An Overview of Routing Theory

IP Routing

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Routing Theory

- topologies and scalability
- basic tools & ideas & attributes
  - » static vs dynamic, flooding, tunnels, control theory
- some issues; e.g., congestion
- algorithms: vector-distance vs link-state

fundamental ideas

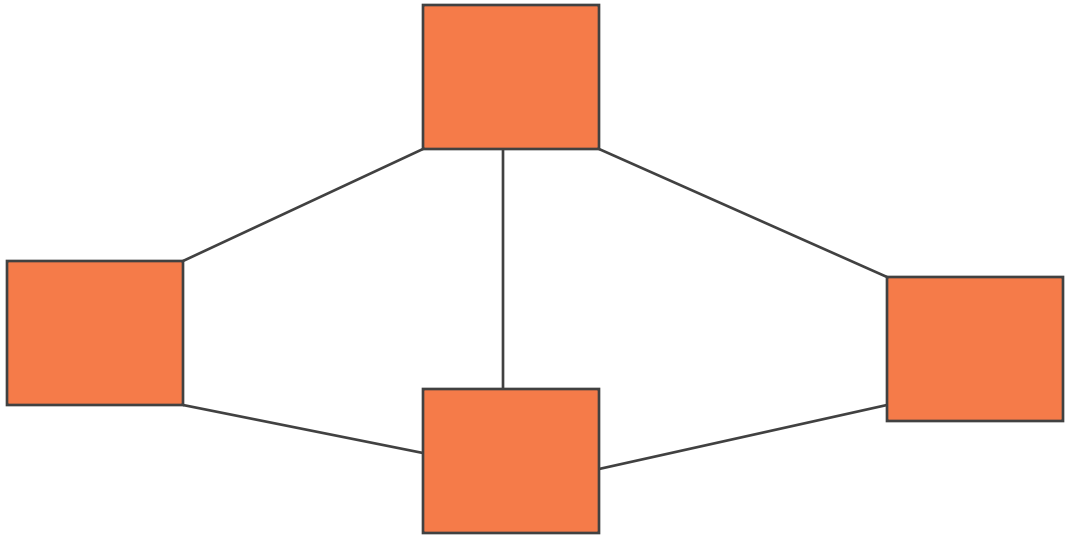
- **routing** - finding a path from one end to the other for a packet
- we need one or more **algorithms** that are most likely **distributed** amongst a set of hosts and router
- what are the properties of said algorithm?
- what issues affect it?

elements of a routing scheme

- **routing protocols** that allow info to be gathered and distributed - routing agents communicate with these protocols
- **routing algorithms** - may be distributed, use protocols and data to determine and disseminate paths
- **routing databases** (tables in routers) (to boardwalk, via new jersey, $100)

a routing domain

a **routing domain** == set of routers under same admin running same routing protocol



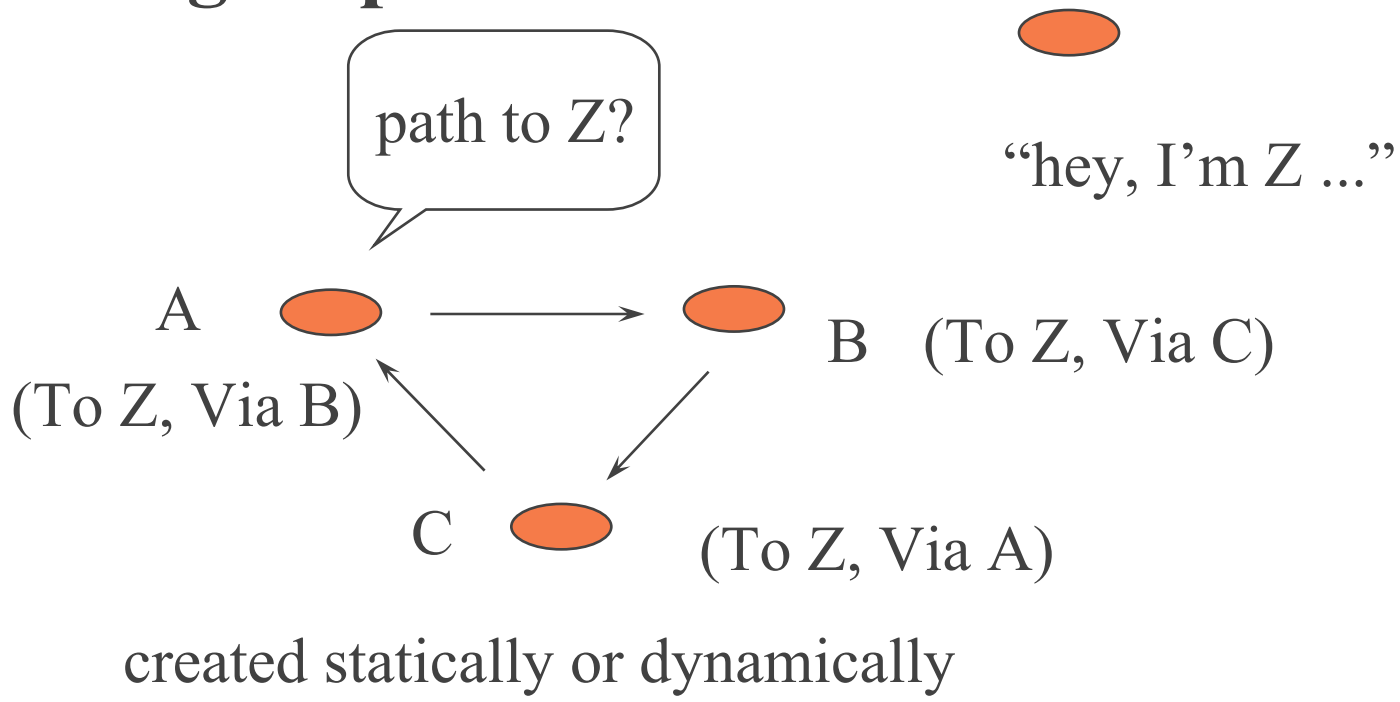
e.g., all these routers are controlled by Joe Bob Inc, run OSPF

ideal routing algorithm

- correct - what if algorithms too complex?
- robust - can deal with router reboot?
  - two problems: loss of router and loss of link (i/f failure ...)
- stable - do routing changes stabilize in distributed system?
  - **convergence** - a state, all routers have "same" routing table
- efficient - all routing and no data not good
- topologically flexible, can allow **aggregation**
- maintainable - admin not too complicated
- **scalable** to many routers, many hosts? (distributed)
- deadlock? - routing **loop-free**?
- secure - can intruders inject routes?

classic problem

- **routing loop**



created statically or dynamically

topology

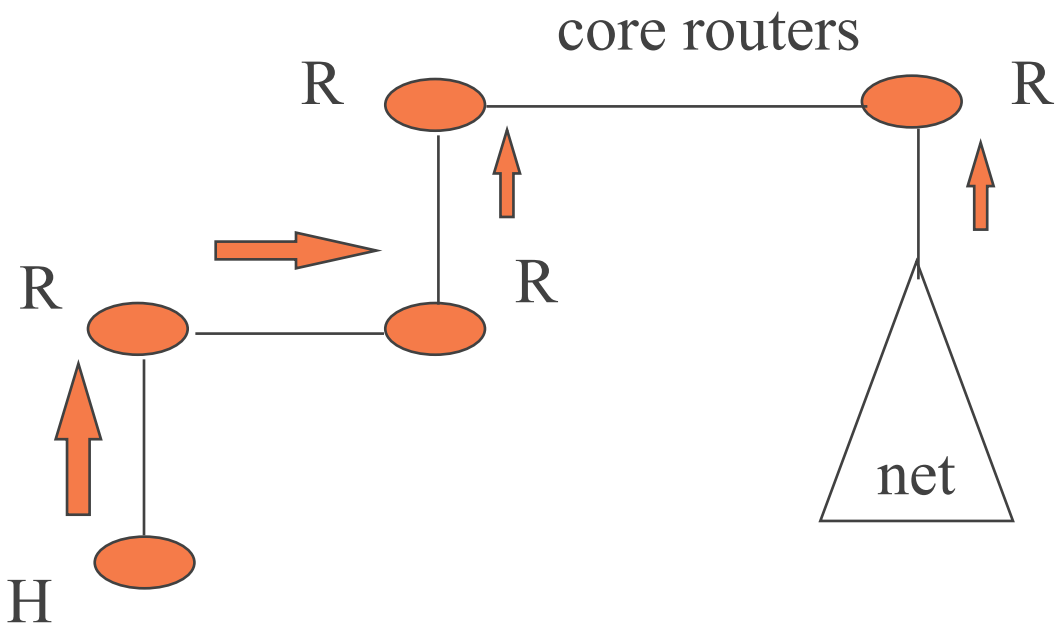
- Tanenbaum mentions logical absurdities
- **no router -** every host wired to every other host (mesh)

