Interdomain Routing

EE122 Fall 2012

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http://inst.eecs.berkeley.edu/~ee122/

Materials with thanks to Jennifer Rexford, Ion Stoica, Vern Paxson and other colleagues at Princeton and UC Berkeley

Gautam will answer questions…..

Announcements

- **Don't worry about the curve,**
  - **Don't worry about your midterm grade**
- **We have a long way to go,**
  - **And we will work with you**
- **But do figure out what you got wrong,**
  - **And remember it for next time**

Announcements

- **Over 200 people will flunk this course….**
  - Only 120 people have "participated"
- I'm not kidding about this.
  - You will flunk if you don't participate.
- Do the math: ~10 more lectures, ~200 people

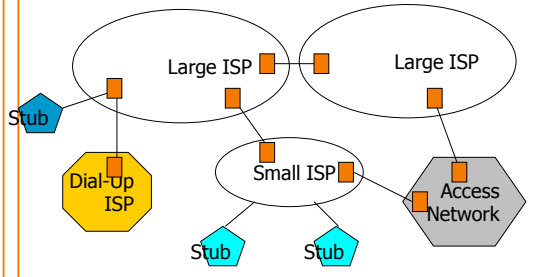
Routing

- Provides paths between **networks**
  - Prefixes refer to the "network" portion of the address
- So far, only considered routing within a domain
  - All routers have same routing metric (shortest path)
- Many issues can be ignored in this setting because there is central administrative control over routers
  - No *autonomy*, *privacy*, *policy* issues for individual routers
- **But we can't ignore those issues any more!**

Internet is more than a single domain…

- Internet not just unstructured collection of networks
  - "Networks" in the sense of prefixes
- Internet is comprised of a set of "autonomous systems" (ASes)
  - Independently run networks, some are commercial ISPs
  - Currently over 30,000 Ases
  - Think AT&T, France Telecom, UCB, IBM, Intel, etc.
- ASes are sometimes called "domains"
  - Hence "interdomain routing"

Internet: a large number of ASes



7

Three levels in routing hierarchy

- Within a single network: to reach individual hosts
  - Learning switches (L2)
- Intradomain: routes between networks (L3)
  - Covered in previous routing lectures (DS, LS)
- Interdomain: routes between ASes (L3)
  - Today's lecture
- **Need a protocol to route between domains**
  - BGP is current standard

Aside: using IP addresses for both intradomain and interdomain routing is Internet's biggest mistake

8

Internet Needed New Routing Paradigm

- The idea of routing through networks was well-known before the Internet
  - Dijkstra's algorithm 1956
  - Bellman-Ford 1958
- The notion of "autonomous systems" which could implement their own private policies was new
  - BGP was hastily designed in response to this need
  - Developed 1989-1995
- ***It has mystified us ever since…..***

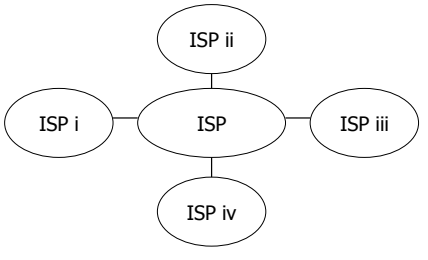
9

Design Exercise

10

Design exercise

- Unit of routing is a domain (treat as logical switch)



11

Design-It-Yourself!

- Domains can pick whatever routes they want
  - No need for it to be shortest path
- Domains can choose who they offer their routes to
  - No need to let every peer route through them
- What does the resulting design look like?
- Take five minutes, and then describe your design

12

One proposal

- Domains exchange "path vectors"
  - To get to domain D, take path Hop1:Hop2:Hop3:Hop4….
- Pick best vector for each destination domain
  - According to own private policy
  - Path vector prevents loops
- Advertise those vectors to whomever they choose
- Problems?
  - Loops? No
  - Quality of paths? Let's see….
  - Convergence? Let's see…..

13

Why doesn't Internet use our design?

