTTP = Hypertext Transfer Protocol SMTP = Simple Mail Transfer Protocol
Transport Layer	TCP = Transmission Control Protocol UDP = User Datagram Protocol
Internet Layer	IP = Internet Protocol ICMP = Internet Control Message Protocol IGMP = Internet Group Management Protocol
Host-to-Network Layer or Link Layer	device drivers (e.g. Ethernet or Token Ring drivers)

Data Encapsulation

Figure: onion-like structure of data encapsulation

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Data Encapsulation

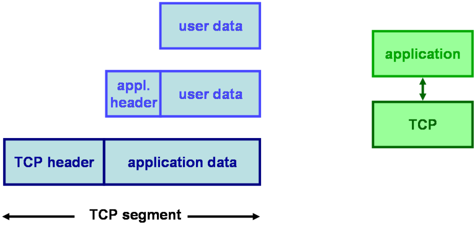

Figure: onion-like structure of dataencapsulation

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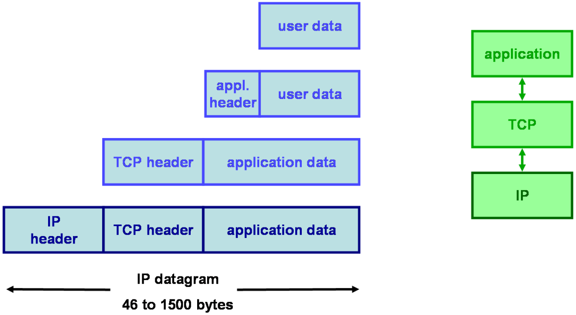

Figure: onion-like structure of dataencapsulation

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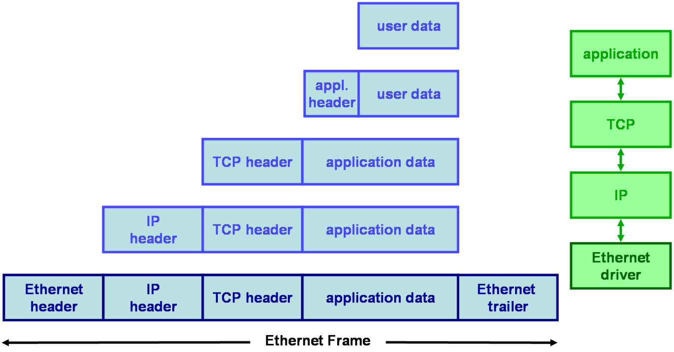

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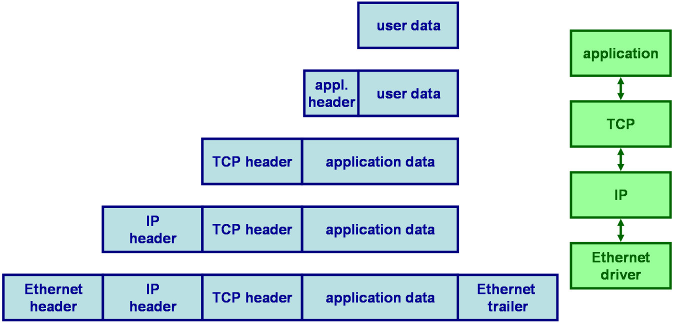


Figure: onion-like structure of dataencapsulation

IPv4

- Two subprotocols: ICMP and IGMP
- Task: transmit datagrams
- Unreliable (simple troubleshooting)
- Connectionless protocol

