Lectures 21,22
Routing algorithms and protocols

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314 S2C 2010

- This is quite a hard topic.
- In two lectures, we can only scratch the surface to explain principles.

If you see Background slide these are optional slides that explain some details, but will not be covered in the exam.

Topics

- Routing – the problem
- Approaches (Shay 10.4)
- Algorithms
  - Dijkstra (Shay 10.5)
  - Bellman-Ford (Shay 10.6)
- Protocols (Shay 10.7)
  - RIP
  - OSPF
  - BGP
- Final points (Shay 10.8)

Routing – related to distance

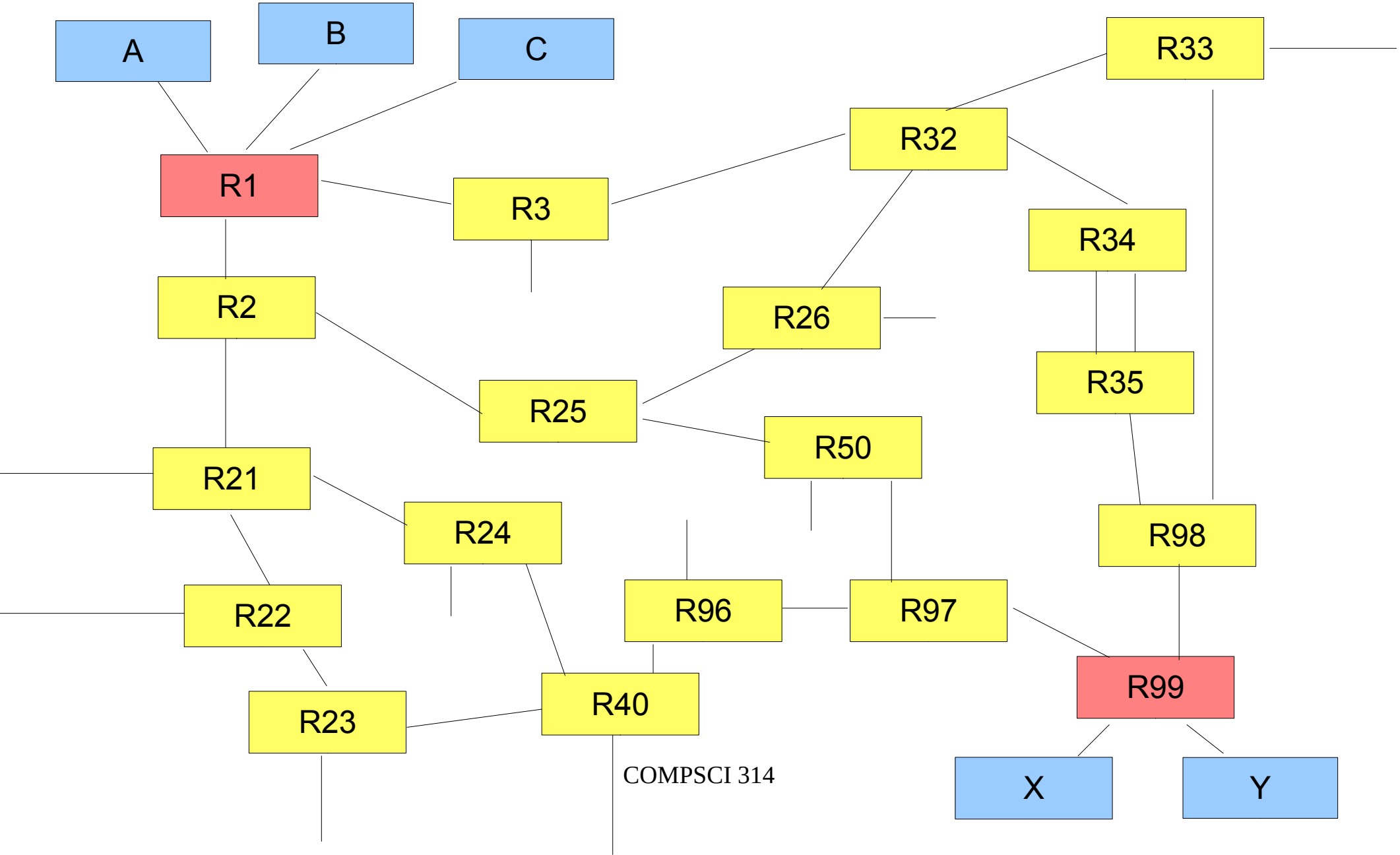
Physical addressing

Logical addressing: routers

- How do we connect devices
  - In the same room?
  - In the next room? (tens) — Cable/radio boundary
  - In the next building? (100s) — + Admin boundary
  - In the next department? — + Funding boundary
  - In the next campus? (1000s) — + Political boundary
  - In the next country? (millions)
  - In the next continent? (billions)

Distance, cost and numbers increase; must share costs and cables, but separate administration

Routing – the problem (1)



Terminology note
(if you haven't done COMPSCI 220)

- This sort of picture shows what mathematicians call a *graph,* and there is a lot of *graph theory*.
- A graph consists of numbered *vertices* connected by *arcs*:

  $\mathbf{V_1 \rightarrow V_2}$ would be the arc from vertex 1 to 2

- For a program, a graph can be thought of as an array of vertices and a matrix of arcs
  - of course, not all arcs exist; **R2→R3** does not exist so its matrix entry will be zero.

Graphs in programs

- Representing a graph:
  - Ordered list of vertex names:
    V_1='A', V_2='R1',...V_{22}='R99',V_{23}='X',V_{24}='Y'
  - List of arcs (i.e. a sparse matrix)
    $A_i = (V_s, V_d, W)$
    - (source, destination, and a parameter for each arc)
- A path through the graph is represented by an ordered list of arcs
  - "Walking the graph" means an algorithm that starts at a given vertex and builds paths by searching the list of arcs that meet up (the destination of one arc is the source of the next).

Routing – the problem (2)

- Choose the best path from A to X, knowing (at A) only the logical address of X.
- “Best” could mean
  - Smallest number of hops
  - Shortest time delay
  - Least congested
  - Cheapest
  - Administratively allowed
  - Easiest to discover
  - Any combination of the above
- Solution must be reasonably quick and guaranteed to avoid loops and deadlocks

Routing – the problem (3)

- The real network is massive
  - Thousands of nodes on campus, millions per country, hundreds of millions worldwide.
- The real network is constantly changing
  - Nodes, routers and links added or removed constantly
  - View of network will be different in different places
- Therefore, algorithms must be scaleable, dynamic and distributed
  - Central static route computation only works for small, very stable networks

Approaches to dynamic routing

- Confine routing intelligence to specialised router boxes
  - End-systems mainly send everything to their default router
- Routers build connectivity maps and exchange routing information with their neighbours
- Two major approaches
  - Distance vector routing: router informs neighbours of its best paths. Each router calculates best paths for itself based on neighbour's paths.
  - Link state routing: router exchanges link status info with its neighbours. Each router relies on accuracy of its neighbours' status info in calculating best paths through the whole map.

DV Routing: Bellman-Ford algorithm

- Router computes a table of its “distance” to each other router in the same network
  - Distance 1 = 1 hop, 2 = 2 hops etc.
- Sends this table to its neighbours
- Recomputes its own table using tables from its neighbours
- Works, but
  - Sending complete tables doesn't scale well and is slow to converge after a change
  - “Link down” condition can lead to loops, as the “distance” increases towards infinity

Bellman-Ford: the computation (1)

- Compute the shortest path from R1 to all Rn knowing the topology of the router graph
  - Initialize each distance **`D(R1,Rn)`**=∞, except **`D(R1,R1)=0`**
  - For each arc **`Rx`**→**`Ry`** in the graph (starting with **`R1`**)

```
if D(R1,Ry)>D(R1,Rx)+1
then D(R1,Ry):= D(R1,Rx)+1
```

  - At this point, each **`D(R1,Rn)`** is the length of the shortest path from R1 to Rn
  - The algorithm also keeps track of the “next hop” router from **`R1`** for the path