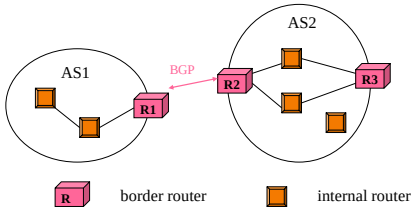
- Two relatively minor quibbles:
  - BGP implemented on routers, not domains
  - Paths are to individual networks, not domains
- Otherwise, this is essentially BGP….
- For the rest of lecture, keep repeating to yourself
  - This is simple
  - This is simple
  - This is simple
  - ….

14

Back to Reality

15

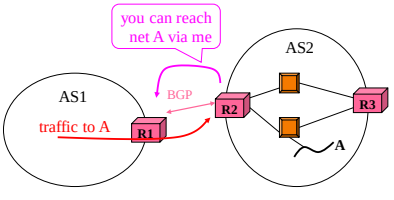
Who speaks BGP?



- Two types of routers
  - Border router (Edge), Internal router (Core)

16

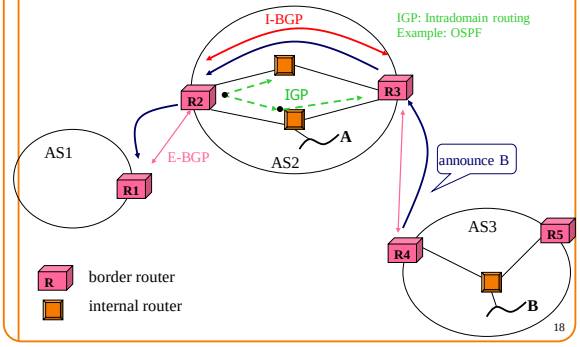
Purpose of BGP



Share connectivity information across ASes

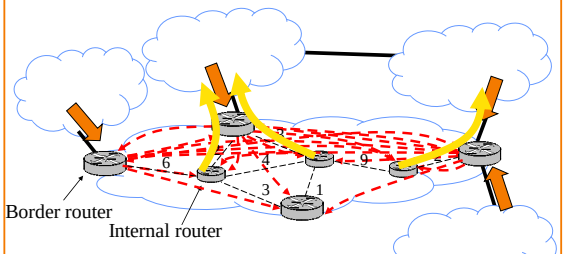
17

I-BGP and E-BGP



18

In more detail

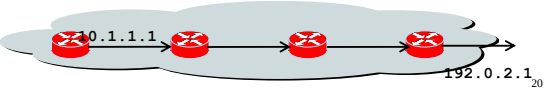


1. Provide internal reachability (**IGP**) ------
2. Learn routes to external destinations (**eBGP**) ➡
3. Distribute externally learned routes internally (**iBGP**) - - ➡
4. Select closest egress (**IGP**) ------

19

Joining BGP and IGP Information

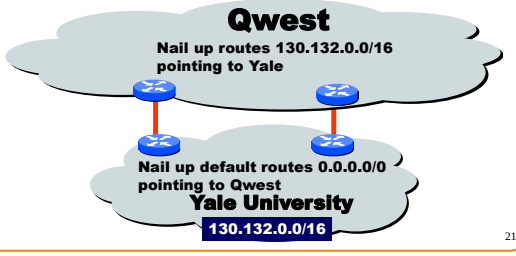
- Border Gateway Protocol (BGP)
  - Announces reachability to external destinations
  - Maps a destination prefix to an egress point
    - 128.112.0.0/16 reached via 192.0.2.1
- Interior Gateway Protocol (IGP)
  - Used to compute paths within the AS
  - Maps an egress point to an outgoing link
    - 192.0.2.1 reached via 10.1.1.1



20

Some Routers Don't Need BGP

- Customer that connects to a single upstream ISP
  - The ISP can introduce the prefixes into BGP
  - … and the customer can simply default-route to the ISP



21

Rest of lecture...