  N * N wires, go ahead add a host...
- **1 router -** for all hosts (star)
  - 1 heck of a routing table
  - this is why core can have problems
  - single point of failure?!
  - everything should be fully connected?!

one solution

- typically a flattened tree to give hierarchy
- at the top a small circle of core routers that know all the routes
- idea: **default route**
  - if you are not in the center AND you don't know what to do with it, send it "UP" to smarter entity

routing hierarchy



this could be the model for an intranet OR
the Internet as a whole (multiple core rings)

default route

R router

levels

- the top level has to know everything
  - in a routing domain, routers know all the routers at level 1
  - in BGP, top of Inet, routers may have full routing table
- routers may also choose to hide interior structure (subnet/CIDR) in order to **aggregate** routing info
  - reduce routing table size elsewhere

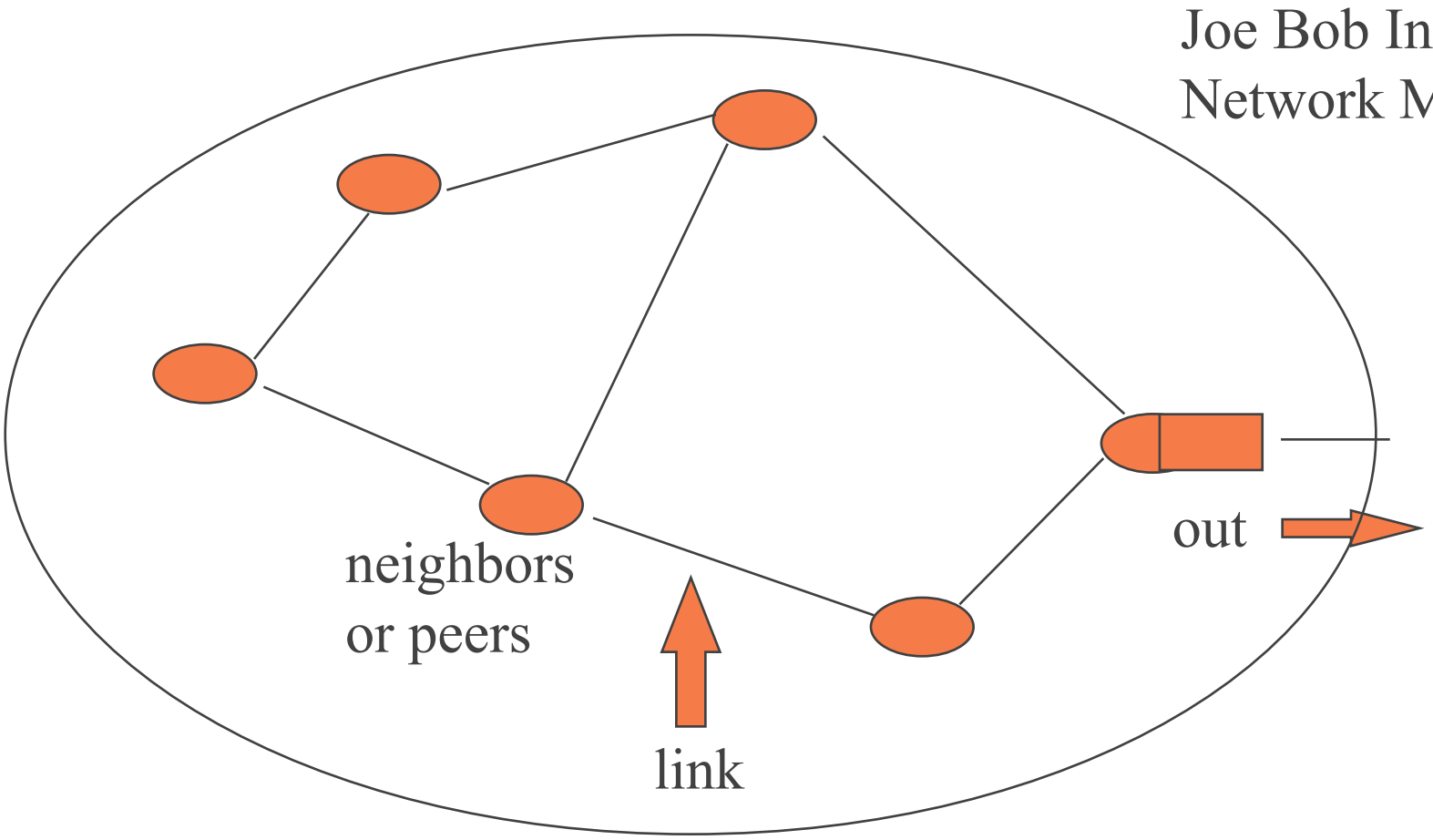
divide routing world into 3 parts

topology	IETF	ISO/OSI
same “link” or wire	none, intra-link?	none, intra-link?
enterprise or campus	Interior Gateway Protocol - IGP	intra-domain routing protocol
between enterprises	Exterior Gateway Protocol - EGP	inter-domain

protocols acc. to topology

topology	IETF	ISO/OSI
intra-link	ARP	ES-IS
intra-domain	RIP, RIP(2), OSPF	IS-IS
inter-domain	EGP, BGP(4)	IDPR

the Interior - RIP or OSPF



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the "world" (from router POV)

scalability is a LARGE concern

- 10's of hosts and a few routers - static routing
- what about putting all of those toasters on the Internet? (what if the net/hosts bigger?)
- one home/office, to business/enterprise, to state, nation, planet, solar system, galaxy...
- components affected include the network address and the router hierarchy

scalability...

- ip's current problems
  - net/hosts via class or even subnet don't match number of hosts really utilized
  - too many routes in core tables (again true post CIDR)
  - ip address allocation from class C slice of pie means in effect majority of numbers are wasted
- scalability affects addresses and how they are sliced up; also router hierarchy
- how much low-level info (e.g., link-level details) can we afford to disseminate upwards?

Some current BGP issues

- # entries > 100000, growing faster than a linear rate?
  - CIDR help in mid-90s has worn out?
- # entries that are /24 or bigger?
  - I.e., not enough aggregation
  - entries may need dampening
- aggravated by mesh redundancy
  - if multi-homed more paths announced to world