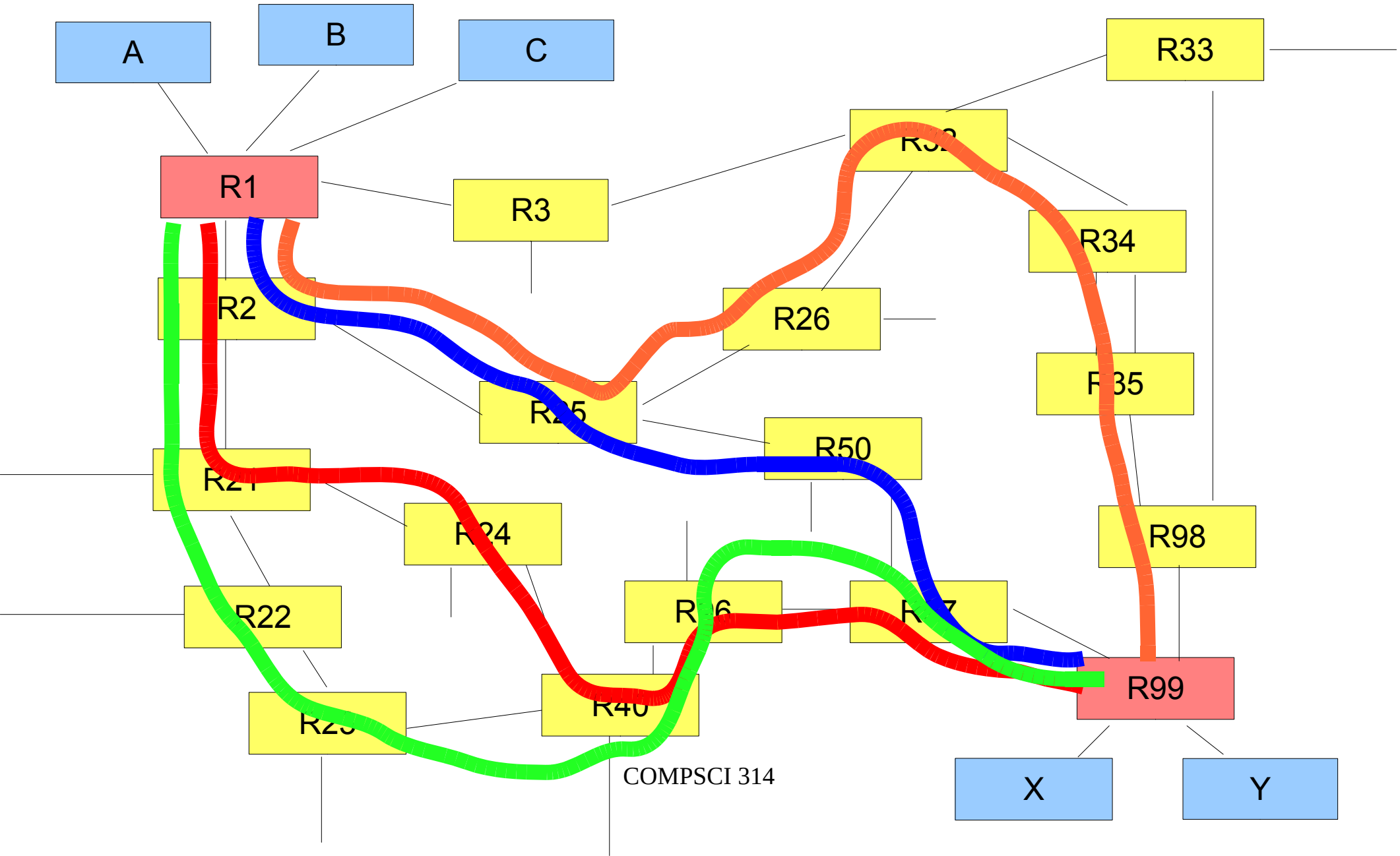
Bellman-Ford: the computation (2)

- That dealt with paths from R1. For complete routing tables, run again starting from R2, R3...
- Note that algorithm processes every arc times every node!
- The "**+1**" above is a simplification where all paths have equal weight. It should be a weight **W(x,y)** to allow for administrative preferences for certain links:

```
if D(R1,Ry)>D(R1,Rx)+W(x,y)
then D(R1,Ry):=D(R1,Rx)+W(x,y)
```

- **W(x,y)<0** is allowed by the algorithm, but can lead to loops, which can be detected if any **D(R1,Ry)>D(R1,Rx)+W(x,y)** condition exists after the algorithm ends

Bellman-Ford paths



Link State Routing: Dijkstra algorithm

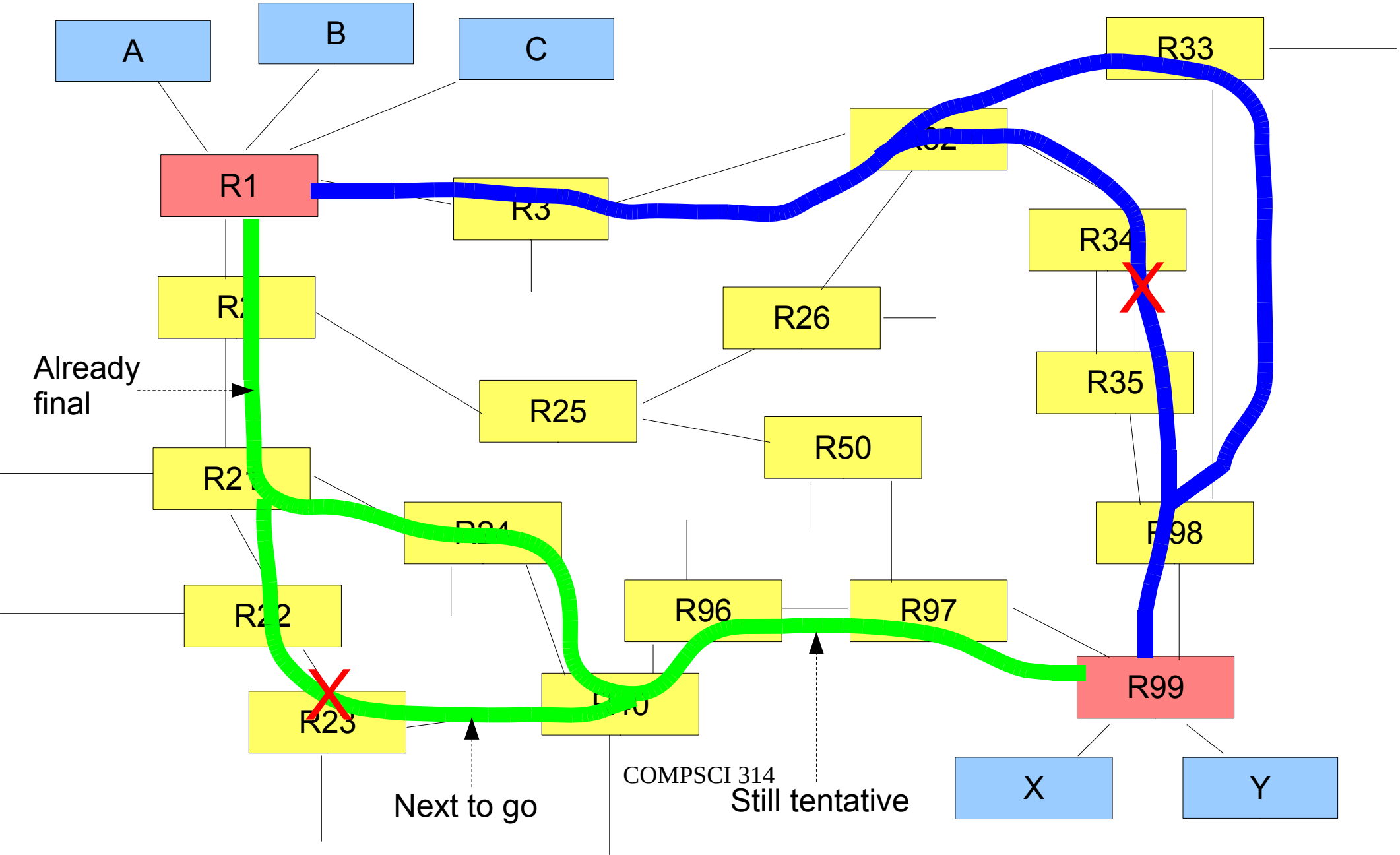
- Also called “shortest path first” or “SPF”
- First we'll describe the algorithm in the abstract
- Then a few comments