- Motivate why BGP is the way it is
  - Two key issues…..
- Discuss some problems with interdomain routing
- Explain some of BGP's details
  - Not fundamental, just series of specific design decisions
  - *Try hard to keep me from reaching this portion….*

22

Factors Shaping Interdomain Routing

- There are two main factors that explain why we can't use previous routing solutions

23

1. ASes are autonomous

- Want to choose their own internal routing protocol
  - Different algorithms and metrics
- Want freedom to route externally based on policy
  - "My traffic can't be carried over my competitor's network"
  - "I don't want to carry transit traffic through my network"
  - **Not expressible as Internet-wide "shortest path"!**
- Want to keep their connections and policies private
  - Would reveal business relationships, network structure

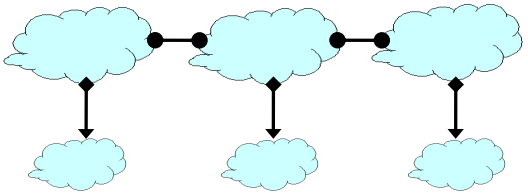
24

2. ASes have business relationships

- Three basic kinds of relationships between ASes
  - AS A can be AS B's *customer*
  - AS A can be AS B's *provider*
  - AS A can be AS B's *peer*
- Business implications
  - Customer pays provider
  - Peers don't pay each other
    - Exchange roughly equal traffic
- Policy implications: *packet flow follows money flow*
  - "When sending traffic, I prefer to route through customers over peers, and peers over providers"
  - "I don't carry traffic from one provider to another provider"

25

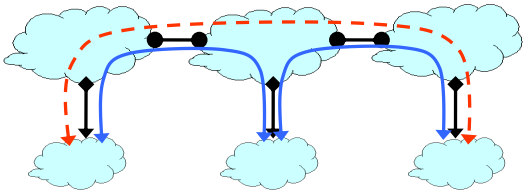
Business Relationships



Relations between ASes	*Business Implications*
provider ⟷ customer	**•Customers pay provider**
peer ⟷ peer	**•Peers don't pay each other**

26

Routing Follows the Money!



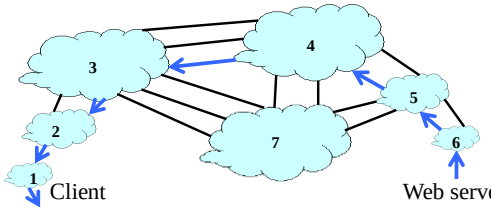
traffic allowed traffic not allowed

- Peers provide transit between their customers
- Peers do not provide transit to each other

27

AS-level topology

- Destinations are IP prefixes (e.g., 12.0.0.0/8)
- Nodes are Autonomous Systems (ASes)
  - Internals are hidden
- Links: connections **and** business relationships



28

What routing algorithm can we use?

- Key issues are *policy* and *privacy*
- Can't use shortest path
  - domains don't have any shared metric
  - *policy choices might not be shortest path*
- Can't use link state
  - would have to flood policy preferences and topology
  - *would violate privacy*

29

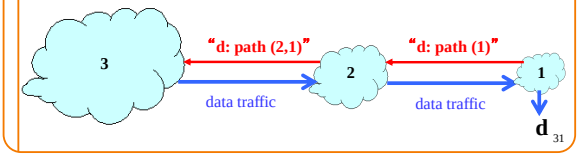
Basic requirements of routing

- Avoid loops and deadends
- How to do this while allowing policy freedom?
- Easiest way to avoid loops?
  - Path vector!

30

Path-Vector Routing

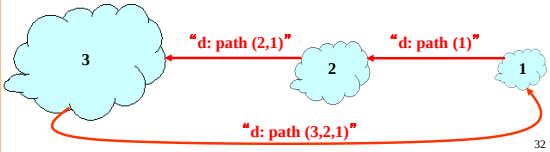
- Extension of distance-vector routing
  - Support flexible routing policies
  - Faster loop detection (no count-to-infinity)
- Key idea: advertise the entire path
  - Distance vector: send *distance metric* per dest d
  - Path vector: send the *entire path* for each dest d



31

Faster Loop Detection

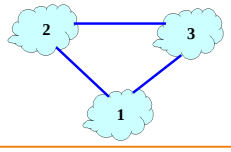
- Node can easily detect a loop
  - Look for its own node identifier in the path
  - E.g., node 1 sees itself in the path "3, 2, 1"
- Node can simply discard paths with loops
  - E.g., node 1 simply discards the advertisement



32

Flexible Policies

- Each node can apply local policies
  - Path selection: Which path to use?
  - Path export: Which paths to advertise?
- Examples
  - Node 2 may prefer the path "2, 3, 1" over "2, 1"
  - Node 1 may not let node 3 hear the path "1, 2"



