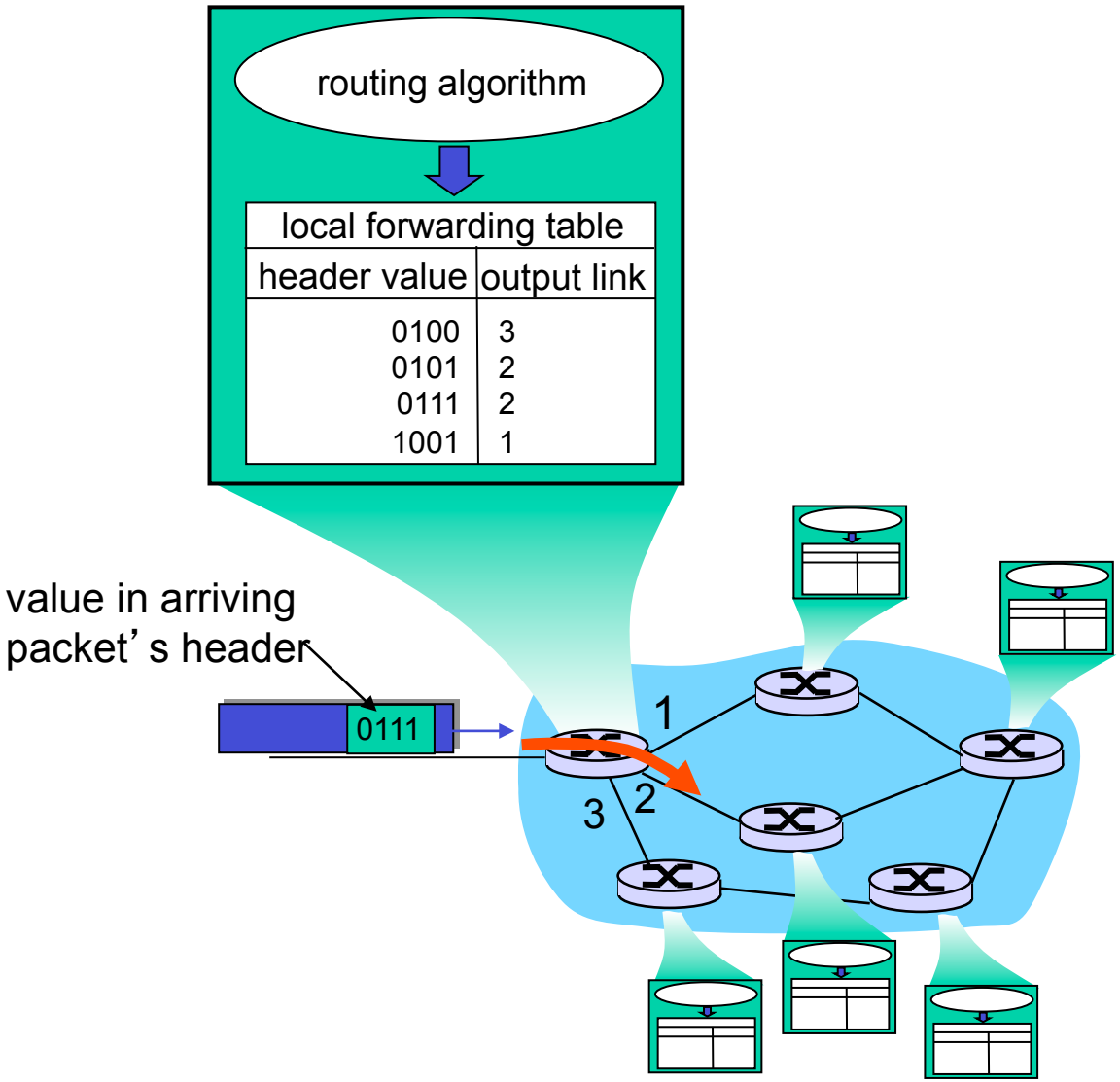
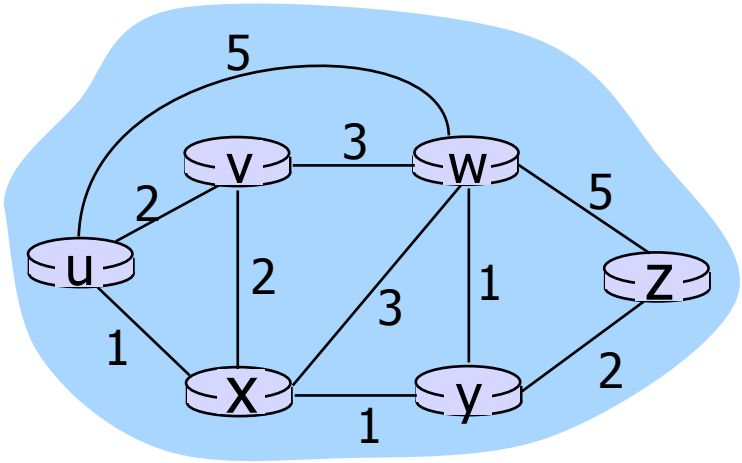
Internet Routing

