Communication Networks

Spring 2022

Laurent Vanbever

nsg.ee.ethz.ch

ETH Zürich (D-ITET)

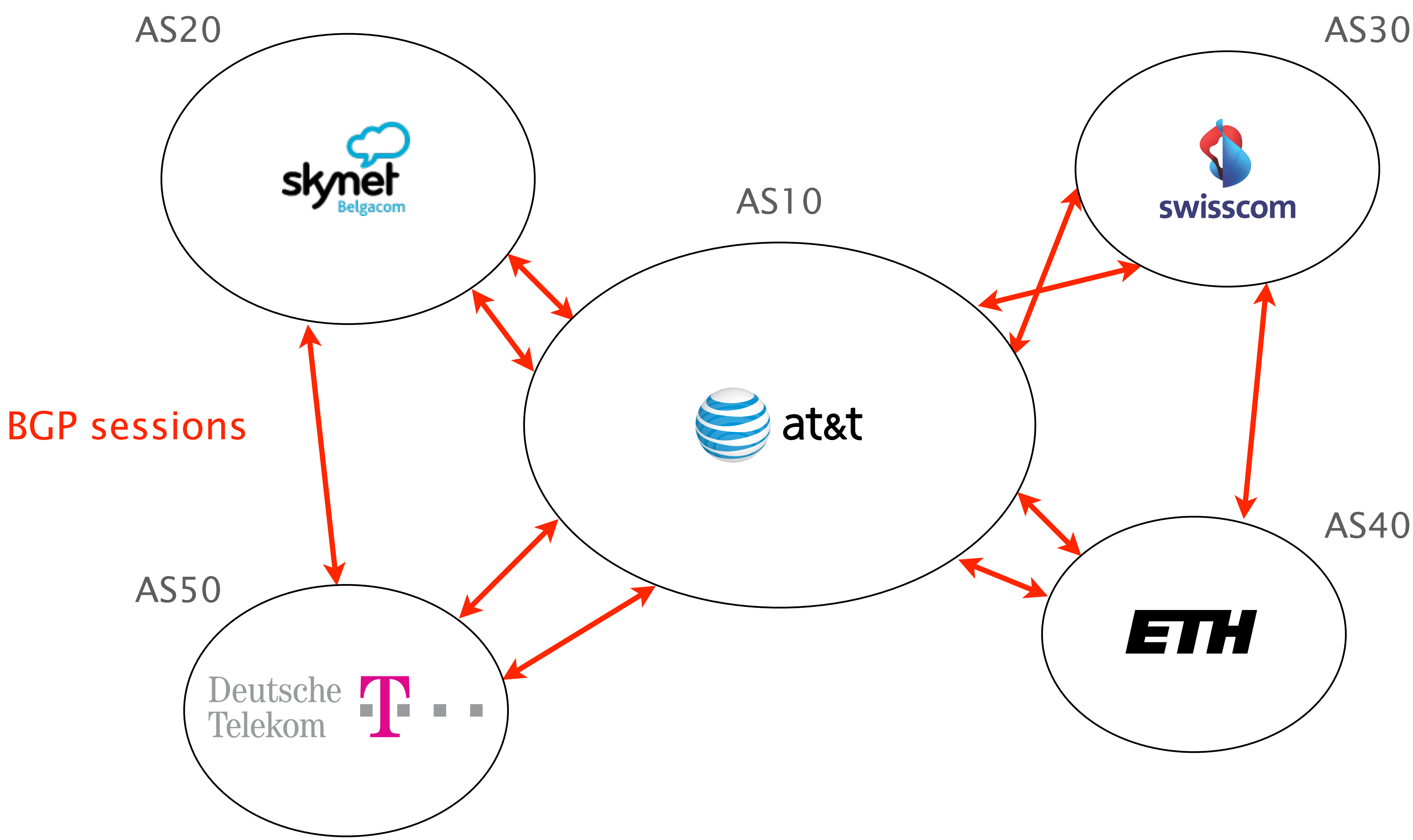
April 11 2022

Materials inspired from Scott Shenker & Jennifer Rexford

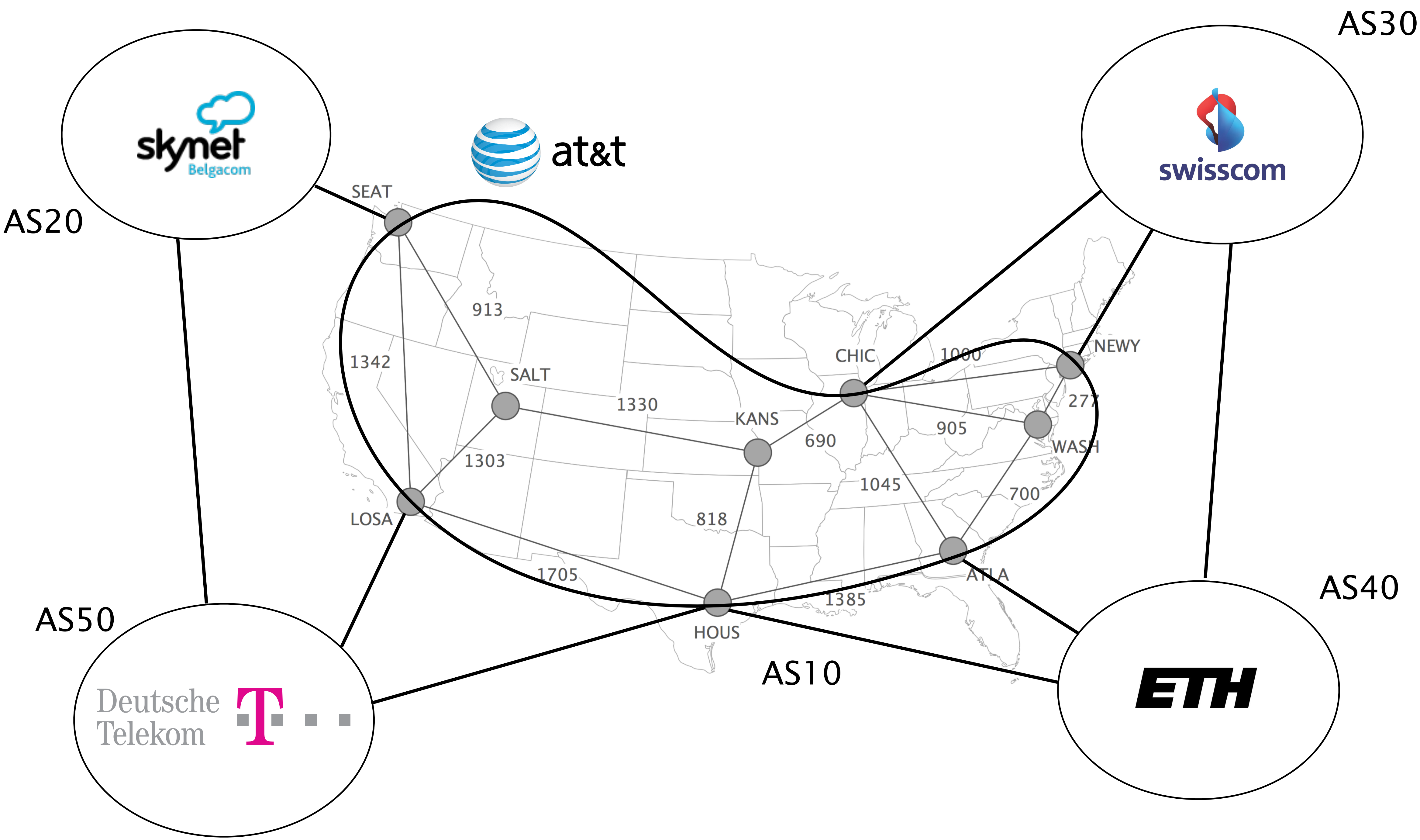
Last week on

Communication Networks

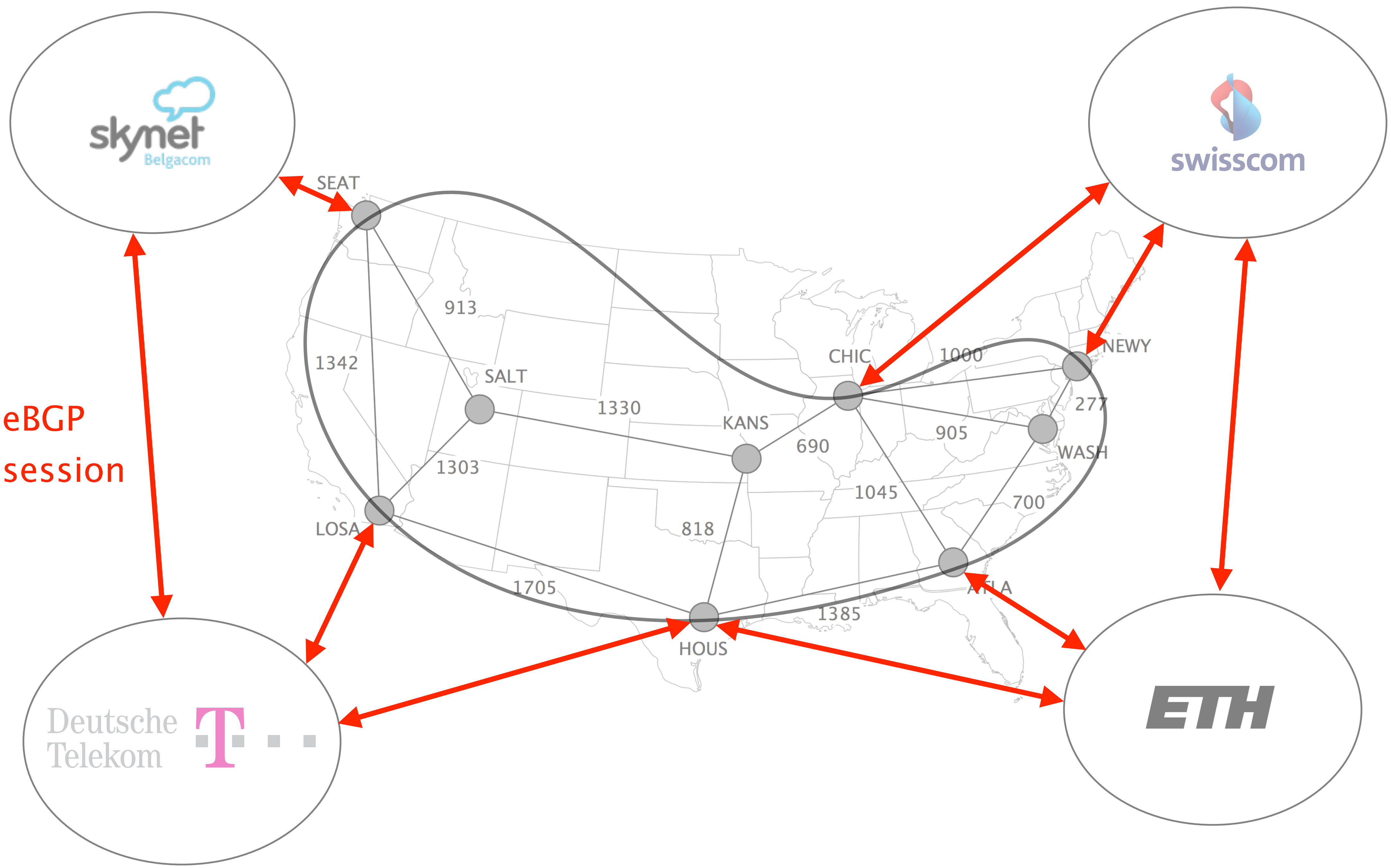
BGP is the routing protocol "glueing" the Internet together



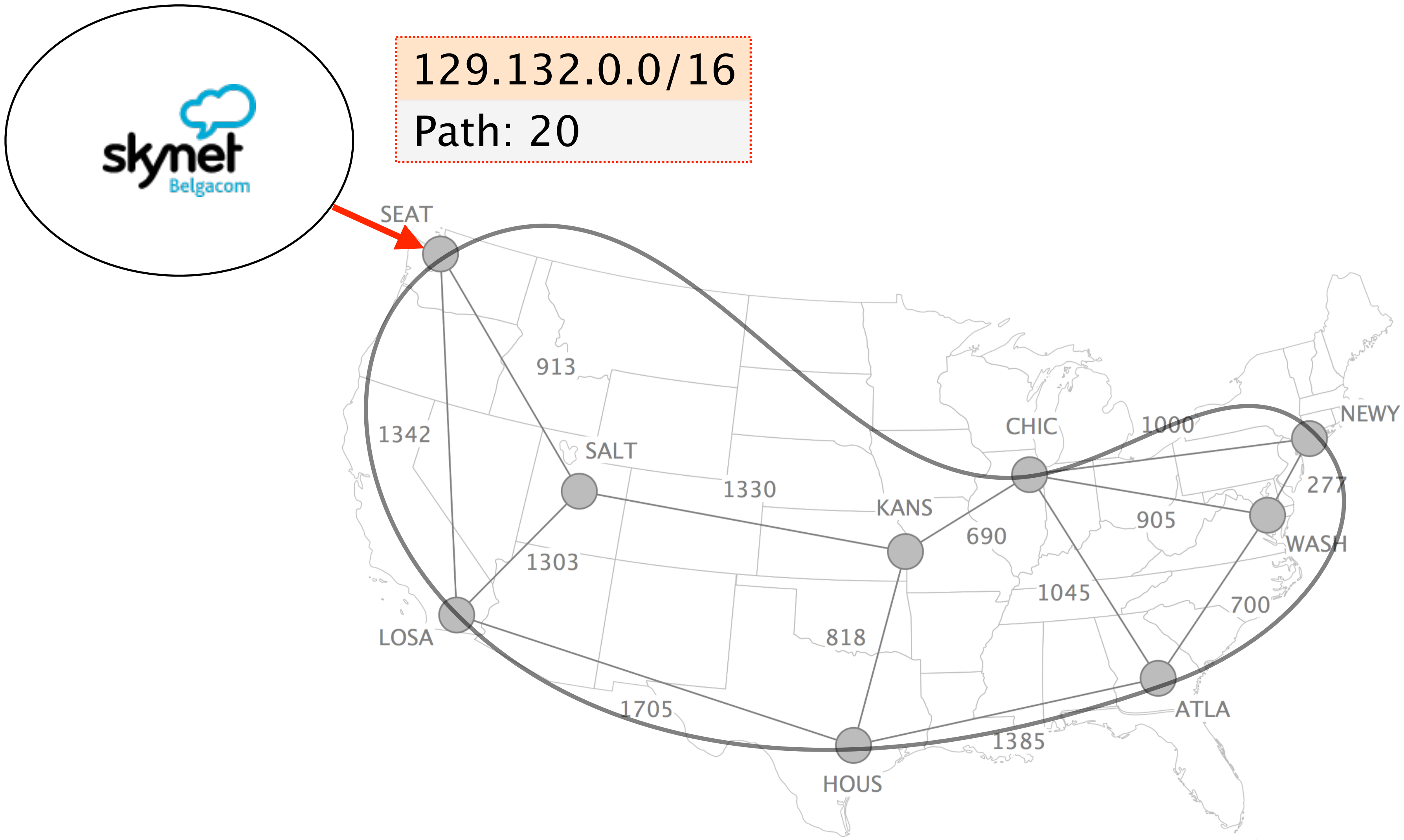
BGP sessions come in two flavors



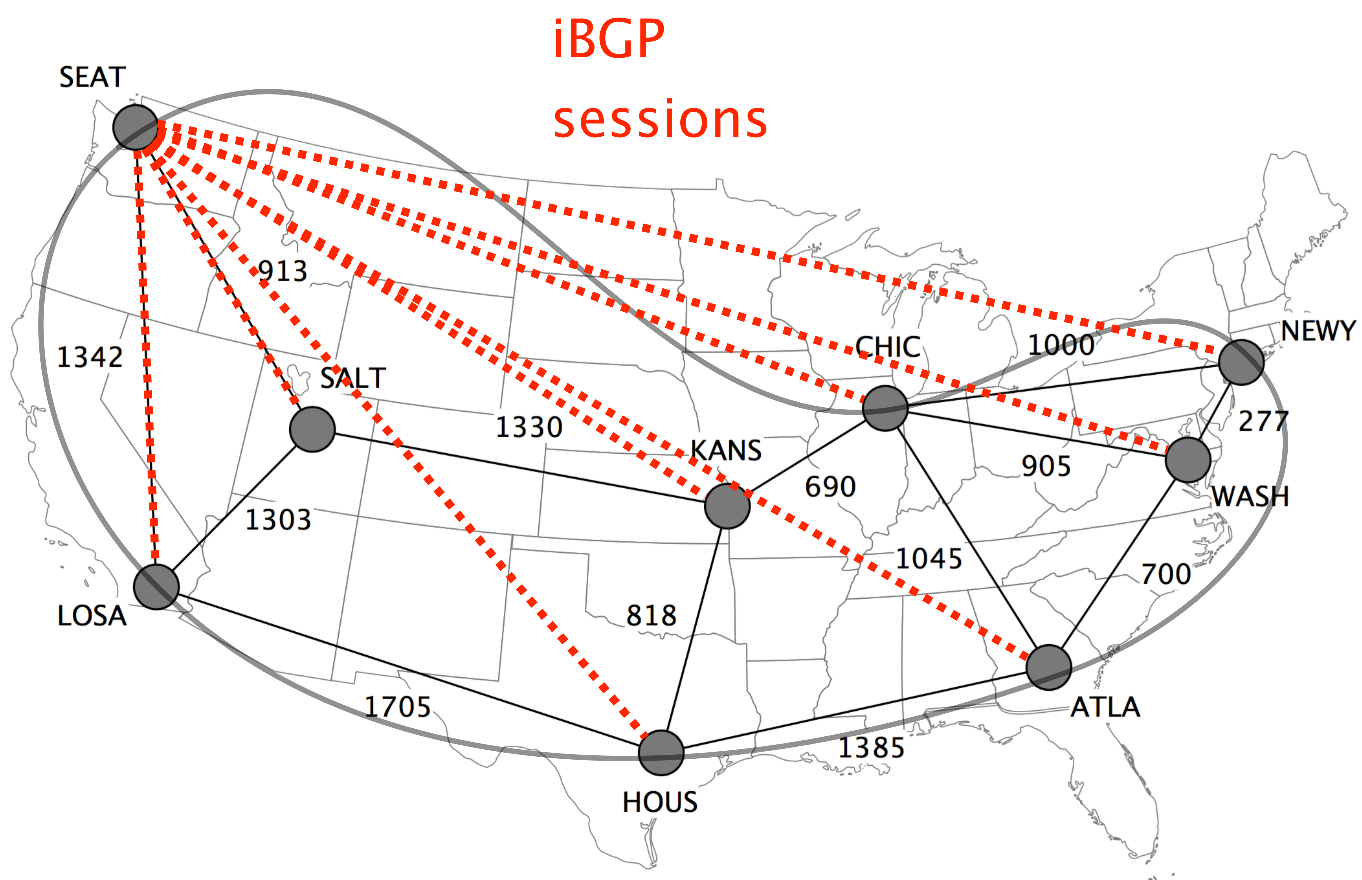
external BGP (eBGP) sessions
connect border routers in different ASes



eBGP sessions are used to learn routes to external destinations



internal BGP (iBGP) sessions connect the routers in the same AS



BGP needs to solve three key challenges: scalability, privacy and policy enforcement

There is a huge # of networks and prefixes

1M prefixes, >70,000 networks, millions (!) of routers

Networks don't want to divulge internal topologies

or their business relationships

Networks needs to control where to send and receive traffic

without an Internet-wide notion of a link cost metric

BGP relies on path-vector routing to support flexible routing policies and avoid count-to-infinity

key idea

advertise the entire path instead of distances

On the wire, BGP is a rather simple protocol composed of four basic messages

type	used to…
OPEN	establish TCP-based BGP sessions
NOTIFICATION	report unusual conditions
UPDATE	inform neighbor of a new best route
	a change in the best route
	the removal of the best route
KEEPALIVE	inform neighbor that the connection is alive

Attributes	Usage
NEXT-HOP	egress point identification
AS-PATH	loop avoidance outbound traffic control inbound traffic control
LOCAL-PREF	outbound traffic control
MED	inbound traffic control

This week on

Communication Networks

Border Gateway Protocol

policies and more

BGP Policies

Follow the Money

Protocol

How does it work?