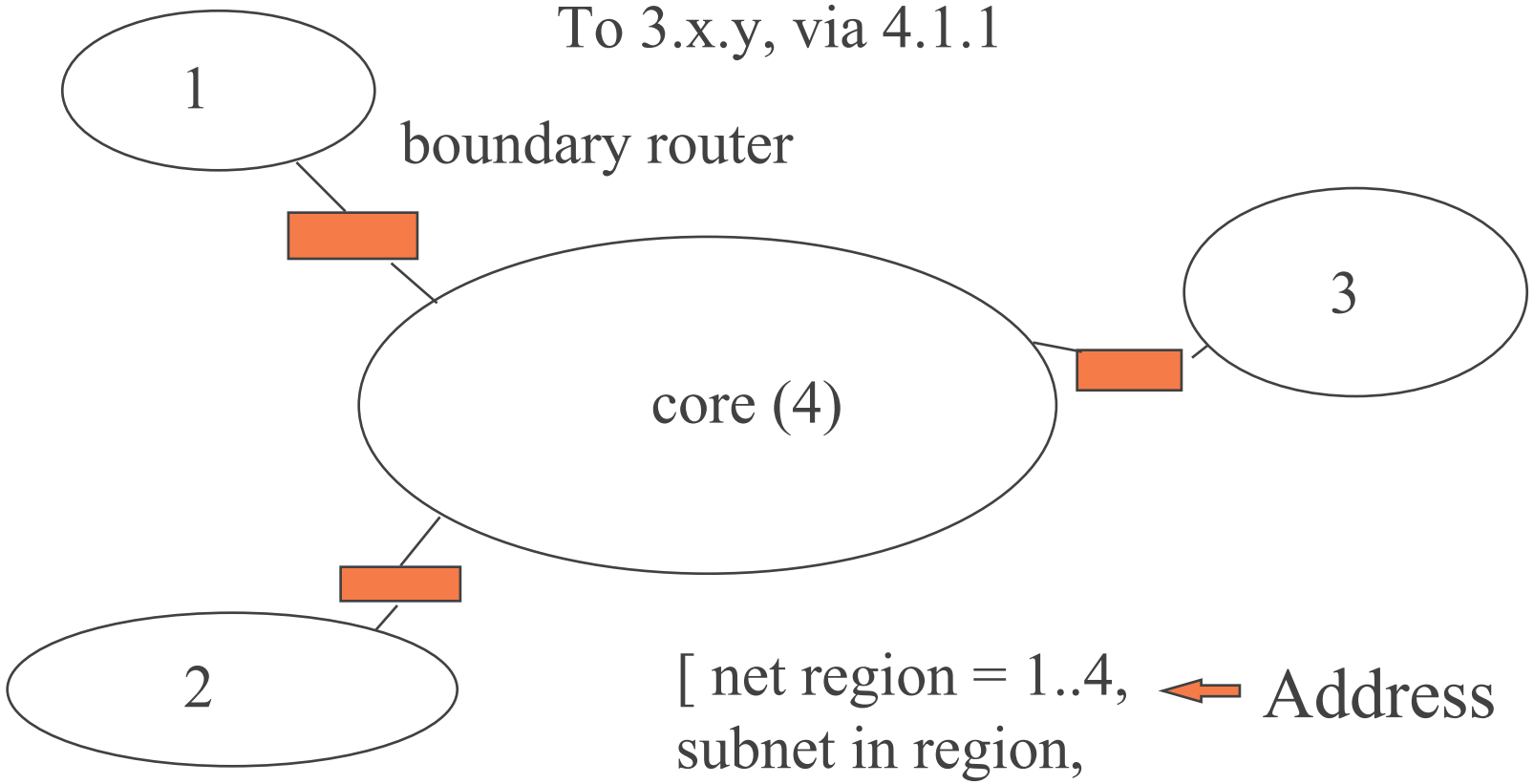
N**2 is not our friend

- Has a tendency to show up in routing protocols/theory because naturally:
- routers (nodes) times links (connections)
- remember Andrew T. and what happens if all nodes directly connect!
- The problem here is memory storage in individual core routers
  - how much memory if a core router must remember: 1. All link metrics, 2. All host attributes, 3. Host X host attributes

to increase scalability, add a prefix

- domain routers as 1st assumption - assume they know all the routes.
- if that isn't scalable, then add new hierarchy and introduce new layer of structure, find points of aggregation
- IP is moving towards this (CIDR)
- phone companies have prefixes (not enough... nobody is perfect)
- NAT, MIP(tunnels), IPv4+AS, all ways of doing this (to say nothing of 128bit addresses)

hierarchy picture



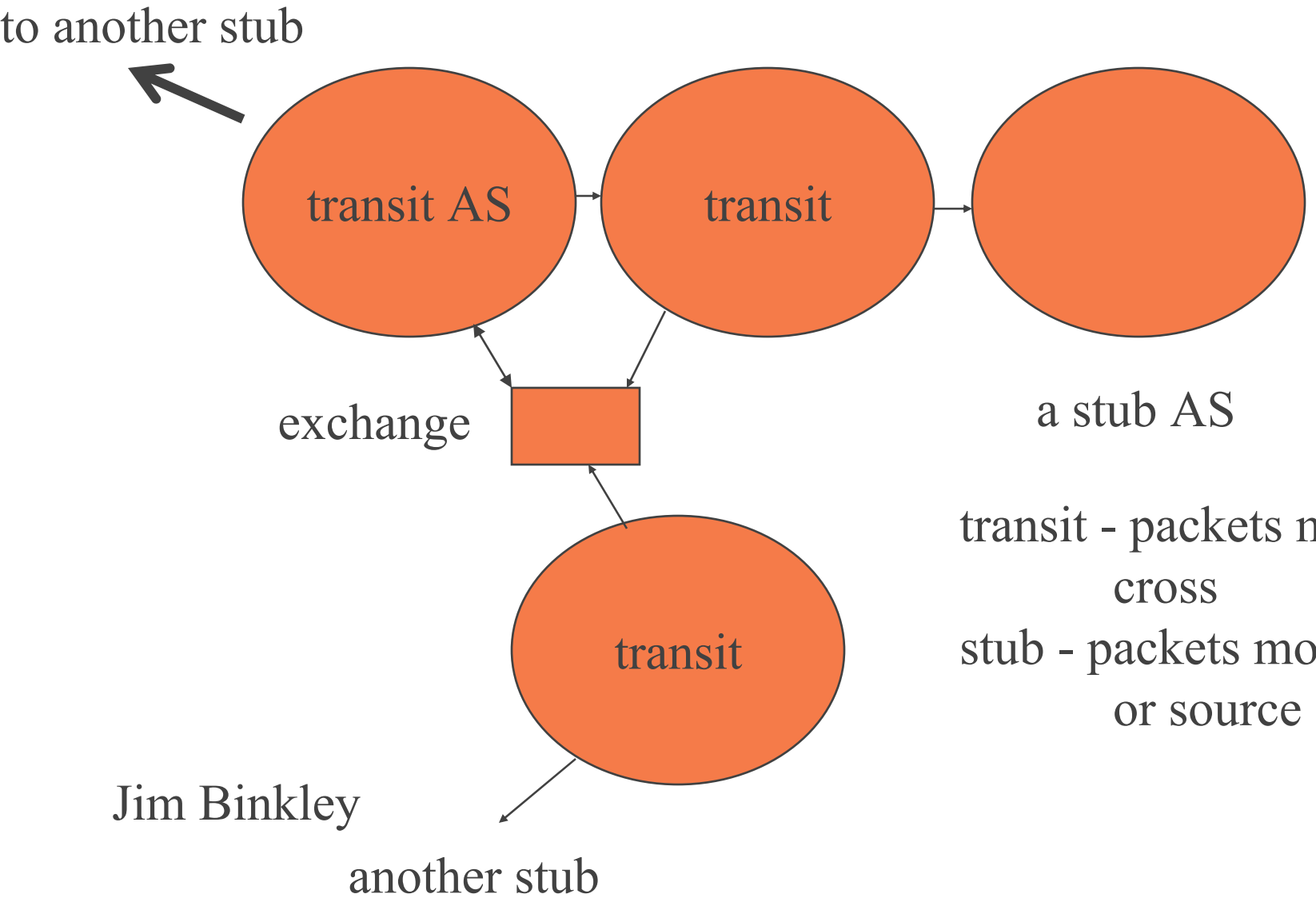
general solution to problem exists

- **when in doubt, add a new prefix** to address and a new SMALLER center to the world
- prefix must **summarize** internal structure
- divide world into
  - center: (layer 1) boundary routers
  - domains: (layer 2) inside routers
- boundary routers have summary routes in them, not all.

btw, this is related to a magical architectural design principle

- add a **layer of indirection** == POWER
- consider IPv6 address (ip part, IEEE mac part)
- Mobile-IP 2-part AWAY address (FA Care-Of-Address, Mobile-IP Home Address)
  - irony here is the power of this is not well understood
- BGP IPv4 “address” is (set of AS #s, IP dst)
- ahem: NAT since this may add to the IP address space pool (a few real ip addr, mapped to many private ip address), under severe constraints