Interplay Between Routing, Forwarding



Graph Abstraction



Graph:

$G = (N,E)$

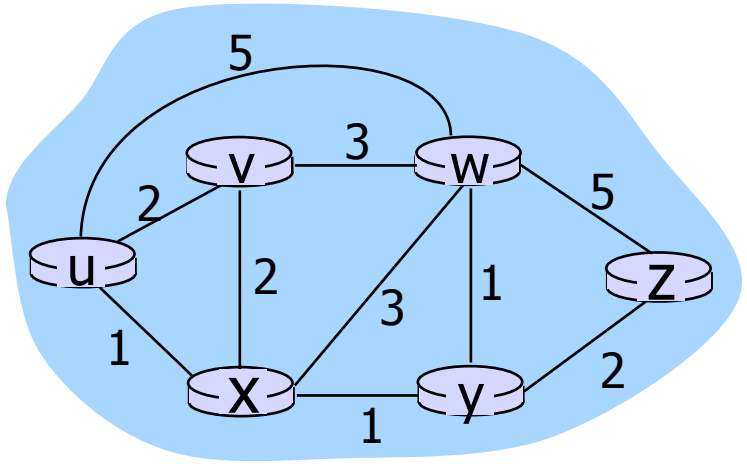
N = set of routers = { u, v, w, x, y, z }

E = set of links =

{ (u,v), (u,x), (v,x), (v,w), (x,w), (x,y), (w,y), (w,z), (y,z) }

Path: Sequence of edges (routers)

Graph Abstraction: Costs



- $c(x,x')$ = cost of link (x,x')
  - e.g., $c(w,z) = 5$
- cost can be always 1, or inversely related to bandwidth, or inversely related to congestion

Cost of path $(x_1,x_2,x_3,\ldots,x_p) = c(x_1,x_2)+c(x_2,x_3)+\ldots+c(x_{p-1},x_p)$

Routing algorithm: alg. that finds "good" path (typically: least cost path)

Internet Design Philosophy (Clark' 88)

In order of importance:

0 Connect existing networks
- Initially ARPANET and ARPA packet radio network

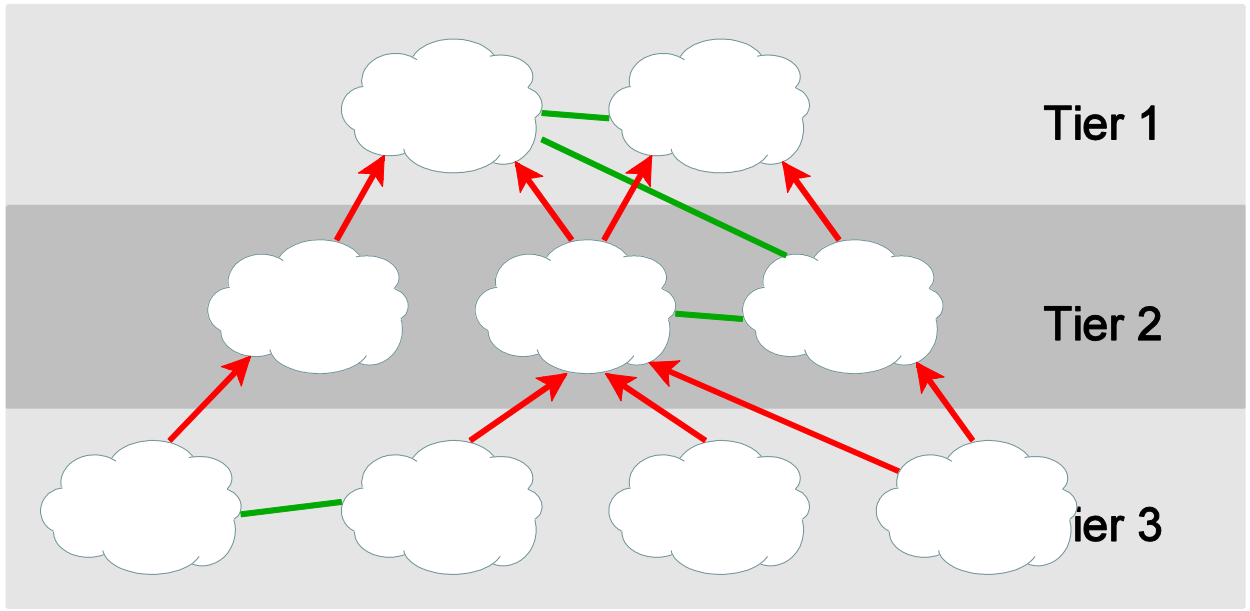
1. Survivability
- Ensure communication service even with network and router failures

2. Support multiple types of services
3. Must accommodate a variety of networks
4. Allow distributed management