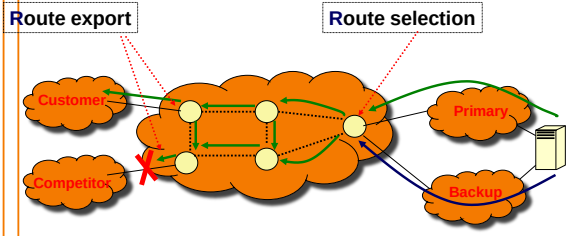
33

Selection vs Export

- Selection policies
  - determines which paths I want **my traffic to take**
- Export policies
  - determines whose traffic I **am willing to carry**
- Notes:
  - any traffic I carry will follow the same path my traffic takes, so there is a connection between the two
  - from a protocol perspective, decisions can be *arbitrary*
    - can depend on entire path (advantage of PV approach)

34

Illustration of Route Advertisements



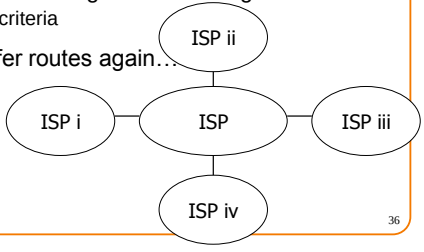
Selection: controls traffic out of the network
Export: controls traffic into the network

Data flows in opposite direction to route advertisement

35

Iterative process

- Domains offer routes to peers
  - Only one route per destination (why?)
  - And they can choose which peers they offer the route to
- Domains choose single route among those offered
  - Using own criteria
- Domains offer routes again…



36

Examples of Standard Policies

- Transit network:
  - Selection: prefer customer to peer to provider
  - Export:
    - Let customers use any of your routes
    - Let anyone route through you to your customer
    - Don't export route to someone on that route (poison reverse)
    - *Block everything else*
- Multihomed (nontransit) network:
  - Export: Don't export routes for other domains
  - Selection: pick primary over backup
    - send directly to peers

37

World of Policies Changing

- ISPs are now "eyeball" and/or "content" ISPs
- Less focus on "transit", more on nature of customers
- No systematic policy practices yet
- Details of peering arrangements are private

38

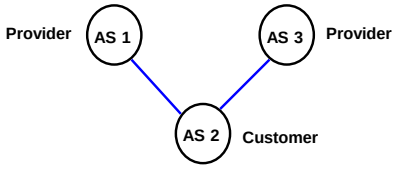
Issues with Path-Vector Policy Routing

- Reachability
- Security
- Performance
- Lack of isolation
- Policy oscillations

39

Reachability

- In normal routing, if graph is connected then reachability is assured
- With policy routing, this does not always hold



40

Security

- An AS can claim to serve a prefix that they actually don't have a route to (blackholing traffic)
  - Problem not specific to policy or path vector
  - Important because of AS autonomy
  - *Fixable: make ASes "prove" they have a path*
- Note: AS can also have incentive to forward packets along a route different from what is advertised
  - Tell customers about fictitious short path…
  - Much harder to fix!

41

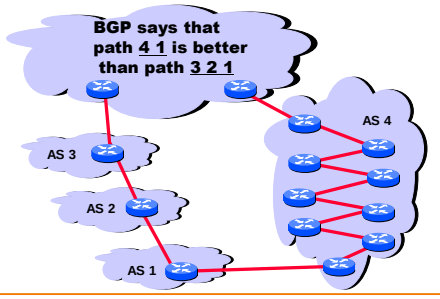
Performance Nonissues

- Internal routing (non)
  - Domains typically use "hot potato" routing
  - Not always optimal, but economically expedient
- Policy not about performance (non)
  - So policy-chosen paths aren't shortest
- Choosing among policy-compliant paths (non)
  - Pick based on Fewest AS hops, which has little to do with actual delay
  - 20% of paths inflated by at least 5 router hops

42

Performance (example)

- AS path length can be misleading
  - An AS may have many router-level hops



43

Real Performance Issue

- Convergence times:
  - BGP outages are biggest source of Internet problems
- Largely due to lack of isolation