Dijkstra: the computation

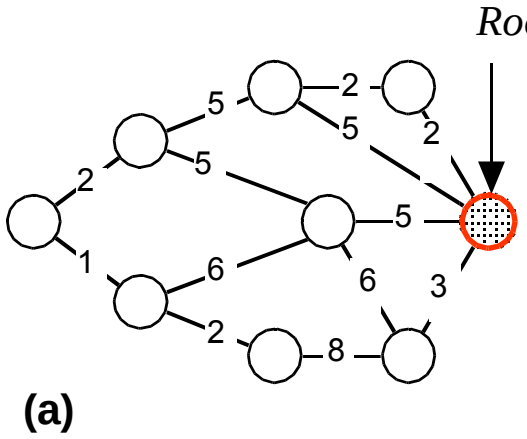
- Initialize each distance **D(R1,Rn)**=∞, except **D(R1,R1)=0**
- Mark all **D**'s as *tentative*, except **D(R1,R1)** as *final*
- For each arc **Rx→Ry** in the graph (starting with **R1**)

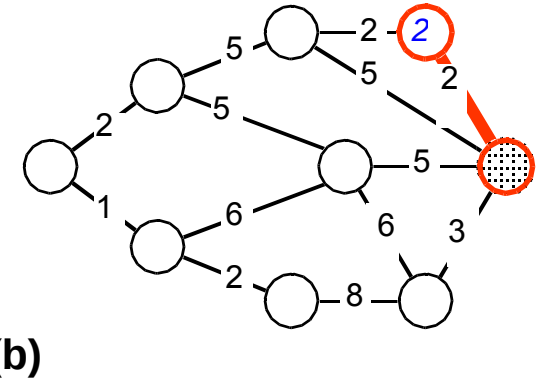
  if D(R1,Ry)>D(R1,Rx)+W(x,y)
  then D(R1,Ry):=D(R1,Rx)+W(x,y)
- When all paths to **Ry** have been checked, **Ry** is removed from scanning of graph and its current **D(R1,Ry)** is marked as *final*
  - i.e. we only minimise the path to **Ry** *once;* in Bellman-Ford we did it for every path through **Ry**
- **W(x,y)<0** is not allowed

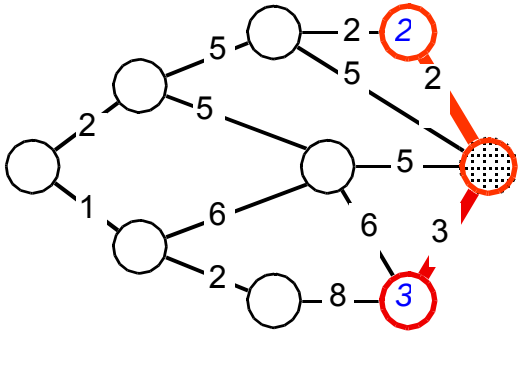
Dijkstra paths (snapshot)

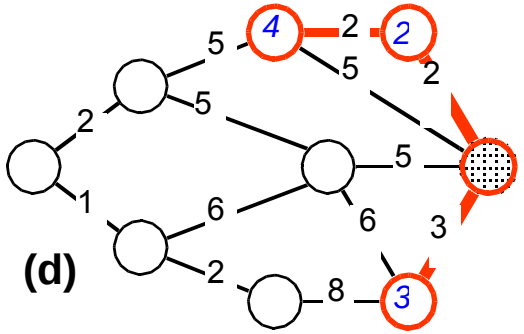


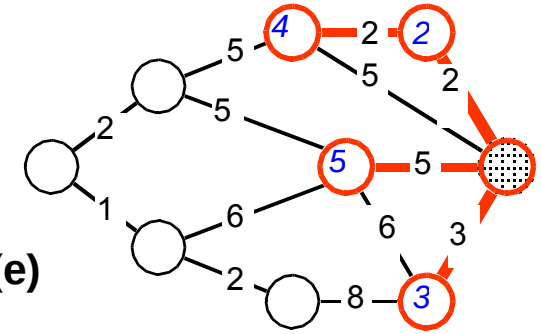
CS314 traditional Dijkstra example: progressive evaluation

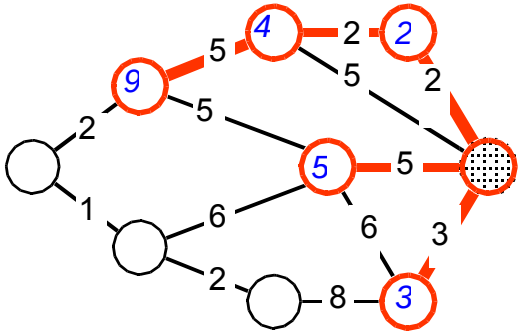


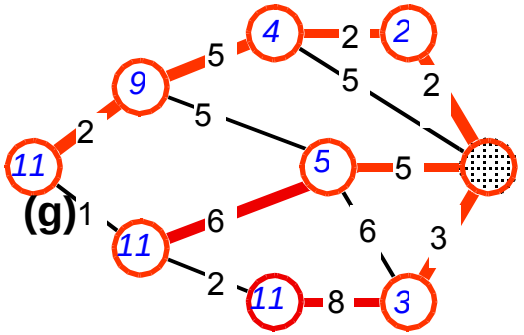












Step (g) brings in three nodes, all with a root cost of 11

Link State: Comments

- Algorithm processes many fewer arcs than Bellman-Ford – once a distance is *final* that node is no longer considered
  - Whether this saving matters depends on size of graph and frequency of changes
- Also, each node receives neighbours' link state tables so doesn't have to start from **`D(R1,Rn)=∞`**
  - Trust neighbours' path lengths – OK if you can trust your neighbours
- Link State versus Distance Vector was quite a battle in the technical community some years ago, so we have a variety of routing protocols in service today. We'll talk about three: RIP (DV), OSPF (LS) and BGP (modified DV).