Inet has multiple centers



transit - packets mostly cross
stub - packets mostly sink or source (ES)

3 ways routes get into routing tables

- static - loaded by network admins
  - put into config to auto-load at boot
  - route add 10.0.0.0 -gw gateway-ip
- dynamic routing
  - done by routing daemons running a routing protocol
- kneejerk modification to host routes by ICMP redirects
  - typically way to populate routing table with default route

static routing

- static pros:
  - simple, may be easiest thing to do in simple topology, especially for leaf host with 1 router only
  - you may be smarter than the routers (want a path they won't give you) - policy routing possible
- static cons:
  - can't react dynamically to crashed router (still need two routers to react though...), anti-redundancy
  - not scalable, not good if you have 100 routers to configure right now (or 1000 hosts)

dynamic routing

- we need a distributed routing protocol
- goals:
  - intelligent (sic?) choice of route based on metric (single more likely than multiple)
  - automatic population of routing table to avoid manual setup
  - redundancy of routing path; i.e., convergence post path failure due to loss of router, interface, or sudden onset of backhoe

theory: routing protocol types

- **centralized** versus **distributed** versus **end-node**
  - center is necessary, can't have defaults everywhere
    - » why not just compute and put in center?
  - if end nodes have route info, and big net,
    - » not scalable, then route tables huge - need to limit size
- some sort of distributed system is conventional answer

types/tools - source routing

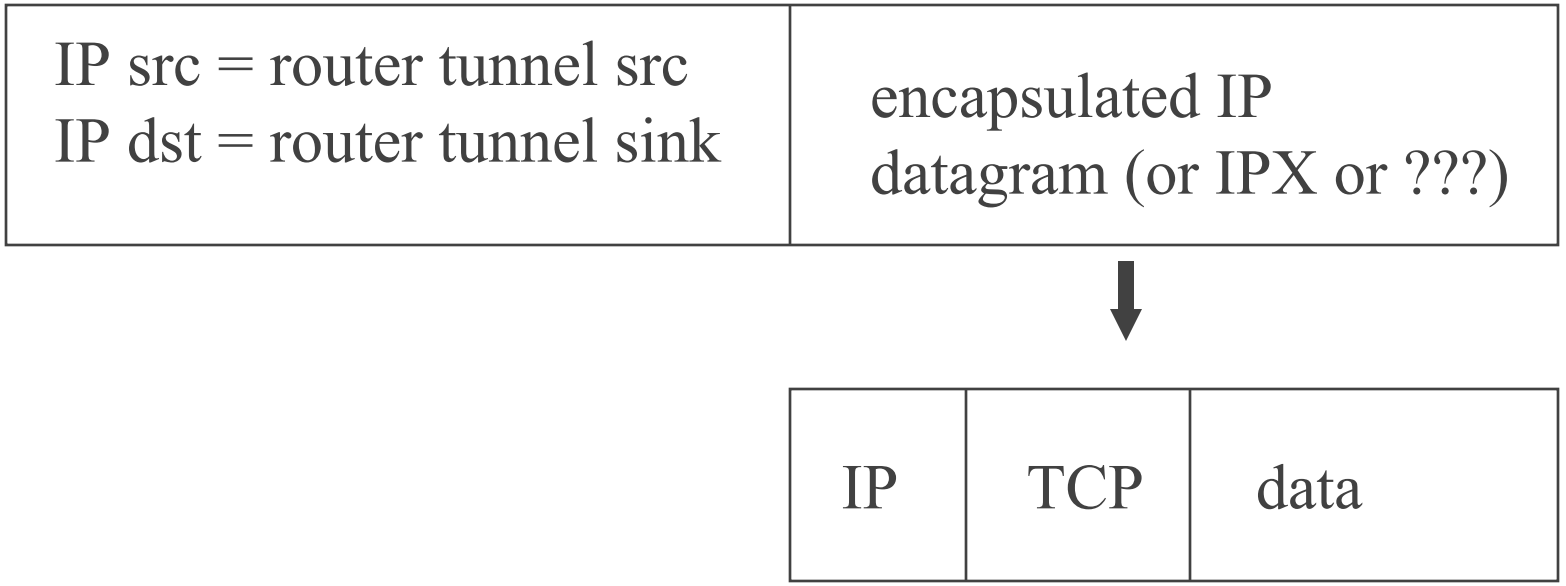
- source-routing vs hop-by-hop
  - end node has exact PATH and datagram follows that path: (first to Joe, then to Bob, then to Grandma's)
  - IP option, but rarely used (strict/loose)
  - challenge to security: what if hostile entity convinces you to route all packets through it?
    - » maybe it can masquerade as you after that?
  - still a **possible tool** - used in BGP, can communicate POLICIES, from Novell to Intel, please Skip Bellevue
  - as scalable as hop by hop?

routing tunnels are basic tool

- tunnels are example of source routing (doh!)
  - strict or loose?
- IP datagram with IP header (IPIP)
  - MBONE DVMRP, Mobile-IP (unicast)
- IPX, APPLETALK datagram inside IP header
  - Cisco GRE tunnels designed as general way to do tunnels (GENERIC ROUTING ENCAPSULATION)
  - IPv6, IPv4 IPv6, or IPv6 IPv4
- security tunnels, IP IPSEC IP, basis of VPNs

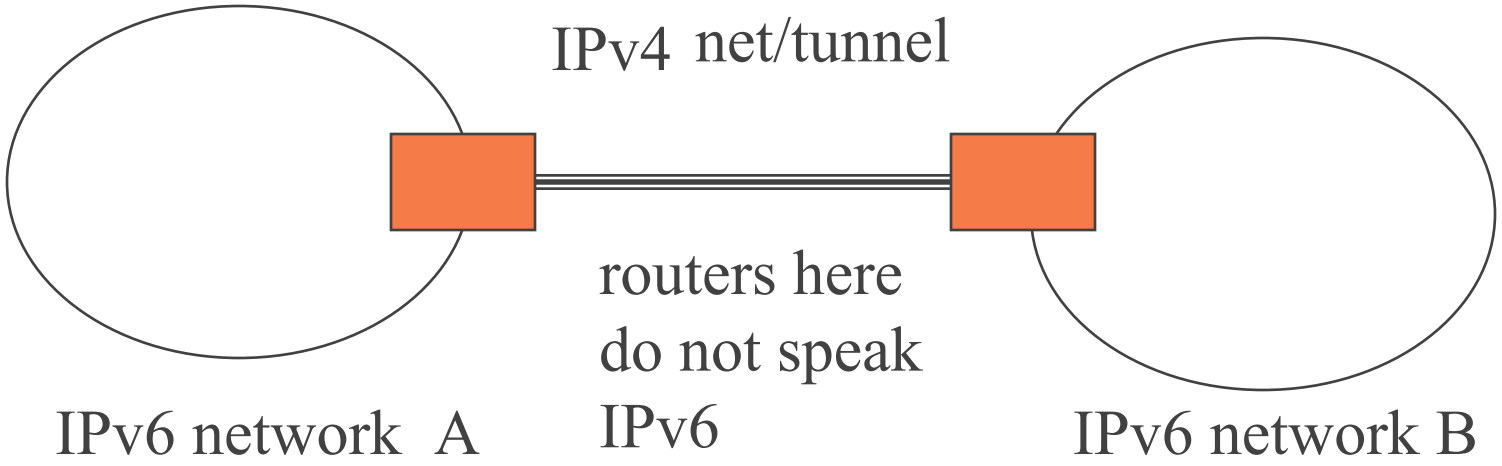
encapsulation scheme

IPIP (btw: IP next proto == 4 for IPIP)