44

Lack of Isolation: dynamics

- If there is a change in the path, the path must be re-advertised to every node upstream of the change
  - Why isn't this a problem for DV routing?
- "Route Flap Damping" supposed to help here, (but ends up causing more problems)

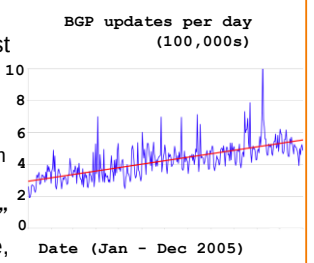


Fig. from [Huston & Armitage 2006]

45

Lack of isolation: routing table size

- Each BGP router must know path to every other IP prefix
  - but router memory is expensive and thus constrained
- Number of prefixes growing more than linearly
- Subject of current research

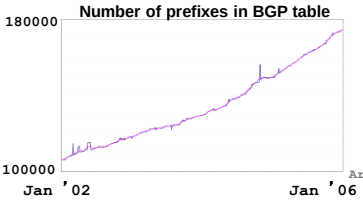


Fig. from [Huston & Armitage 2006]

46

Five Minute Break

Any questions?

47

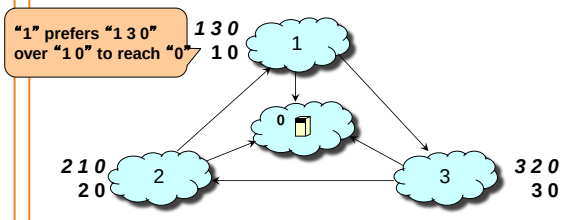
What can go wrong?

- Routing state is valid iff no loops or deadends
  - BGP has neither
- So what can go wrong?
- There is no guarantee that the algorithm converges!

48

Persistent Oscillations due to Policies

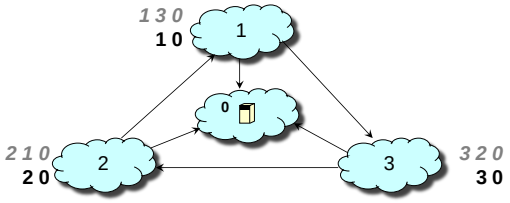
Depends on the interactions of policies



49

Persistent Oscillations due to Policies

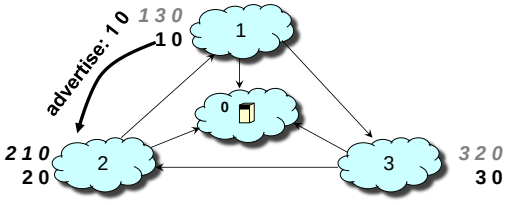
Initially: nodes "1", "2", and "3" know only shortest path to "0"



50

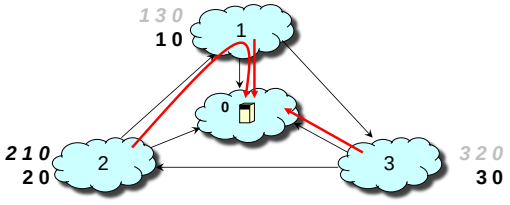
Persistent Oscillations due to Policies

"1" **advertises** its path "1 0" to "2"



51

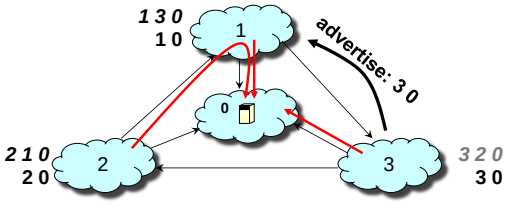
Persistent Oscillations due to Policies



52

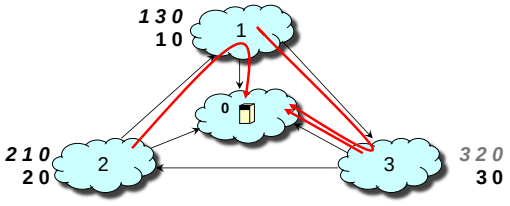
Persistent Oscillations due to Policies

"3" **advertises** its path "3 0" to "1"