5. Allow host attachment with a low level of effort
6. Be cost effective
7. Allow resource accountability

Different ordering of priorities would make a different architecture!

Routing Hierarchy

- Why
  - Different networks
  - Different administration
  - Different goals



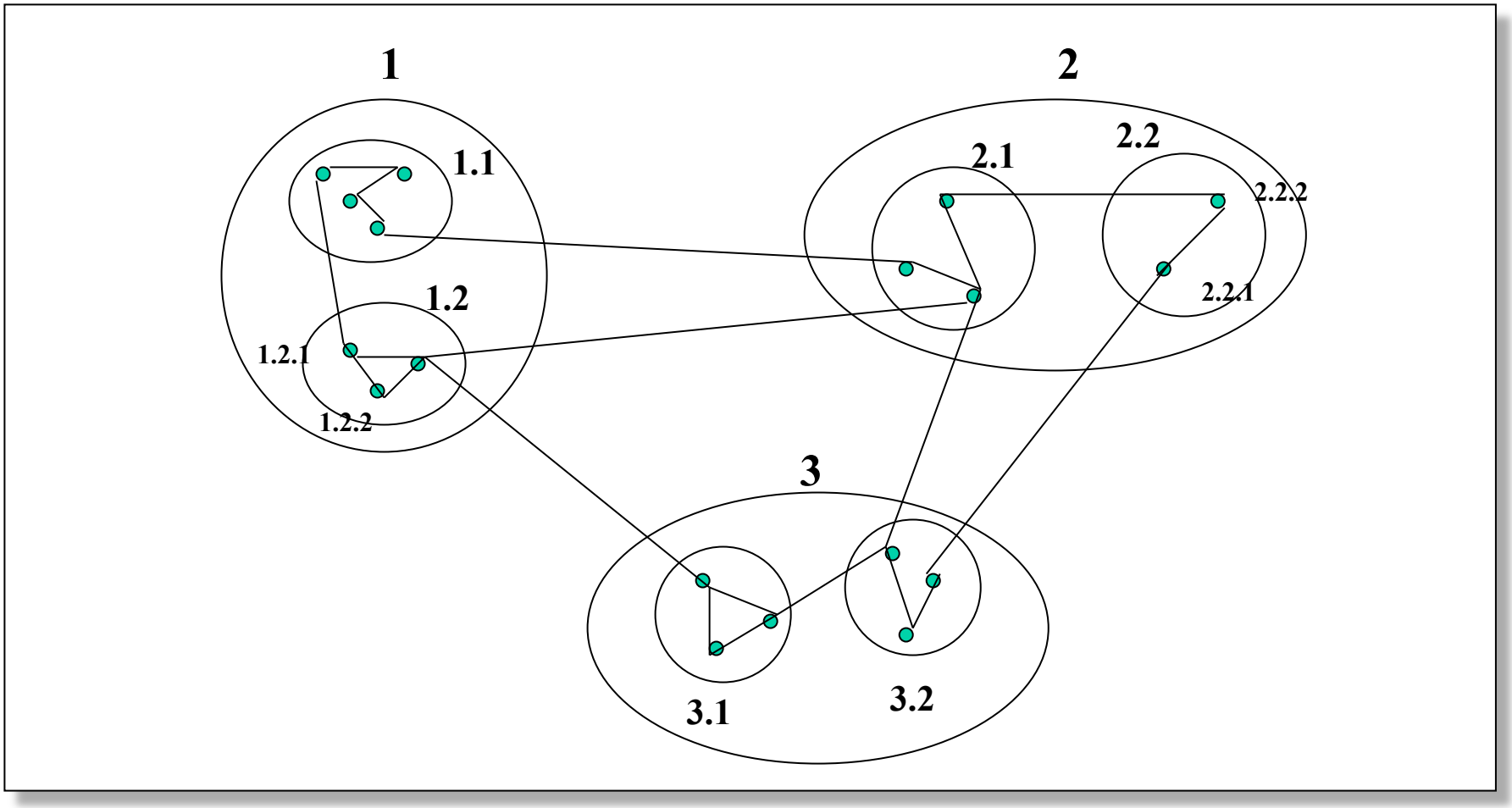
Routing Hierarchy (cont.)

