Lecture 7:

The Network Layer

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Outline

- Network-layer functions
  - forwarding
  - routing
- Network-layer types
  - virtual-circuit networks
  - datagram networks
- IP forwarding
- IP routing

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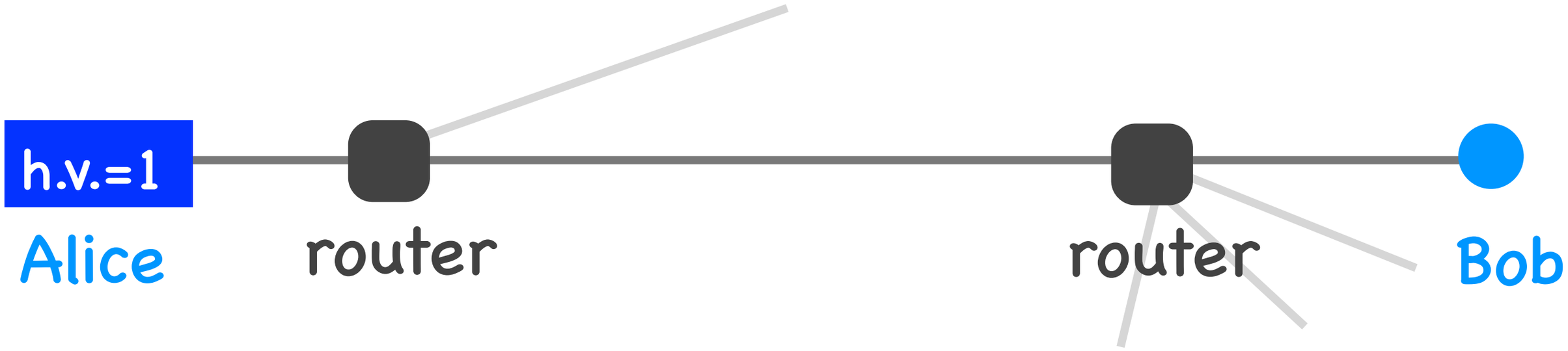
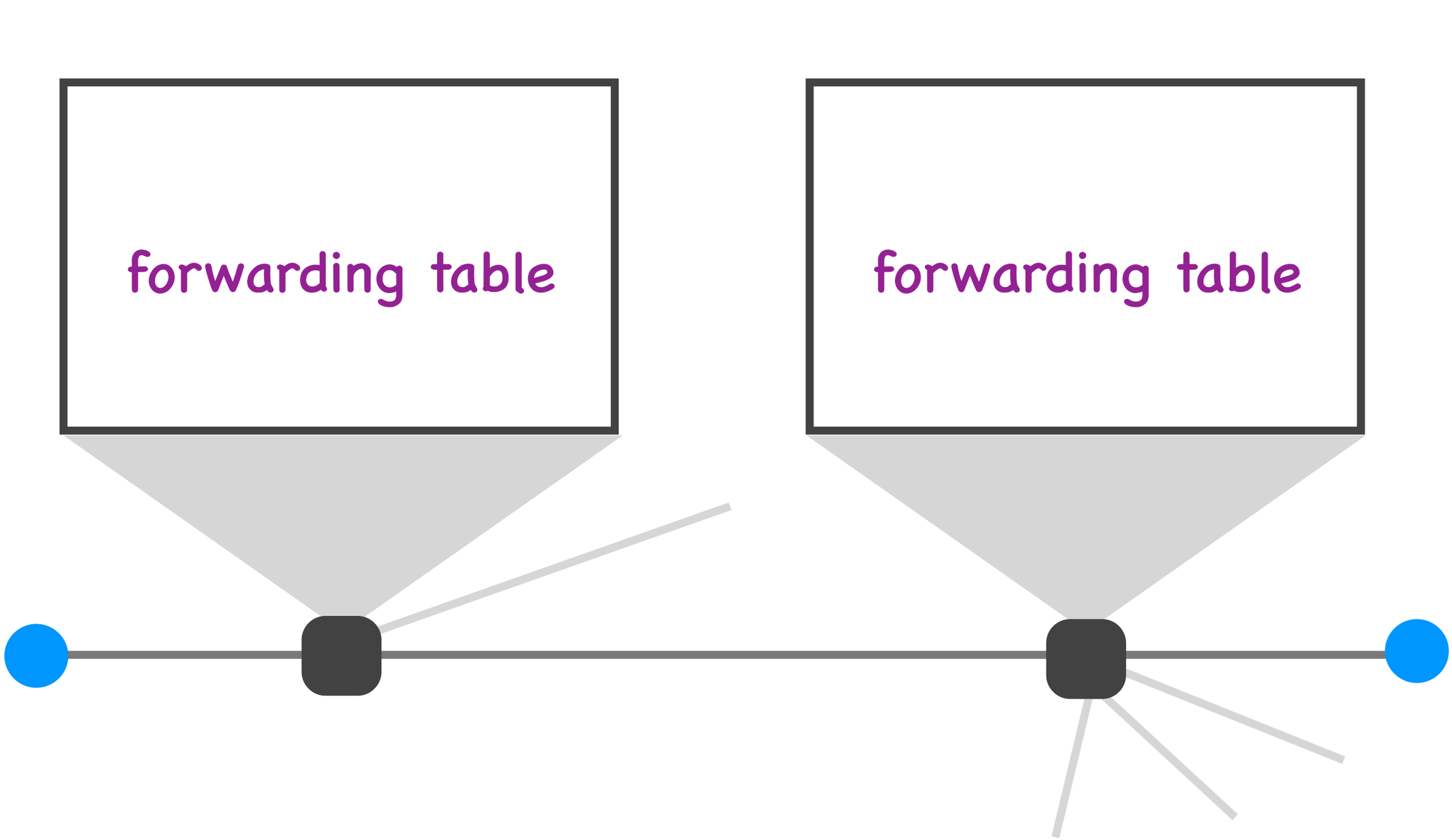

h.v.=1
Alice
router
router
Bob

forwarding table

forwarding table



header value	output link
0	1
1	2
2	2
3	1

header value	output link
0	3
1	1
2	2
3	4

Forwarding

- Local process that takes place at a router and determines output link for each packet
- How: read value from packet's network-layer header, search forwarding table for output link