53

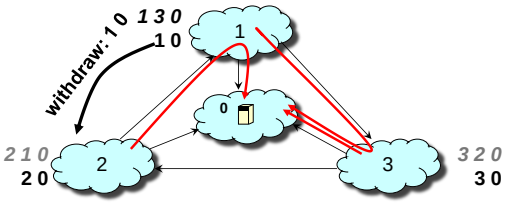
Persistent Oscillations due to Policies



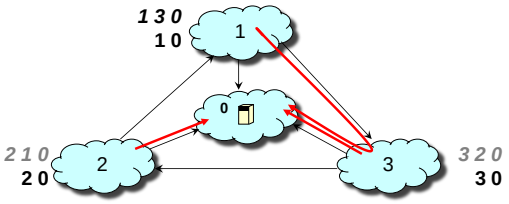
54

Persistent Oscillations due to Policies

"1" **withdraws** its path "1 0" `from` "2" since is no longer using it

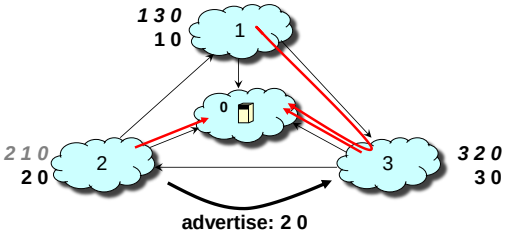


Persistent Oscillations due to Policies

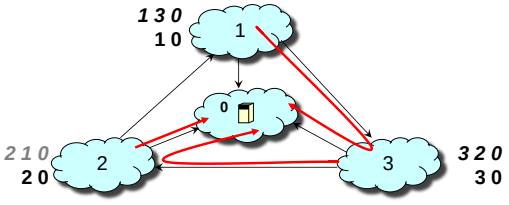


Persistent Oscillations due to Policies

"2" **advertises** its path "2 0" to "3"

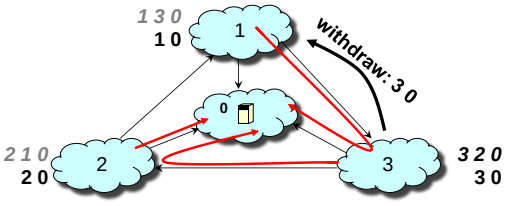


Persistent Oscillations due to Policies



Persistent Oscillations due to Policies

"3" **withdraws** its path "3 0" `from` "1" since is no longer using it



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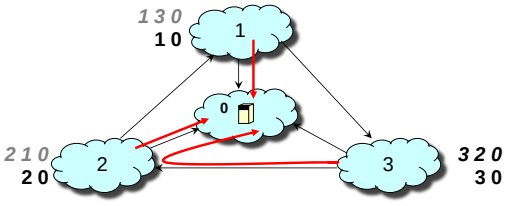
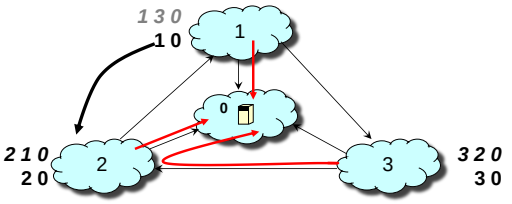
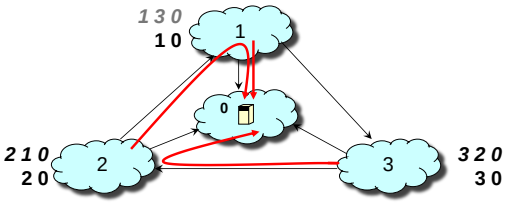


Persistent Oscillations due to Policies

"1" **advertises** its path "1 0" to "2"

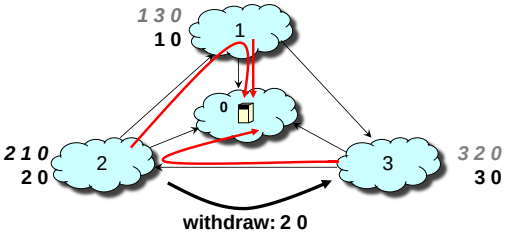


Persistent Oscillations due to Policies



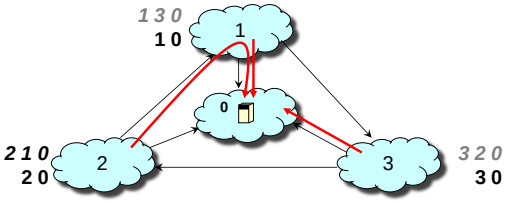
Persistent Oscillations due to Policies

"2" **withdraws** its path "2 0" from "3" since is no longer using it



Persistent Oscillations due to Policies

Depends on the interactions of policies



We are back to where we started!