- Key observation
  - Need less information with increasing distance to destination
- Two radically different approaches for routing
  - The area hierarchy
    - Chosen in the Internet
  - The landmark hierarchy

Areas

- Divide network into areas
  - Areas can have nested sub-areas
  - Constraint: no path between two sub-areas of an area can exit that area
- Hierarchically address nodes in a network
  - Sequentially number top-level areas
  - Sub-areas of area are labeled relative to that area
  - Nodes are numbered relative to the smallest containing area

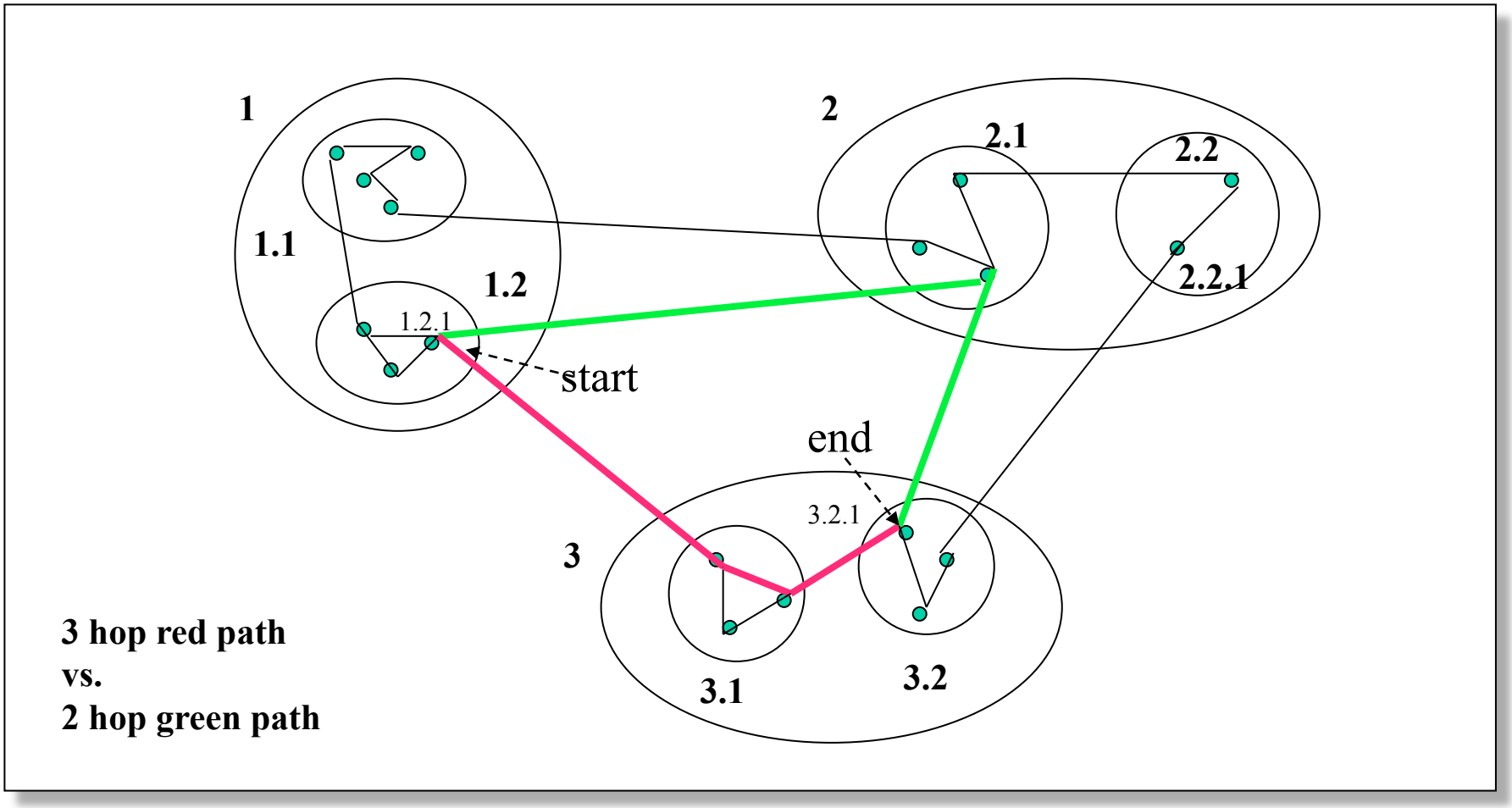
The Area Hierarchy



Routing

- Within area
  - Each node has routes to every other node
- Outside area
  - Each node has routes for other top-level areas only
  - Inter-area packets are routed to nearest appropriate border router
- Advantage:
  - Routing manageable due to reduced problem size
- Disadvantage:
  - Can result in sub-optimal paths