3 Problems

security, performance, …

BGP suffers from many rampant problems

Problems	Reachability
	Security
	Convergence
	Performance
	Anomalies
	Relevance

Problems

Reachability

Security

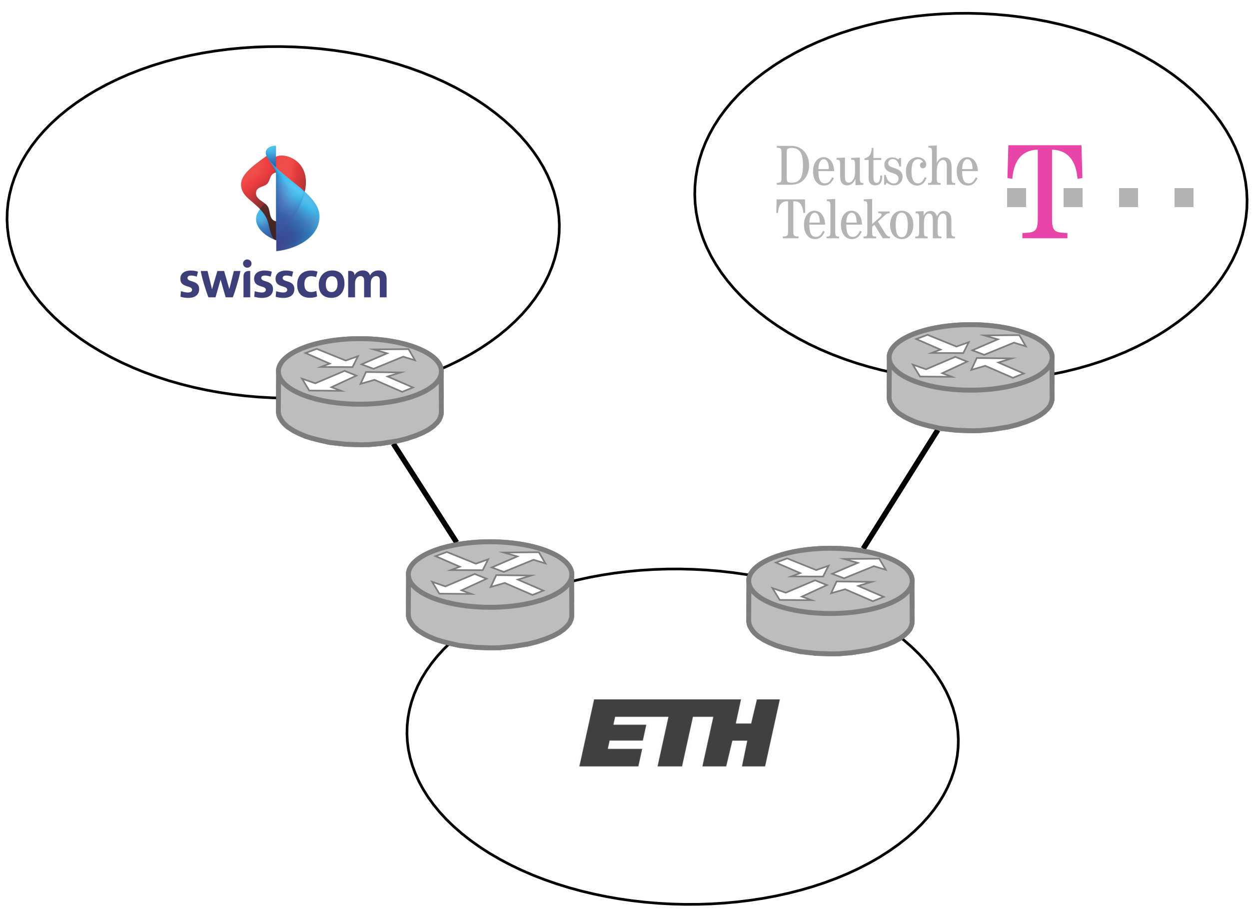
Convergence

Performance

Anomalies

Relevance

Unlike normal routing, policy routing does not guarantee reachability even if the graph is connected



Because of policies,

Swisscom cannot reach DT

even if the graph is connected

Problems

Reachability

Security

Convergence

Performance

Anomalies

Relevance

Many security considerations are absent from the BGP specification

ASes can advertise any prefixes

even if they don't own them!

ASes can arbitrarily modify route content

e.g., change the content of the AS-PATH

ASes can forward traffic along different paths

than the advertised one

BGP (lack of) security

#1	BGP does not validate the origin of advertisements
#2	BGP does not validate the content of advertisements

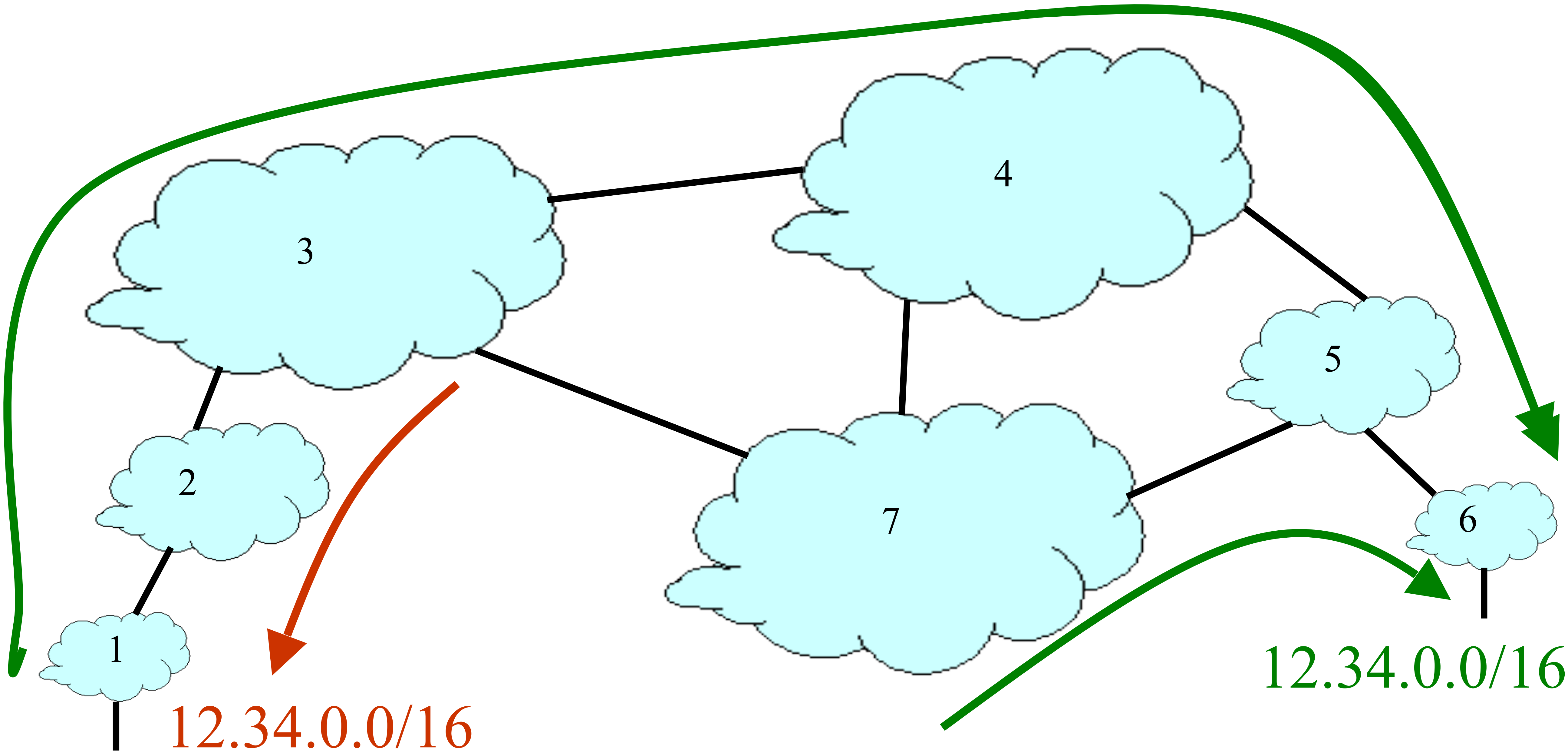
BGP (lack of) security

#1	BGP does not validate the origin of advertisements
#2	BGP does not validate the content of advertisements

IP Address Ownership and Hijacking

- IP address block assignment
  - Regional Internet Registries (ARIN, RIPE, APNIC)
  - Internet Service Providers
- Proper origination of a prefix into BGP
  - By the AS who owns the prefix
  - … or, by its upstream provider(s) in its behalf
- However, what's to stop someone else?
  - Prefix hijacking: another AS originates the prefix
  - BGP does not verify that the AS is authorized
  - Registries of prefix ownership are inaccurate

Prefix Hijacking

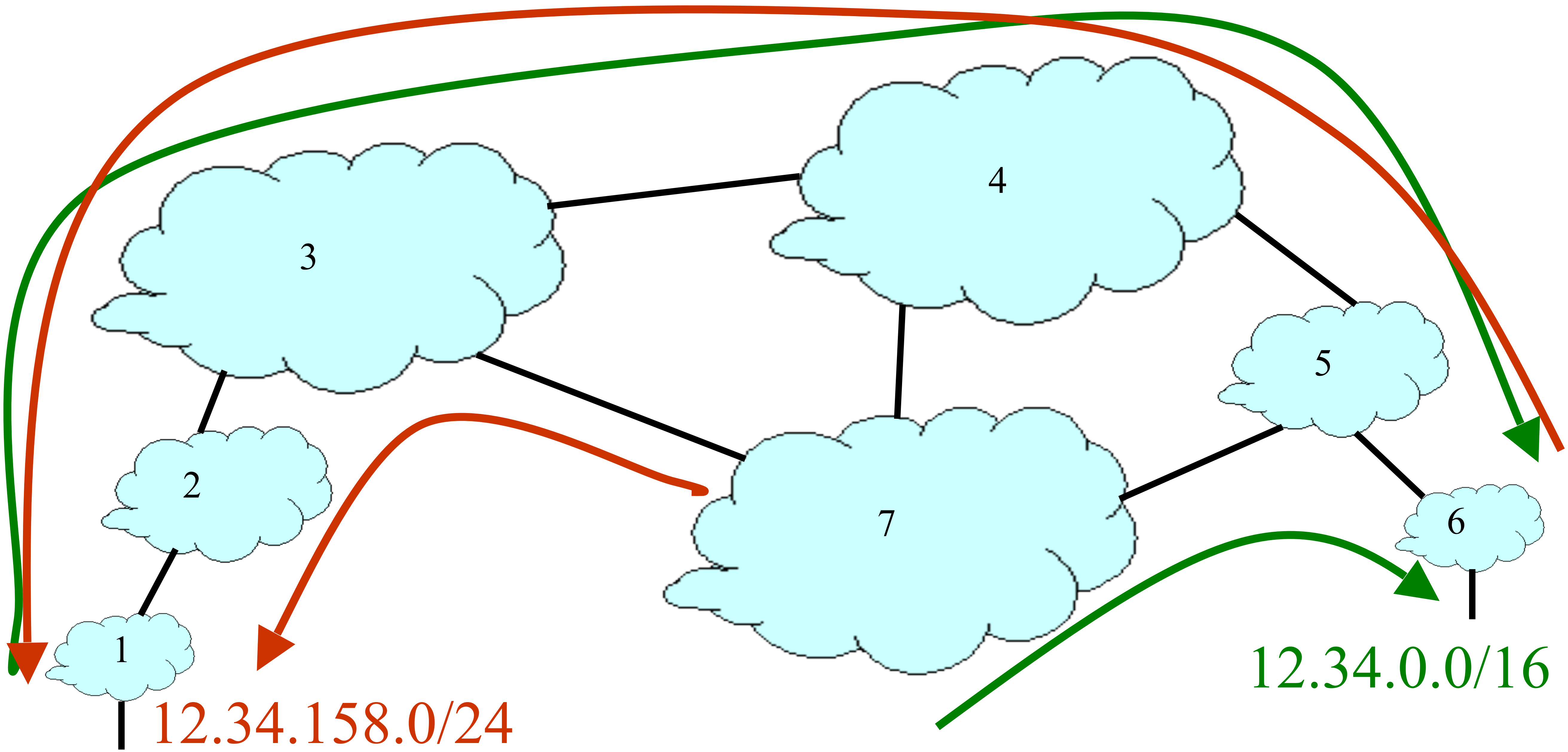


- Blackhole: data traffic is discarded
- Snooping: data traffic is inspected, then redirected
- Impersonation: traffic sent to bogus destinations

Hijacking is Hard to Debug

- The victim AS doesn't see the problem
  - Picks its own route, might not learn the bogus route
- May not cause loss of connectivity
  - Snooping, with minor performance degradation
- Or, loss of connectivity is isolated
  - E.g., only for sources in parts of the Internet
- Diagnosing prefix hijacking
  - Analyzing updates from many vantage points
  - Launching traceroute from many vantage points

Sub-Prefix Hijacking



- Originating a more-specific prefix
  - Every AS picks the bogus route for that prefix
  - Traffic follows the longest matching prefix

How to Hijack a Prefix

- The hijacking AS has
  - Router with BGP session(s)
  - Configured to originate the prefix
- Getting access to the router
  - Network operator makes configuration mistake
  - Disgruntled operator launches an attack
  - Outsider breaks in to the router and reconfigures
- Getting other ASes to believe bogus route
  - Neighbor ASes do not discard the bogus route
  - E.g., not doing protective filtering

YouTube Outage on Feb 24, 2008

- YouTube (AS 36561)
  - Web site www.youtube.com (208.65.152.0/22)
- Pakistan Telecom (AS 17557)
  - Government order to block access to YouTube
  - Announces 208.65.153.0/24 to PCCW (AS 3491)
  - All packets to YouTube get dropped on the floor
- Mistakes were made
  - AS 17557: announce to everyone, not just customers
  - AS 3491: not filtering routes announced by AS 17557
- Lasted 100 minutes for some, 2 hours for others

Timeline (UTC Time)

- 18:47:45
  - First evidence of hijacked /24 route in Asia
- 18:48:00
  - Several big trans-Pacific providers carrying the route
- 18:49:30
  - Bogus route fully propagated
- 20:07:25
  - YouTube starts advertising /24 to attract traffic back
- 20:08:30
  - Many (but not all) providers are using valid route

Timeline (UTC Time)

- 20:18:43
  – YouTube announces two more-specific /25 routes
- 20:19:37
  – Some more providers start using the /25 routes
- 20:50:59
  – AS 17557 starts prepending ("3491 17557 17557")
- 20:59:39
  – AS 3491 disconnects AS 17557
- 21:00:00
  – Videos of cats flushing toilets are available again!

Another Example: Spammers

- Spammers sending spam
  - Form a (bidirectional) TCP connection to mail server
  - Send a bunch of spam e-mail, then disconnect
- But, best not to use your real IP address
  - Relatively easy to trace back to you
- Could hijack someone's address space
  - But you might not receive all the (TCP) return traffic
- How to evade detection
  - Hijack unused (i.e., unallocated) address block
  - Temporarily use the IP addresses to send your spam

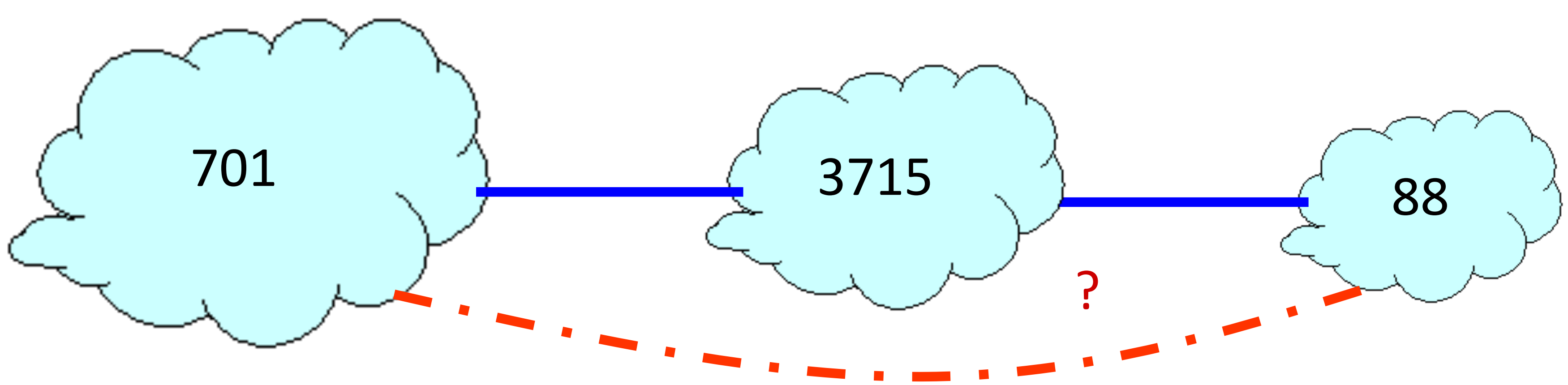
BGP (lack of) security

#1 BGP does not validate the origin of advertisements

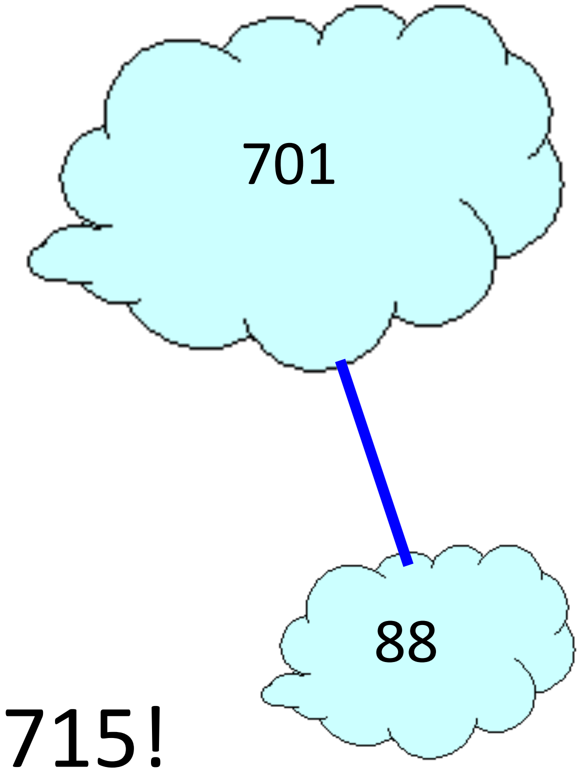
#2 BGP does not validate the content of advertisements

Bogus AS Paths

- Remove ASes from the AS path
  - E.g., turn “701 3715 88” into “701 88”
- Motivations
  - Attract sources that normally try to avoid AS 3715
  - Help AS 88 look like it is closer to the Internet’s core
- Who can tell that this AS path is a lie?
  - Maybe AS 88 *does* connect to AS 701 directly



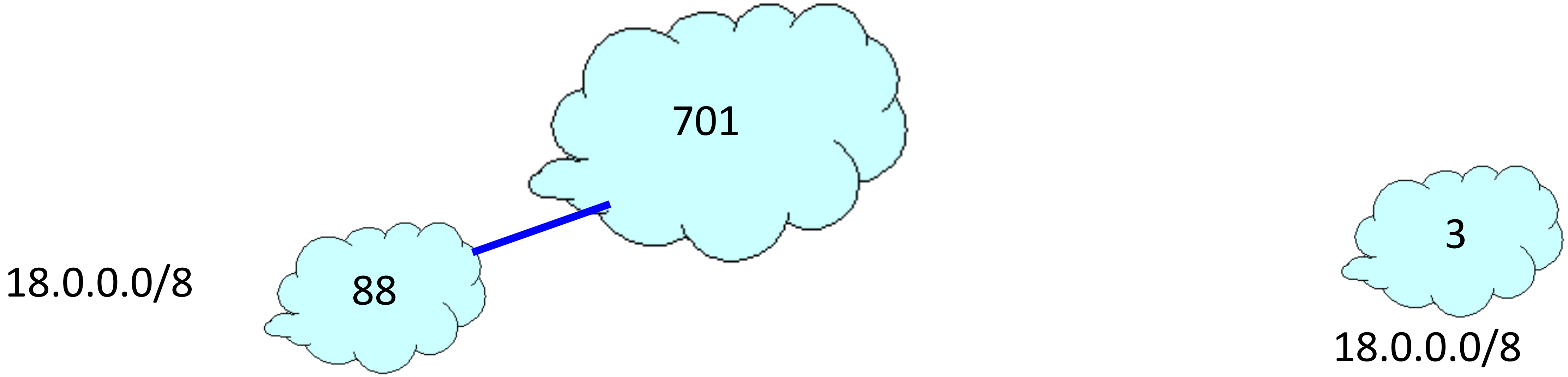
Bogus AS Paths



- Add ASes to the path
  - E.g., turn "701 88" into "701 3715 88"
- Motivations
  - Trigger loop detection in AS 3715
    - Denial-of-service attack on AS 3715
    - Or, blocking unwanted traffic coming from AS 3715!
  - Make your AS look like is has richer connectivity
- Who can tell the AS path is a lie?
  - AS 3715 could, if it could see the route
  - AS 88 could, but would it really care?