IPv4 Header

```
 IP Header Format
 0                   1                   2                   3
 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1 2 3 4 5 6 7 8 9 0 1
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|Version|  IHL  |Type of Service|          Total Length         |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|         Identification        |Flags|      Fragment Offset    |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|  Time to Live |    Protocol   |         Header Checksum       |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                       Source Address                          |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                    Destination Address                        |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                    Options                    |    Padding    |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

Figure: IPv4 Header

IPv4 Addresses and DNS

- 32-bit-addresses, e.g. 65.114.4.69.
- Until 1993:
  - Host-ID: identification number for a computer (assigned by network administrator)
  - Net-ID: network address (assigned by the Internet Network Information Center)
- Since 1993: CIDR = Classless Inter-Domain Routing
  - Variable splitting of IP address
  - Subnetmask

    IP-Address: `10000100.11100110.10010110.11110011`

    Subnetmask: `11111111.11111111.11111111.00000000`
- DNS = Domain Name System

Overview

Packet Forwarding

- Routing tables to determine the next vertex
- IP refers to the interface of a computer
  - Destination address = interface's IP ⇒ Delivery to transport layer
  - Destination address = other IP of routing table ⇒ Packet is forwarded
  - None of the above cases: default gateway
- TTL entry
  - Forwarding decreases this entry by one
  - If the entry is 0: ICMP-message
  - Prevents infinte packet forwarding

Overview

Routing

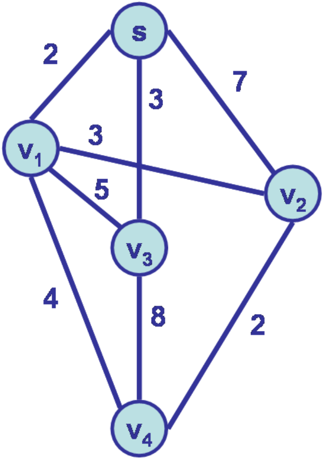
- Static routing: routing tables are created manually
  $\Rightarrow$Only for small networks
- Dynamical routing: routing-tables are created automatically
  protocols: RIP, OSPF
- Constant way

Let $G = (V, E)$ be a weighted graph containing a starting vertex $s \in V$ and weights $w_e \in \mathbb{R}_0^+$ for all edges $e \in E$. Searched are all paths from the starting vertex to all other vertices, which have the least sum of weights.