IP tunneling mesh

IPv4 | IPv6 datagram virtual network

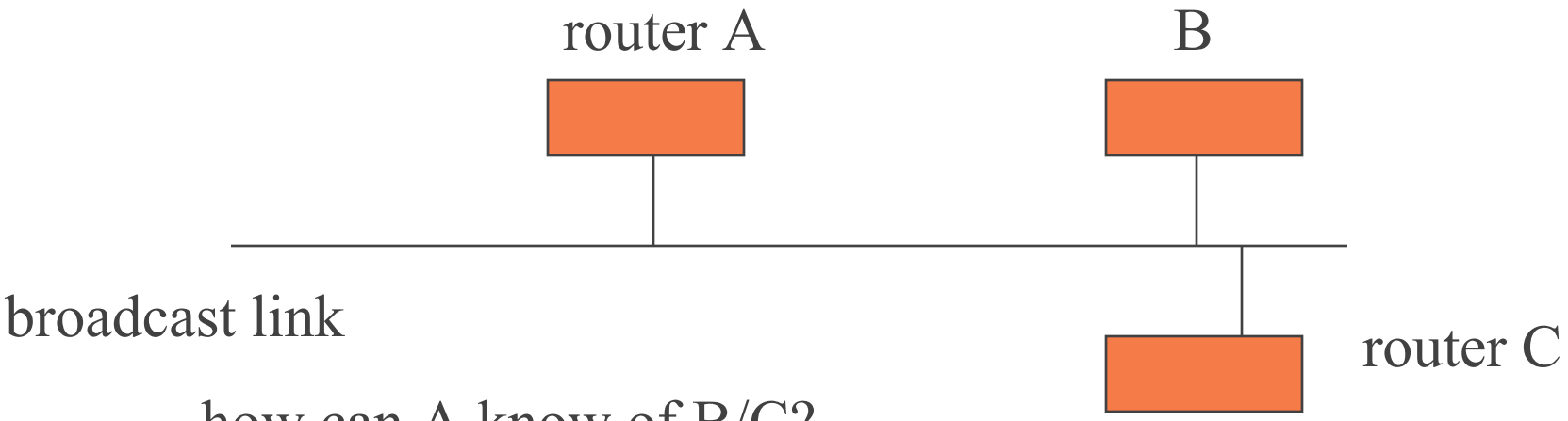


route to net B, forward to A border router, which
will encapsulate and send to B border router

control-theory

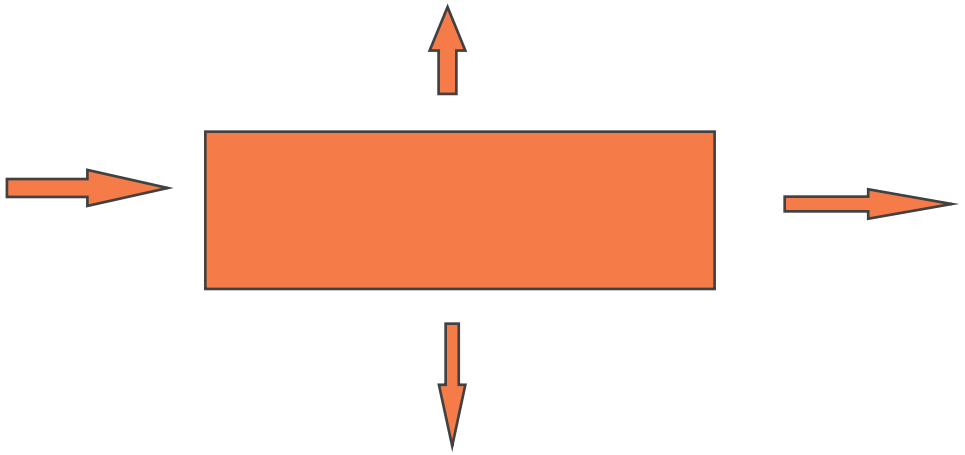
- routing is **control**, without it, data cannot flow
- chicken&egg problem: routing in terms of **addressability** must exist a priori before routing can occur
  - I can't send you packets if I can't find you ...
  - think about this in terms of every routing protocol
  - addressability is fundamentally link dependent
  - sometimes we rely on manual configuration (serial)
  - sometimes information automatically gathered (arp or multicast on ethernet)

addressability problem



types/tools - flooding

- flooding - assume N interfaces
  - packet comes in N(1)
  - packet goes out N(2)..N(N)



be careful with flooding...

flooding, cont.

- important routing algorithm “tool” - used in many routing algorithms in some sense
- strong pro and con/s
- **pro - perfect routing**, you follow the best path (redundancy here is a feature!)
- **con - “perfect congestion” -** you use up too much bandwidth
- **con** – you may loop packets

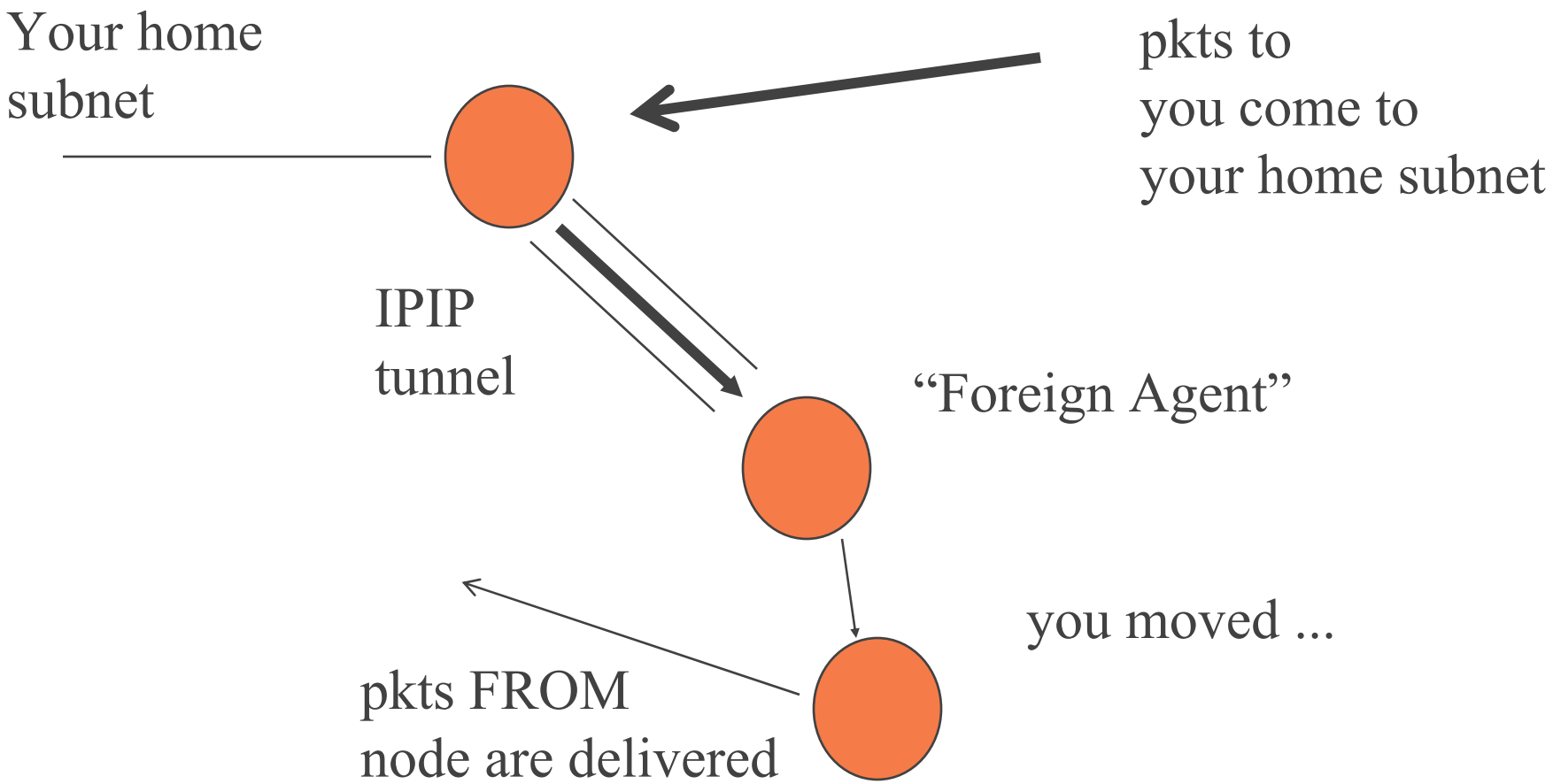
flooding may be constrained of course

- you might simply use broadcast to send info
- you may pass judgement on the info before you send it out the “other” interfaces
  - not forward it if it is not new
  - or interesting
- many routing protocols rely on some sort of flooding (even BGP, although not link-layer)