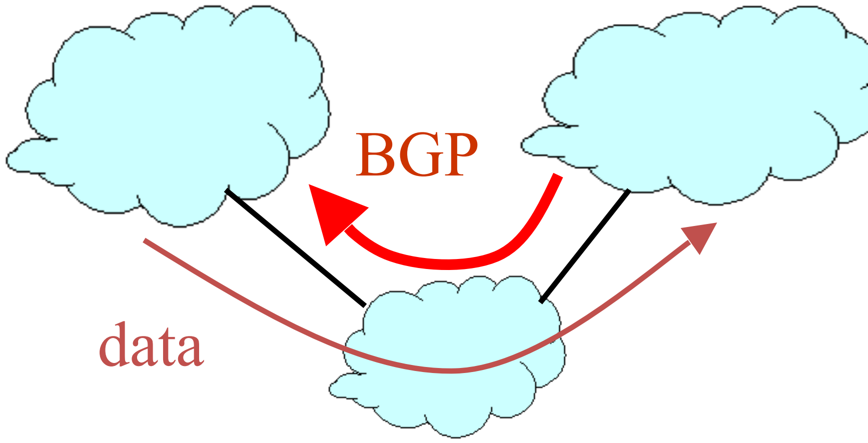
Bogus AS Paths

- Adds AS hop(s) at the end of the path
  - E.g., turns "701 88" into "701 88 3"
- Motivations
  - Evade detection for a bogus route
  - E.g., by adding the legitimate AS to the end
- Hard to tell that the AS path is bogus…
  - Even if other ASes filter based on prefix ownership



Invalid Paths

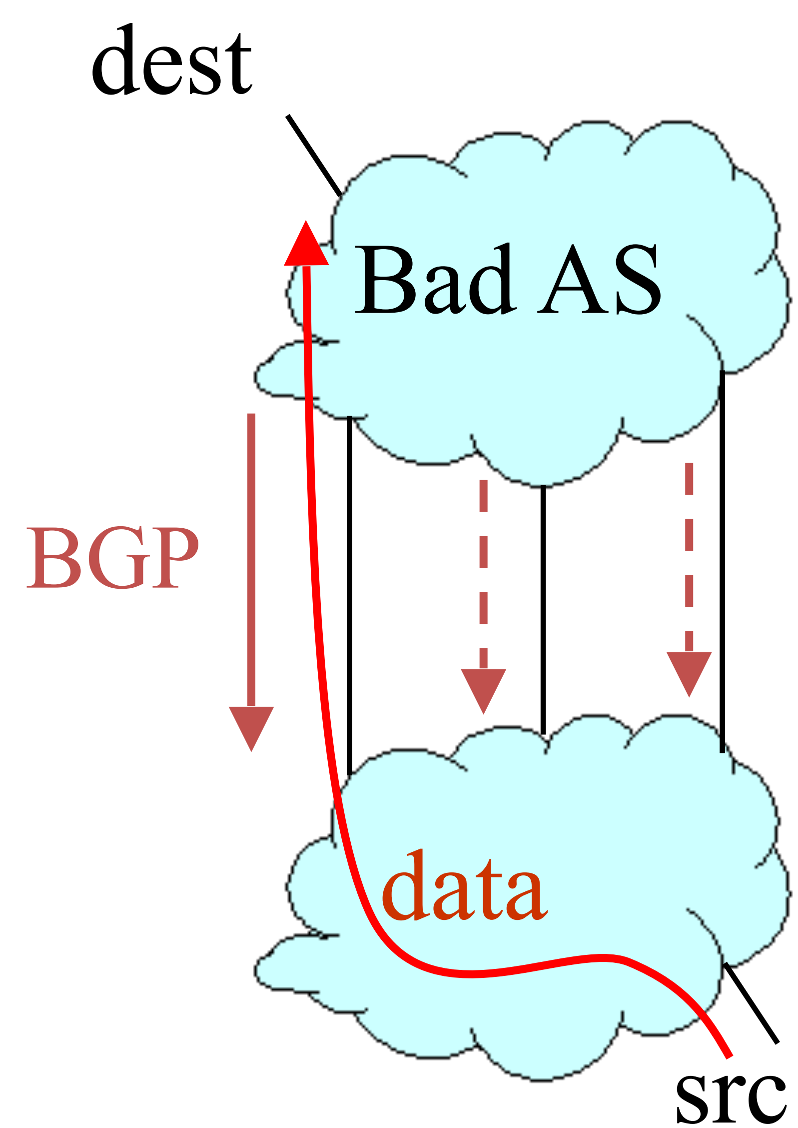
- AS exports a route it shouldn't
  - AS path is a valid sequence, but violated policy
- Example: customer misconfiguration
  - Exports routes from one provider to another
- Interacts with provider policy
  - Provider prefers customer routes
  - Directing all traffic through customer



- Main defense
  - Filtering routes based on prefixes and AS path

Missing/Inconsistent Routes

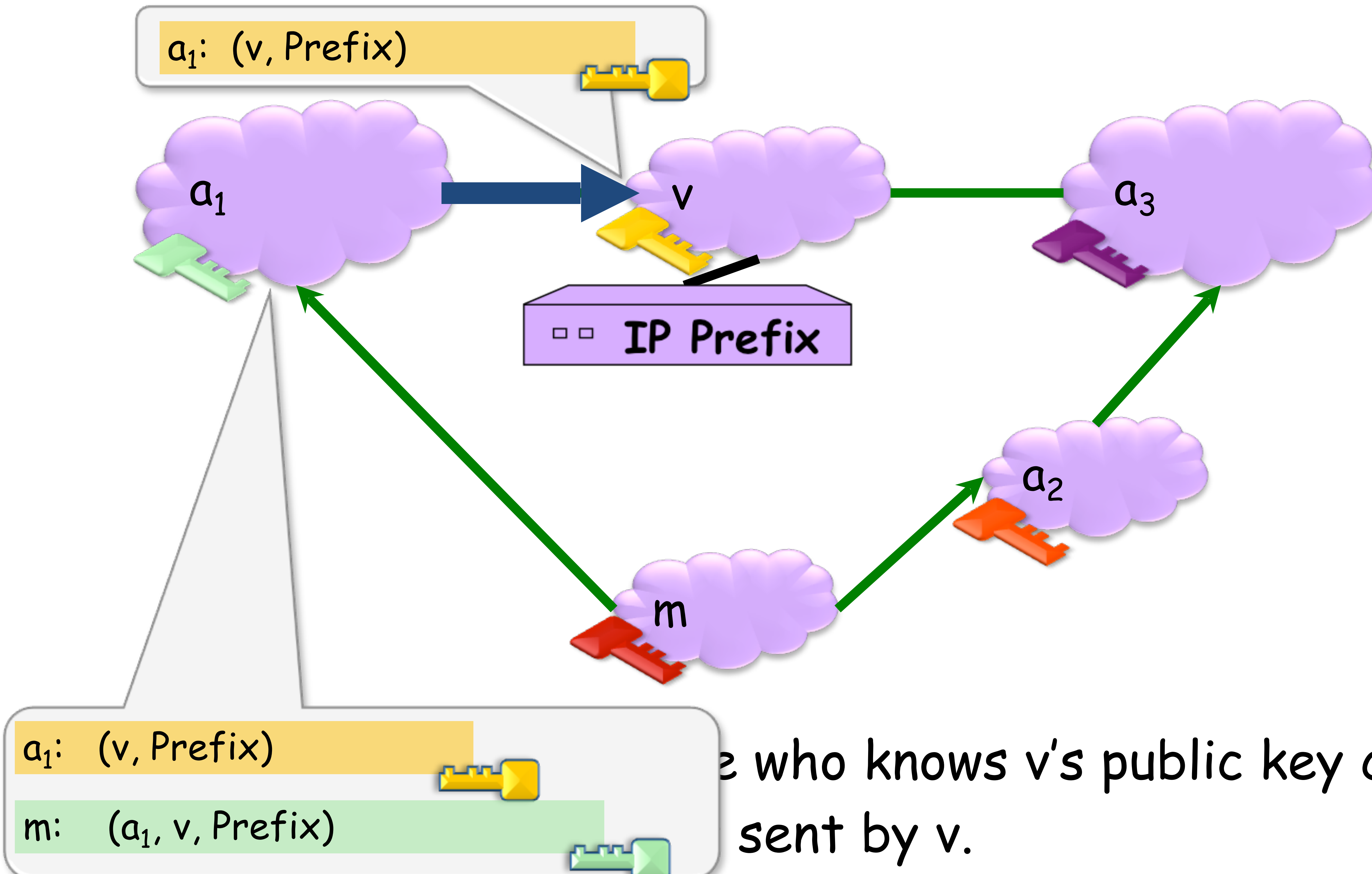
- Peers require consistent export
  - Prefix advertised at all peering points
  - Prefix advertised with same AS path length
- Reasons for violating the policy
  - Trick neighbor into “cold potato”
  - Configuration mistake
- Main defense
  - Analyzing BGP updates, or traffic,
  - … for signs of inconsistency



Proposed Enhancements to BGP

Secure BGP

Origin Authentication + cryptographic signatures



e who knows v's public key can
sent by v.

S-BGP Secure Version of BGP

- Address attestations
  - Claim the right to originate a prefix
  - Signed and distributed out-of-band
  - Checked through delegation chain from ICANN
- Route attestations
  - Distributed as an attribute in BGP update message
  - Signed by each AS as route traverses the network
- S-BGP can validate
  - AS path indicates the order ASes were traversed
  - No intermediate ASes were added or removed

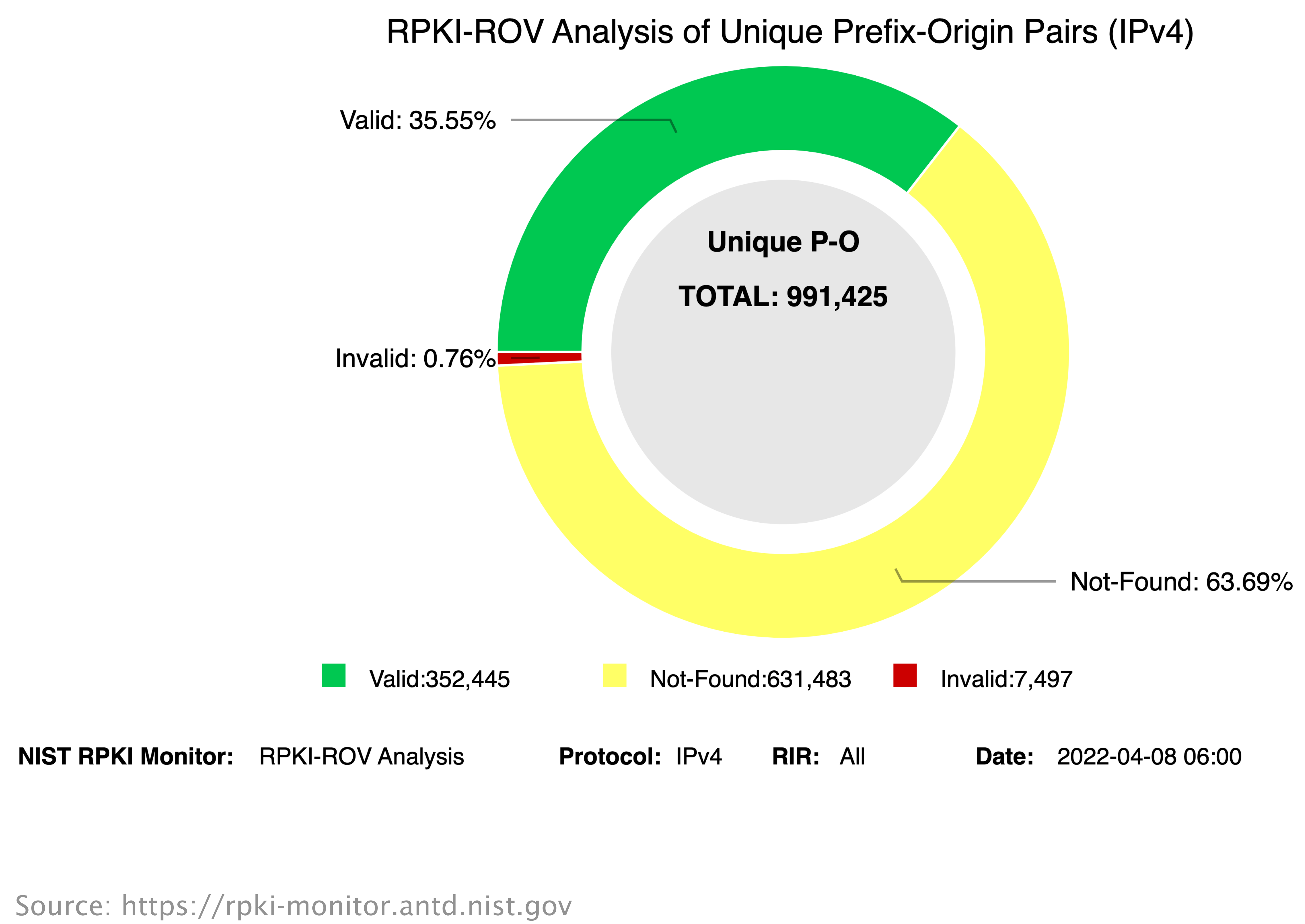
S-BGP Deployment Challenges

- Complete, accurate registries of prefix “owner”
- Public Key Infrastructure
  - To know the public key for any given AS
- Cryptographic operations
  - E.g., digital signatures on BGP messages
- Need to perform operations quickly
  - To avoid delaying response to routing changes
- Difficulty of incremental deployment
  - Hard to have a “flag day” to deploy S-BGP

BGP Security Today

BGP Security Today

- Resource Public Key Infrastructure (RPKI)
  - A framework to support improved BGP security:
    1. A secure way to map AS numbers to IP prefixes.
    2. A distributed repository system for storing and disseminating the mappings.
- RPKI operations
  - RPKI relies on cryptographic certificates (X.509)
  - The certificate infrastructure mimics the way IP prefixes are distributed: from IANA, to Regional Internet Registries (RIR), to end-customers.
  - A Route Origination Authorization (ROA) states which AS is authorised to originate certain IP prefixes.


RPKI-ROV Analysis of Unique Prefix-Origin Pairs (IPv4)
Valid: 35.55%
Invalid: 0.76%
Not-Found: 63.69%
Unique P-O
TOTAL: 991,425
Valid:352,445
Not-Found:631,483
Invalid:7,497
NIST RPKI Monitor: RPKI-ROV Analysis
Protocol: IPv4
RIR: All
Date: 2022-04-08 06:00
Source: https://rpki-monitor.antd.nist.gov

Problems

Reachability

Security

Convergence

Performance

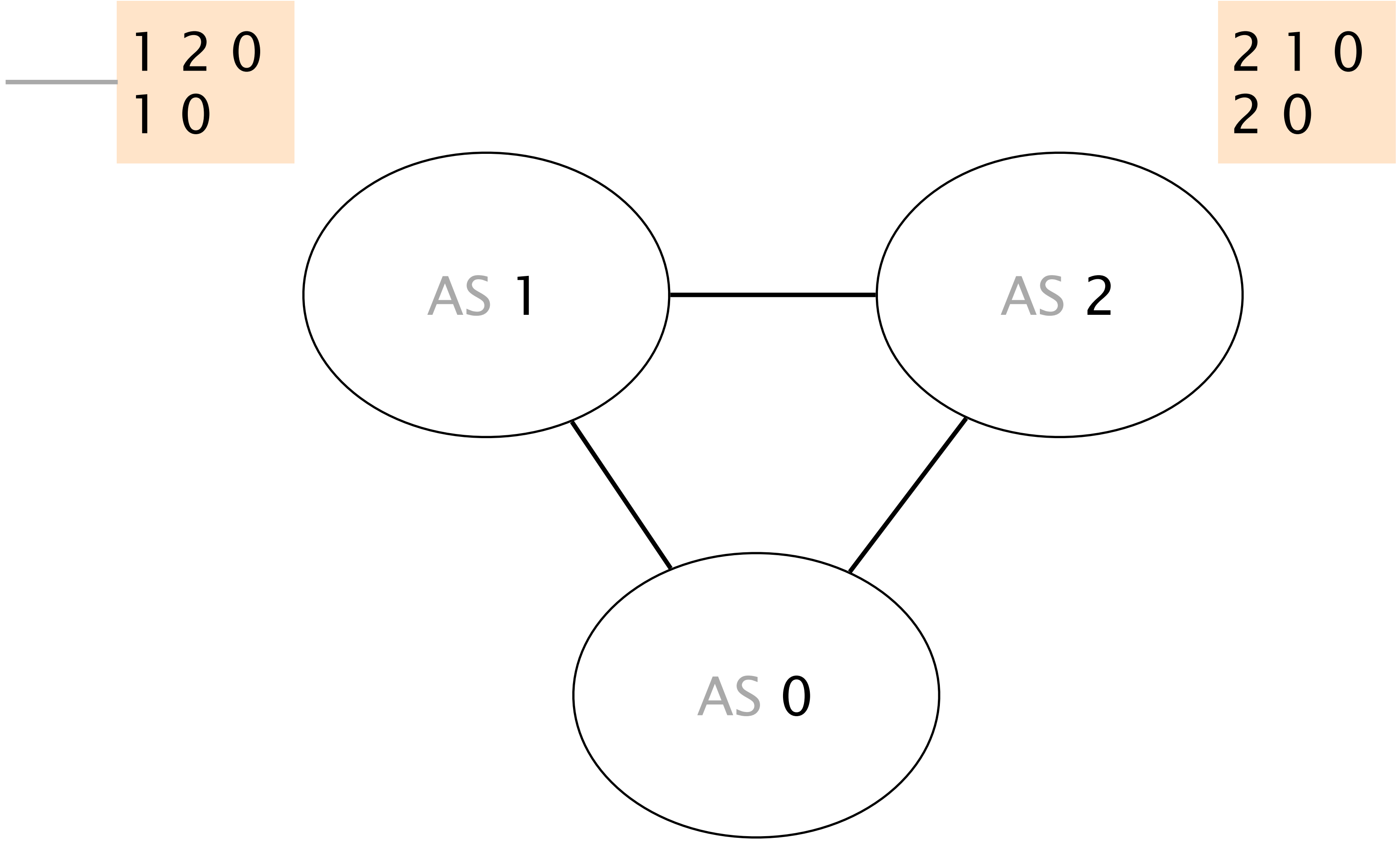
Anomalies

Relevance

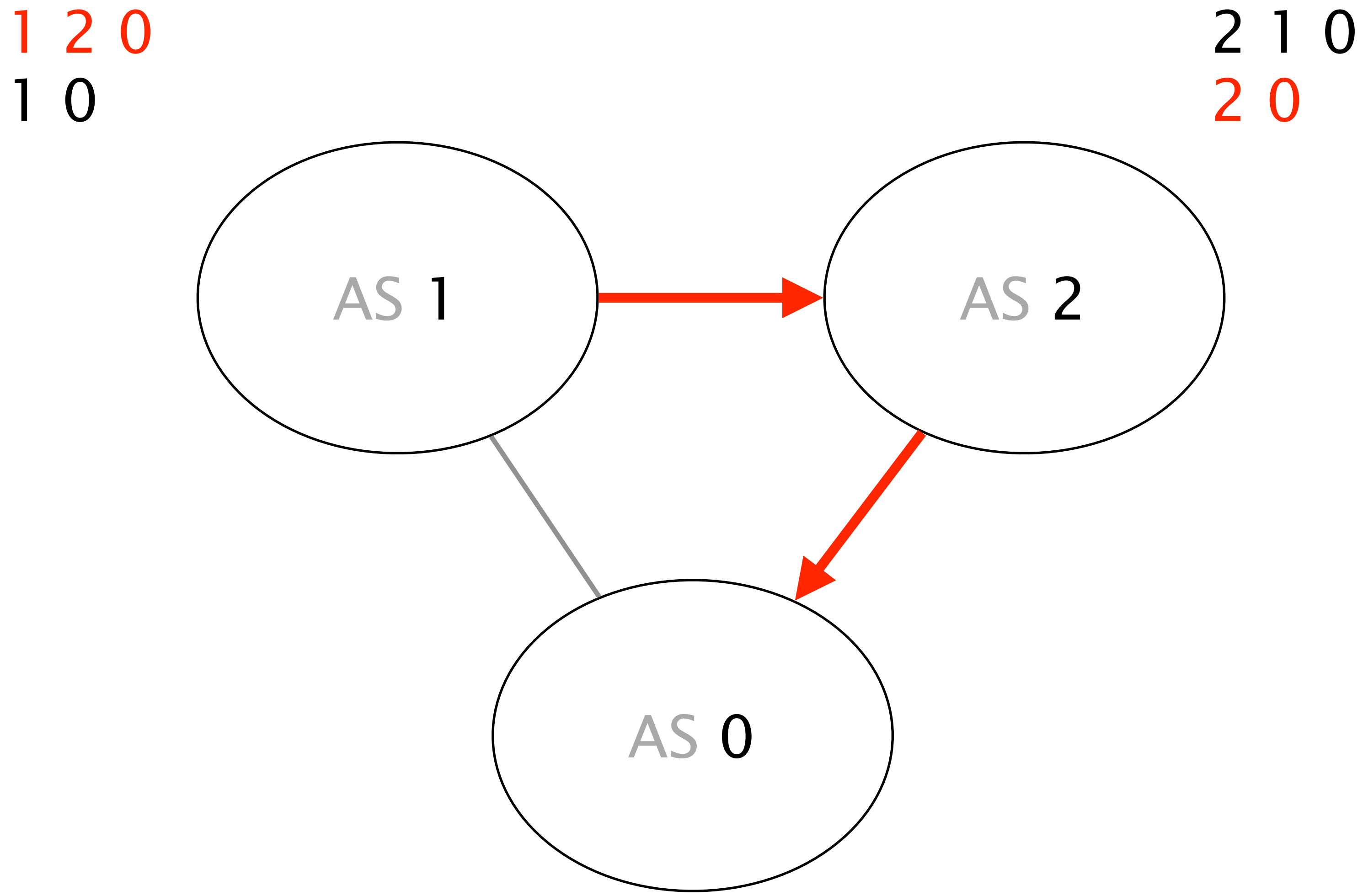
With arbitrary policies,
BGP may have multiple stable states

preference list

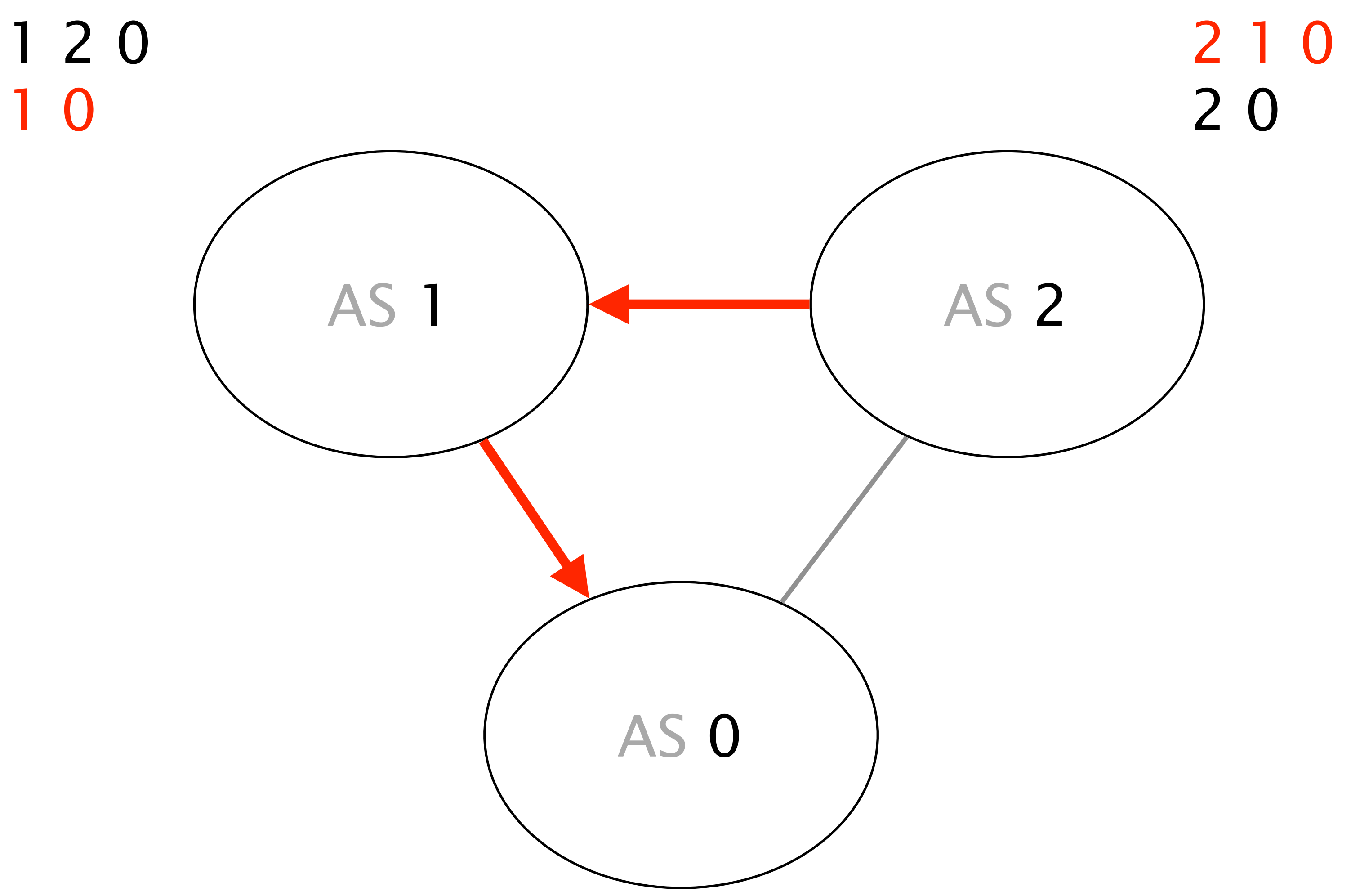
1 prefers to reach 0
via 2 rather than directly