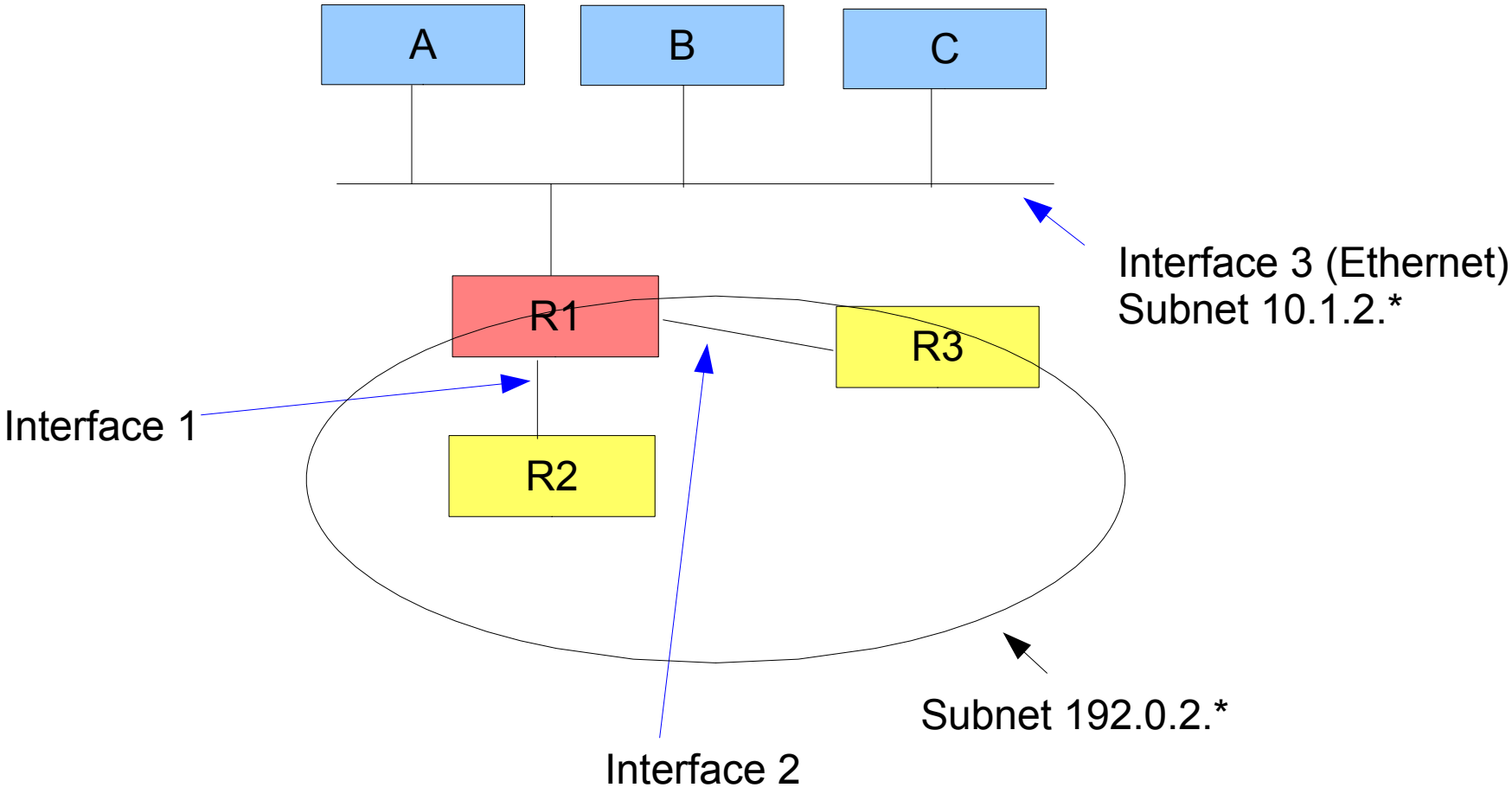
IGP and EGP

- IGP = Interior Gateway Protocol
  - A name for any site-wide routing protocol used within a campus or company network, or within a single ISP's network
  - (Routers were originally called *gateways*)
  - Examples: RIP, OSPF
- EGP = Exterior Gateway Protocol
  - A name for any wide-area routing protocol used to interconnect sites and ISPs
  - Sometimes know as IDR (inter-domain routing)
  - The only example in use is BGP4

RIP: Routing Information Protocol

- The original Internet DV protocol for IGP use
  - Remember that in real life, Bellman-Ford is executed as a distributed algorithm – each router computes the paths from itself to others.
  - Thus, each router keeps a table of destinations:
    - IP address of destination
    - IP address of first hop towards destination
    - Interface number for first hop
    - Distance metric for destination
    - Timestamp when entry was last updated
  - The router's complete distance vector can be read out of this table

R1 and its interfaces



Notional Initial DV table for R1

Name	Dest IP	1st hop IP	Interface	Distance	Timestamp
R1	192.0.2.1	0.0.0.0	0	0	0
R2	192.0.2.2	0.0.0.0	1	∞	0
R3	192.0.2.3	0.0.0.0	2	∞	0
A	10.1.2.3	0.0.0.0	3	∞	0
B	10.1.2.5	0.0.0.0	3	∞	0
C	10.1.2.17	0.0.0.0	3	∞	0

Notes:

- R1 points to itself using the loopback address and distance zero.
- The other distances are set to infinity.
- R1 also shows itself as the 1st hop to its neighbours.
- All timestamps are initialized before we start.
- In practice, end systems like A, B, C don't run RIP; the router can discover them on the LAN and is pre-configured with the summarised destination....

Actual Initial DV table for R1

Name	Dest IP	1st hop IP	Interface	Distance	Timestamp
R1	192.0.2.1	0.0.0.0	0	0	0
R2	192.0.2.2	0.0.0.0	1	16	0
R3	192.0.2.3	0.0.0.0	2	16	0
None	10.1.2.*	0.0.0.0	3	1	0

Notes:

- There is no way out of configuring this externally; the router cannot guess any of it.
- In reality, destinations are address + bit mask; A, B and C can be summarised as address 10.1.2.0, mask 255.255.255.0 . This means all addresses from 10.1.2.0 to 10.1.2.255 .
- 10.1.2.* stands for 10.1.2.0, mask 255.255.255.0 .
- 192.0.2.1 stands for 192.0.2.1, mask 255.255.255.255
- RIP uses 16 as infinity
- Now we have a simple distance vector that can be passed to R2 and R3.

Contents of RIP messages
from router to router (simplified)

- Command
  - 1: request sending of neighbour's DV
  - 2: response including sender's DV
- Route tag
  - Says if the route is within the RIP domain or outside the RIP domain (e.g. wide area route)
- Address and mask – as above
- Next hop address – if not the current router
  - Zero means the default route via current router
- Metric
  - A value up to 15 (number of hops)

Why is infinity equal to 16?

- By convention, RIP considers a metric of 16 to be infinity.
- Real networks should never be designed so that any normal path needs 16 hops
  - Even my messy example has at most 8 hops
- By having a low value for “infinity”, RIP will not waste too many cycles when re-computing routes after a link breakage
  - If a destination has become unreachable, we will stop looking for a path when the length exceeds 15

How RIP operates

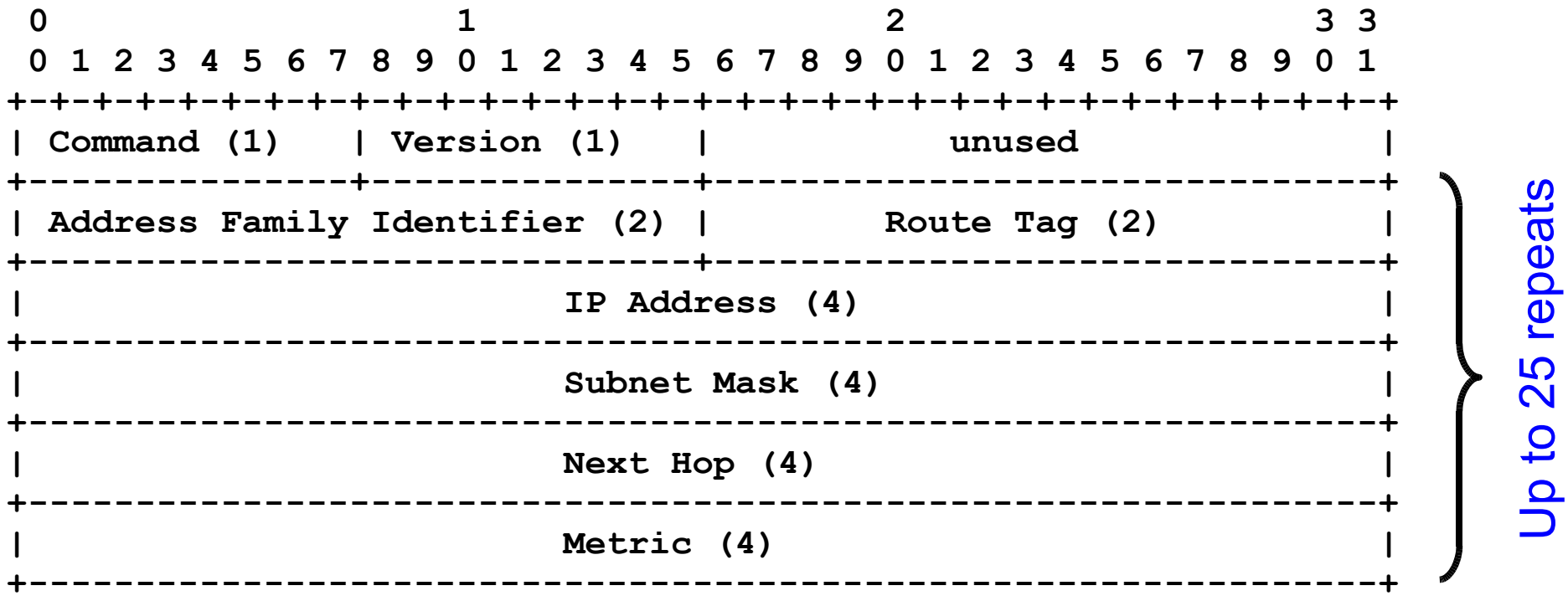
- Each router sends its full DV in one or more Response messages
  - On startup
  - Every 30 seconds
  - Whenever something changes (e.g. a link goes down)
  - When a Request message is received
- Recalculates its DV whenever it receives a Response
  - Which includes running Bellman-Ford algorithm
- That is enough for all routers to have up-to-date routing tables
  - Unless rate of changes is too great for the messages and calculations to keep up

Comments on RIP

- We've skipped some details.
  - If you've studied RIP in more detail, e.g. in INFOSYS courses, you will notice simplifications.
- RIP messages are quite noisy with many unused bits.
- Convergence time can be large when conditions are bad (e.g. recovering from power failure in a building)
- RIP therefore doesn't work well in large, complex networks.
- Generally, OSPF is considered better today.