Policy Oscillations (cont'd)

- Policy autonomy vs network stability
  - Policy oscillations possible with even small degree of autonomy
  - focus of much recent research
- Not an easy problem
  - PSPACE-complete to decide whether given policies will eventually converge!
- However, if policies follow normal business practices, stability is guaranteed
  - "Gao-Rexford conditions"

Theoretical Results (in more detail)

- If preferences obey Gao-Rexford, BGP is safe
  - Safe = guaranteed to converge
- If there is no "dispute wheel", BGP is safe
  - But converse is not true
- If there are two stable states, BGP is unsafe
  - But converse is not true
- If domains can't lie about routes, and there is no dispute wheel, BGP is incentive compatible

Rest of lecture....

- BGP details
- Stay awake as long as you can.....

67

Border Gateway Protocol (BGP)

- Interdomain routing protocol for the Internet
  - –Prefix-based path-vector protocol
  - –Policy-based routing based on AS Paths
  - –Evolved during the past 20 years

- **1989 : BGP-1 [RFC 1105]**
  - **Replacement for EGP (1984, RFC 904)**
- **1990 : BGP-2 [RFC 1163]**
- **1991 : BGP-3 [RFC 1267]**
- **1995 : BGP-4 [RFC 1771]**
  - **Support for Classless Interdomain Routing (CIDR)**

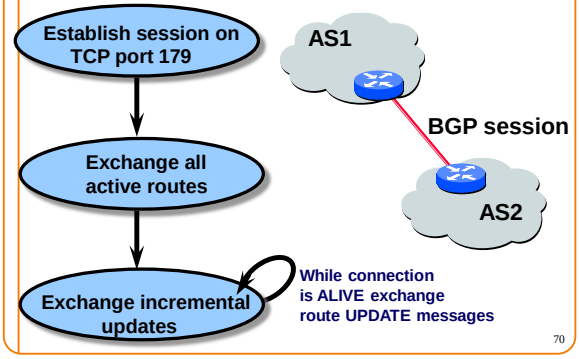
68

BGP Routing Table

```
ner-routes>show ip bgp
BGP table version is 6128791, local router ID is 4.2.34.165
Status codes: s suppressed, d damped, h history, * valid, > best, i - internal
Origin codes: i - IGP, e - EGP, ? - incomplete
   Network          Next Hop            Metric LocPrf Weight Path
* i3.0.0.0         4.0.6.142             1000     50      0 701 80 i
* i4.0.0.0         4.24.1.35                0    100      0 i
* i12.3.21.0/23    192.205.32.153           0     50      0 7018 4264 6468 ?
* e128.32.0.0/16   192.205.32.153           0     50      0 7018 4264 6468 25 e
```

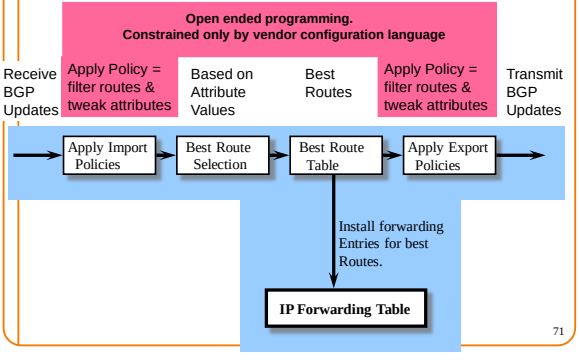
69

BGP Operations



70

BGP Route Processing



71

Selecting the best route

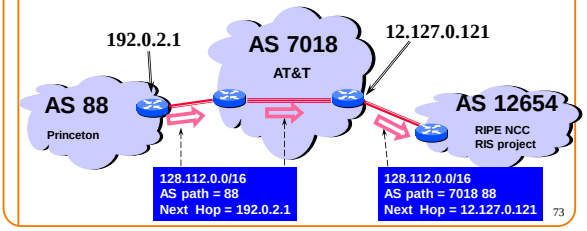
- Attributes of routes set/modified according to operator instructions
- Routes compared based on attributes using (mostly) standardized rules