If AS2 is the first to advertise 2 0,
the system stabilizes in a state where AS 1 is happy

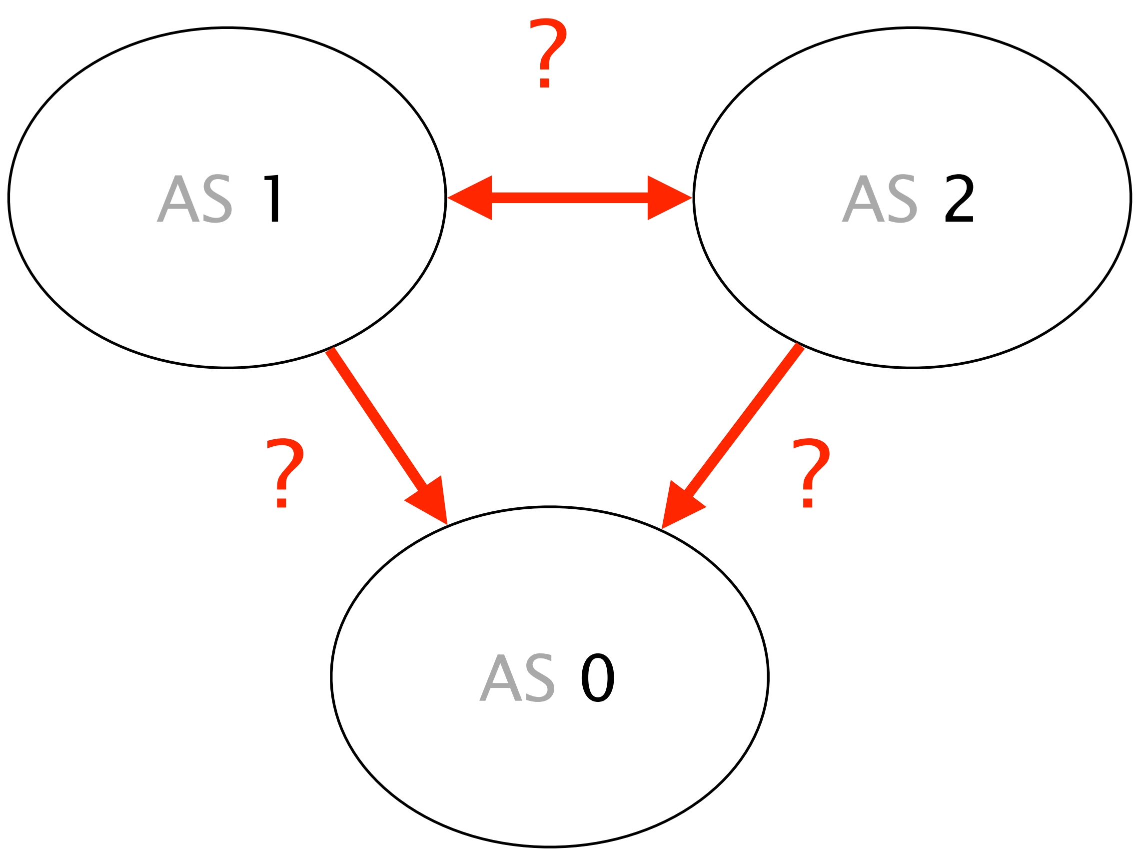


If AS1 is the first one to advertise 1 0,
the system stabilizes in a state where AS 2 is happy



The actual assignment depends on the ordering between the messages

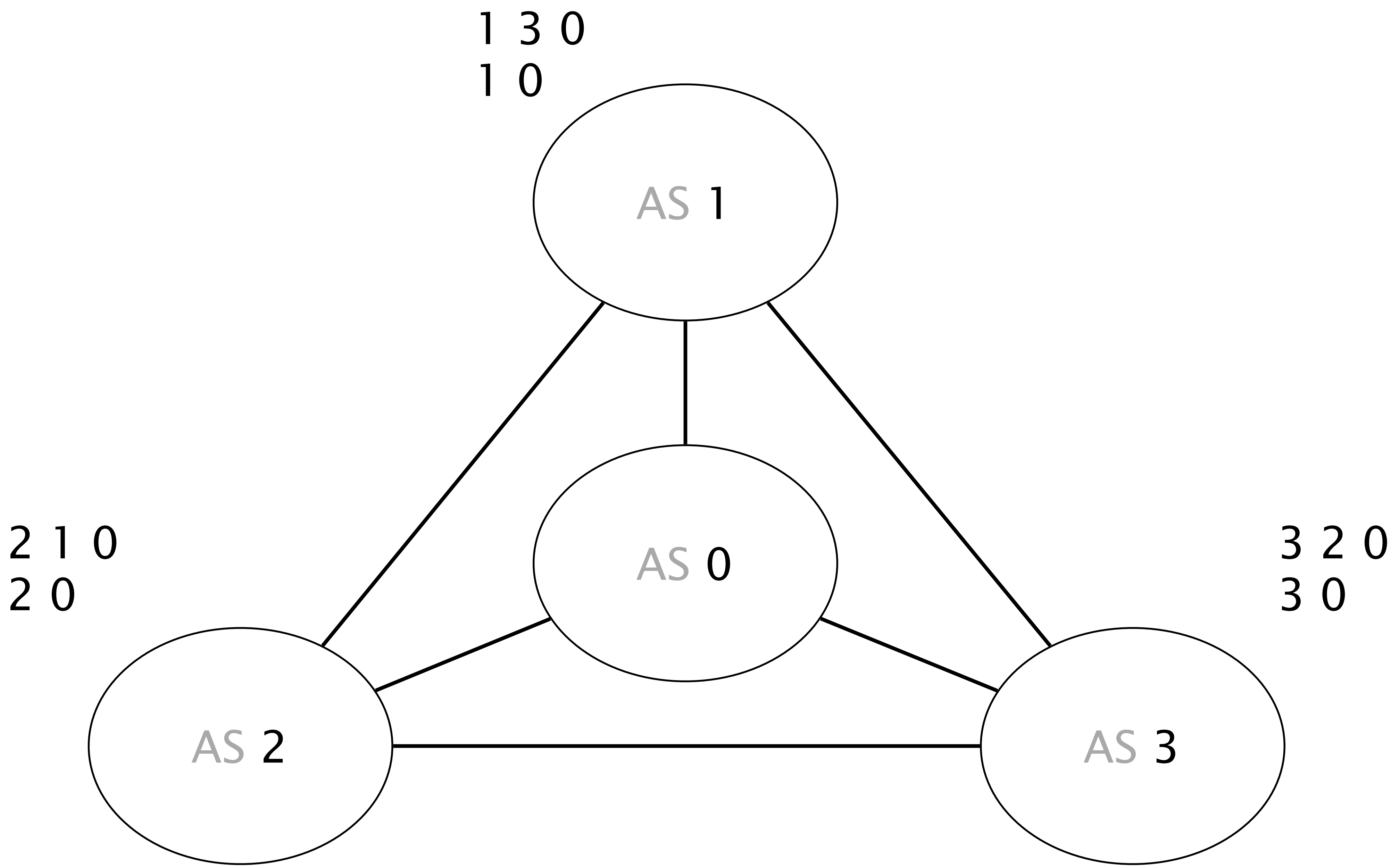
Note that AS1/AS2 could change the outcome by manual intervention

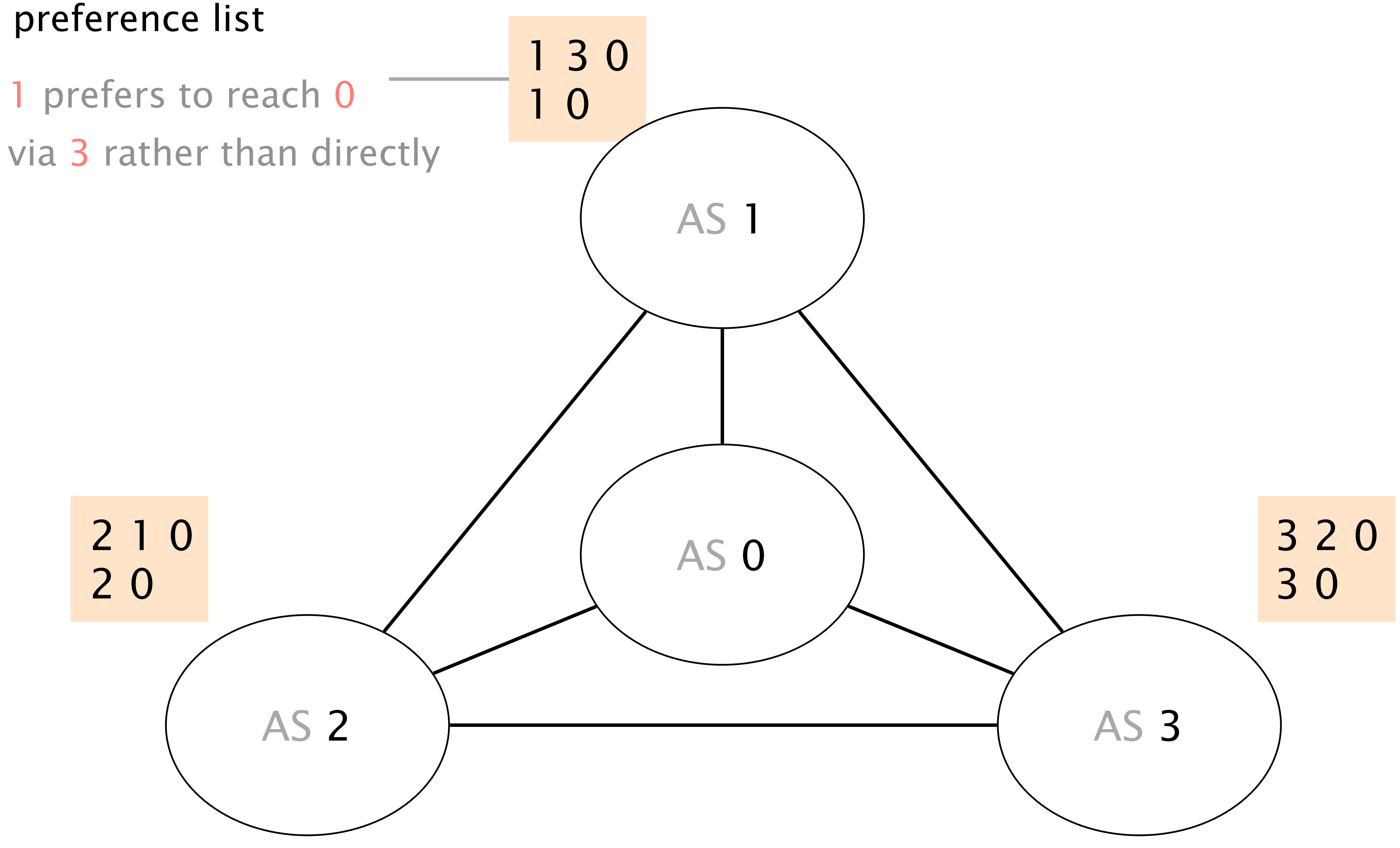


… this is not always possible *

* https://www.nanog.org/meetings/nanog31/presentations/griffin.pdf

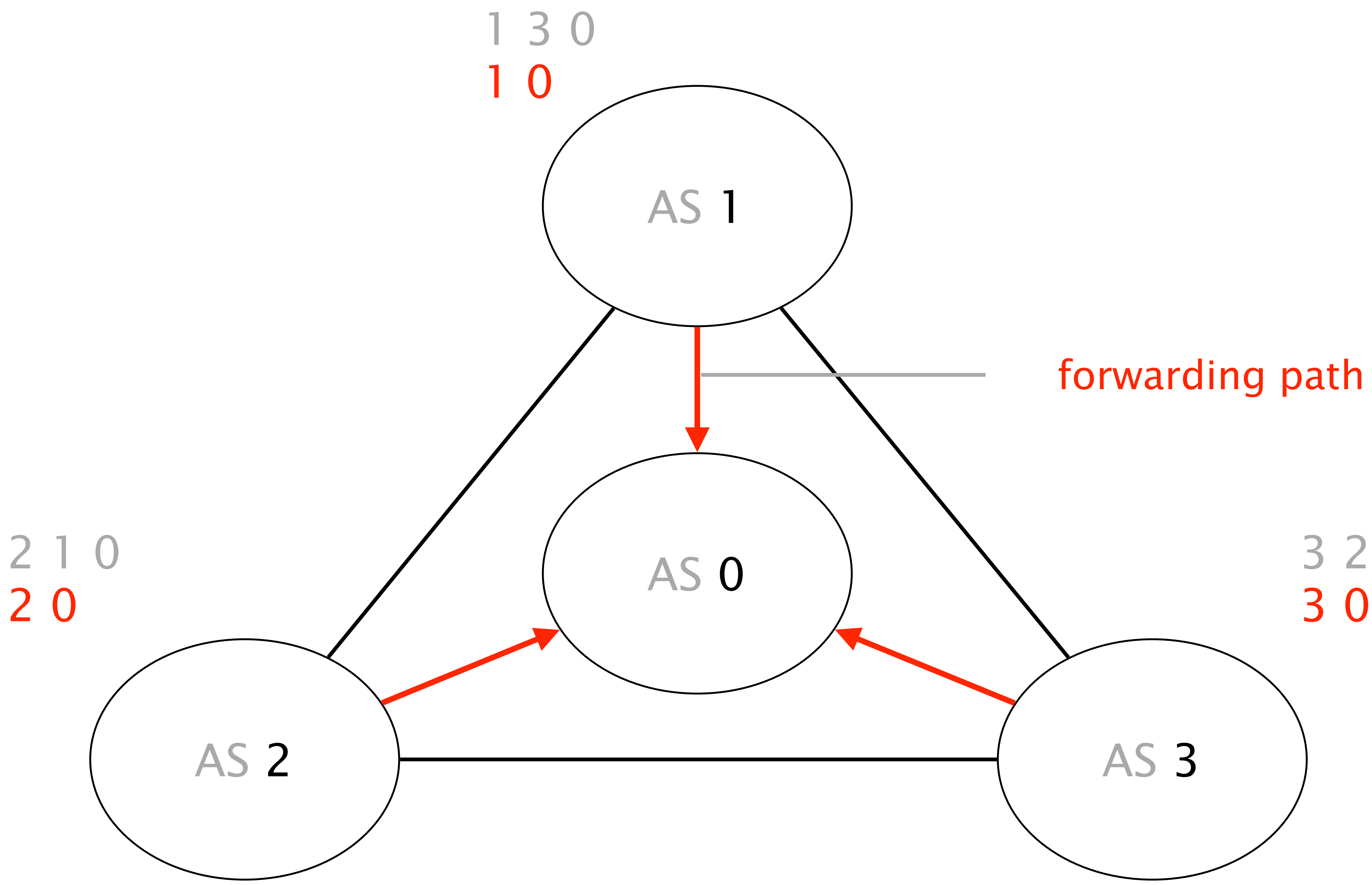
With arbitrary policies,
BGP may fail to converge


1 3 0
1 0
AS 1
2 1 0
2 0
AS 0
3 2 0
3 0
AS 2
AS 3

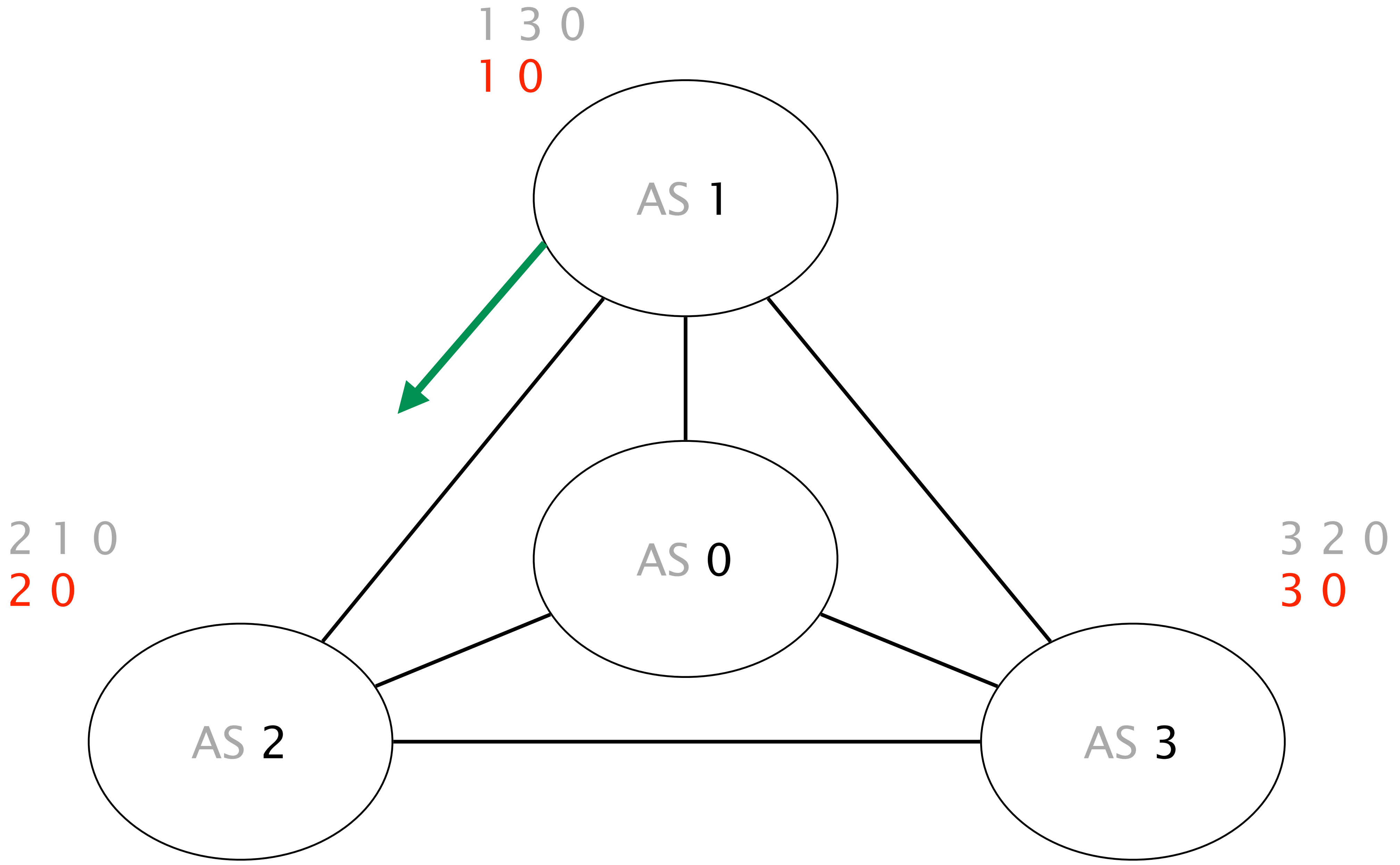


preference list
1 prefers to reach 0
via 3 rather than directly
1 3 0
1 0
2 1 0
2 0
3 2 0
3 0
AS 1
AS 0
AS 2
AS 3