Background slide

Binary format of RIP messages



Get used to this form of protocol data unit drawing – it's how all basic Internet standards show bits and bytes. This shows 24 bytes in 6 rows of 4 bytes.

Background slide

Constructing a RIP packet for R1 (1)

```
Command: (2)     00000010
Version: (2)     00000010
Unused:          00000000 00000000
AFI,tag: (2+2)   00000000 00000010 00000000 00000000
R1's address:    11000000 00000000 00000010 00000001
Mask:            11111111 11111111 11111111 11111111
Next hop:(self)  00000000 00000000 00000000 00000000
Metric: (0)      00000000 00000000 00000000 00000000
AFI,tag: (2+2)   00000000 00000010 00000000 00000000
R2's address:    11000000 00000000 00000010 00000010
Mask:            11111111 11111111 11111111 11111111
Next hop:(self)  00000000 00000000 00000000 00000000
Metric: (16)     00000000 00000000 00000000 00010000
```

Background slide

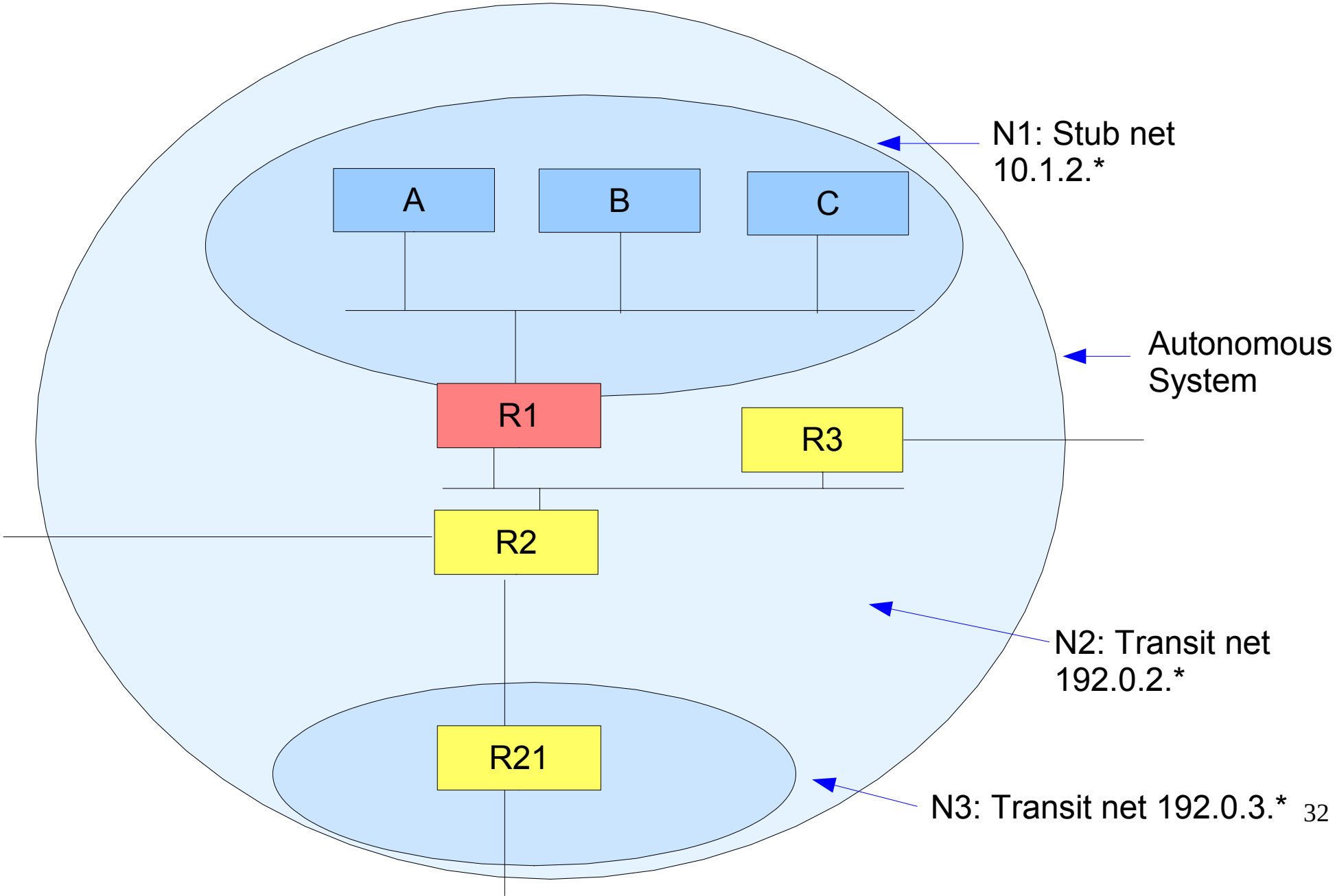
Constructing a RIP packet for R1 (2)

```
AFI,tag: (2+2)  00000000 00000010 00000000 00000000
R3's address:   11000000 00000000 00000010 00000011
Mask:           11111111 11111111 11111111 11111111
Next hop:(self) 00000000 00000000 00000000 00000000
Metric: (16)    00000000 00000000 00000000 00010000
AFI,tag: (2+2)  00000000 00000010 00000000 00000000
LAN address:    00001010 00000001 00000010 00000000
Mask:           11111111 11111111 11111111 00000000
Next hop:(self) 00000000 00000000 00000000 00000000
Metric: (1)     00000000 00000000 00000000 00000001
```

OSPF: Open Shortest Path First

- A common Internet LS protocol for IGP use
  - Dijkstra is executed as a distributed algorithm – each router computes its own shortest paths.
  - Conceptually, OSPF runs within a finite domain known as an Autonomous System (AS).
    - It distinguishes routers from networks within the AS.
    - Networks can be stub or transit networks.
  - Each router keeps a Link State database,
  - The router's Link State Advertisements (LSAs) to its neighbours can be read out of this database.

OSPF conceptual model



Contents of Link State database

- The vertices in the network graph will be: **`N1, N2, N3, R1, R2, R3, R21`**
- Arcs will be **`Rx→Ry, Nx→Ry or Rx→Ny`** (never **`Nx→Ny`**)
- For each destination, LS database lists
  - IP address (and mask) of destination
  - IP address of first hop towards destination
  - Interface number for first hop
  - Distance metric for destination
- External networks (outside the AS) will typically have large metrics