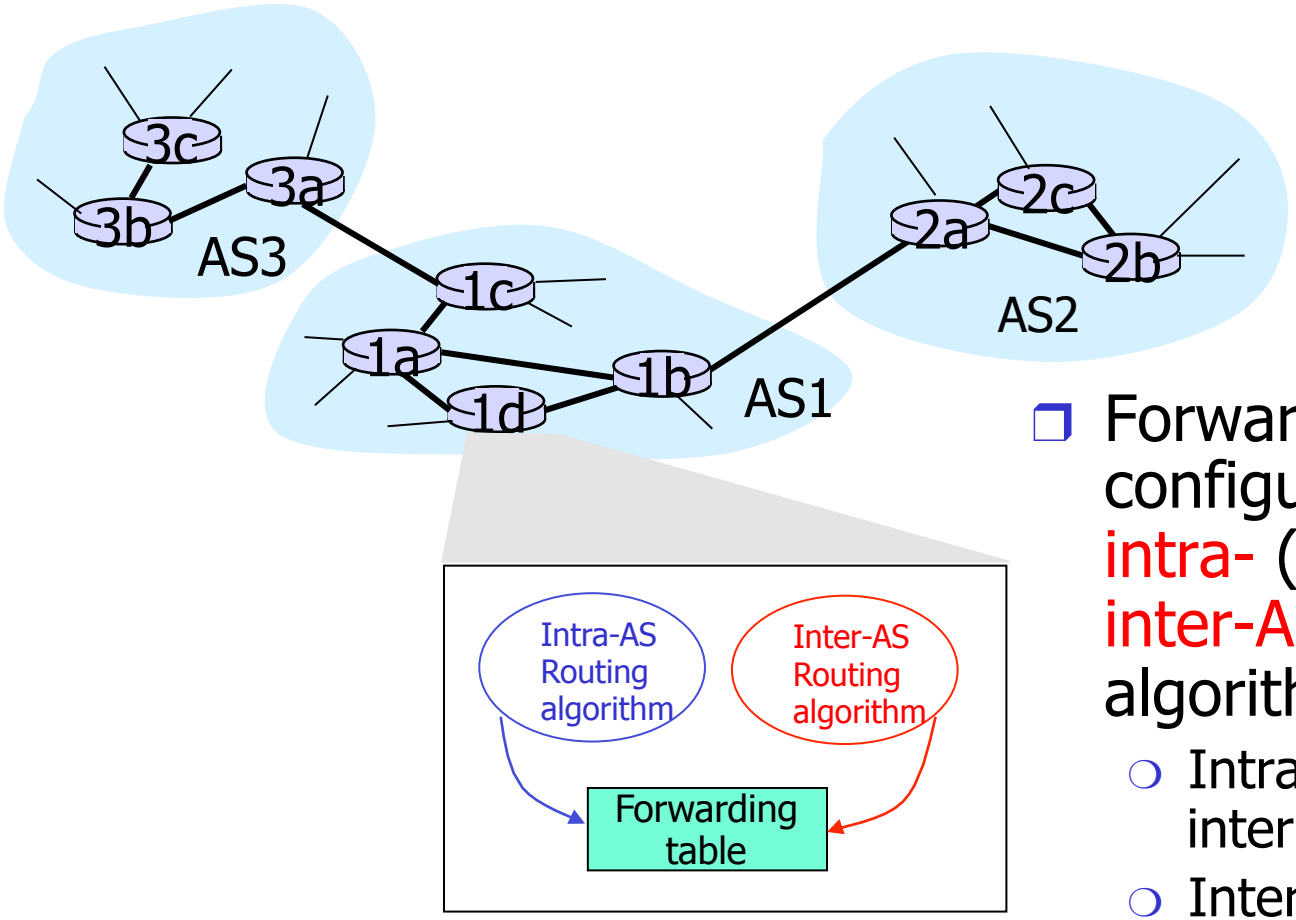
Path Sub-optimality



Internet's Area Hierarchy

- What is an Autonomous System (AS)?
  - A set of routers under a single technical administration, using an *interior gateway protocol (IGP)* and common metrics to route packets within the AS and using an *exterior gateway protocol (EGP)* to route packets to other AS's
  - Sometimes AS's use multiple IGPs and metrics, but appear as single AS's to other AS's
- Each AS assigned unique ID
- AS's peer at network exchanges

Interconnected ASes



- Forwarding table is configured by both intra- (IGP) and inter-AS (EGP) routing algorithm
  - Intra-AS sets entries for internal dsts
  - Inter-AS & Intra-As sets entries for external dsts

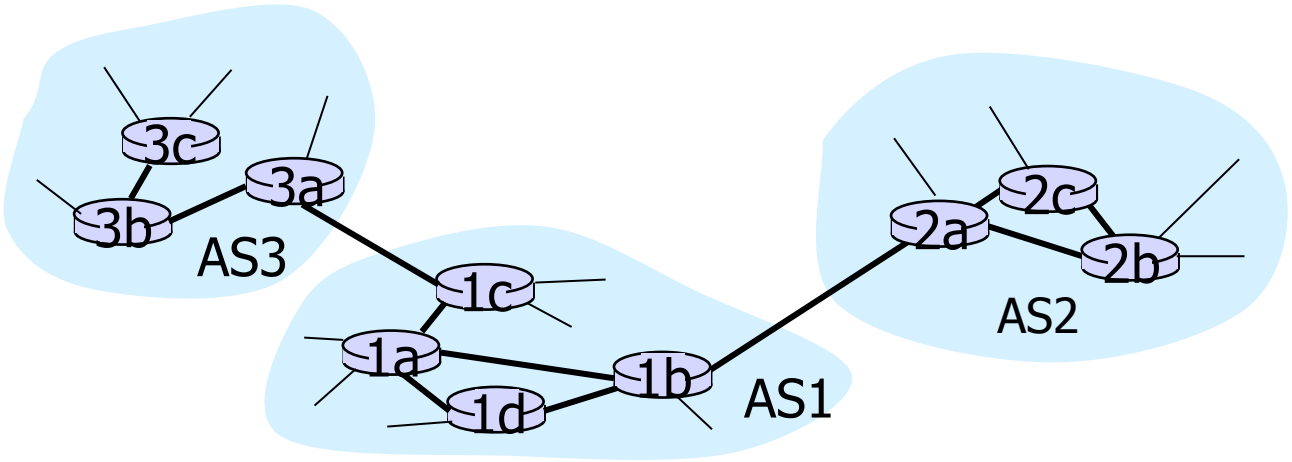
Inter-AS tasks

- Suppose router in AS1 receives datagram for dst outside of AS1
  - Router should forward packet towards a gateway routers, but which one?