Initially, all ASes only know the direct route to 0

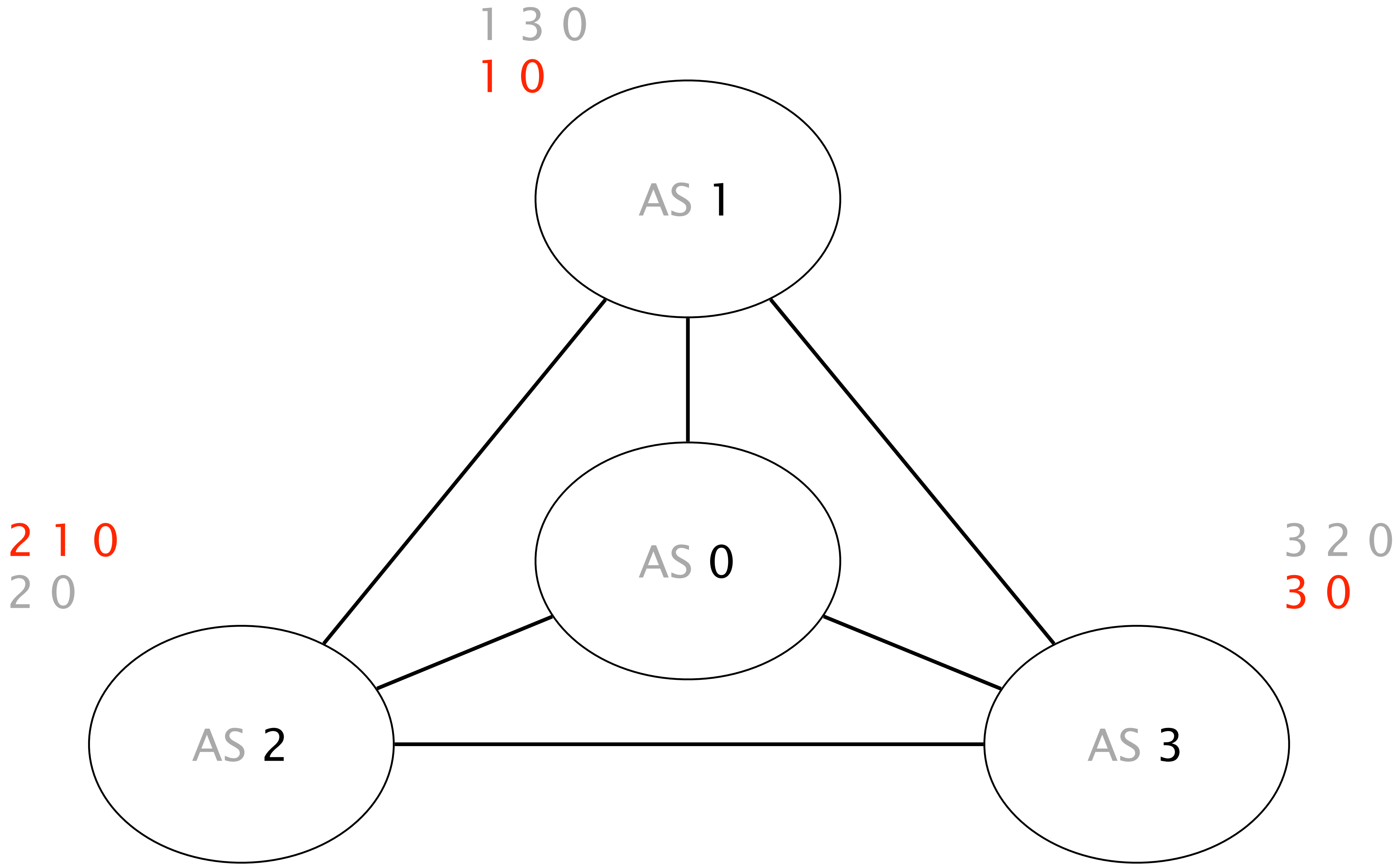


AS 1 advertises its path to AS 2

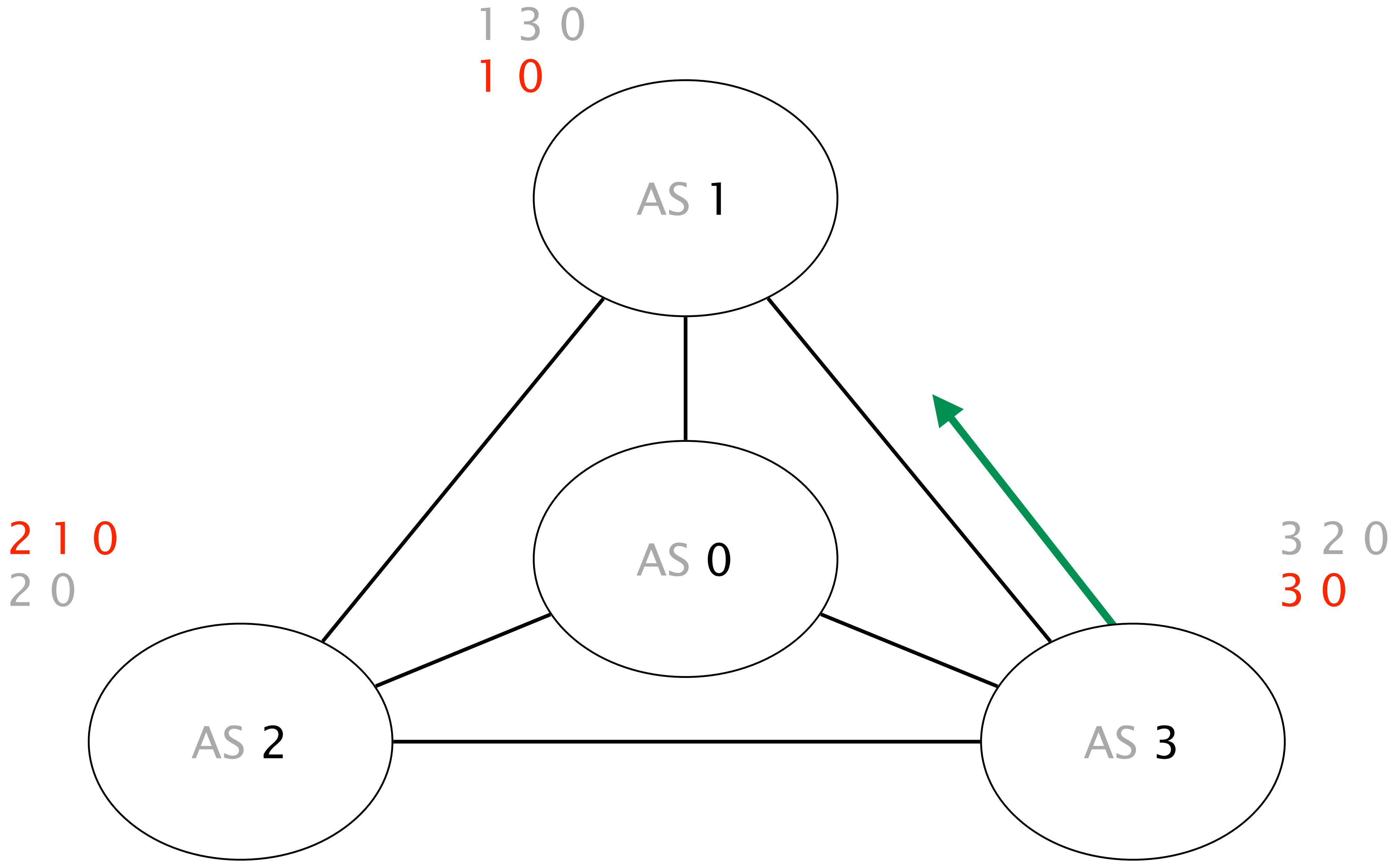


Upon reception,

AS 2 switches to 2 1 0 (preferred)

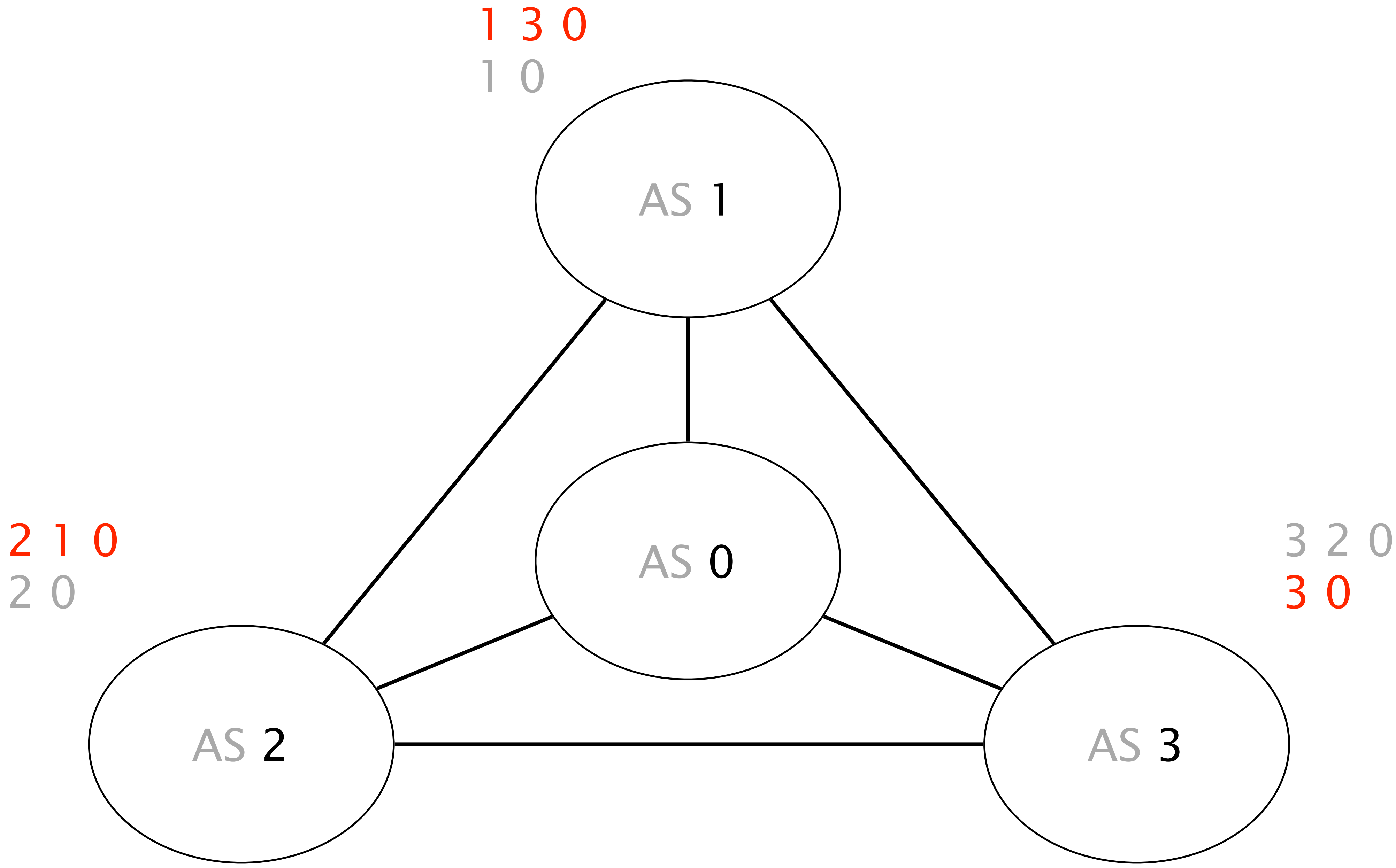


AS 3 advertises its path to AS 1

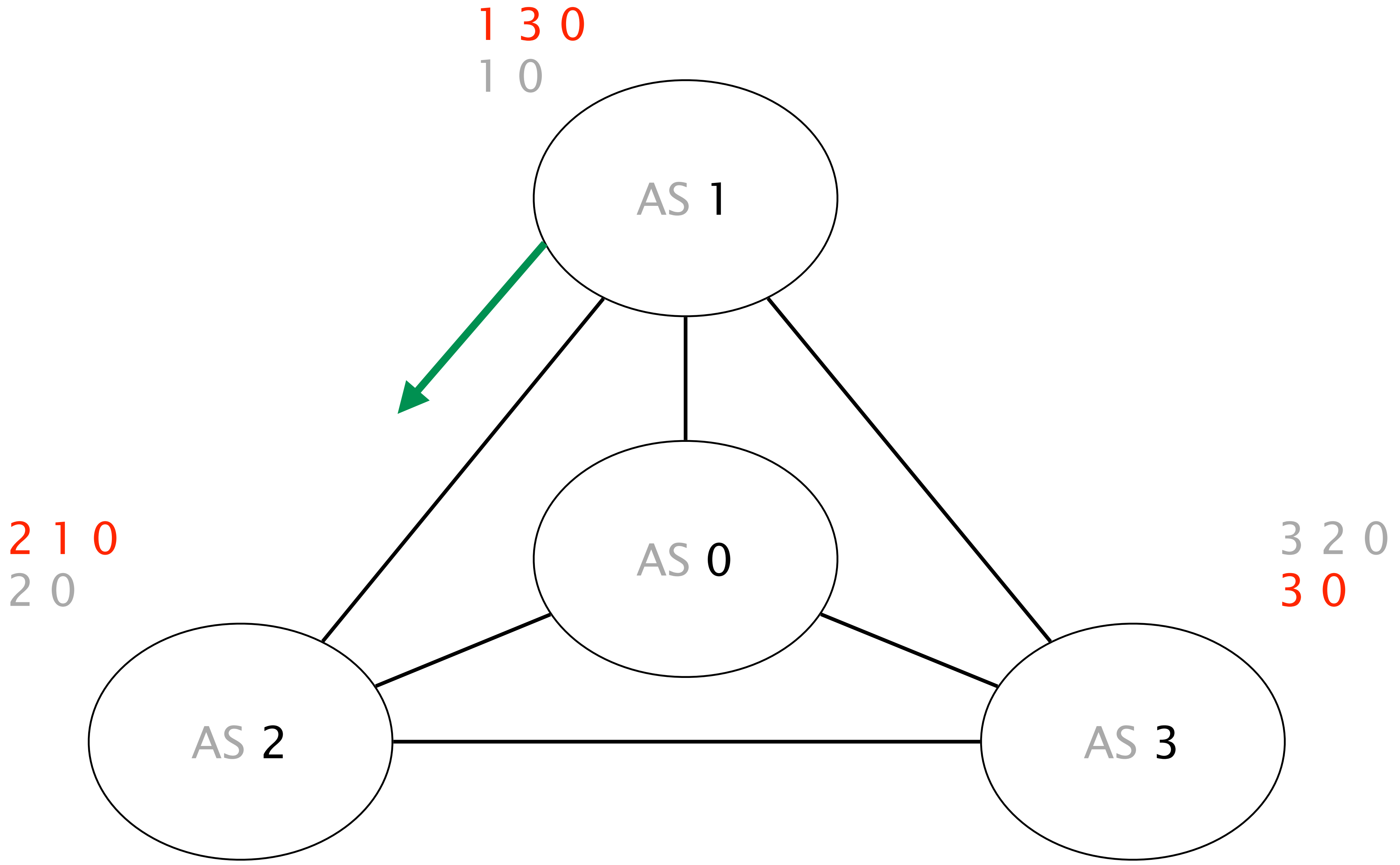


Upon reception,

AS 1 switches to 1 3 0 (preferred)