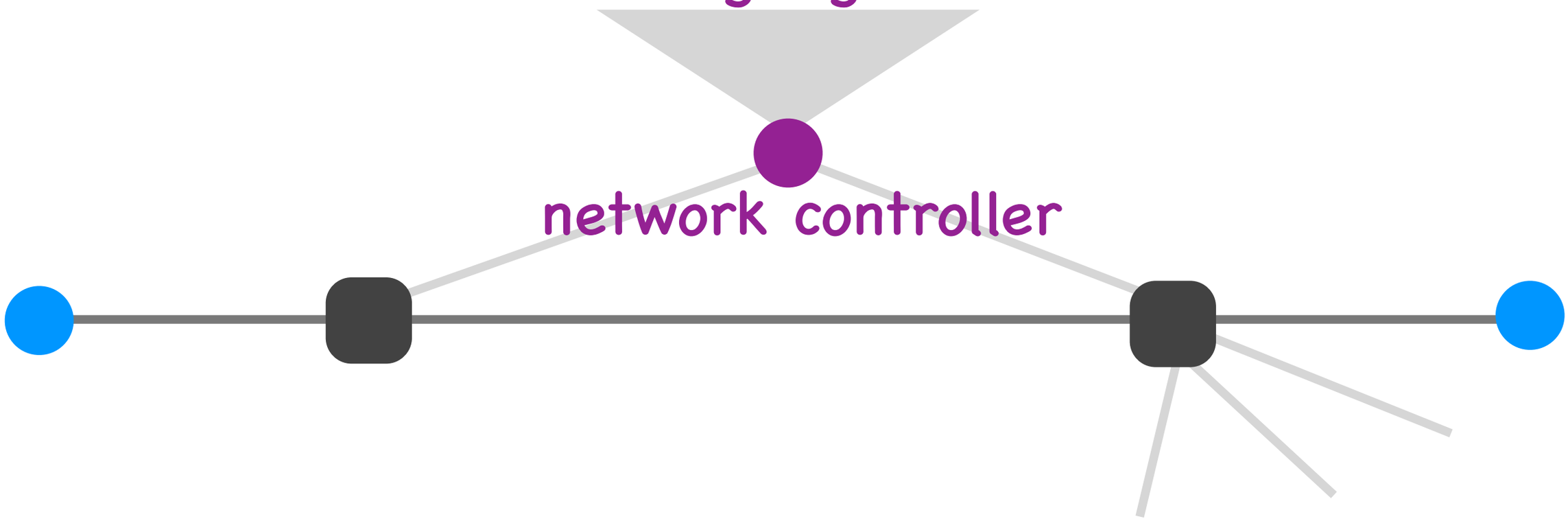
manually

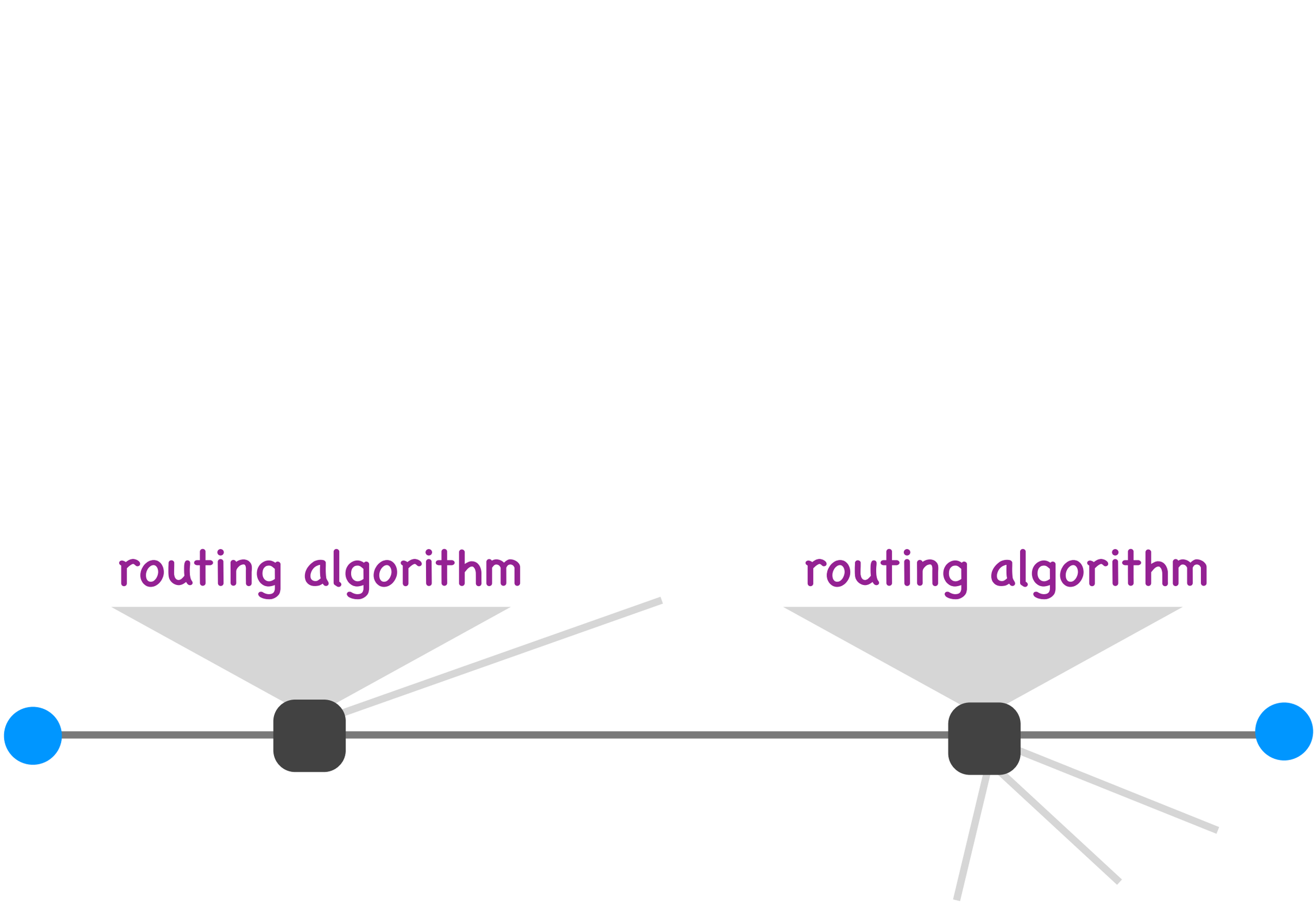
header value	output link
0	1
1	2
2	2
3	3

typically: routing

header value	output link
0	3
1	1
2	2
3	4

routing algorithm




routing algorithm
routing algorithm

Routing

- Network-wide process that populates forwarding tables
- How: routing algorithm run on a logically centralised network controller or the routers themselves