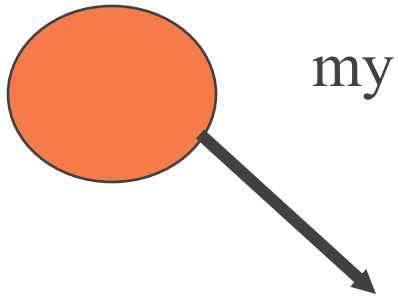
routing is 2 1-way problems

- path between A and Z may not be the same
- asymmetric routing NOT unusual
- consider Mobile-IP
  - solves problem of packets TO remote host
    - » packets tunneled from HOME to AWAY
  - not packets FROM remote host
    - » ordinary “default” routing
- consider multi-homed stub with default route

Mobile-IP as one-way IPIP tunnel

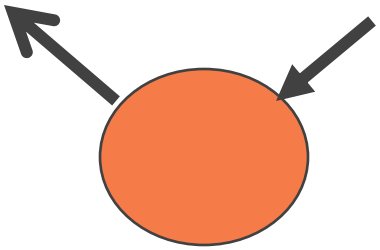


asymmetric paths



my routing domain

the wilds of the Inet ....

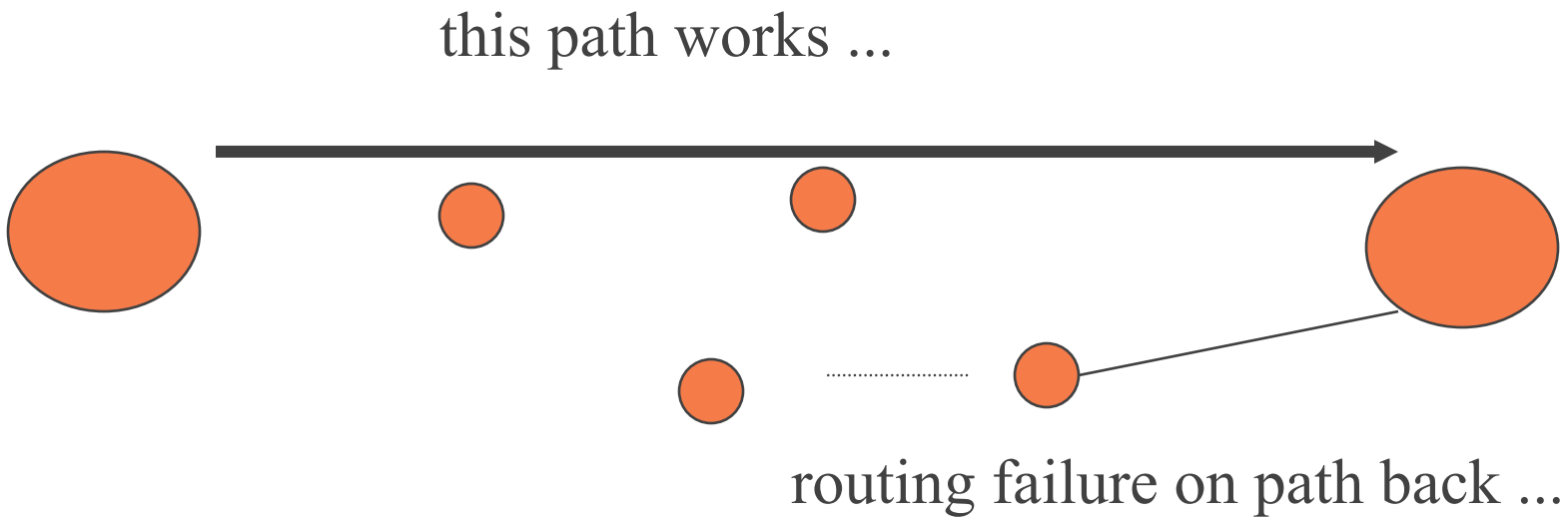


default
route

pkts in

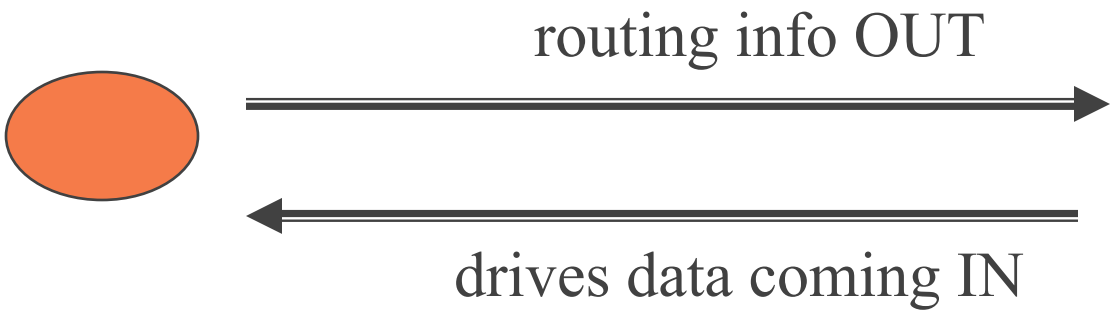
multi-homed stub
with default route

you may have to debug twice



control idea: routes vs data

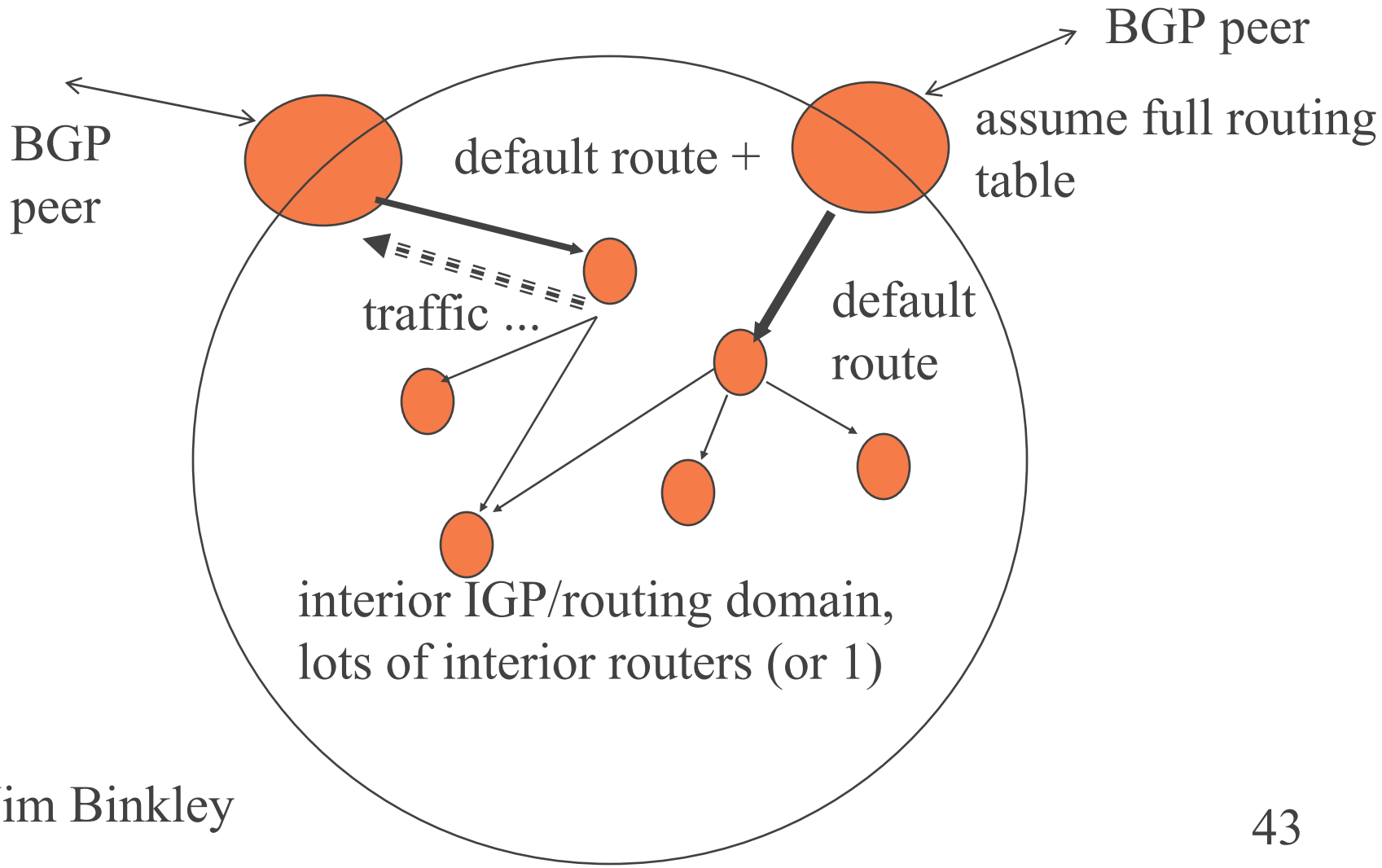
- on a given link, you might SEND routing info, which will cause
- data to COME BACK on that path



here I am, talk to me!!!