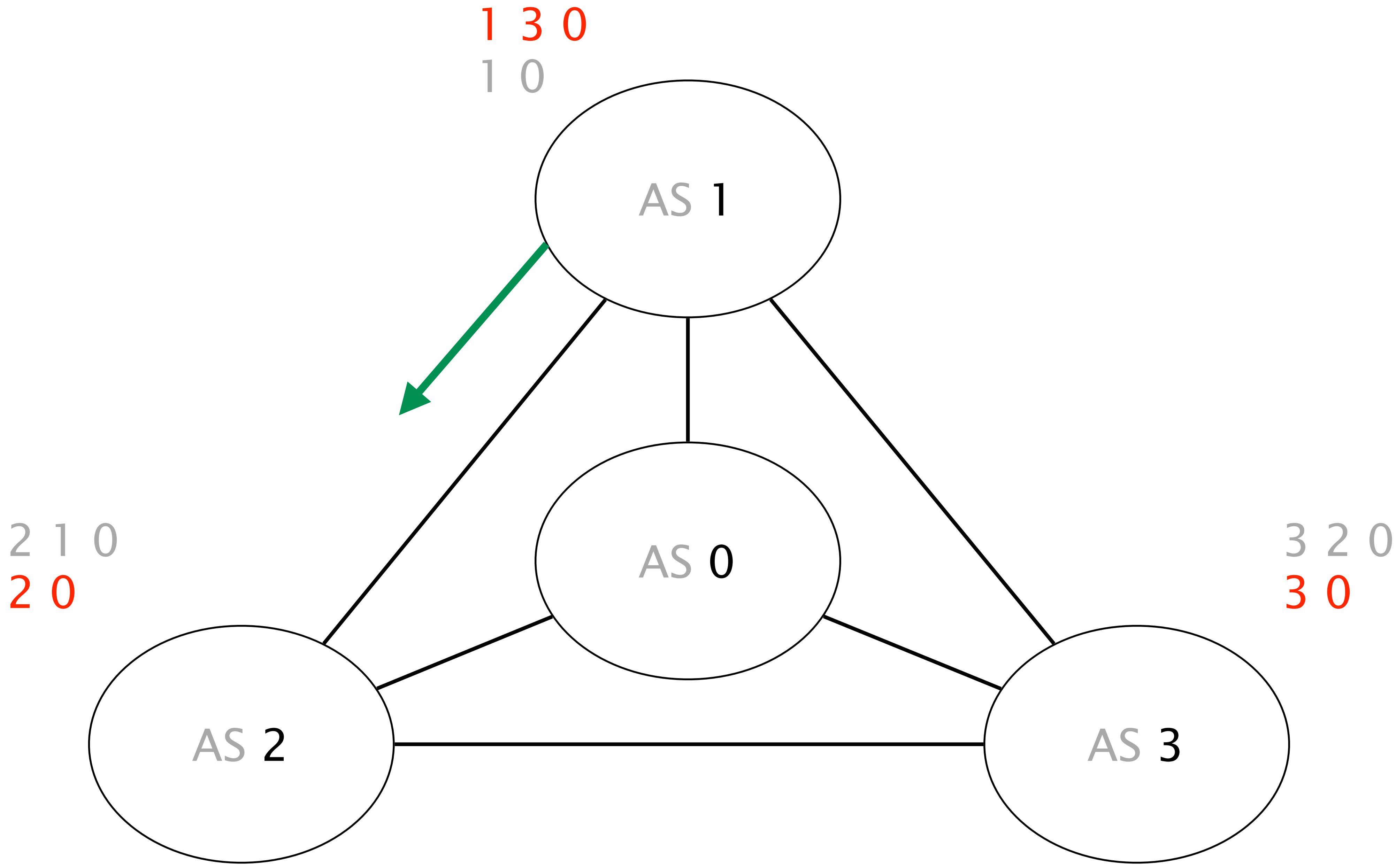


AS 1 advertises its new path 1 3 0 to AS 2

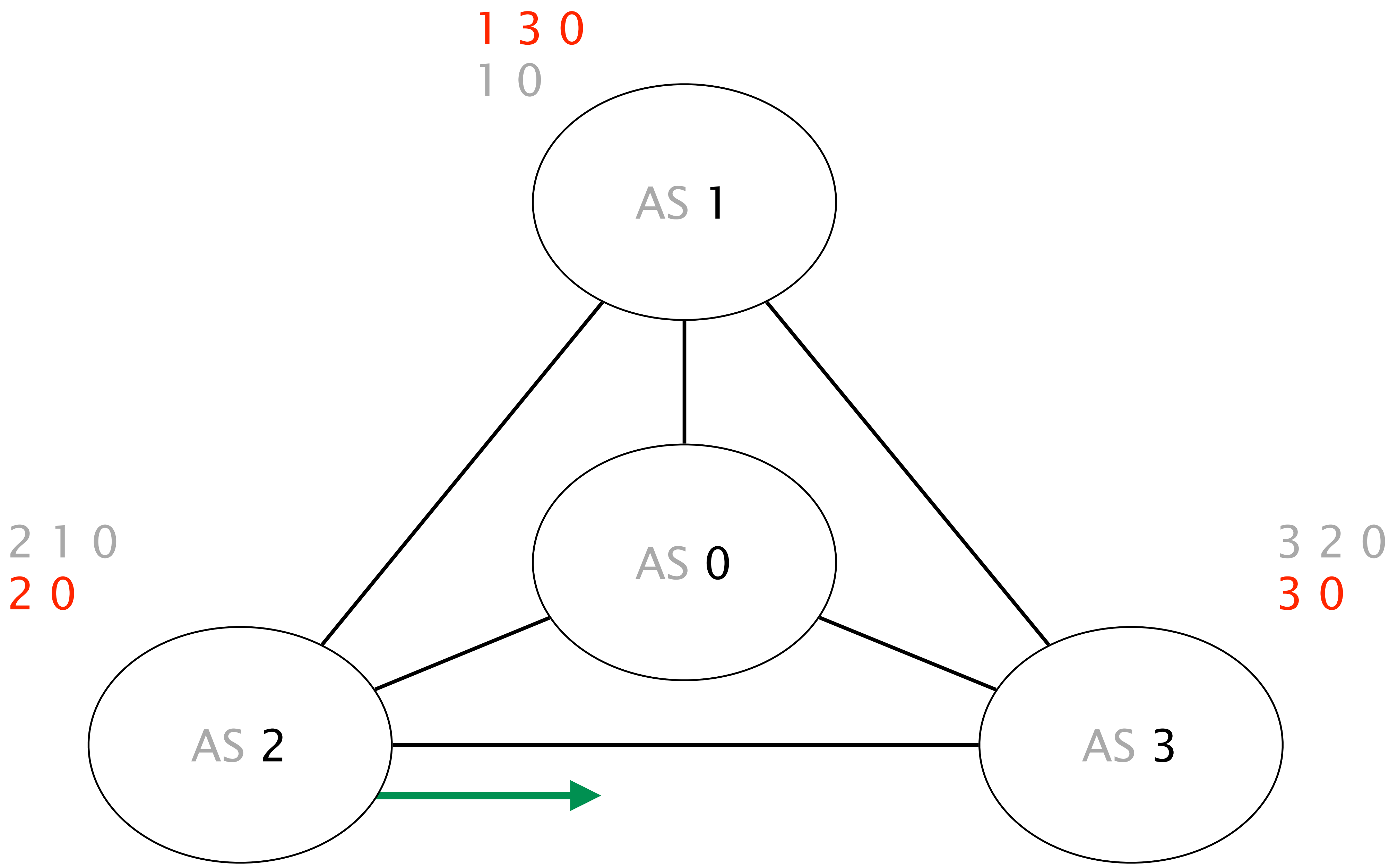


Upon reception,

AS 2 reverts back to its initial path 2 0

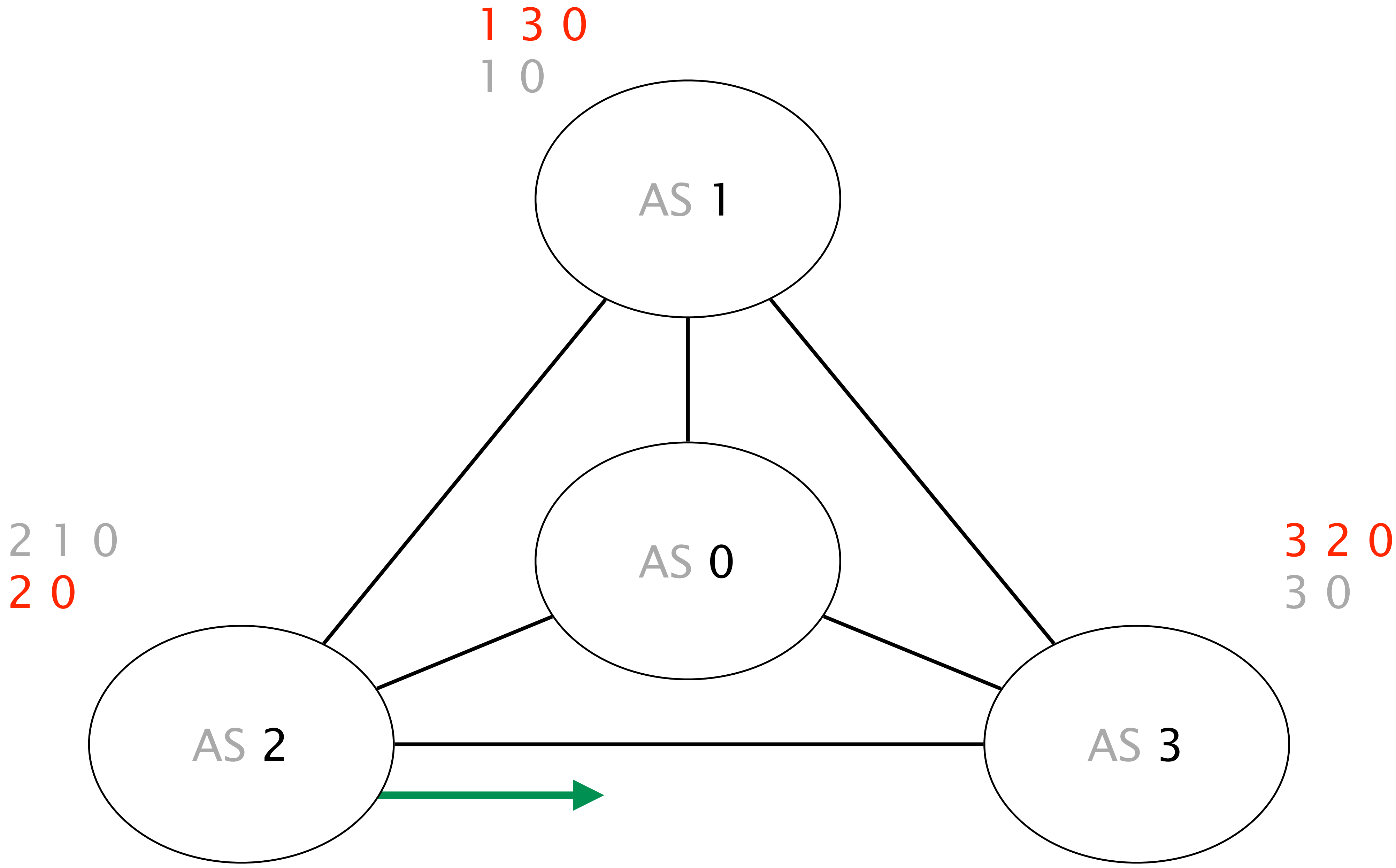


AS 2 advertises its path 2 0 to AS 3

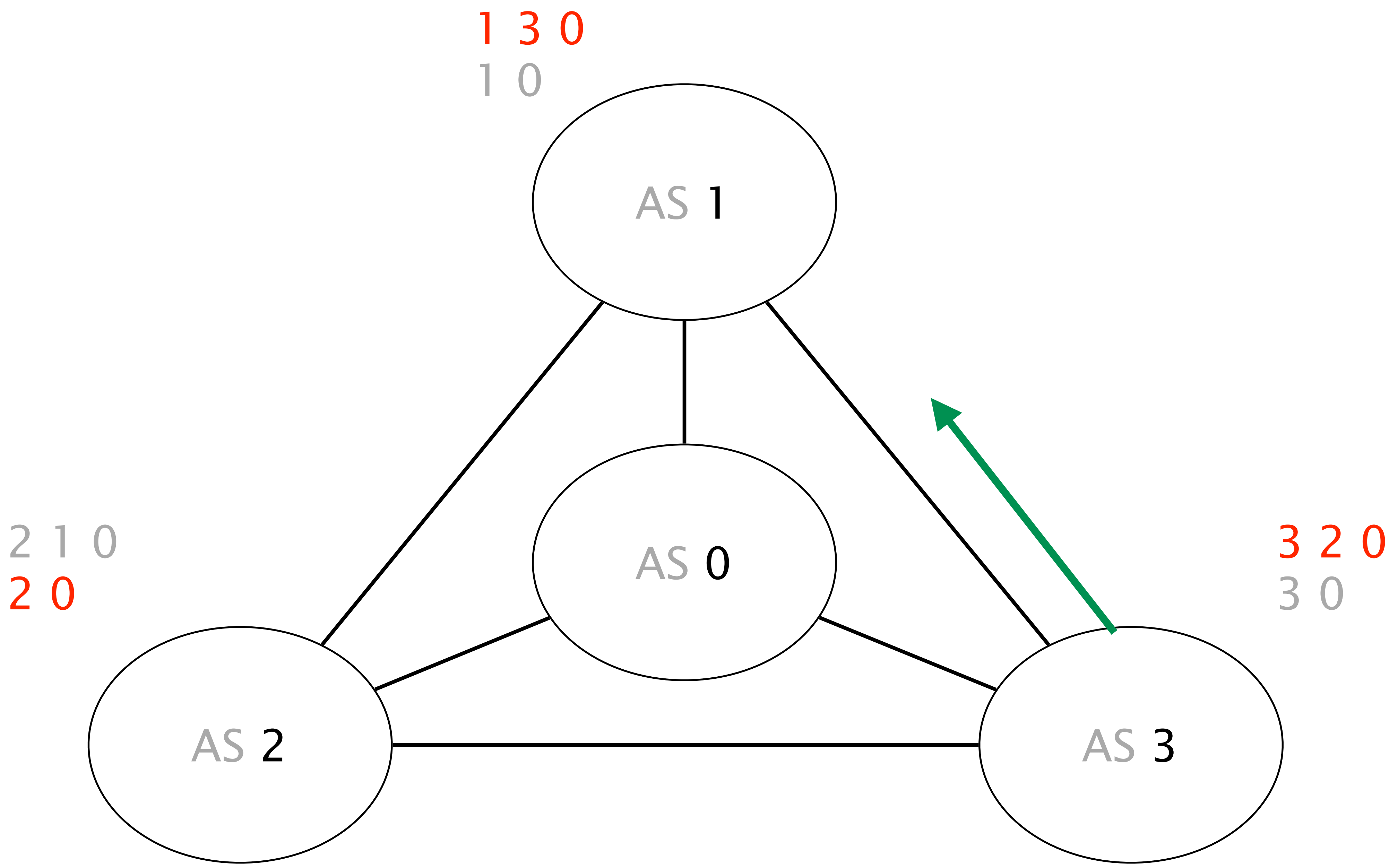


Upon reception,

AS 3 switches to 3 2 0 (preferred)

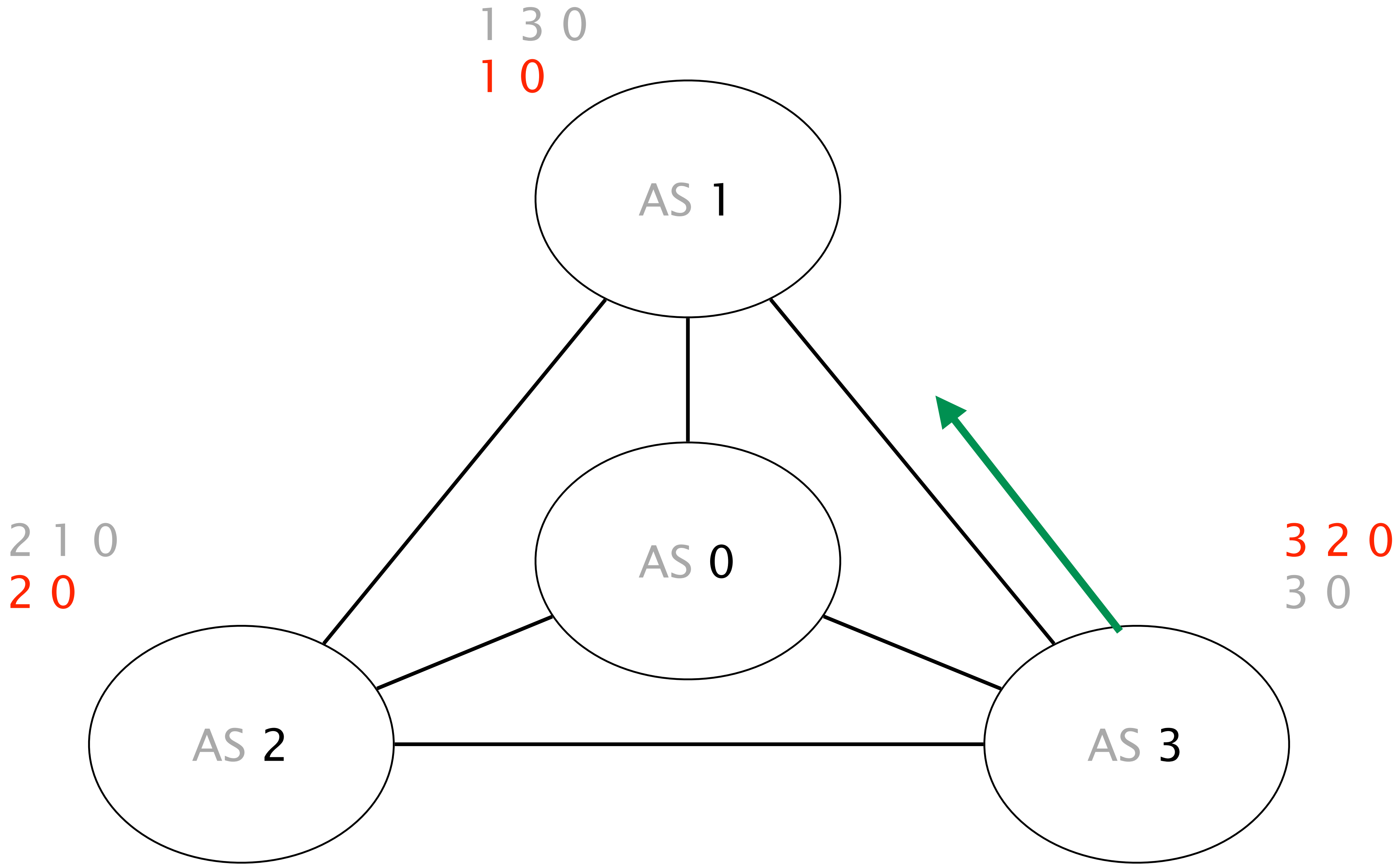


AS 3 advertises its new path 3 2 0 to AS 1

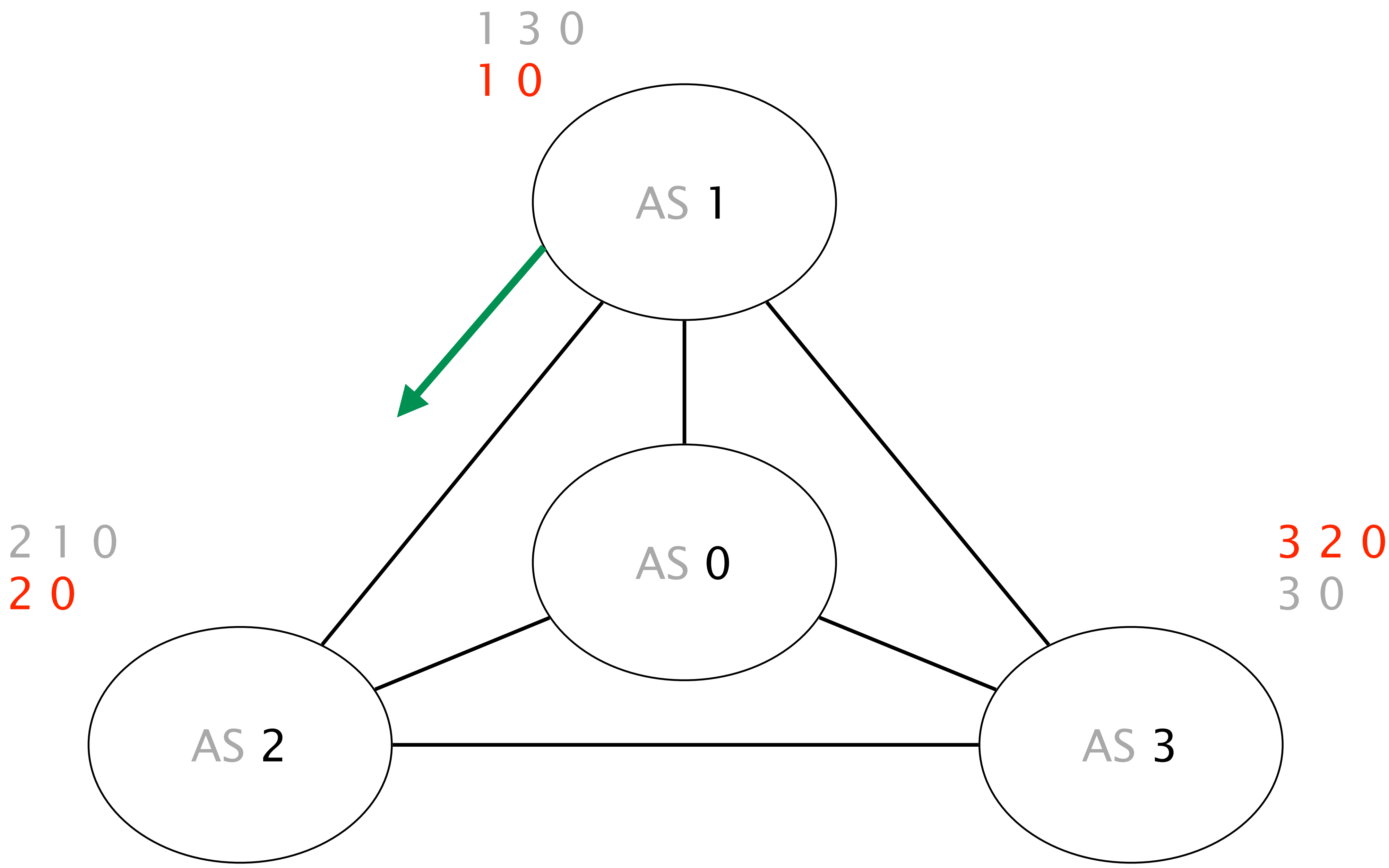


Upon reception,

AS 1 reverts back to 1 0 (initial path)

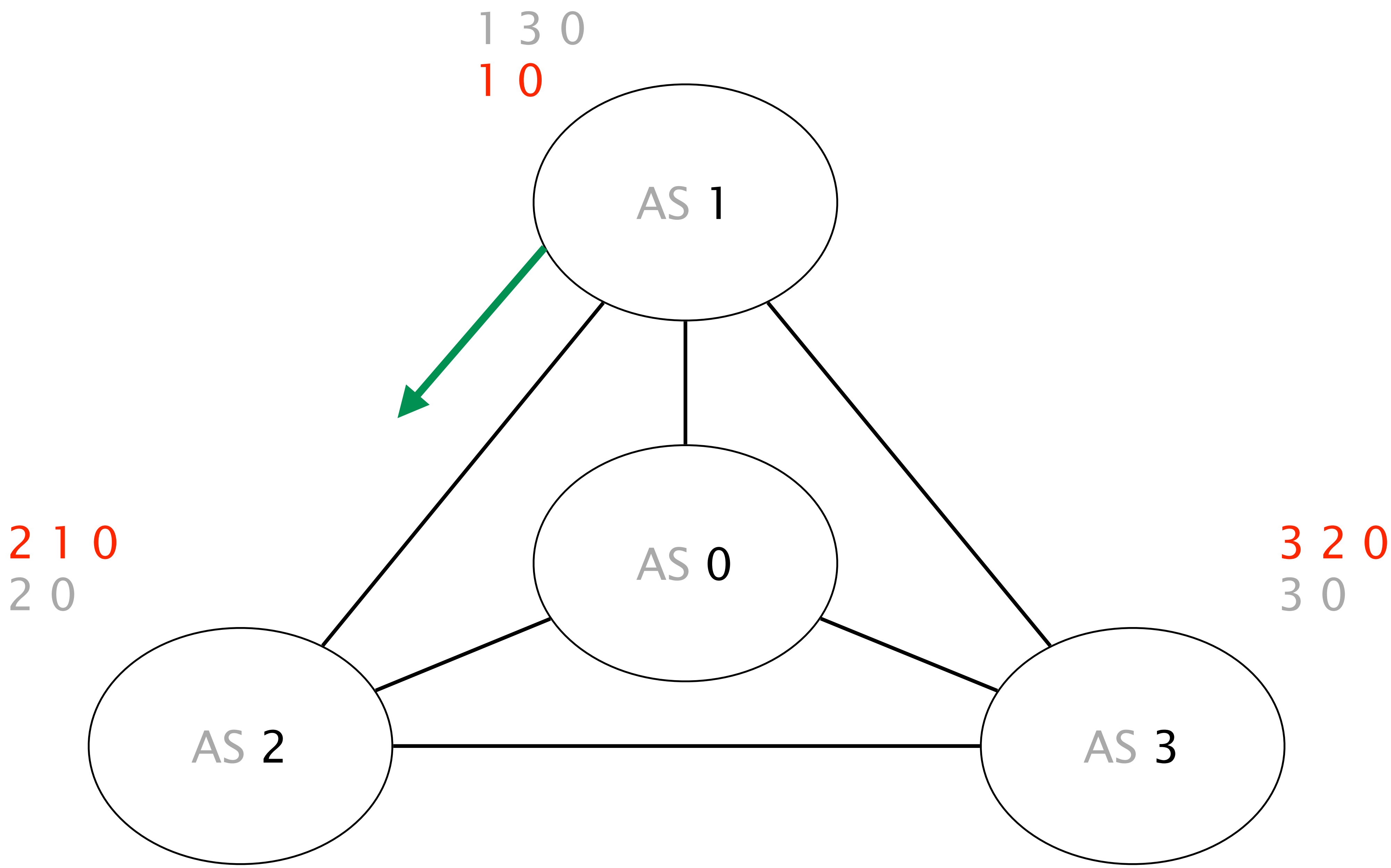


AS 1 advertises its new path 1 0 to AS 2

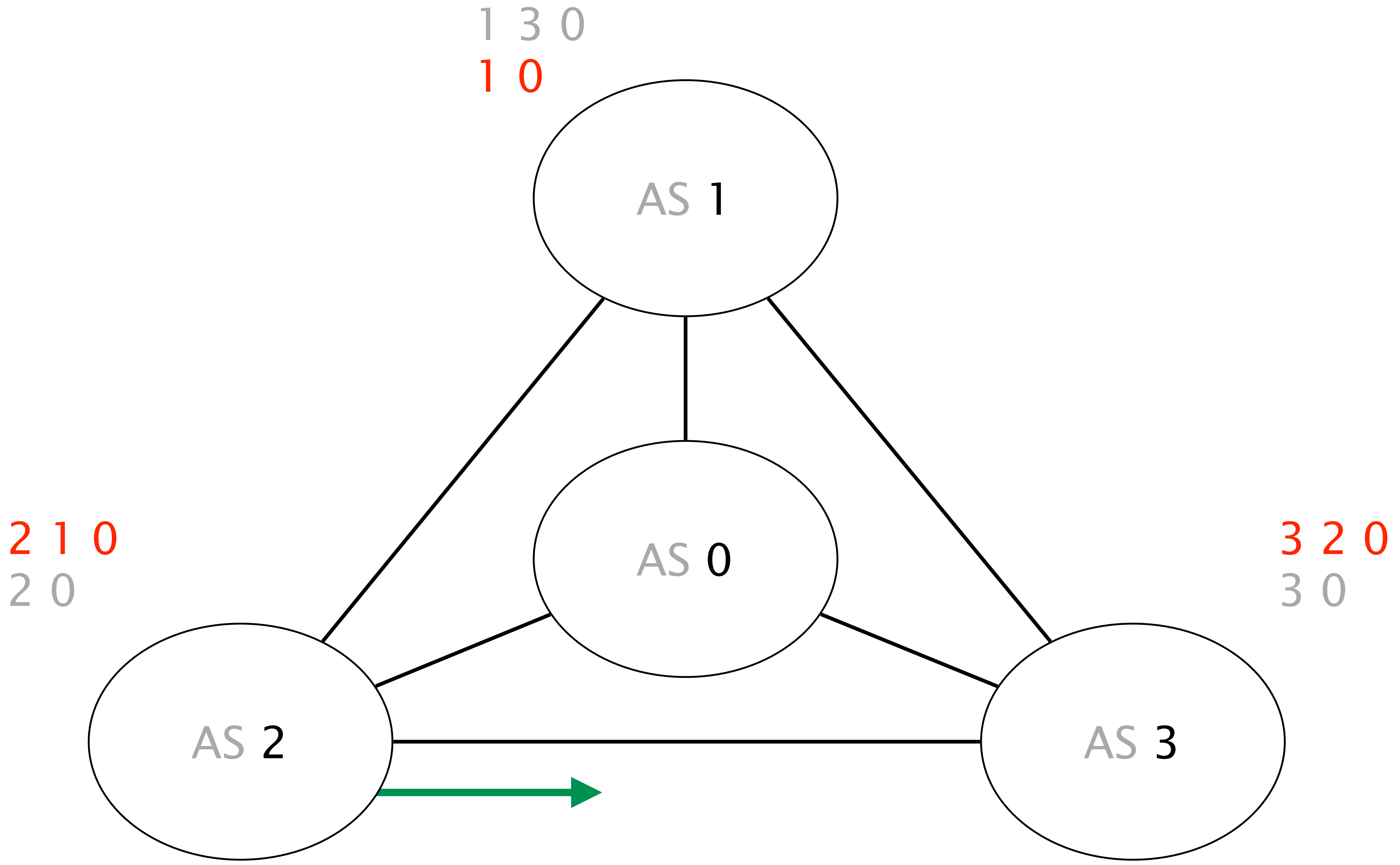


Upon reception,

AS 2 switches to 2 1 0 (preferred)