Forwarding vs. routing

- Forwarding determines output link for each packet
- Routing populates forwarding tables

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Possible guarantees

- Guaranteed (in-order) delivery
- Guaranteed maximum delay
- Guaranteed minimum throughput
- Security (confidentiality, authenticity)

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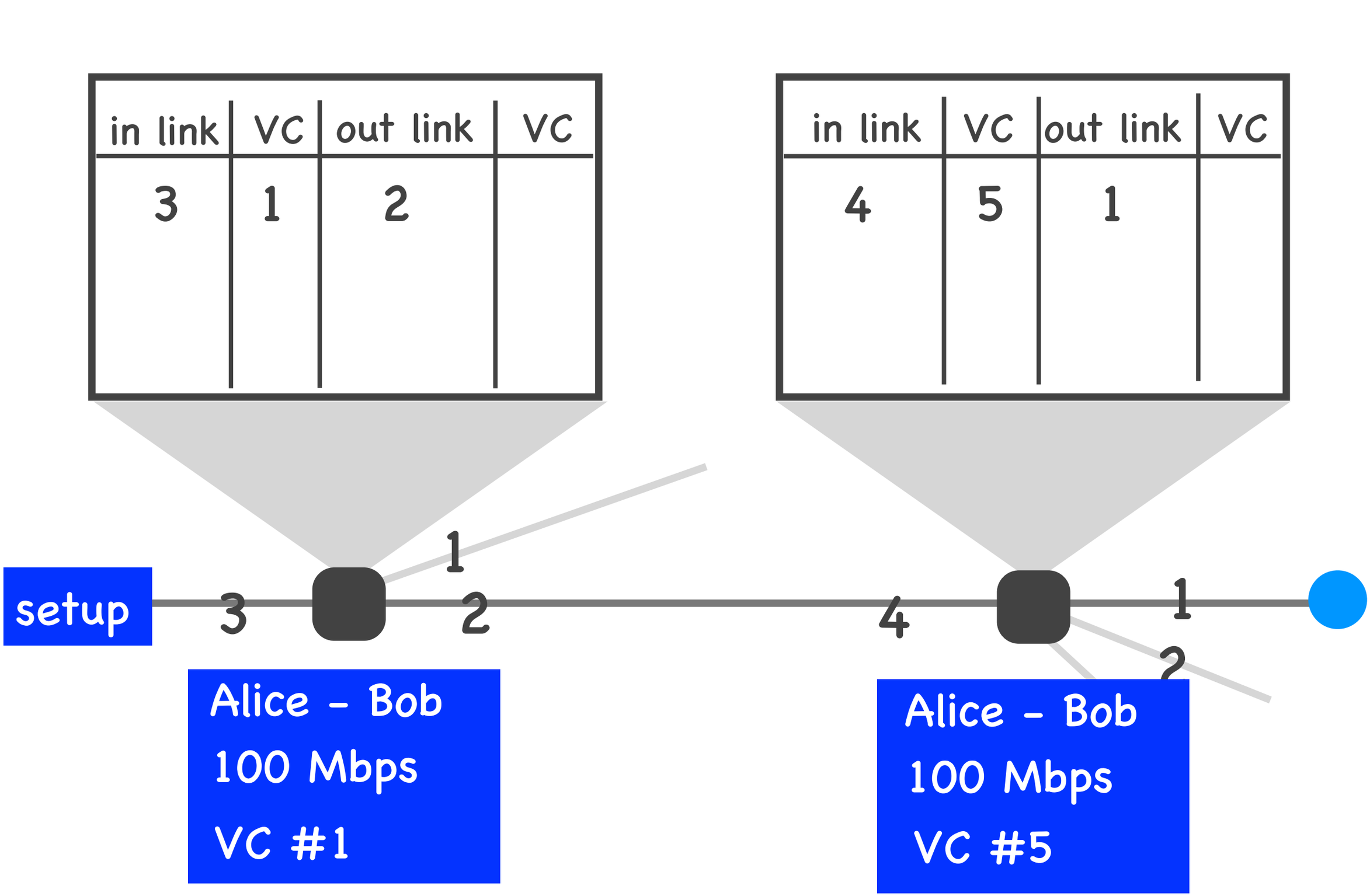
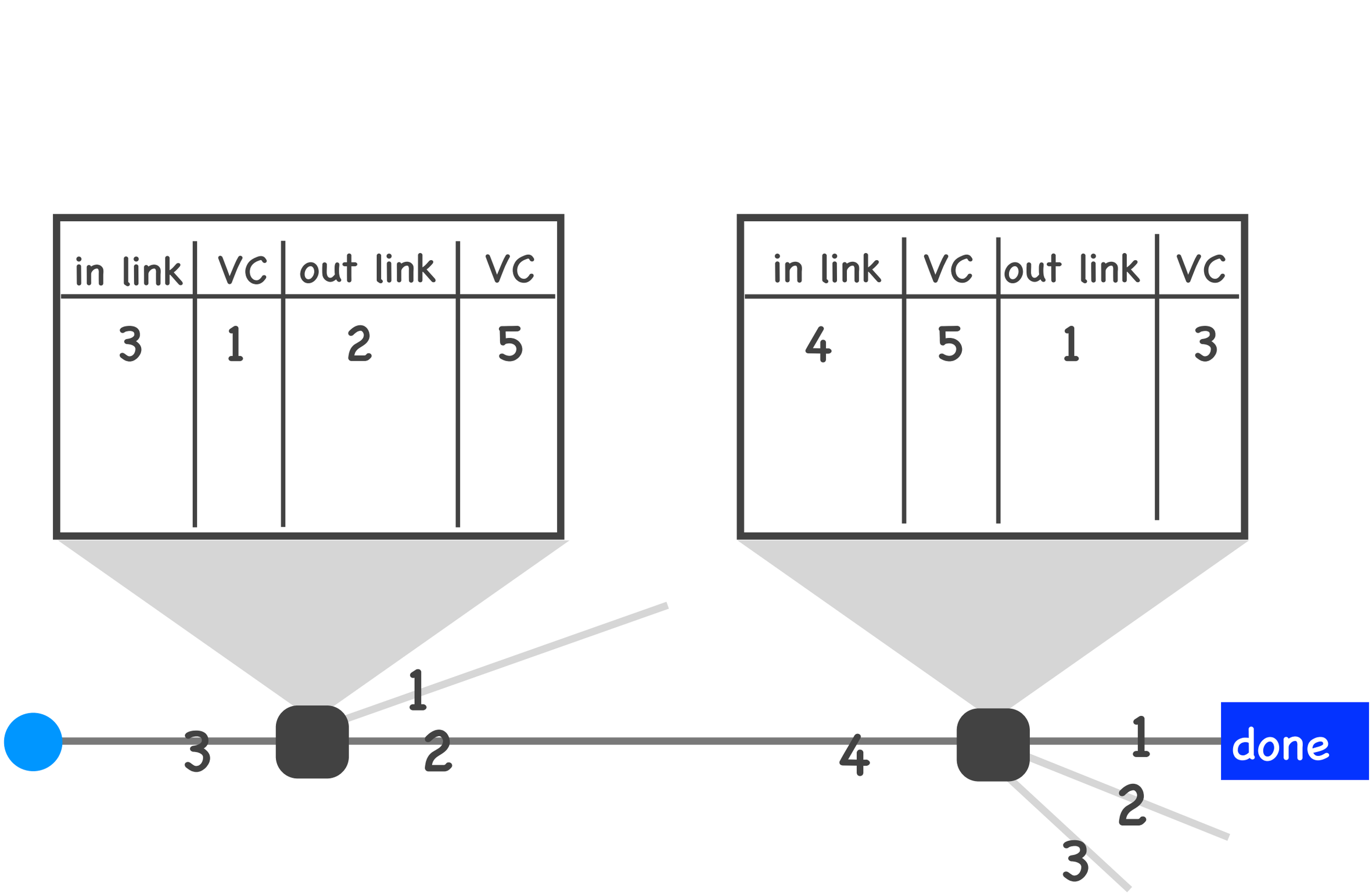
in link	VC	out link	VC
3	1	2	