data flows opposite of control

example: multi-homed stub, 2 default routes



issues - congestion

- does not refer to bronchial condition
- connectionless routers have only so many buffers, too many packets, they drop them
- things get worse at the “freeway exchanges”
- does routing protocol add congestion burden?
- how do we prevent/detect congestion?
- obviously circuit-switches don’t have this problem **once circuit is set, but they waste bandwidth**

congestion?

- ways to prevent congestion:
  - add carrying capacity - big pipe theory
  - shutup, especially if high-volume src
- how do we notify network about it?
  - TCP detects congestion when sender notes that ACKS are missing, slow, or duplicated, sender slows rate of sending, **this is END to END method**, routers not involved (David Clark/MIT, end to end paper)
  - some schemes have routers forward or pass back congestion bits

congestion schemes - routers involved

- IP sends back ICMP source quench message to sender (deprecated)
  - pro: you sent it the right way
  - con: you poured gas on the fire
- ISO CNLP sets flag in network header
  - pro: doesn't add data to net
  - con: congestion notification is sent to the DESTINATION (oh, goody)
    - » destination calls sender with POTS? "shutup"

congestion cont.

- TCP solution is not bad BUT
  - what about protocols that use Internet that don't implement or can't sensibly implement it?
    - » NFS or Novell could but don't, drive TCP out
    - » audio/video transmission is steady-state data flow
- congestion detection is an open question
- large issue in QOS terms

issues - link costs

- we need a **metric**, which one?
  - **cost**? not appropriate within domain but between; e.g., which long-distance company?
  - **hop count** - how many routers do we traverse
  - available bandwidth - go least congested route
  - **speed** of underlying network, use ATM as opposed to 1200 baud modem?
  - **time**: shortest path in terms of time
    - » time is typically an app ...

issues - link costs (metrics)

- if link costs change, that information must converge of course
- **we typically only use one metric within a domain**
- **we typically only use static metrics, not dynamic metrics (e.g., not congestion, but hop count)**
- we could have multiple metrics in use?!
  - say hop count, power use, radio strength for mobile wireless nodes?
- question: would more complex algorithms (if possible) that dynamically account for link costs do qualitative better job than current simple algorithms or just use bandwidth?

type of service

- my packets before your packets!
- might want to prioritize certain traffic classes; .e.g., 1 control., 2. isochronous., 3 bursty
- **policy-based routing** (pb constraints) - decree a certain path, or outlaw a certain path
  - source and static routing can be useful here
  - BGP claims to do "policy" - recognize that many routing theory types think NOT ENUF!!!

packet color overview

1. 3 mechanisms needed for packet classification
2. some way to setup a logical circuit
    1. end to end protocol or router-router protocol
        1. packets with classifier X should be treated like first-class passengers
    2. per packet classifier (flow ID, mac address)
    3. router/switch scheduling algorithm
        1. if packet classifier, then give it a buffer

issues - some misc. ones

- **load-balancing**- if we have two equal routes to X, can we split the load between them?
  - **equal cost multi path**
- **migrating** routing algorithms - you have RIP and now you want to switch to OSPF (and no rebooting multiple times)
  - can you run both?, switching one by one is disruptive
- **route redistribution** - at routing domain boundary, how exactly do you take info from one routing protocol and inject into another? (Cisco route maps)
- **routing partition** repair - if two paths to one net, and one goes down, can routers fix it in face of **hierarchy**?

a bit more on that

- **partition**
  - basically means 2 nets, 1 link, the link blew up (or came back), now what?
    - » is there a way to glue the two nets together thru some other path?
    - » is there a way to optimize traffic when the nets reconnect in order to minimize control traffic
- **aggregation** - in general, if routing is control, can we minimize it
  - by lumping addresses together ...
  - downside./s: too much routing, too many routes

types: vector-distance

- vector-distance algorithms:
  "**tell the neighbors about the world**"
- **vector** is destination (net/host)
- **distance** is metric (hopcount)
- if we called it destination-metric, other people would understand (good point, Dr. Perlman)
- you flood your destination, hopcount info to your directly connected neighbor routers
- RIP is an example, but so is BGP, IGRP, EIGRP, and remember the fuzzballs ... (time as metric)

types: link-state

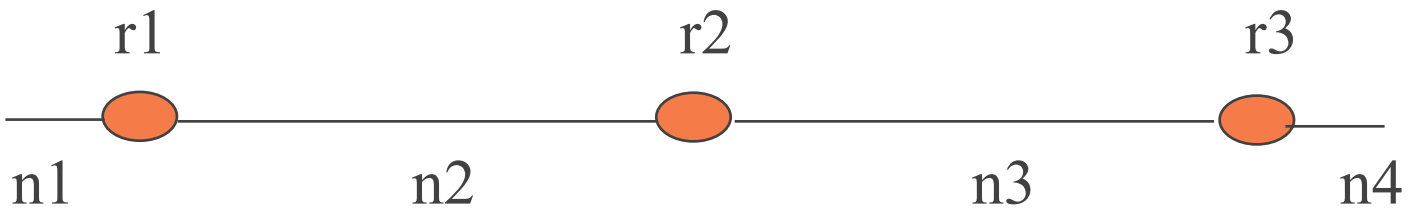
- link-state or shortest path first (SPF) **"tell the world about your neighbors"**
- find out who is up locally, and flood that information to the entire set of routers
- they can use the "link-state" to build a shortest path map to everybody
- LS is compute-intensive. VD is bandwidth intensive.

vector-distance algorithm

- examples: RIP, BGP, IGRP, EIGRP
- algorithmic elements:
  - send: every N seconds out all connected interfaces
    broadcast 2-tuples :
    (to network X, hop count Y) ...
  - recv: if new tuple, add to routing table
    if better tuple, change existing
    if "dead" tuple, remove
  - timeout: if no refresh, timeout entry in N * Y seconds
    - » broadcast may be lost, therefore timeout is slower

vector-distance

- assume 3 routers, and that directly connected nets are in routing tables to start with. How does following converge?



r1 table: (n1, 1)
(n2, 1)

slow convergence/count to infinity

- vector-distance like this (RIP) has defects
- changes can be sent when they occur, but must recompute a bit so convergence takes time (made worse by possible loops)
- count to infinity problem can occur too - routing loop until hopcount reaches impossible value

count to infinity

C crashes, B knows C crashed but hasn't told A,
but unfortunately A talks to B first
B is told by A: I can get to C in two hops (and note
it doesn't mention to B that the path is thru B)
B says AHA!, that means I can get to C in three hops
and reports that to A
A says AHA!, it's now four hops to B and tells B
etc...