Overview

Dijktra’s Algorithm

Shortest Path Tree



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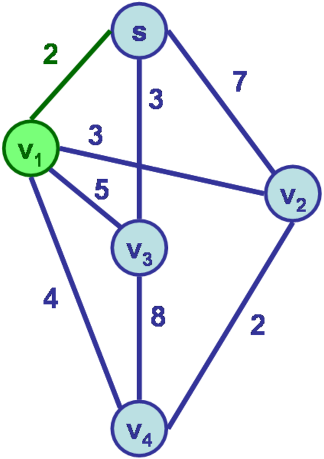
Shortest Path Tree



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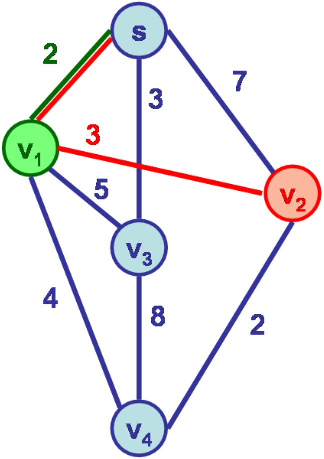

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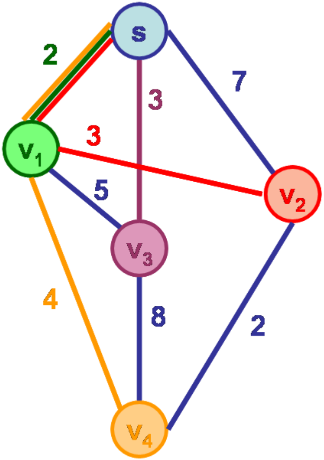
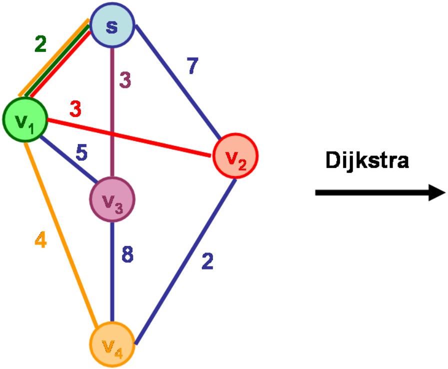
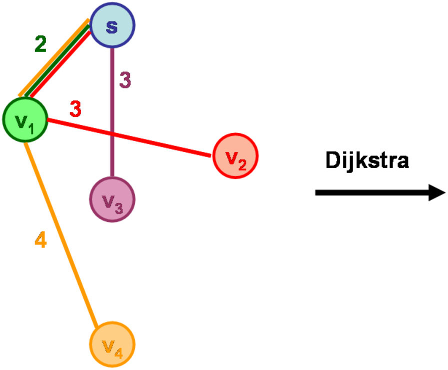




Vertex	Predecessor
v_1	s
v_2	v_1
v_3	s
v_4	v_1



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Dijkstra's Algorithm

- Result: Table of predecessors with edges of shortest-path-tree (Predecessor(u), u)
- Shortest-Path-Tree is built gradually
- Greedy algorithm
- One step: add the vertex with the shortest distance to the starting vertex s
- Similar to breadth-first search

Dijkstra's Algorithm

Input: $G = (V, E)$, $s \in V$, $w : E \rightarrow \mathbb{R}_0^+$

for all $v \in V$ **do**

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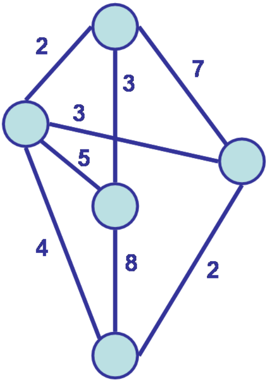

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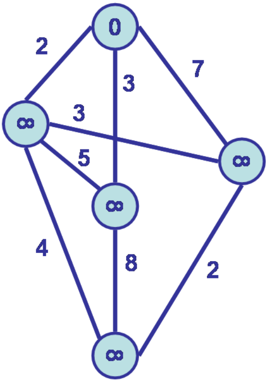

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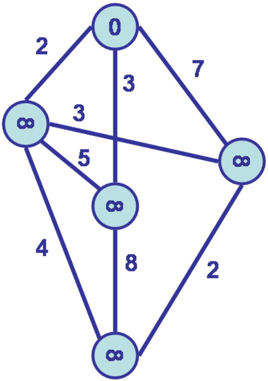

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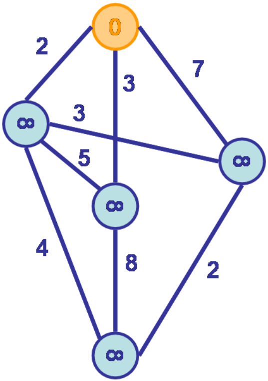

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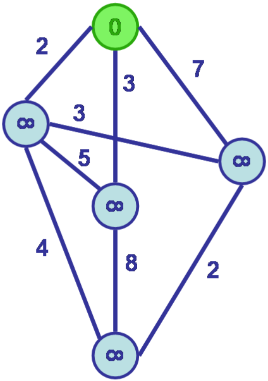

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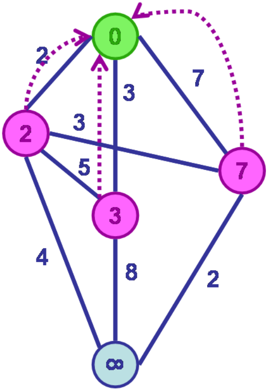

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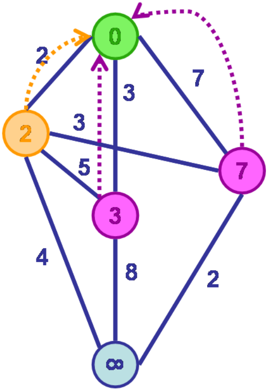

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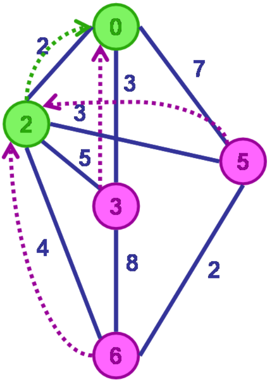

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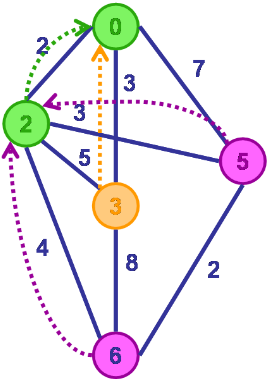

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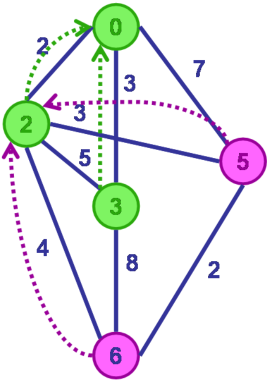

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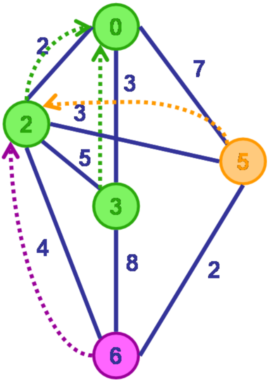

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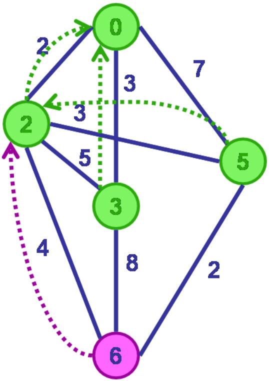

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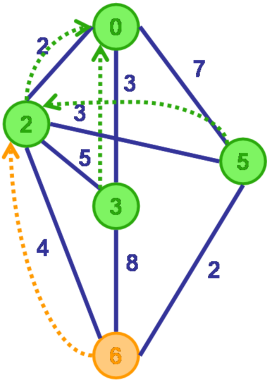