in link	VC	out link	VC
4	5	1	



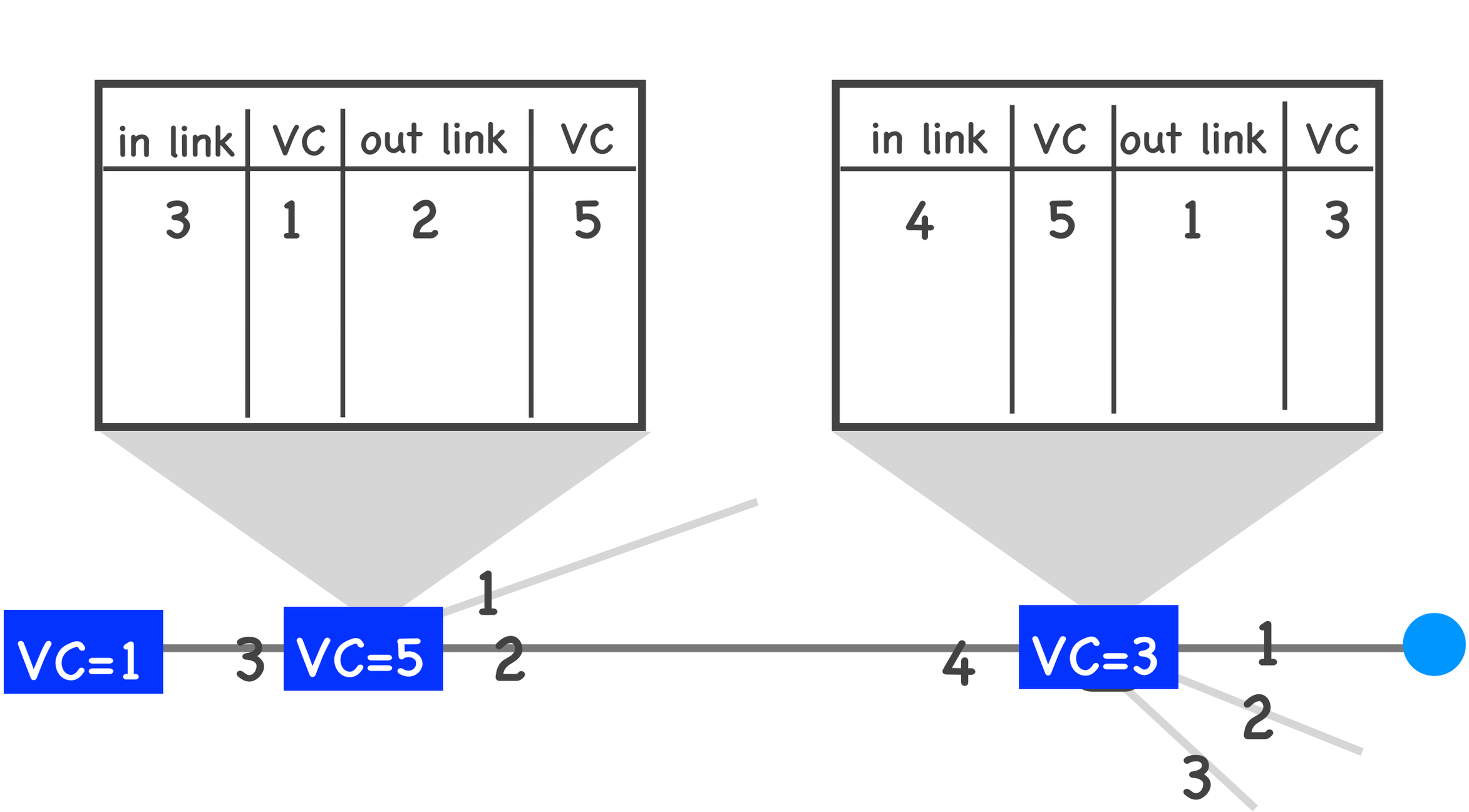
in link	VC	out link	VC
3	1	2	5

in link	VC	out link	VC
4	5	1	3



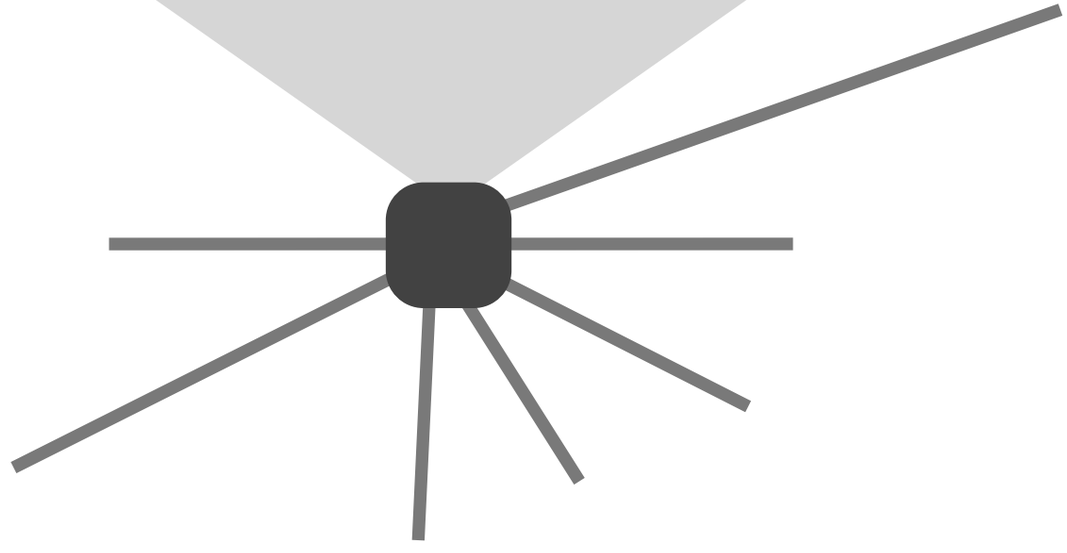
in link	VC	out link	VC
3	1	2	5

in link	VC	out link	VC
4	5	1	3



millions of concurrent connections

in link	VC	out link	VC
3	1	2	5
1	3	2	2
2	10	5	6
3	3	2	7
5	4	7	3
6	1	7	4



Virtual-circuit network

- Uses connection switching = network-layer connections
- Appropriate for performance guarantees
- Forwarding state: per connection