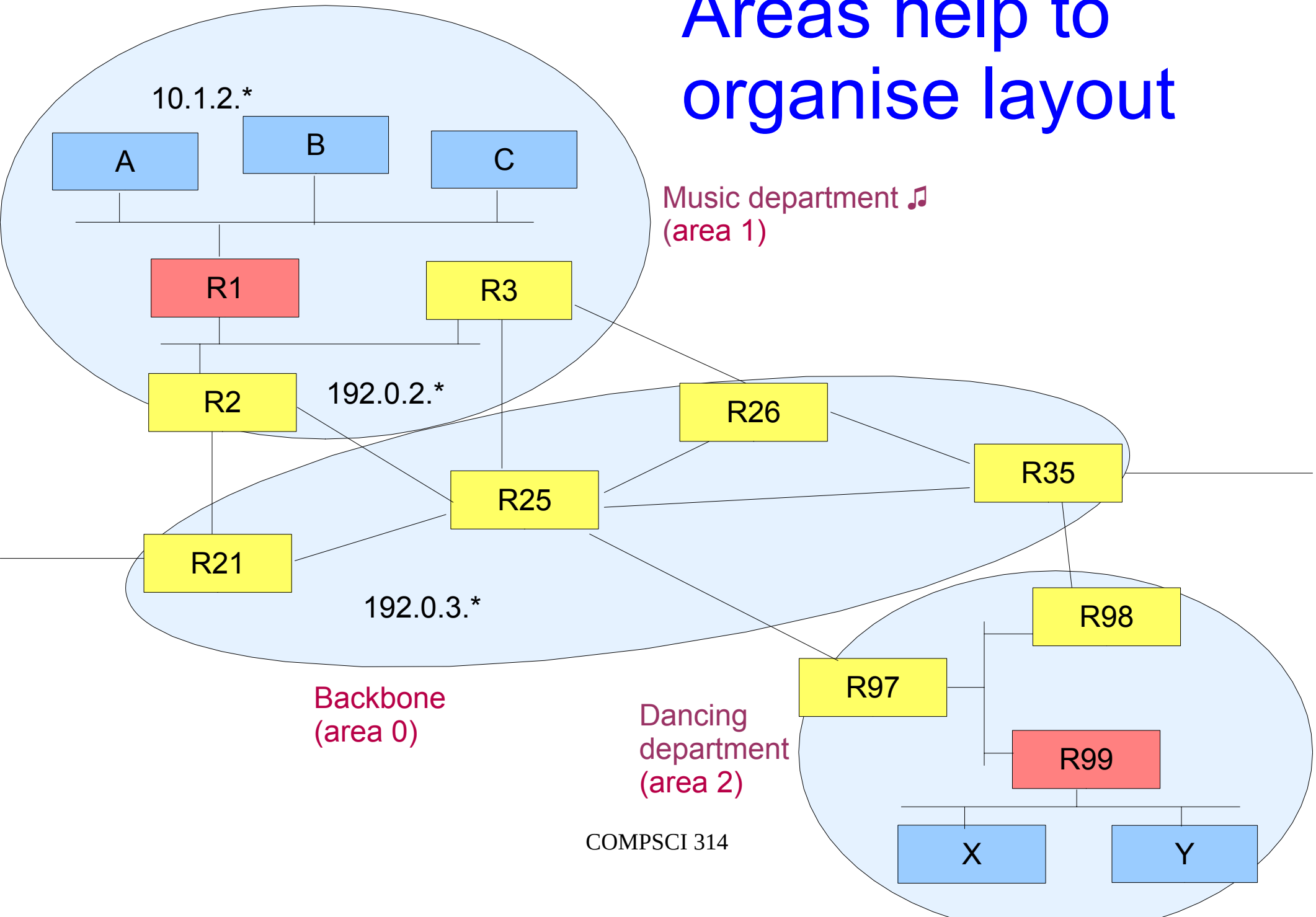
Splitting very large AS's

- OSPF already allows an AS to contain logically separate networks.
- For a large campus, it is possible to split the AS into logically separate “areas” which each run their own SPF computations.
  - Reduces overhead within each area
  - Area 0 then acts as a campus backbone
  - Inter-area routes cross the backbone
- More efficient operation in a large network
  - Glitches in one department don't affect another

Flavours of OSPF router

- Internal
  - Connected to LANs and links within an Area
- Designated
  - When >1 routers on a LAN, one is designated to send LSAs
- Area Border
  - Connected to the backbone Area and at least one normal Area. Computes routes for each.
- Backbone
  - Connected to the backbone Area
- AS Boundary
  - Advertises routes to the outside world

Areas help to organise layout



OSPF message types

1	Hello	Discover/maintain neighbours
2	Database Description	Summarise database contents
3	Link State Request	Request database download
4	Link State Update	Send database update
5	Link State Ack	Acknowledge an update (not abbreviated as LSA)

- Link State Updates carry the LSAs (Link State Advertisements) of the sending router and LSAs from its upstream routers.
- Within an Area, LSAs describe link state in detail, similar to RIP
- Beyond an Area, LSAs summarise routes per network

What causes an LSA to be updated?

- Its lifetime expires
- Interface up/down
- Designated router for a LAN changes
- Change of state of neighbour router
- Intra-area route changes in border router
- Inter-area route changes
- Border router attaches to new area
- Backbone topology change (virtual route change)
- External route change
- AS Boundary router down

How OSPF operates

- Each router sends its LSAs in one or more Link State Update messages
  - When timer expires
  - Whenever an LSA changes
  - When a LS Request message is received
- Recalculates its LSAs whenever it receives an LSU Response
  - Which includes running Dijkstra algorithm
- That is enough for all routers to have up-to-date routing tables
- We've skipped many details.
  - Convergence times and scaleability significantly better than RIP

Background slide

What's in an OSPF LSA

- Five types of LSA:
  1 Router-LSAs – link state for each interface
  2 Network-LSAs – routers for a transit subnet
  3,4 Summary-LSAs – inter-Area link state
  5 AS-external-LSAs – external link state

Background slide

Main items in a Router-LSA

```
LS type = 1                          ;indicates router-LSA Link State
Link State ID = 192.0.2.1            ;R1's Router ID
Advertising Router = 192.0.2.1       ;R1's Router ID
        #links = 2
                Link ID = 192.0.2.3      ;IP address of Desig. Rtr.
                Link Data = 192.0.2.1    ;R1's IP interface to net
                Type = 2                 ;connects to transit net
                metric = 1

                Link ID = 10.1.2.0           ;IP Network number
                Link Data = 255.255.255.0    ;Network mask
                Type = 3                     ;connects to stub net
                metric = 2
```

Background slide

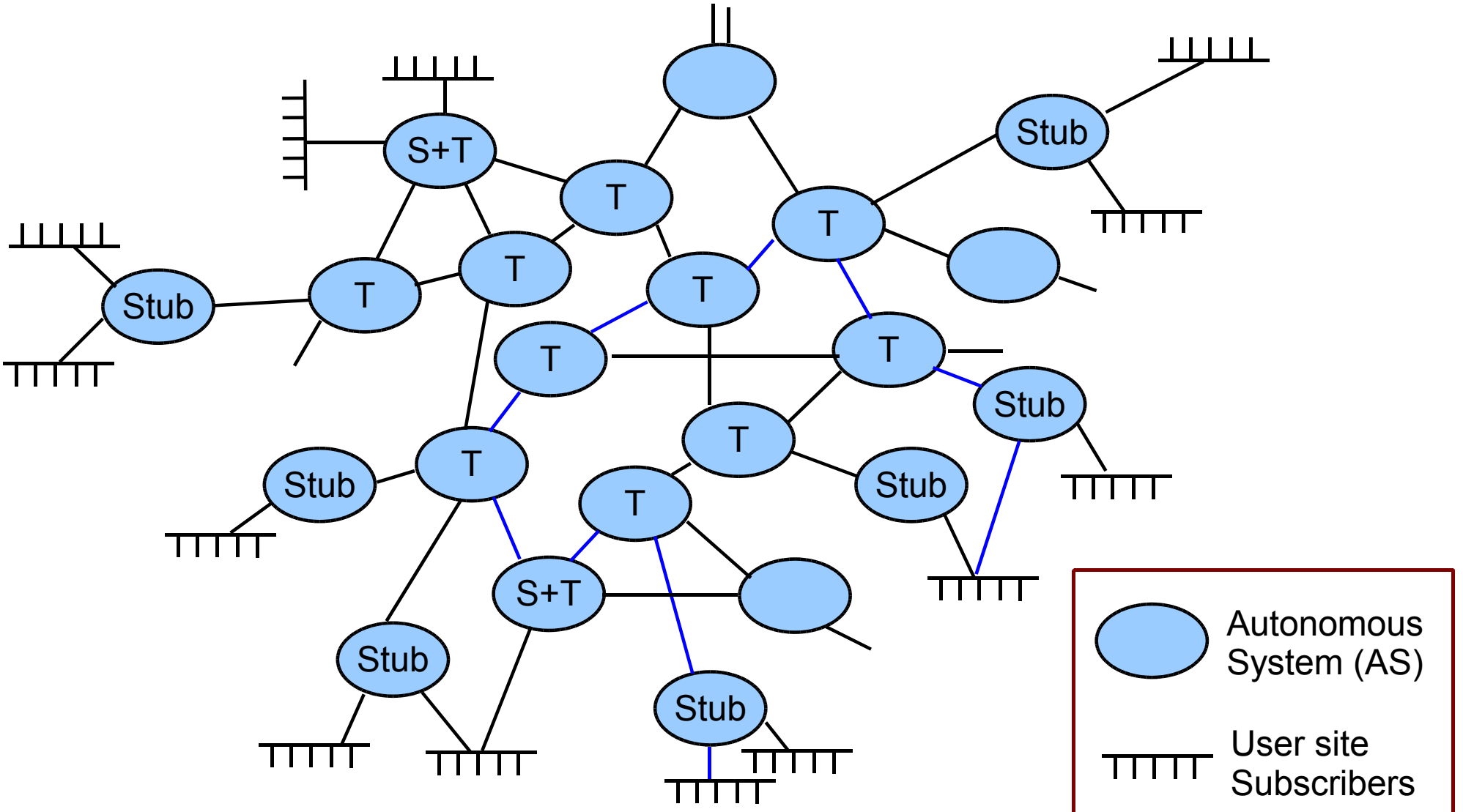
Main items in a Network-LSA

```
LS type = 2                          ;indicates network-LSA Link State
Link State ID = 192.0.2.3            ;IP address of Desig. Rtr.
Advertising Router = 192.0.2.3       ;R3's Router ID
        Network Mask = 255.255.255.0
              Attached Router = 192.0.2.3    ;Router ID
              Attached Router = 192.0.2.1    ;Router ID
              Attached Router = 192.0.2.2    ;Router ID
```