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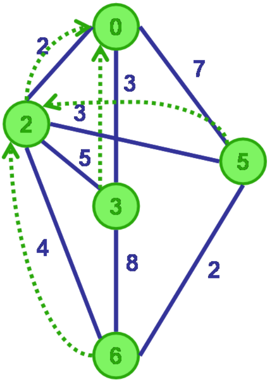

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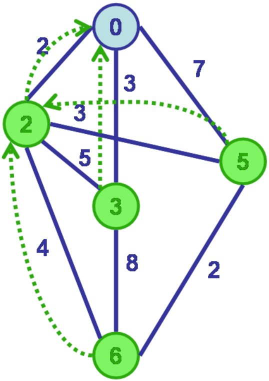
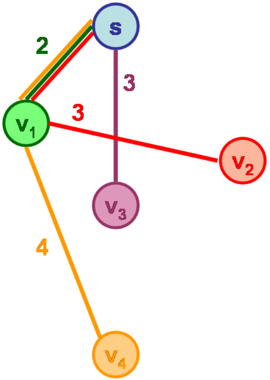
      Distance$[v] \leftarrow$ Distance$[u] + w_{(u,v)}$

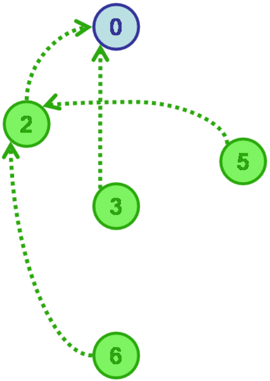
      Predecessor$[v] \leftarrow u$

return $\{(\text{Predecessor}(u), u) | u \in V \text{ and } u \neq \text{Predecessor}(u)\}$



Dijkstra's Algorithm
Example





Overview

Link-State-Routing

- Practical realization of Dijkstra’s Algorithm
- Every vertex needs to know all connections of the network
- Broadcast: spreading connection information through the network
- Low costs for communication in a running state

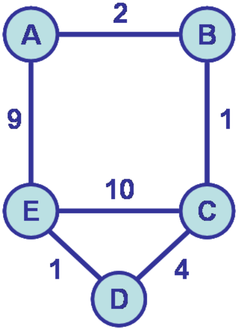
Distance-Vector-Routing

Distance Table for A

from A	over B	E	Routing Table Entry
to B	2	15	B
C	3	19	B
D	7	10	B
E	13	9	E

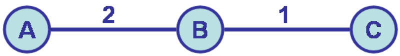
Distance Table for C

from C	over B	D	E	Routing Table Entry
to A	3	14	18	B
B	1	9	16	B
D	6	4	11	D
E	7	5	10	D



Distance-Vector-Routing

Count-to-Infinity-Problem



Distance Table for A

from A	over B	Routing Table Entry
to B	2	B
C	3	B

Distance Table for B

from B	over A	over C	Routing Table Entry
to A	2	4	A
C	5	1	C

Distance Table for A

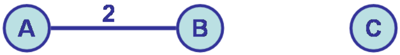
from A	over B	Routing Table Entry
to B	2	B
C	3	B

Distance Table for B

from B	over A	C	Routing Table Entry
to A	2	4	A
C	5	1	C

from A	over B	Routing Table Entry
to B	2	B
C	3	B

from B	over A	C	Routing Table Entry
to A	2	-	A
C	5	-	A



Distance Table for A

from A	over B	Routing Table Entry
to B	2	B
C	3	B

Distance Table for B

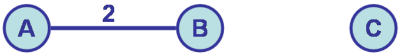
from B	over A	over C	Routing Table Entry
to A	2	-	A
C	5	-	A

from A	over B	Routing Table Entry
to B	2	B
C	7	B

from B	over A	over C	Routing Table Entry
to A	2	-	A
C	5	-	A

Distance-Vector-Routing

Count-to-Infinity-Problem



Distance Table for A

from A	over B	Routing Table Entry
to B	2	B
C	7	B

Distance Table for B

from B	over A	over C	Routing Table Entry
to A	2	-	A
C	5	-	A

from A	over B	Routing Table Entry
to B	2	B
C	7	B

from B	over A	over C	Routing Table Entry
to A	2	-	A
C	9	-	A

Distance-Vector-Routing