  - input link, VC #, output link, VC #
  - populated by connection setup (with help from routing)

Connections & state

- Many different kinds of connections
  - transport-layer (TCP) connections
  - network-layer connections

- Connection => per-connection state
  - at transport layer = at end-systems (OK)
  - at network layer = at all the routers (not OK)

- State => complexity
  - to be discussed

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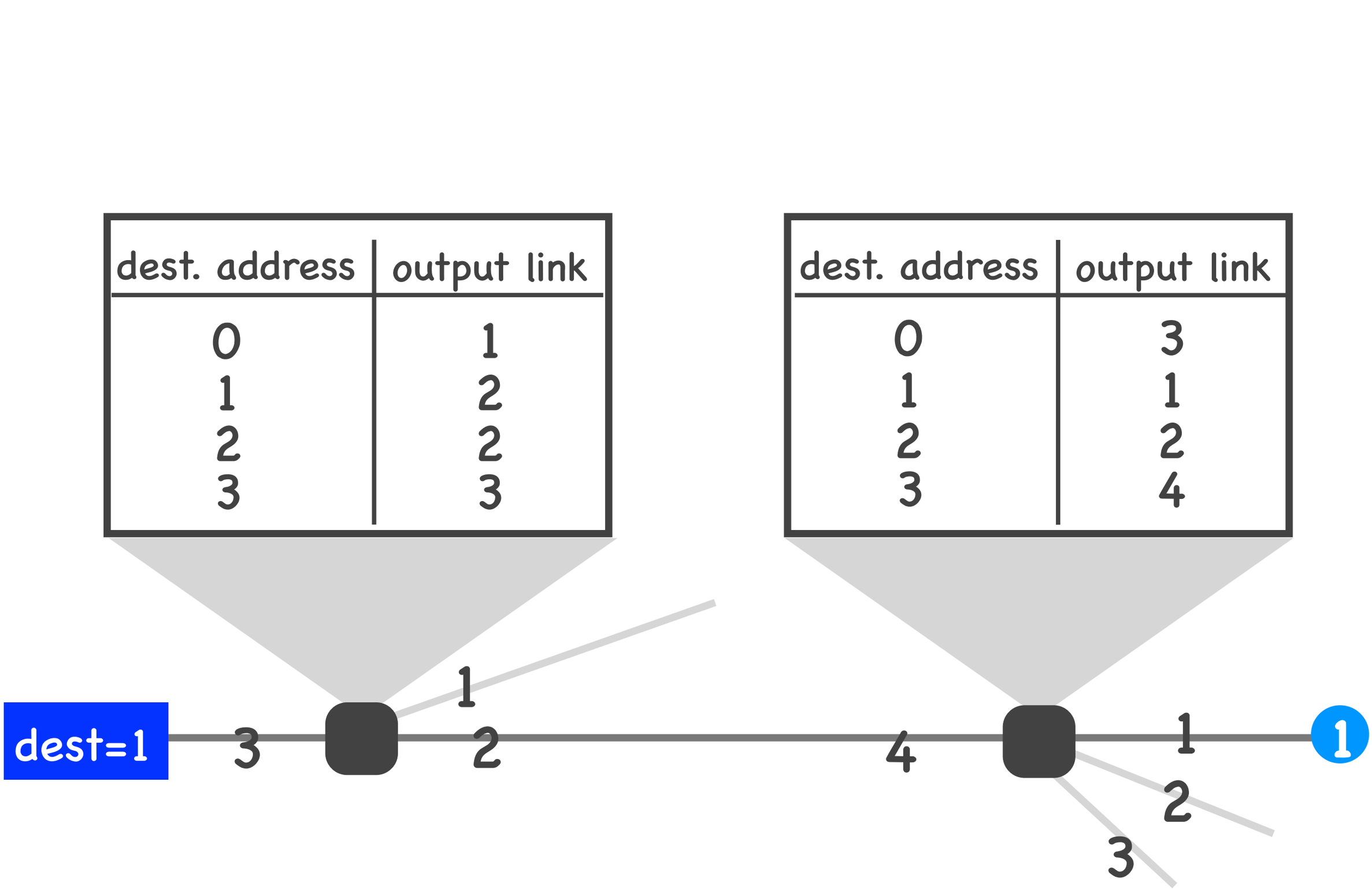
- IP routing