AS1 needs:

1. To learn which dsts are reachable through AS2 and which through AS3
2. To propagate this reachability info to all routers in AS1

Job of inter-AS routing!

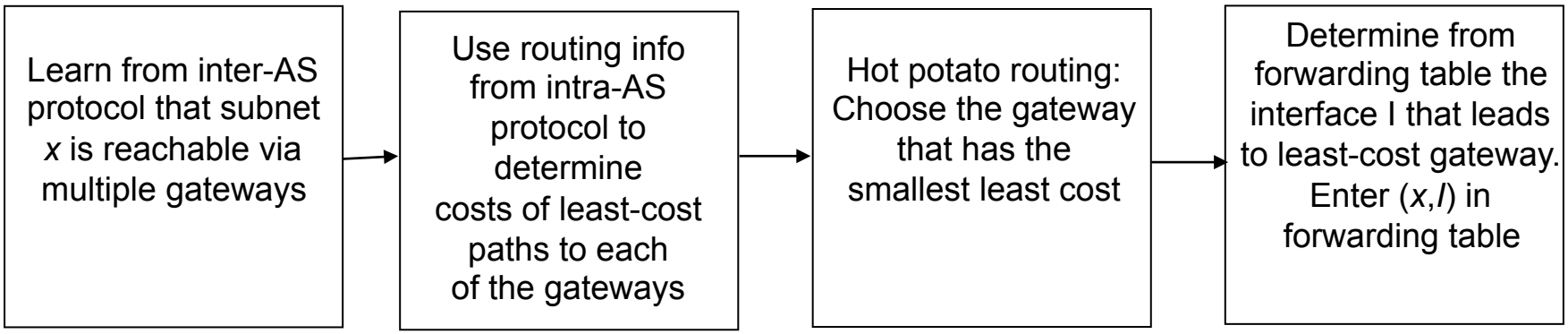


Example:
Setting Forwarding Table in Router 1d

- Suppose AS1 learns from the inter-AS protocol that subnet *x* is reachable from AS3 (gateway 1c) but not from AS2.
- Inter-AS protocol propagates reachability info to all internal routers.
- Router 1d determines from intra-AS routing info that its interface *I* is on the least cost path to 1c.
- Puts in forwarding table entry *(x,I)*.

Example: Choosing Among Multiple ASes

- Suppose AS1 learns from the inter-AS protocol that subnet *x* is reachable from AS3 *and* from AS2.
- To configure forwarding table, router 1d must determine towards which gateway it should forward packets for dst *x*.
- This is also the job on inter-AS routing protocol!
- Hot potato routing: send packet towards closest of two routers.



Internet Intra-AS Routing

- Also known as Interior Gateway Protocols (IGP)
- Most common Intra-AS routing protocols:
  - RIP: Routing Information Protocol
  - OSPF: Open Shortest Path First
  - ISIS: Intermediate-System-to-Intermediate-System (ISO 10589)
  - IGRP: Interior Gateway Routing Protocol (Cisco proprietary)
  - EIGRP: Enhanced Interior Gateway Routing Protocol (Cisco proprietary)

Internet Inter-AS Routing:

- BGP (Border Gateway Protocol): *the* de facto standard
- BGP allows a subnet to advertise its existence to rest of the Internet: *"I am here"*
- BGP provides each AS a means to:
  1. Obtain subnet reachability information from neighboring ASs.
  2. Propagate the reachability information to all routers internal to the AS.
  3. Determine "good" routes to subnets based on reachability information and policy.

Routing Tasks

- Neighbor
  - Discovery
  - Maintenance
- Database
  - Granularity
  - Maintenance – updates
  - Synchronization
- Routing table
  - Metric
  - Calculation
  - Update