RIP max hop count (infinity) is 16

split-horizon fixup (vector-distance)

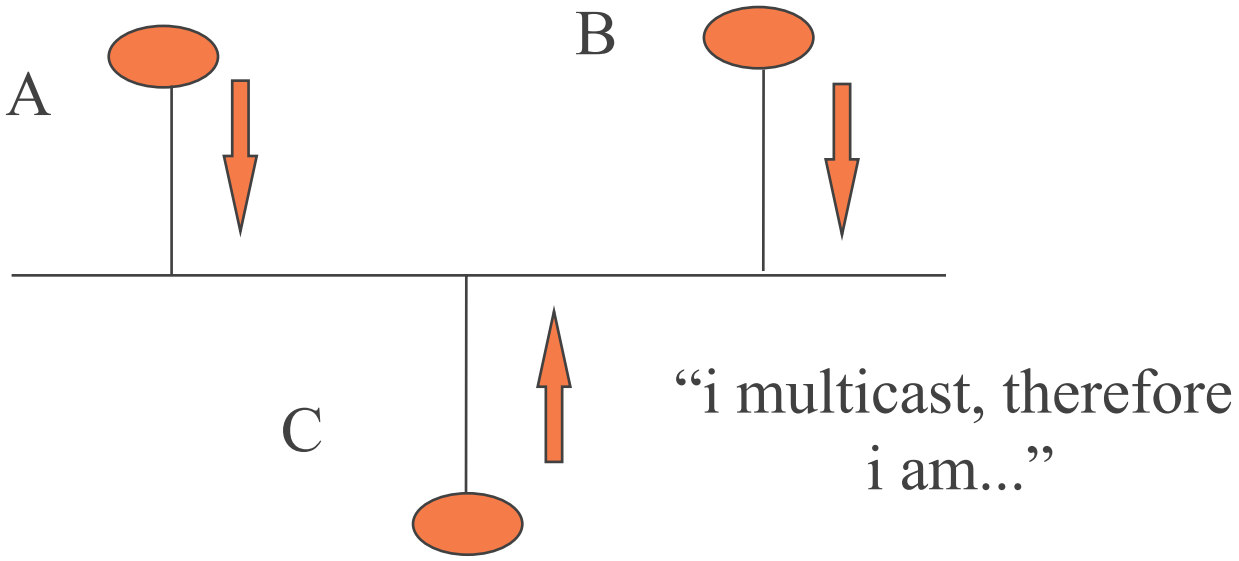
- A tells B that its distance to C is infinity
  - (because B is the direction A gets the info from)
- when link goes away, B will know that there is no path to C, and tell A
- doesn't work in all cases

link-state algorithm

- "tell the world about your neighbors"
- examples: OSPF, IS-IS, NLSP, IDPR
- link-state requires each participating router to keep map of complete topology
- in 3 parts
  - 1. determine neighbor connectivity
  - 2. send ("flood") link-state packet that states which link neighbors are up
  - 3. use Dijkstra shortest-path first to compute best path to that network

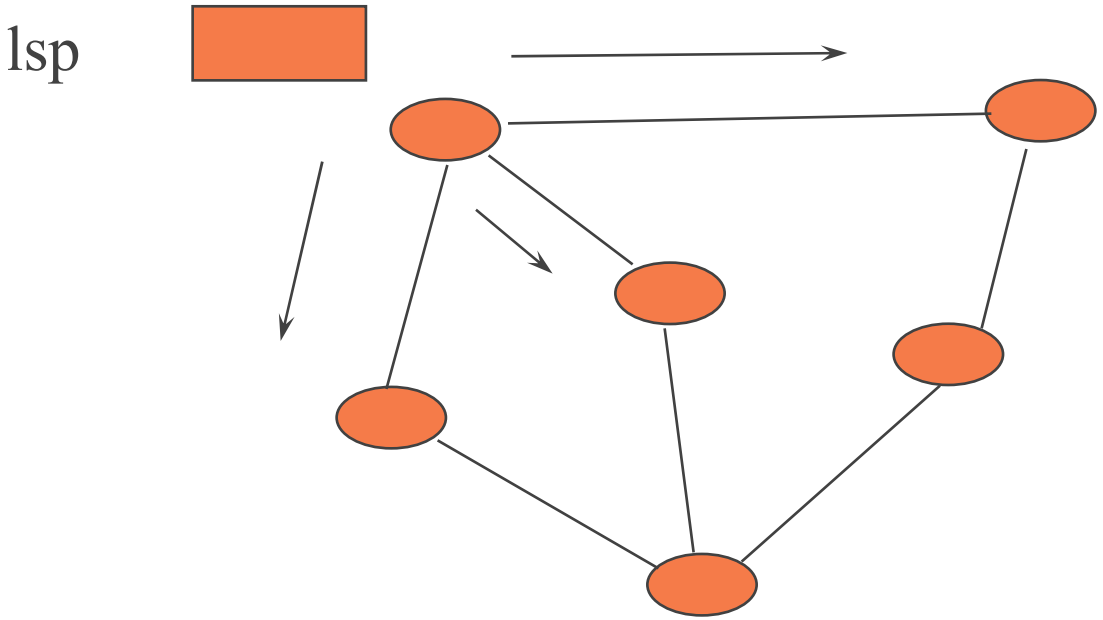
link-state#determine link-state

- "ping" neighbors to determine if they are up or they may broadcast (multicast) their existance



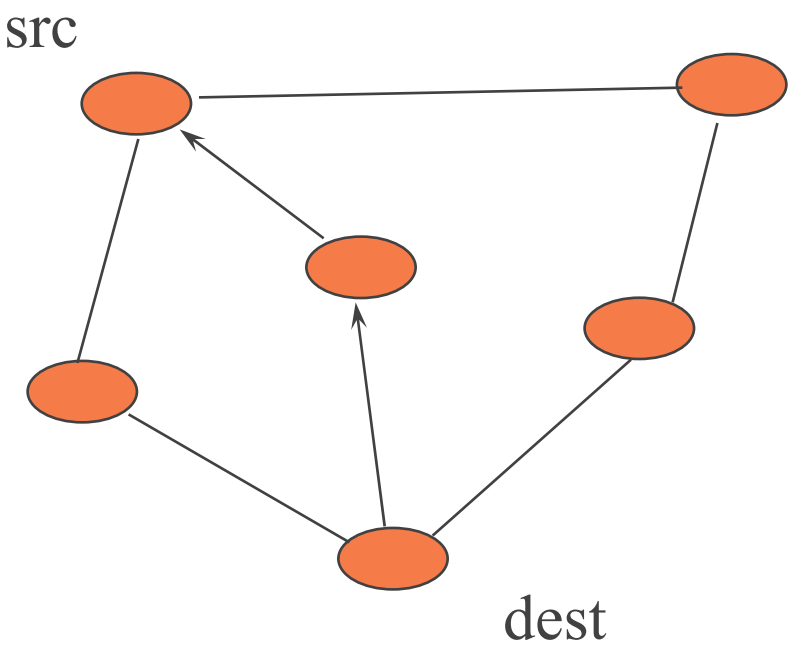
link-state#send LSP

- each participating router “floods” (very carefully) routing domain with LSP



link-state#compute shortest path

- each participating router takes LSPs, stores them, and computes shortest path to sender



link-state: pros/cons

- pros
  - converges faster, no count to infinity problem + router can forward LSP immediately, must recompute DV
  - more functionality; e.g., **each router has map of net**, can make network debugging easier
- cons
  - more compute than vd (does this matter?)
- tossups
  - bandwidth? vd broadcasts summary version of route table, ls routers send LSP around net

basic tools for admins:

- **ping**, basic reachability, pkt loss, latency
- **traceroute**, latency and hop count
  - remember paths may be asymmetric
  - traceroute "-g" may/may not work
- **ttcp**, memory to memory xfer speed
  - Cisco is building it into IOS now
  - can measure tcp-based thruput, also UDP packet fling (one way)..
- sniffers, free tcpdump (www.tcpdump.org).

higher-level wonders

- very well may involve SNMP
  - **MRTG** and its descendants
    - » Cricket, and other front-ends
  - graphs SNMP integers on strip-charts
    - » port byte counts in/out
- Commercial tools
  - commercial monitors, sniffers, intrusion detection
  - snmp RMON probes or rough/free equivalents (ntop)
  - network mgmt. GUI wonders (HP openview/Cisco/IBM, Network Associates, etc., etc.)