Best-effort delivery

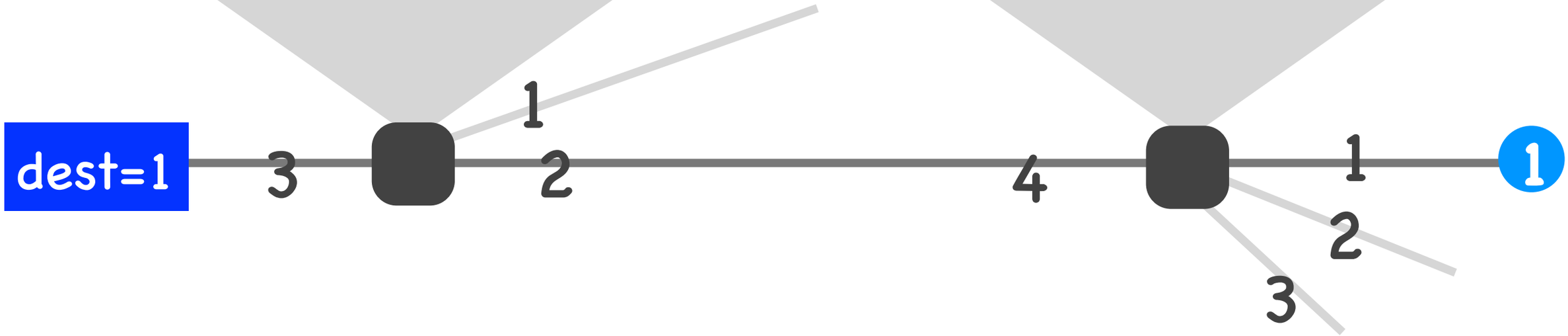
dest. address	output link
0	1
1	2
2	2
3	3

dest. address	output link
0	3
1	1
2	2
3	4



dest. address	output link
0 - 1000	2
1001 - 1500	1
1501 - 1502	3
otherwise	1

dest. address	output link
0 - 255	1
256 - 46780	2
46781 - ...	3
otherwise	4



dest. address range			output link
0 - 3	0000 - 0011	00**	1
4 - 7	0100 - 0111	01**	2
8 - 11	1000 - 1011	10**	3
12 - 15	1100 - 1111	11**	4

0100

dest. address range			output link
0 - 2	0000 - 0010	00**	1
3	0011	0011	2
4, 6, 7	0100, 0110, 0111	01**	3
5	0101	0101	2
8 - 15	1000 - 1111	1***	4

0101

dest. address range			output link
0 - 1	0000 - 0001	000*	1
2 - 3	0010 - 0011	001*	2
4 - 7	0100 - 0111	01**	3
8	1000	1000	2
9 - 15	1001 - 1111	1***	4

prefixes

longest prefix matching

IP / datagram network

- Uses packet switching =
  no network-layer connections
- Appropriate for best-effort service
- Forwarding state: per destination prefix
  - destination prefix, output link
  - populated by routing

Why the datagram approach?

- It makes forwarding tables smaller
  - no per-connection state in routers
- It makes routers simpler
  - no support for connection setup and teardown in routers

dest. address range			output link
0 - 3	0000 - 0011	00**	1
4 - 7	0100 - 0111	01**	2
8 - 11	1000 - 1011	10**	3
12 - 15	1100 - 1111	11**	4

dest. address range			output link
0 - 2	0000 - 0010	00**	1
3	0011	0011	2
4, 6, 7	0100, 0110, 0111	01**	3
5	0101	0101	2
8 - 15	1000 - 1111	1***	4

dest. address range			output link
0 - 1	0000 - 0001	000*	1
2	0010	0010	2
3	0011	0011	3
4, 6, 7	0100, 0110, 0111	01**	2
5	0101	0101	4
8 - 15	1000 - 1111	1***	1
10	1010	1010	3

Location-dependent addresses

- Address embeds location information
  - address proximity implies location proximity
- Significantly reduces forwarding state
  - per destination prefix
  - (otherwise, it would be per destination)

IP address format

IP address = number from 0 to $2^{32}-1$

```
11011111 00000001 00000001 00000001

  223  .   1    .   1    .   1
```