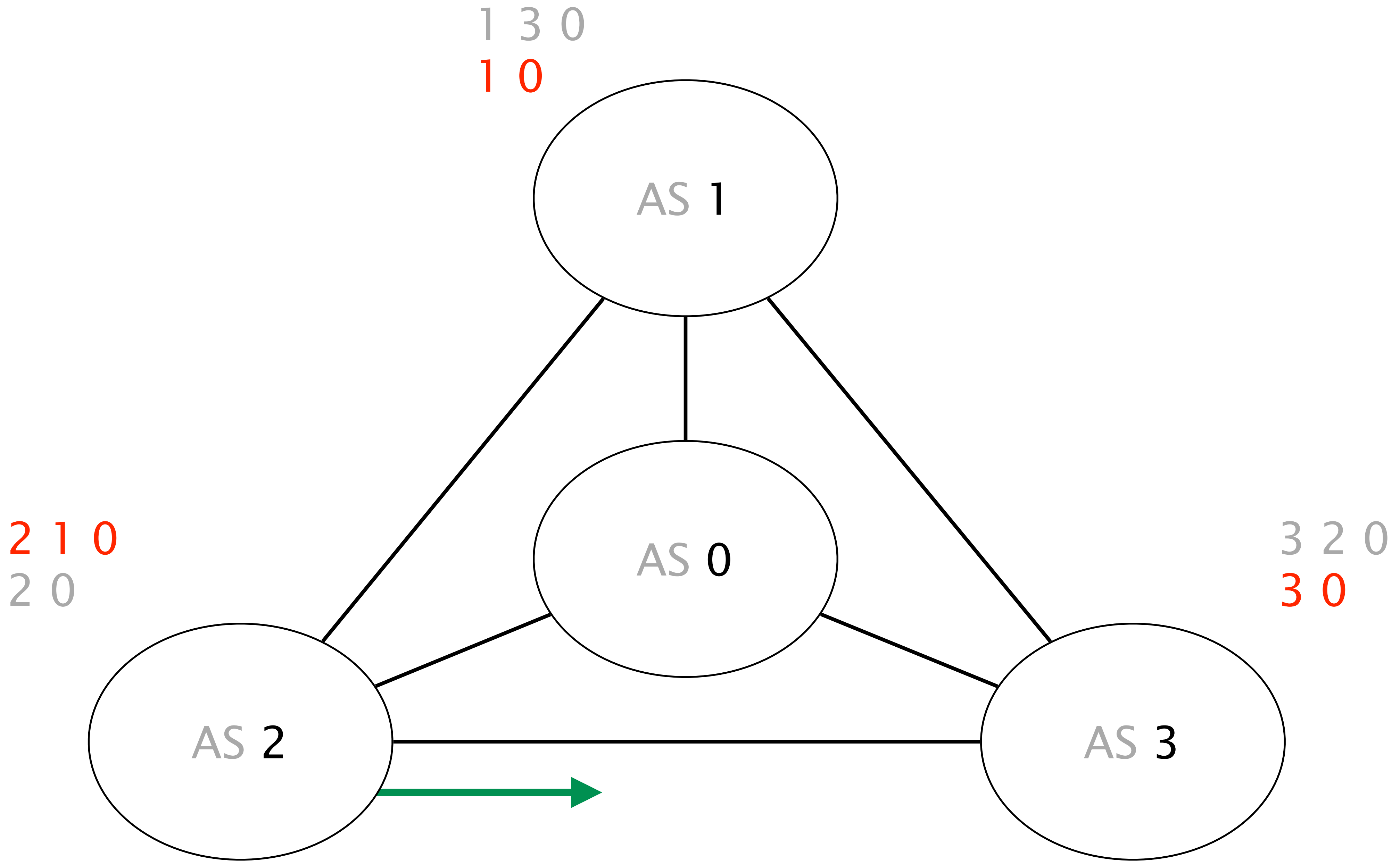


AS 2 advertises its new path 2 1 0 to AS 3

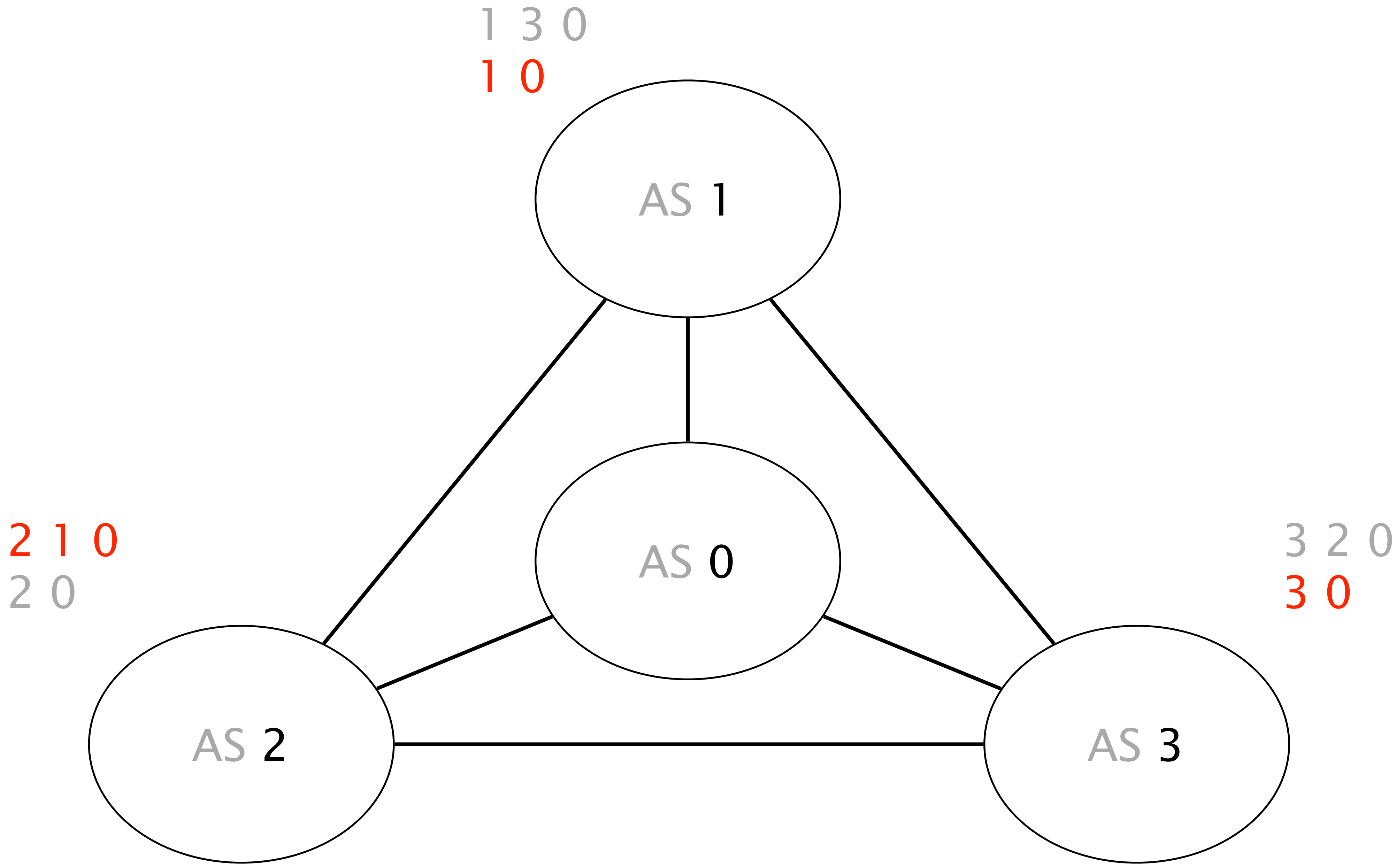


Upon reception,

AS 3 switches to its initial path 3 0



We are back where we started, from there on, the oscillation will continue forever



Policy oscillations are a direct consequence of policy autonomy

ASes are free to chose and advertise any paths they want

network stability argues against this

Guaranteeing the absence of oscillations is hard

even when you know all the policies!

Guaranteeing the absence of oscillations is hard

even when you know all the policies!

How come?

Theorem

Computationally, a BGP network is as “powerful” as

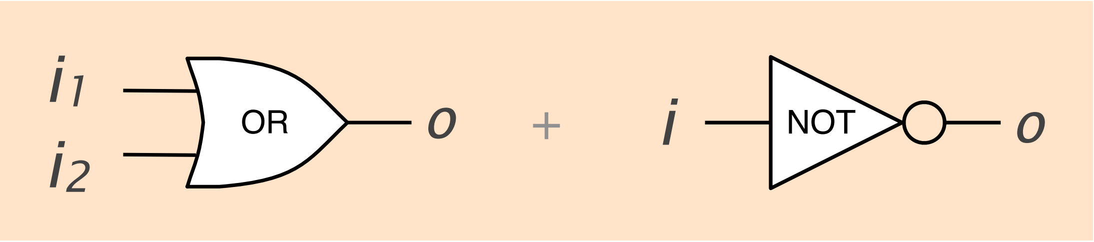
see “Using Routers to Build Logic Circuits: How Powerful is BGP?”

How do you prove such a thing?

How do you prove such a thing?

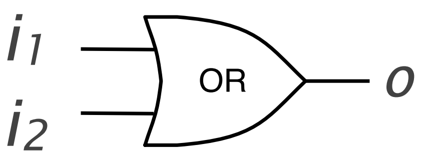
Easy, you build a computer using BGP…

Logic gates

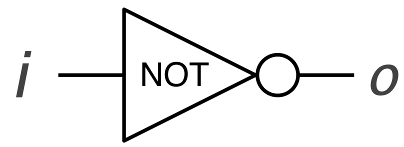


Logic gates

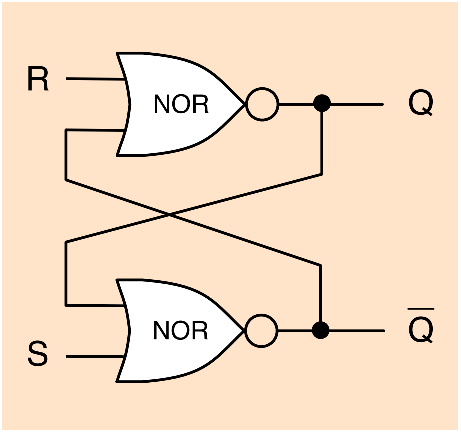
Memory



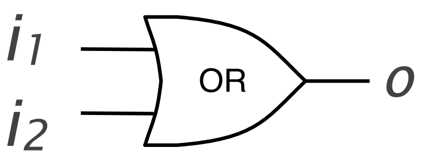
+



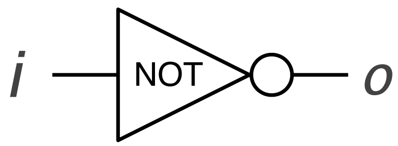
+



Logic gates

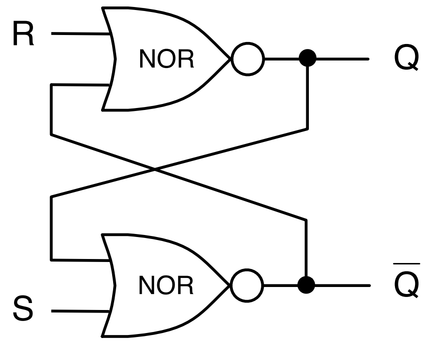


+



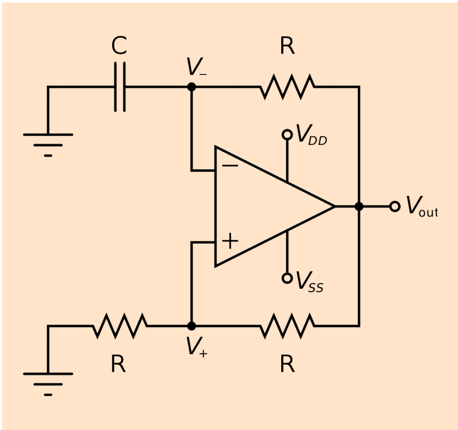
+

Memory

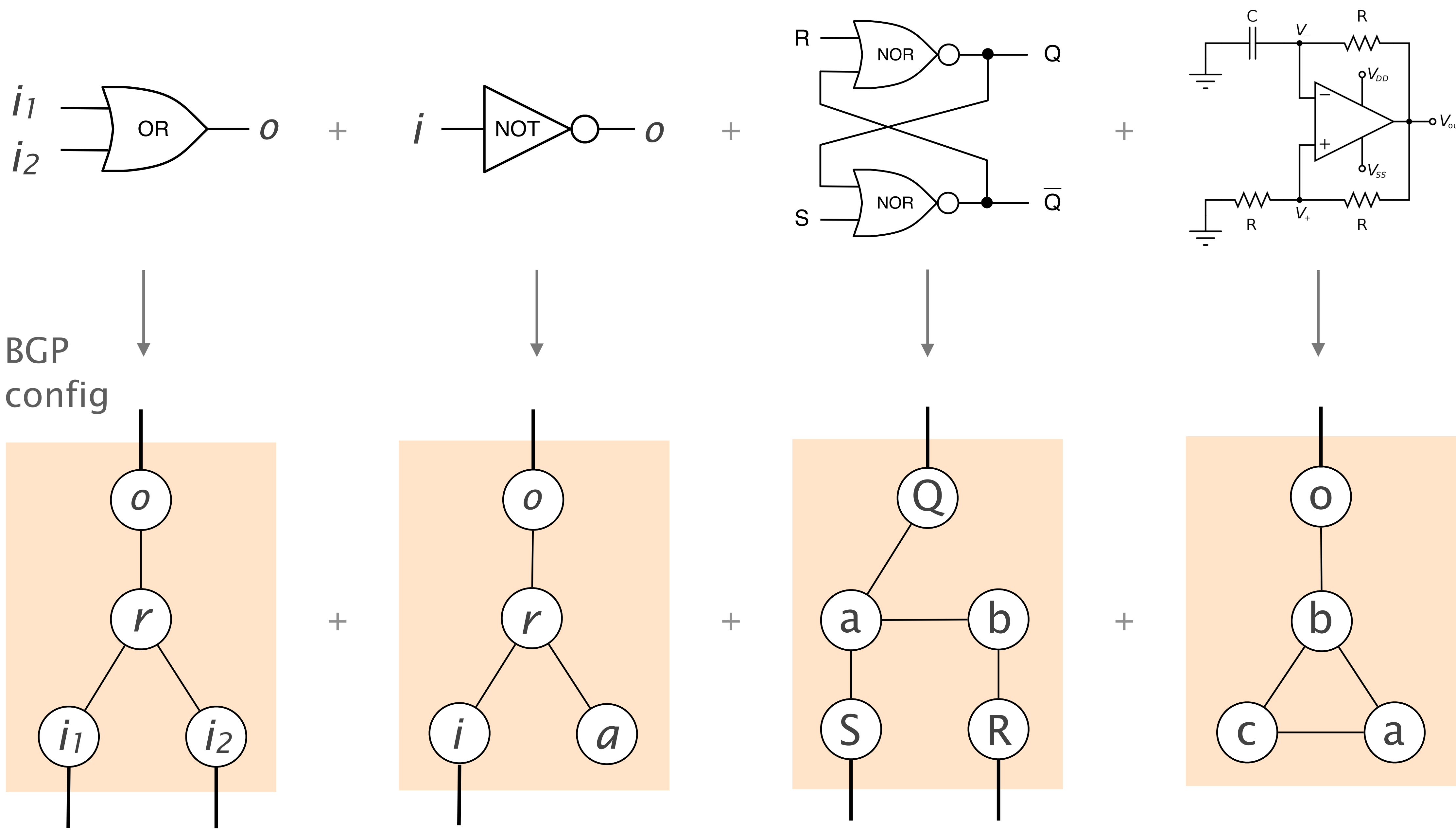


+

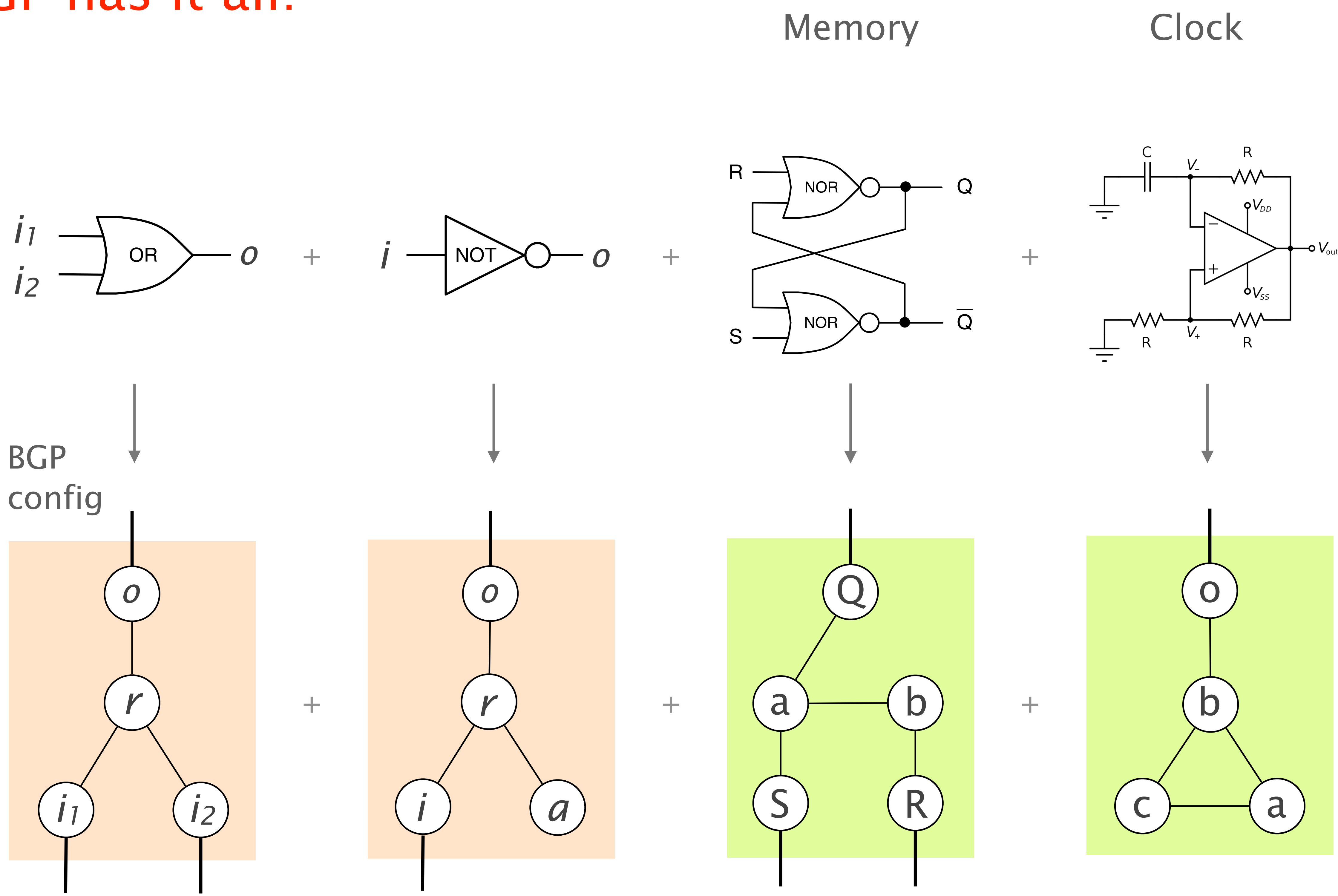
Clock



BGP has it all!



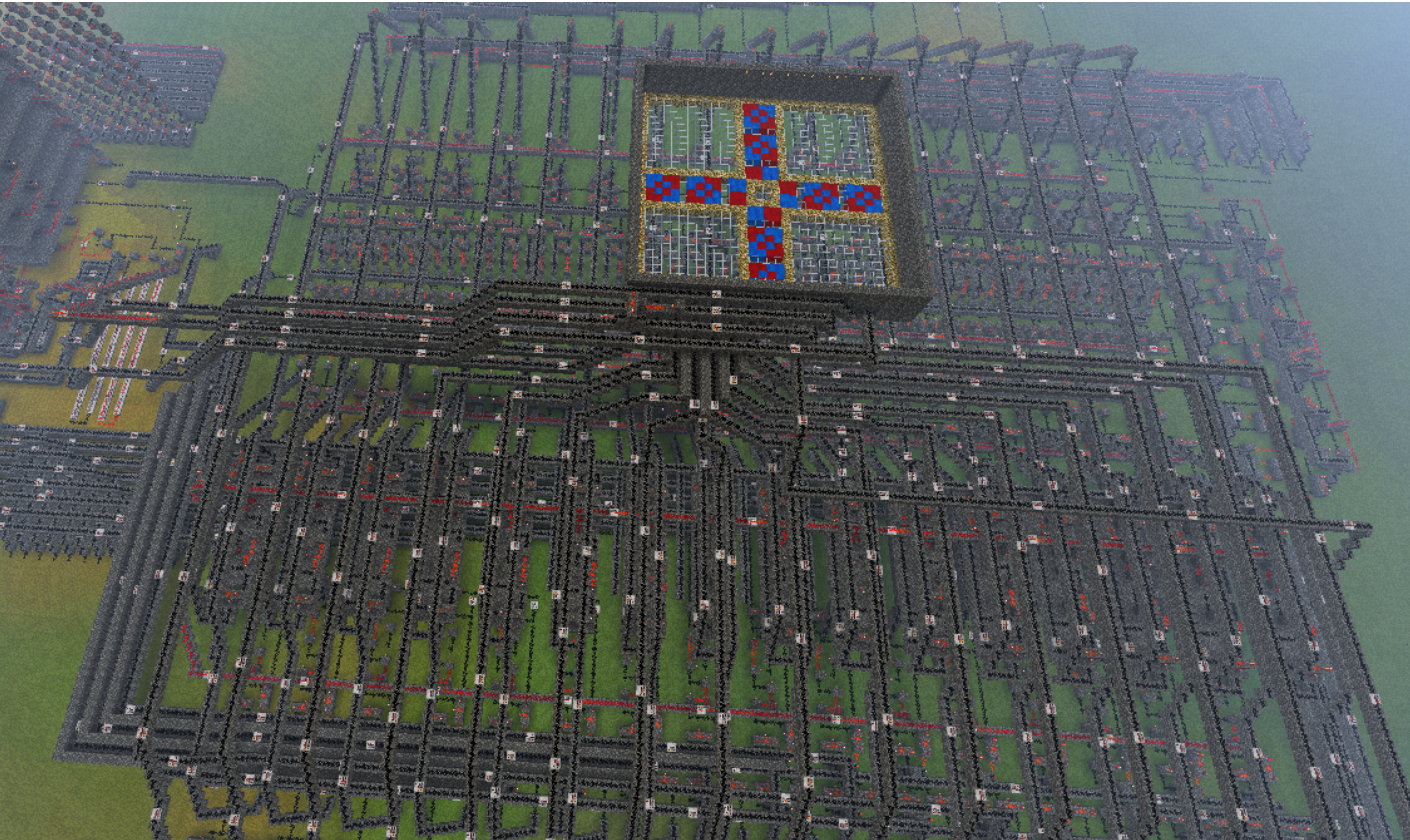
BGP has it all!



famous incorrect BGP configurations (Griffin et al.)