Solutions for the Count-to-Infinity-Problem

- Poisoned Reverse
  - Spread information about a lost connection
  - Lost connection: distance is set infinity
- Split Horizon
  - Cannot ask router from which it had learned about the connection
- Problem: both algorithms do not work reliably

Overview

Autonomous Systems

- Impossible to generate routing-tables for all existing routers (too many)
- Implementation of a hierarchy: partition into autonomous systems
- Boundary routers connect the different autonomous systems
- Path for a packet:
  - Intra-AS-Routing
  - Inter-AS-Routing

Overview

- Uses Distance-Vector-Routing algorithm
- New connected computer
    - Only knows distances to neighbors
    - Asks for routing-tables of neighbors
- Routing tables are exchanged regularly
- Advertisement: offer of new routers
- Problems:
    - Routing information does not spread fast
    - Count-to-Infinity Problem

Intra-AS-Routing

Open Shortest Path First = OSPF

- LSD = Link-State-Database: List of all neighbored routers
- Dijkstra's algorithm used to calculate the shortest path
- Larger networks are devided:
  - Local area
  - Backbone
- Today used for IPv4 and IPv6

Intra-AS-Routing

Interior-Gateway-Routing-Protocol = IGRP

- Based on Distance-Vector-Routing Protocol
- RIP: 15 network vertices away ⇒ network is called out of reach
  IGRP: increased to 255
- Better scalability (metric of costs)
- Routing loops are avoided

Overview

Inter-AS-Routing

- BGP = Border Gateway Protcol
- Table with entries about subnets or entries with IP-address-prefixes
- Based on Path-Vector-Protocol

Other Services of IP

- ICMP = Internet Control Message Protocol
- Ping
  - ICMP-Echo-Request-packet
  - ICMP-Echo-Reply-packet
- Traceroute
  - Calculates the route inbetween two computers
  - Measures time for delivery

Conclusion

- The main protocol of the Internet Layer, IP, is a connectionless and unreliable datagram delivery service.
- Dijkstra's Algorithm is used to solve the Shortest Path Problem for Routing.
- Since the Internet contains millions of computers, it is devided into autonomous systems.

- Outlook
  - There was no good solution to the Count-to-Infinity Problem presented.
  - What happens to packets as they pass through other layers?