IP prefix format

IP prefix = range of IP addresses

223.1.1.0 / 24 ← mask

11011111 00000001 00000001 00000000

11011111 00000001 00000001 ********

223.1.1.*

IP prefix format

IP prefix = range of IP addresses

223.1.1.74 / 24 ← mask

11011111 00000001 00000001 01001001

11011111 00000001 00000001 ********

223.1.1.*

IP prefix format

IP prefix = range of IP addresses

223.1.1.74 / 24 ← mask

223.1.1.0 / 24

223.1.1.113 / 24

223.1.1.*

IP prefix format

IP prefix = range of IP addresses

223.1.1.0 / 8 ← mask

11011111 00000001 00000001 00000000

11011111 ******** ******** ********

223.*.*.*

IP prefix format

IP prefix = range of IP addresses

223.1.1.0 / 12 ← mask

11011111 00000001 00000001 00000000

11011111 0000**** ******** ********

from: 11011111 00000000 00000000 00000000

to: 11011111 00001111 11111111 11111111

IP prefix format

IP prefix = range of IP addresses

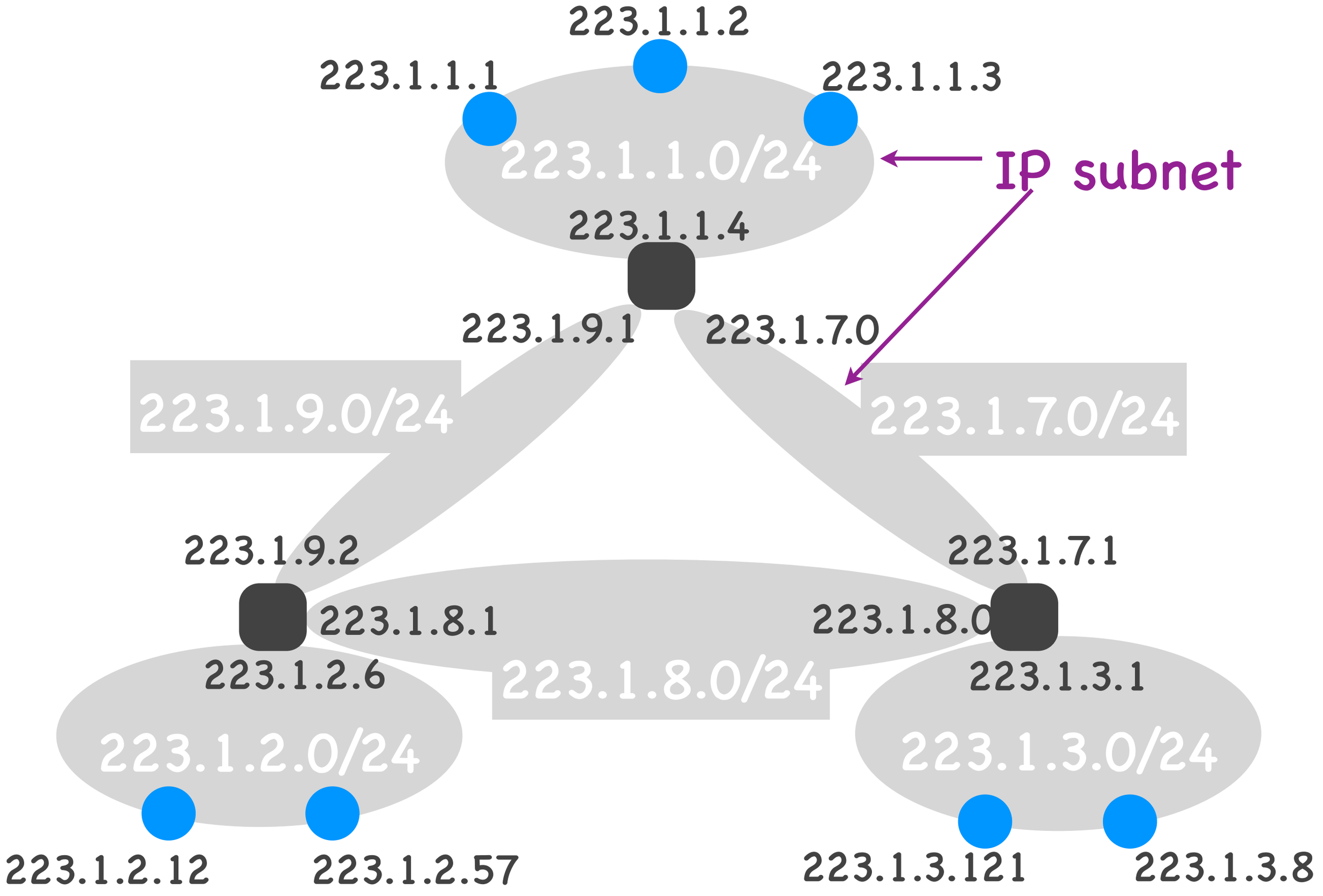
223.1.1.0 / 12 ← mask

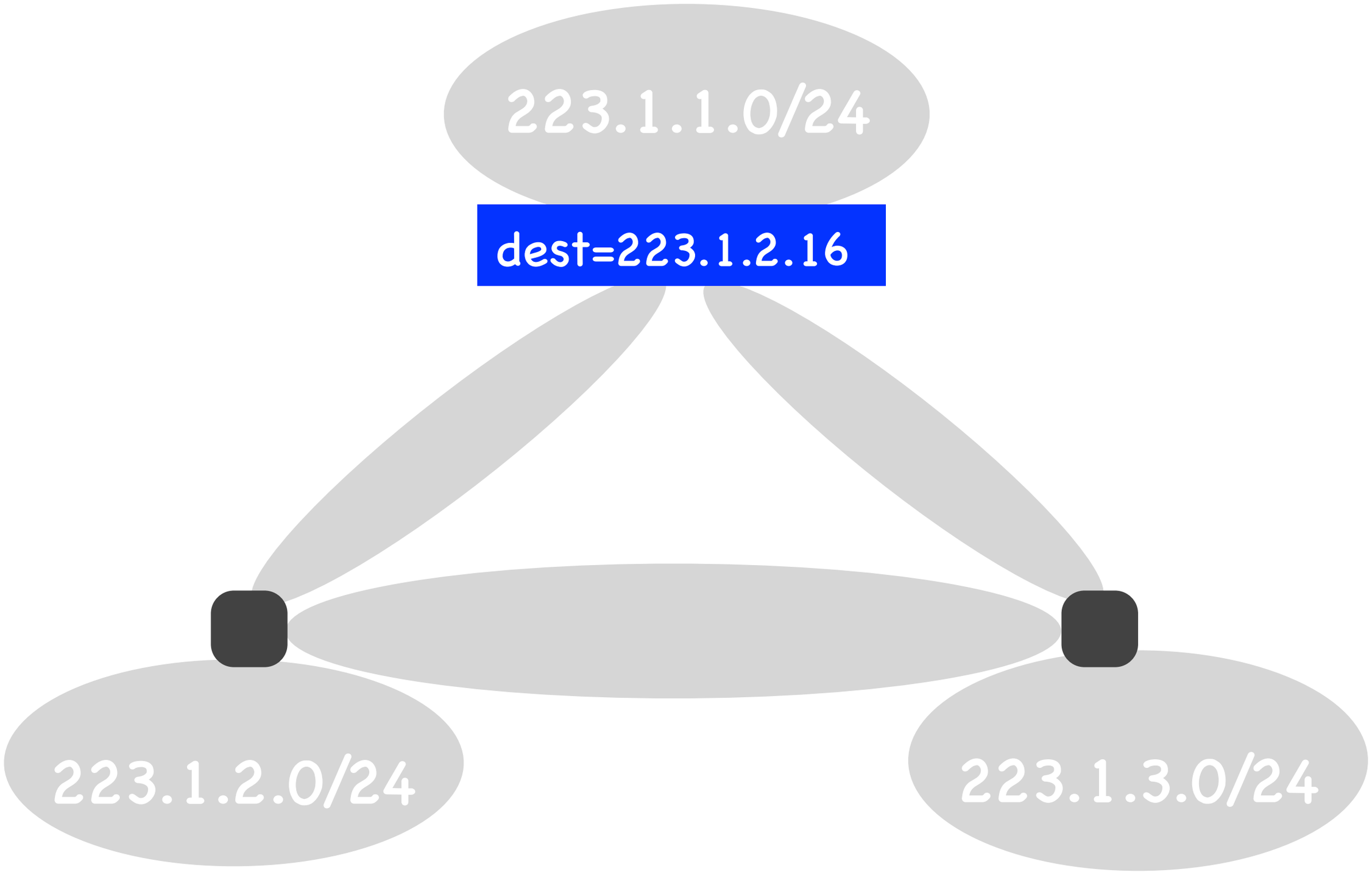
11011111 00000001 00000001 00000000

11011111 0000**** ******** ********

from: 223.0.0.0

to: 223.15.255.255


223.1.1.2
223.1.1.1
223.1.1.3
223.1.1.0/24
IP subnet
223.1.1.4
223.1.9.1
223.1.7.0
223.1.9.0/24
223.1.7.0/24
223.1.9.2
223.1.7.1
223.1.8.1
223.1.8.0
223.1.2.6
223.1.8.0/24
223.1.3.1
223.1.2.0/24