1. Highest local preference (all equal by default…
2. Shortest AS path length …so default = shortest paths)
3. Lowest origin type (IGP < EGP < incomplete)
4. Lowest MED
5. eBGP- over iBGP-learned
6. Lowest IGP cost
7. Lowest next-hop router ID

72

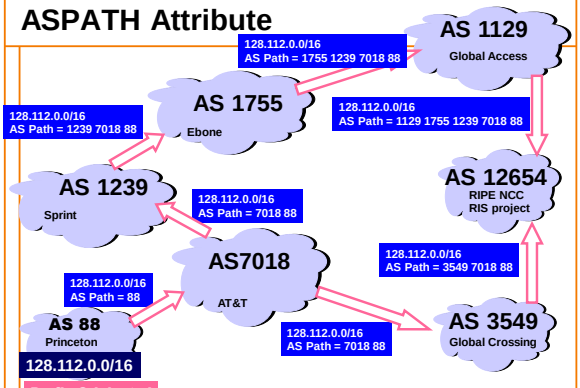
Attributes

- Destination prefix (e.g,. 128.112.0.0/16)
- Routes have attributes, including
  - AS path (e.g., "7018 88")
  - Next-hop IP address (e.g., 12.127.0.121)



73

ASPATH Attribute



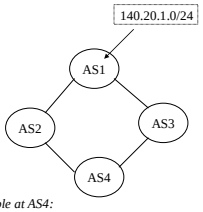
74

Local Preference attribute

Policy choice between different AS paths

The higher the value the more preferred

Carried by IBGP, local to the AS.



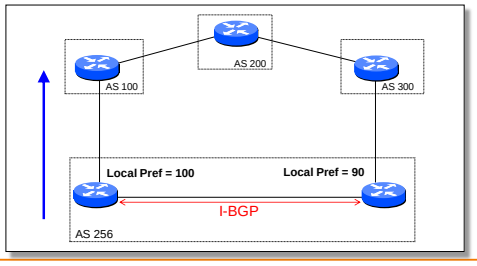
BGP table at AS4:

Destination	AS Path	Local Pref
140.20.1.0/24	AS3 AS1	300
140.20.1.0/24	AS2 AS1	100

75

Internal BGP and Local Preference

- Example
  - Both routers prefer the path through AS 100 on the left
  - … even though the right router learns an external path



76

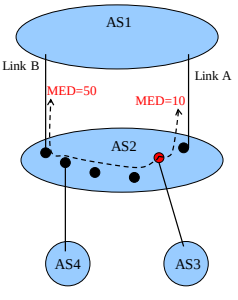
Origin attribute

- Who originated the announcement?
- Where was a prefix *injected* into BGP?
- IGP, BGP or Incomplete (often used for static routes)

77

Multi-Exit Discriminator (MED) attr.

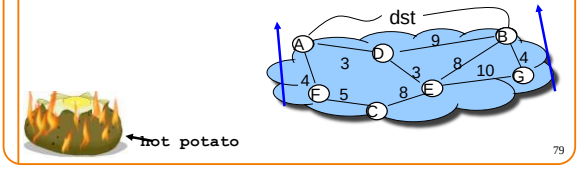
- When ASes interconnected via 2 or more links
- AS announcing prefix sets MED (AS2 in picture)
- AS receiving prefix uses MED to select link
- A way to specify how close a prefix is to the link it is announced on



78

IGP cost attribute

- Used in BGP for hot-potato routing
  - Each router selects the closest egress point
  - … based on the path cost in intradomain protocol
- Somewhat in conflict with MED



Lowest Router ID

- Last step in route selection decision process
- "Arbitrary" tiebreaking
- But we do sometimes reach this step, so how ties are broken matters

Summary

- BGP is essential to the Internet
  - ties different organizations together
- Poses fundamental challenges....
  - leads to use of path vector approach
- ...and myriad details
- What to know:
  - fundamentals, oscillations, standard policies