BGP4: Border Gateway Protocol v4

- The only Exterior Gateway Protocol (EGP) in use today
- BGP4 is a modified Distance Vector protocol, sometimes called a Path Vector protocol
- It provides routing between *Autonomous Systems*, which are networks running their own IGP internally.

Overview of the BGP4 system



T = Transit AS
S+T = Stub + Transit AS

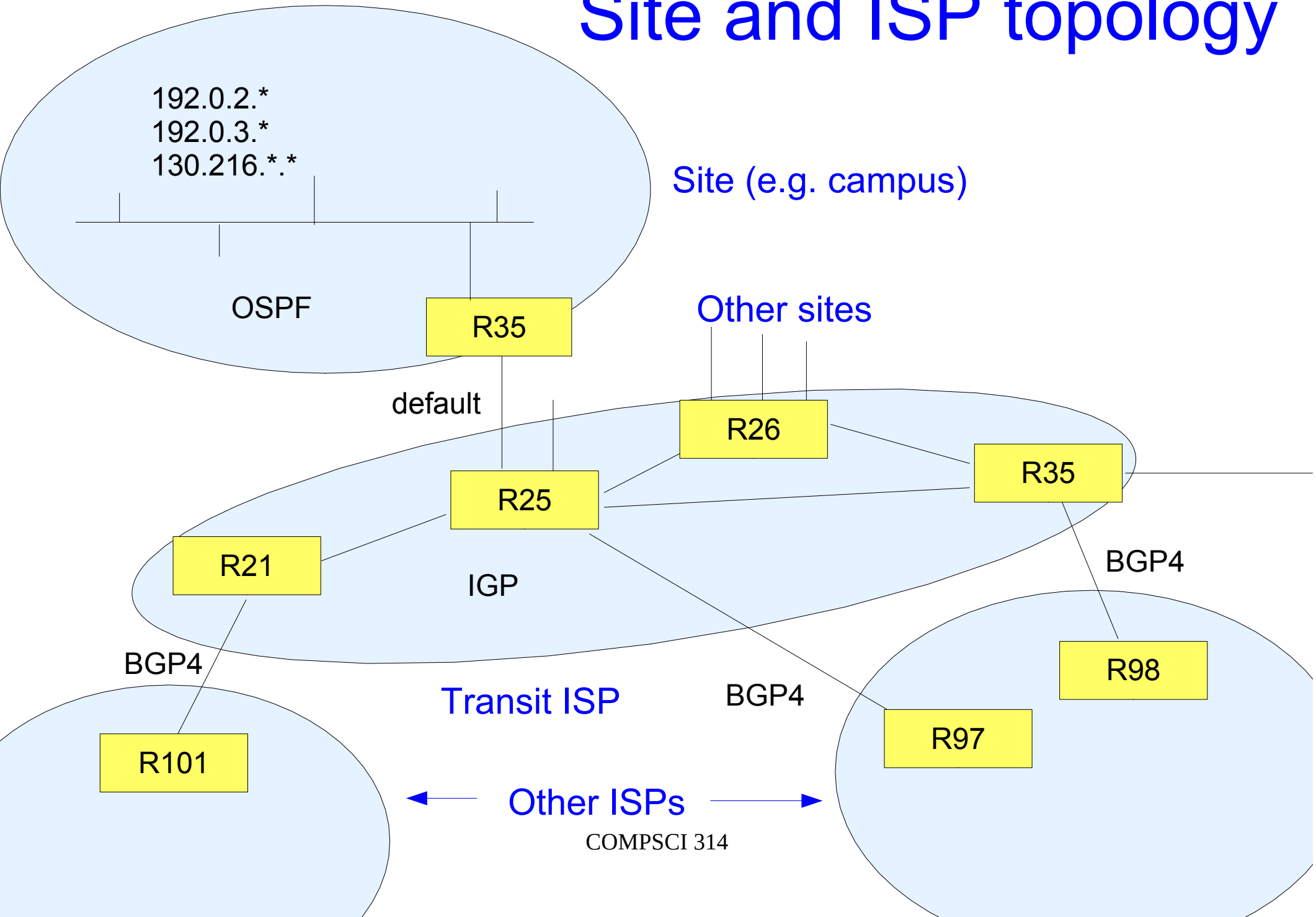
The problem BGP solves

- Assume every site is running an IGP. The world now needs to find routes to the site, for a set of networks, e.g.

  192.0.2.*, 192.0.3.*, 130.216.*.*

  - A site may have several unrelated address blocks.
  - A consumer ISP looks like a site
  - In the world, there are hundreds of 1000s of sites
- How can any site find routes to any other site?
  - Starting point: the *default route* 0.0.0.0 in the IGP points to a site exit router
  - The ISP accepts packets via an ingress router
  - It needs IGP routes to its customer sites and BGP routes to everything else