223.1.3.0/24
223.1.2.12
223.1.2.57
223.1.3.121
223.1.3.8


223.1.1.0/24
dest=223.1.2.16
223.1.2.0/24
223.1.3.0/24

IP subnet

- (Informal) Contiguous network area that does not "contain" any routers
- All its end-systems and incident routers have IP addresses from the same IP prefix

IP address assignment

- Each organization obtains IP prefixes
  - from its ISP or from a regulatory body
- Network operator assigns IP addresses
  - to router interfaces: manually
  - to end-systems: manually or through DHCP

223.1.1.0/24

223.1.1.4

223.1.9.1

223.1.1.16

IP dst=223.1.9.2
IP src=223.1.1.16

IP dst=223.1.1.16
IP src=223.1.9.2

223.1.9.2

10.0.0.1

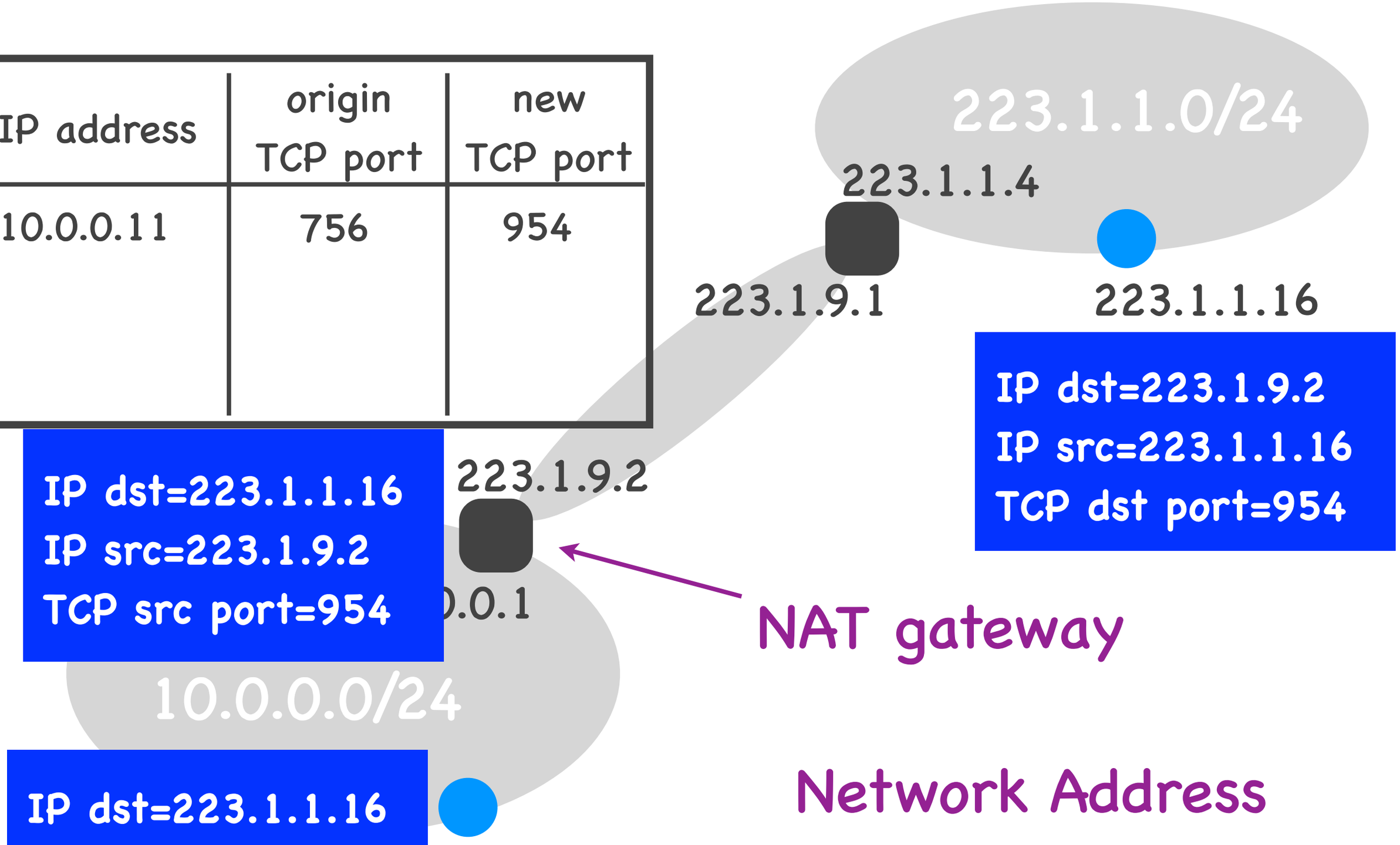
10.0.0.0/24

IP dst=223.1.1.16
IP src=10.0.0.11

10.0.0.11

private address space

IP address	origin TCP port	new TCP port
10.0.0.11	756	954



NAT gateway

Network Address Translation (NAT)

Network Address Translation

- Resolves IP address depletion problem
- Requires per-connection state at the border routers of the private IP subnets
- End-systems inside private IP subnets are unreachable from the outside world

To read, if networks interest you:

- Broadcasting & DHCP
  - Ed. 6, p. 371 | Ed. 7, p. 370
- ICMP & Traceroute
  - Ed. 6, p. 379 | Ed. 7, p. 447
- IPv6
  - Ed. 6, p. 382 | Ed. 7, p. 376