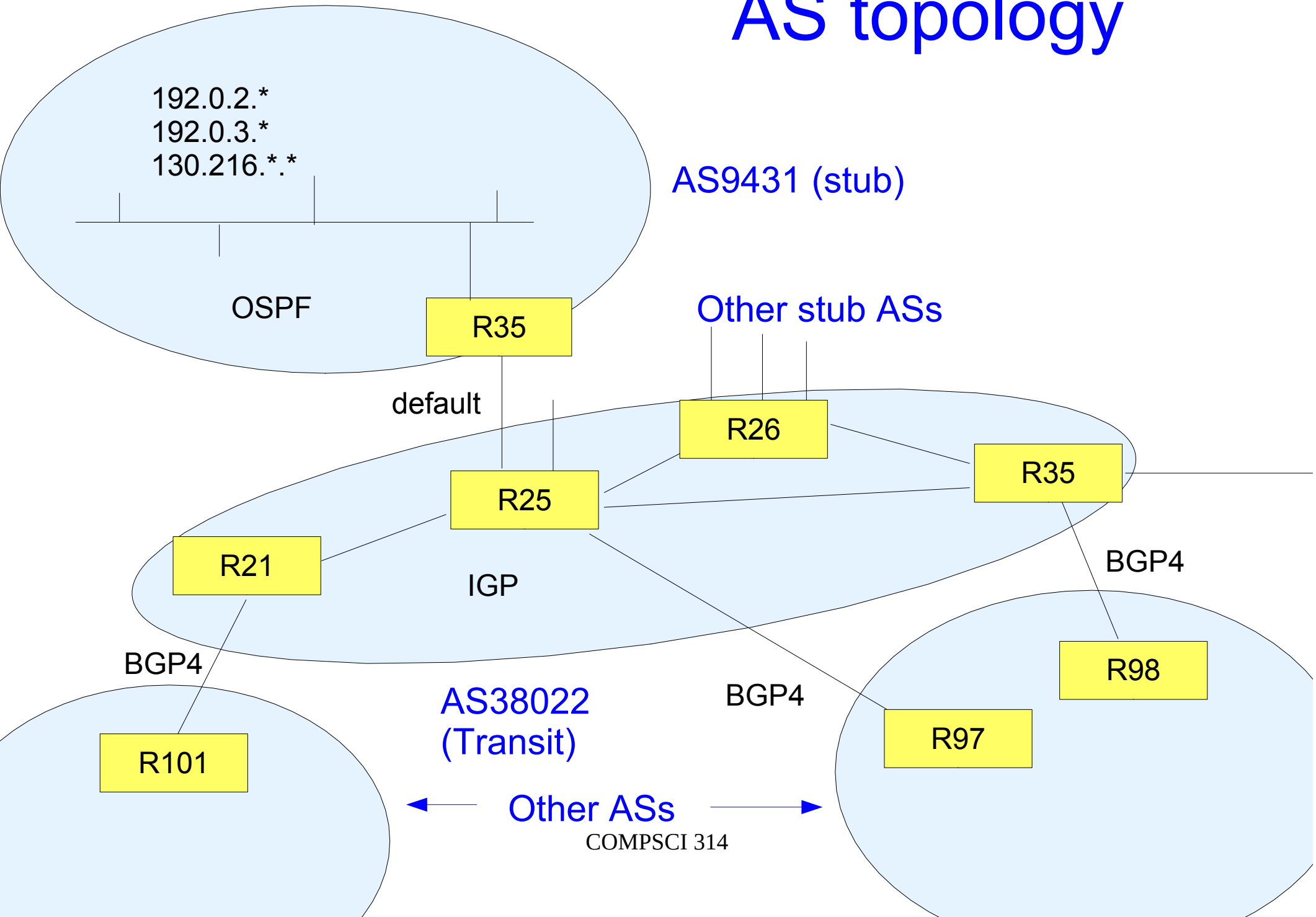
Site and ISP topology



BGP4 AS Paths

- BGP formalises the concept of Autonomous System
  - Over-simplifying, each ISP and each major customer has an AS number.
  - Several ASs can in fact be federated so they appear externally as a single AS.
- An AS path is basically a list of AS numbers that leads to a given destination
  - A destination is a network address/mask, usually called a *prefix* in BGP
  - 130.216/16 means a 16 bit prefix: 130.216.0.0 with mask 255.255.0.0

AS topology


192.0.2.*
192.0.3.*
130.216.*.*
AS9431 (stub)
OSPF
R35
Other stub ASs
default
R26
R35
R25
R21
IGP
BGP4
BGP4
R98
AS38022
(Transit)
BGP4
R97
R101
Other ASs

About AS numbers

- An AS path to 130.216/16 will end with ..., AS38022, AS9431
- AS numbers were 16 bits but are being expanded to 32 bits, since ~50,000 have been handed out already.

BGP messages

- Open
  - Sent when a link to a neighbour BGP speaker comes up
- Update
  - Routing information (see below)
- Notification
  - Sent when a link to a neighbour BGP speaker is intentionally closed
- Keepalive

Note – no Request message in BGP

BGP update messages

- BGP speakers send updates to their BGP neighbours
- They contain various *attributes* per destination
  - Origin of information (IGP or EGP)
  - AS Path
  - IP address of next hop (if not the sender of the update)
  - Unreachable (if announcing a path failure)
  - Metric (only within an AS; BGP does not weight links)
  - Community (see below)

BGP communities

- BGP supports routing *policies* instead of weights.
- The *community* attribute, if used, acts as a label for a group of destinations, so that policy rules can be applied to the group.
    - Example rule: do not use paths to this community that include AS5168.

BGP operation

- When a BGP router receives an update
  - It filters the update according to local policy rules, discarding AS paths that its policy rejects.
  - Then runs Bellman-Ford over the resulting DV table (but uses AS path length as the metric, hence the phrase “path vector”).
  - Then generates update messages for its other neighbours.
- When a BGP router observes a link failure
  - It updates its DV table, runs Bellman-Ford, and generates update messages for its neighbours.

Aggregation

- Today's global BGP4 table has about 330,000 entries (>5 per AS number).
  - See history at http://bgp.potaroo.net/
- It's only that small because BGP *aggregates* adjacent prefixes in a binary tree.
  - 192.0.2.0/24 and 192.0.3.0/24 can be aggregated as 192.0.2.0/23, etc.
  - Two prefixes that share an AS path are aggregated if possible, before advertising the path.

BGP in practice

- BGP4 is the routing protocol that makes the Internet work.
  - Without BGP aggregation, the Internet would have melted down many years ago, with several times more entries in the global table.
  - Today, hardware improvements are roughly keeping up with growth.
  - But the number of dynamic updates is some cause for concern. What if updates start to arrive faster than they can be processed and passed on to the neighbours?

Missing routing topics

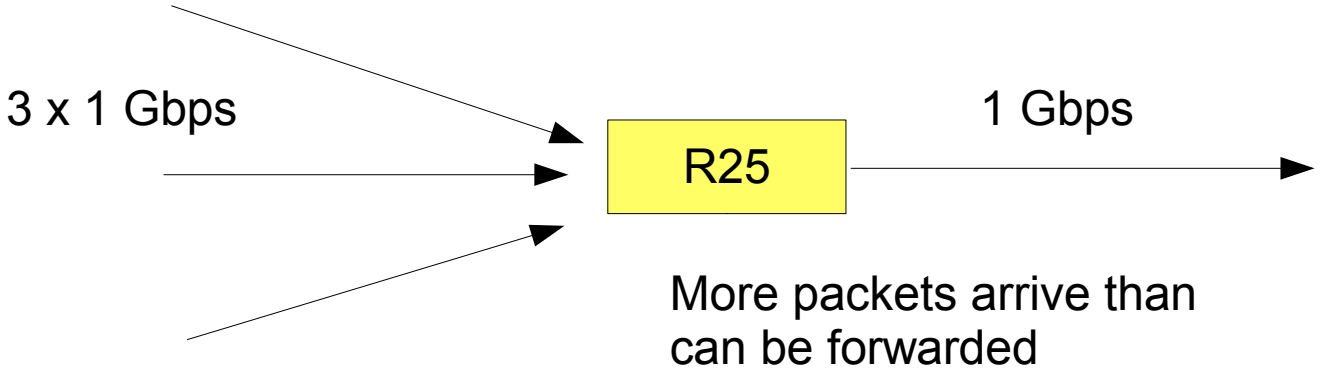
- No time in this course to discuss MPLS (MultiProtocol Label Switching).
  - "Layer 2.5" technique for building semi-permanent switched paths across a backbone network.
  - Used by many ISPs underneath the traditional IGP
- Alternative IGPs
  - IS-IS
    (Intermediate System - Intermediate System).
  - iBGP (interior BGP, used as an IGP by many ISPs)
  - EIGRP (Cisco proprietary IGP)
- Multicast routing (one source, many destinations)

Data structures inside a router: RIBs and FIBs

Background slide

- RIB: Routing Information dataBase
  - The routing table resulting from RIP, OSPF, BGP4, etc.
  - Generally, it's computed and accessed by software.
- FIB: Forwarding Information dataBase
  - A simple table that tells the hardware which interface to send a packet on:
  - IP Address – Mask – Interface number
  - Generally computed by software, but read by specialist hardware operating at line speed (100 Mbps to several Gbps)
  - At 1 Gbps you have ~4 microseconds to process a packet, so the FIB lookup must take a fraction of a microsecond.

Handling congestion



- Ideally, networks are designed to avoid bottlenecks, but sometimes bursts of traffic will cause congestion and buffer overflow.
  - Buffer overflow at both ends of a link could cause deadlock, with both ends unable to send to the other.
- IP is an “unreliable” protocol - congested routers discard excess traffic unpredictably when buffers fill up.
  - We'll see later how this affects upper layer protocols

Routing – related to distance

- How do we connect devices
  - In the same room?
  - In the next room? (tens)
  - In the next building? (100s)
  - In the next department?
  - In the next campus? (1000s)
  - In the next country? (millions)
  - In the next continent? (billions)

Hubs, switches

Cable/radio boundary

OSPF + Admin boundary

MPLS + Funding boundary

BGP4 + Political boundary

Distance, cost and numbers increase; must share costs and cables, but separate administration

References

- Shay 10.3 to 10.8
- Advanced text book (*completely optional*):

Interconnections (2nd edition)
by Radia Perlman (Addison-Wesley)
Published 1999 but still unbeaten

- The technical specs for all Internet protocols are published free as numbered “RFCs” (originally “Request for Comment”). They make tough reading and are *completely optional* for this course.
  http://www.rfc-editor.org/rfcsearch.html
  - RIP: RFC 1723
  - OSPF: RFC 2328
  - BGP4: RFC 4271