Instead of using Minecraft
for building a computer… use BGP!

Hack III, Minecraft's largest computer to date



Together, BGP routers form

the largest computer in the world!

Router-level view of the Internet, OPTE project

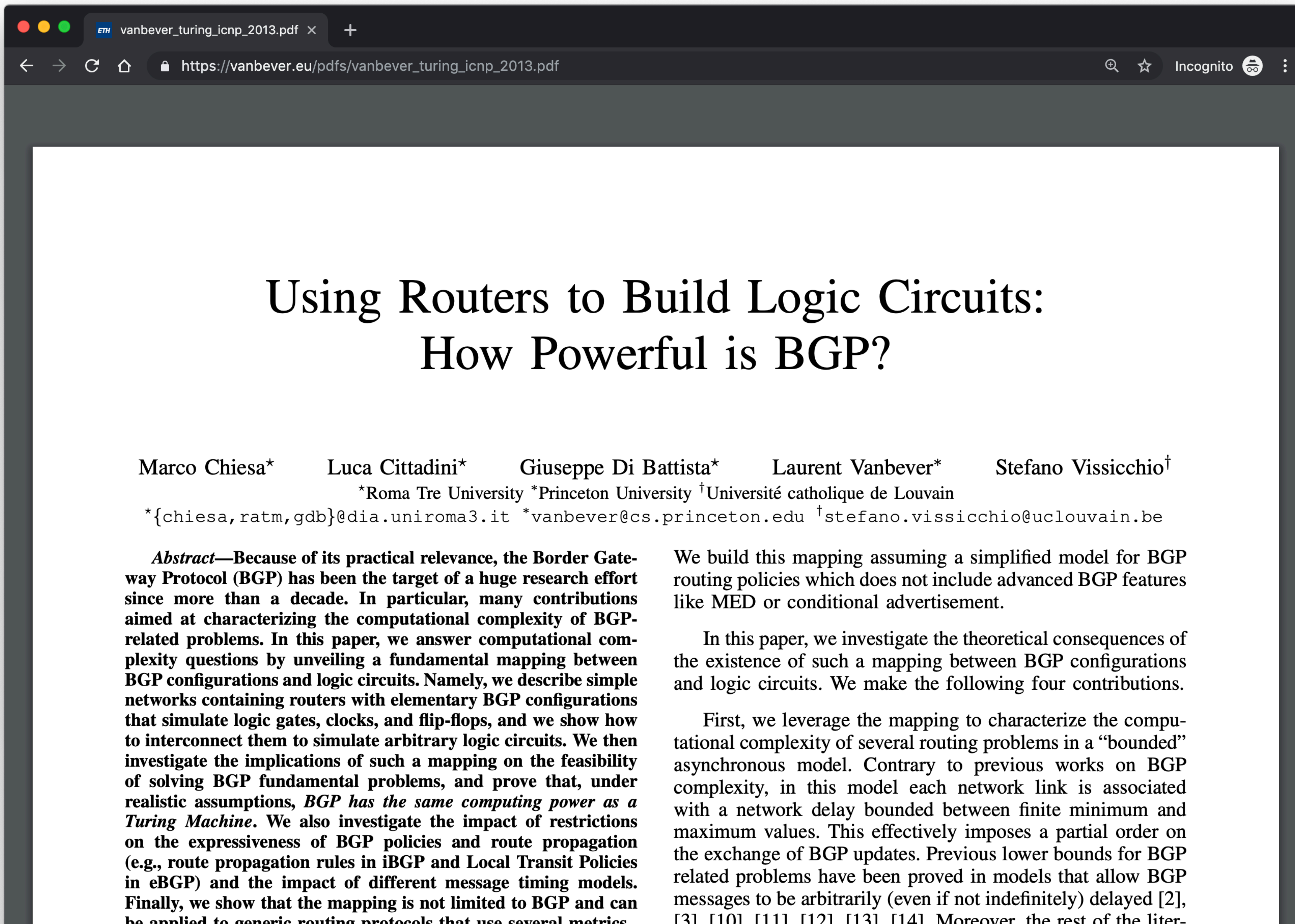
Checking BGP correctness is as hard as checking the termination of a general program

Theorem 1 Determining whether a finite BGP network converges is PSPACE-hard

Theorem 2 Determining whether an infinite BGP network converges is Turing-complete

Check our paper for more details

https://vanbever.eu/pdfs/vanbever_turing_icnp_2013.pdf



Using Routers to Build Logic Circuits: How Powerful is BGP?

Marco Chiesa* Luca Cittadini* Giuseppe Di Battista* Laurent Vanbever* Stefano Vissicchio†
*Roma Tre University *Princeton University †Université catholique de Louvain
*{chiesa,ratm,gdb}@dia.uniroma3.it *vanbever@cs.princeton.edu †stefano.vissicchio@uclouvain.be

***Abstract*—Because of its practical relevance, the Border Gateway Protocol (BGP) has been the target of a huge research effort since more than a decade. In particular, many contributions aimed at characterizing the computational complexity of BGP-related problems. In this paper, we answer computational complexity questions by unveiling a fundamental mapping between BGP configurations and logic circuits. Namely, we describe simple networks containing routers with elementary BGP configurations that simulate logic gates, clocks, and flip-flops, and we show how to interconnect them to simulate arbitrary logic circuits. We then investigate the implications of such a mapping on the feasibility of solving BGP fundamental problems, and prove that, under realistic assumptions, *BGP has the same computing power as a Turing Machine*. We also investigate the impact of restrictions on the expressiveness of BGP policies and route propagation (e.g., route propagation rules in iBGP and Local Transit Policies in eBGP) and the impact of different message timing models. Finally, we show that the mapping is not limited to BGP and can**

We build this mapping assuming a simplified model for BGP routing policies which does not include advanced BGP features like MED or conditional advertisement.

In this paper, we investigate the theoretical consequences of the existence of such a mapping between BGP configurations and logic circuits. We make the following four contributions.

First, we leverage the mapping to characterize the computational complexity of several routing problems in a "bounded" asynchronous model. Contrary to previous works on BGP complexity, in this model each network link is associated with a network delay bounded between finite minimum and maximum values. This effectively imposes a partial order on the exchange of BGP updates. Previous lower bounds for BGP related problems have been proved in models that allow BGP messages to be arbitrarily (even if not indefinitely) delayed [2], In practice though,

BGP does not oscillate “that” often

known as “Gao-Rexford” rules

Theorem

If all AS policies follow the cust/peer/provider rules,
BGP is guaranteed to converge

Intuition

Oscillations require “preferences cycles”
which make no economical sense

Problems

Reachability

Security

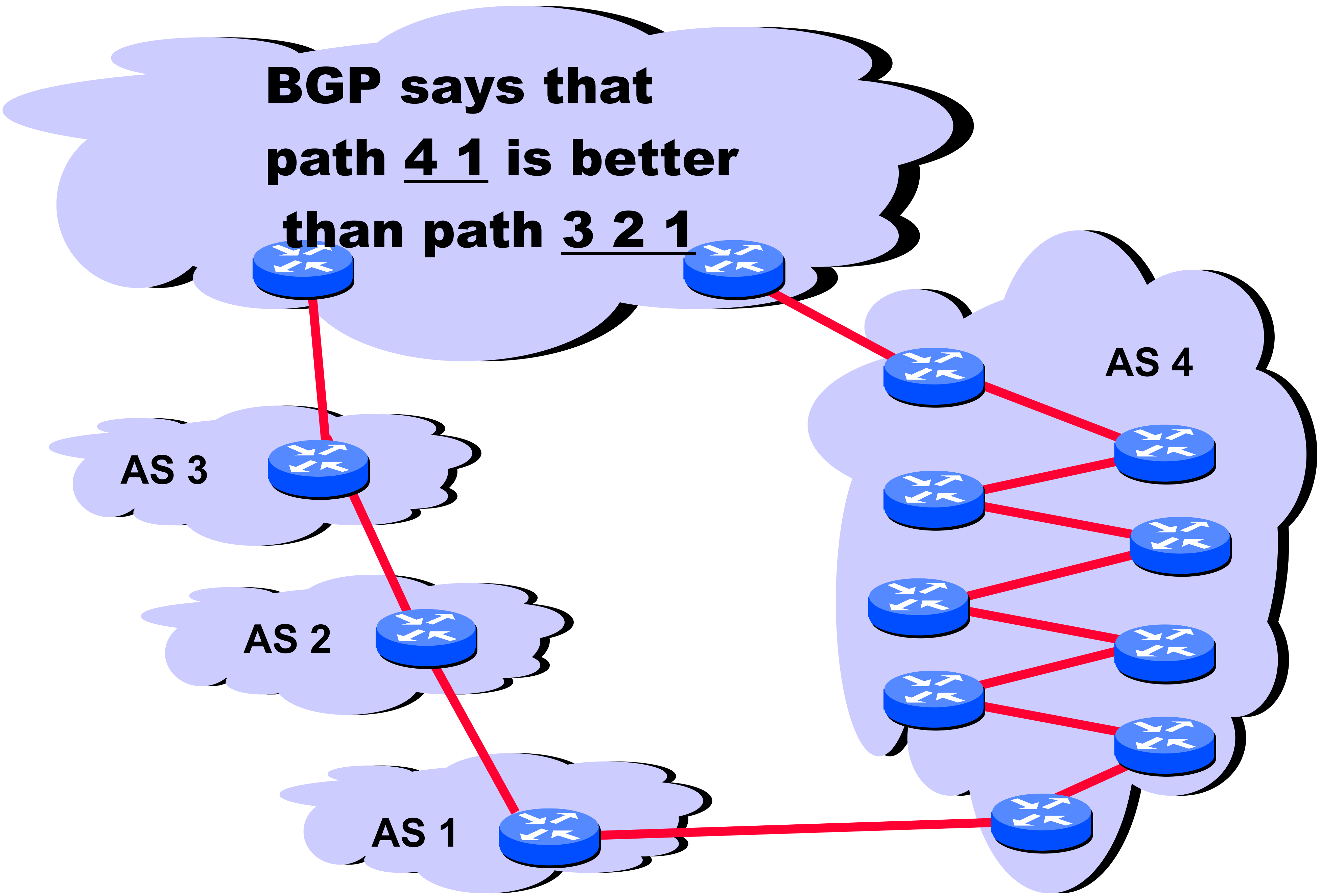
Convergence

Performance

Anomalies

Relevance

BGP path selection is mostly economical,
not based on accurate performance criteria



Problems

Reachability

Security

Convergence

Performance

Anomalies

Relevance

BGP configuration is hard to get right

BGP is both “bloated” and underspecified

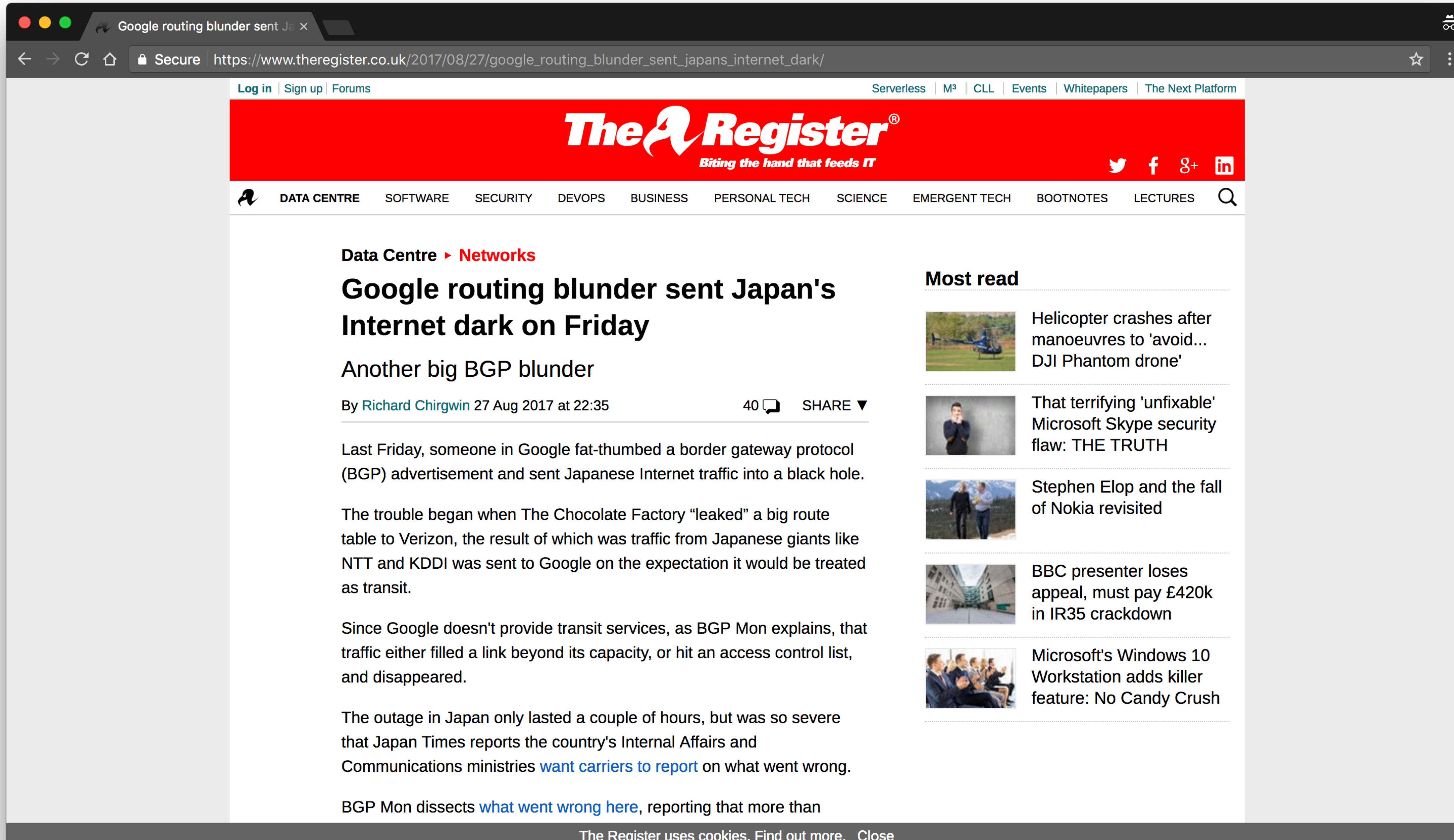
lots of knobs and (sometimes, conflicting) interpretations

BGP is often manually configured

humans make mistakes, often

BGP abstraction is fundamentally flawed

disjoint, router-based configuration to effect AS-wide policy



Log in | Sign up | Forums

Serverless | M³ | CLL | Events | Whitepapers | The Next Platform

The Register®

Biting the hand that feeds IT

DATA CENTRE SOFTWARE SECURITY DEVOPS BUSINESS PERSONAL TECH SCIENCE EMERGENT TECH BOOTNOTES LECTURES

Data Centre ▸ Networks

Google routing blunder sent Japan's Internet dark on Friday

Another big BGP blunder

By Richard Chirgwin 27 Aug 2017 at 22:35 40 SHARE ▼

Last Friday, someone in Google fat-thumbed a border gateway protocol (BGP) advertisement and sent Japanese Internet traffic into a black hole.

The trouble began when The Chocolate Factory "leaked" a big route table to Verizon, the result of which was traffic from Japanese giants like NTT and KDDI was sent to Google on the expectation it would be treated as transit.

Since Google doesn't provide transit services, as BGP Mon explains, that traffic either filled a link beyond its capacity, or hit an access control list, and disappeared.

The outage in Japan only lasted a couple of hours, but was so severe that Japan Times reports the country's Internal Affairs and Communications ministries want carriers to report on what went wrong.

BGP Mon dissects what went wrong here, reporting that more than

Most read

Helicopter crashes after manoeuvres to 'avoid... DJI Phantom drone'

That terrifying 'unfixable' Microsoft Skype security flaw: THE TRUTH

Stephen Elop and the fall of Nokia revisited

BBC presenter loses appeal, must pay £420k in IR35 crackdown

Microsoft's Windows 10 Workstation adds killer feature: No Candy Crush

https://www.theregister.co.uk/2017/08/27/google_routing_blunder_sent_japans_internet_dark/

In August 2017

Someone in Google fat-thumbed a
Border Gateway Protocol (BGP) advertisement
and sent Japanese Internet traffic into a black hole.

In August 2017

Someone in Google fat-thumbed a
Border Gateway Protocol (BGP) advertisement
and sent Japanese Internet traffic into a black hole.

[…] Traffic from Japanese giants like NTT and KDDI
was sent to Google on the expectation
it would be treated as transit.

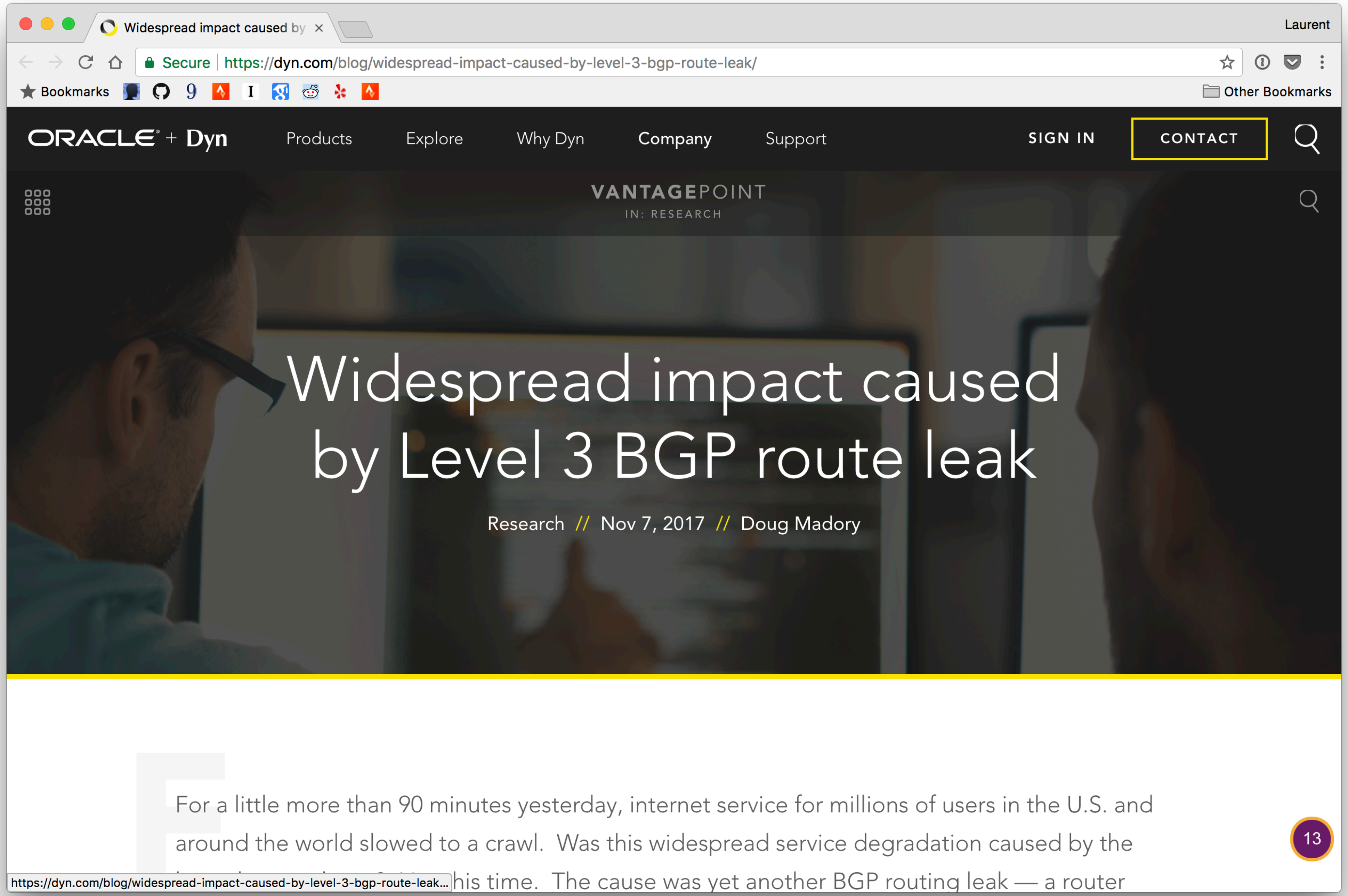
In August 2017

Someone in Google fat-thumbed a
Border Gateway Protocol (BGP) advertisement
and sent Japanese Internet traffic into a black hole.

[…] Traffic from Japanese giants like NTT and KDDI
was sent to Google on the expectation
it would be treated as transit.

The outage in Japan only lasted a couple of hours
but was so severe that […] the country's
Internal Affairs and Communications ministries
want carriers to report on what went wrong.

Another example,
this time from November 2017



https://dyn.com/blog/widespread-impact-caused-by-level-3-bgp-route-leak/

For a little more than 90 minutes […],

Internet service for millions of users in the U.S. and around the world slowed to a crawl.

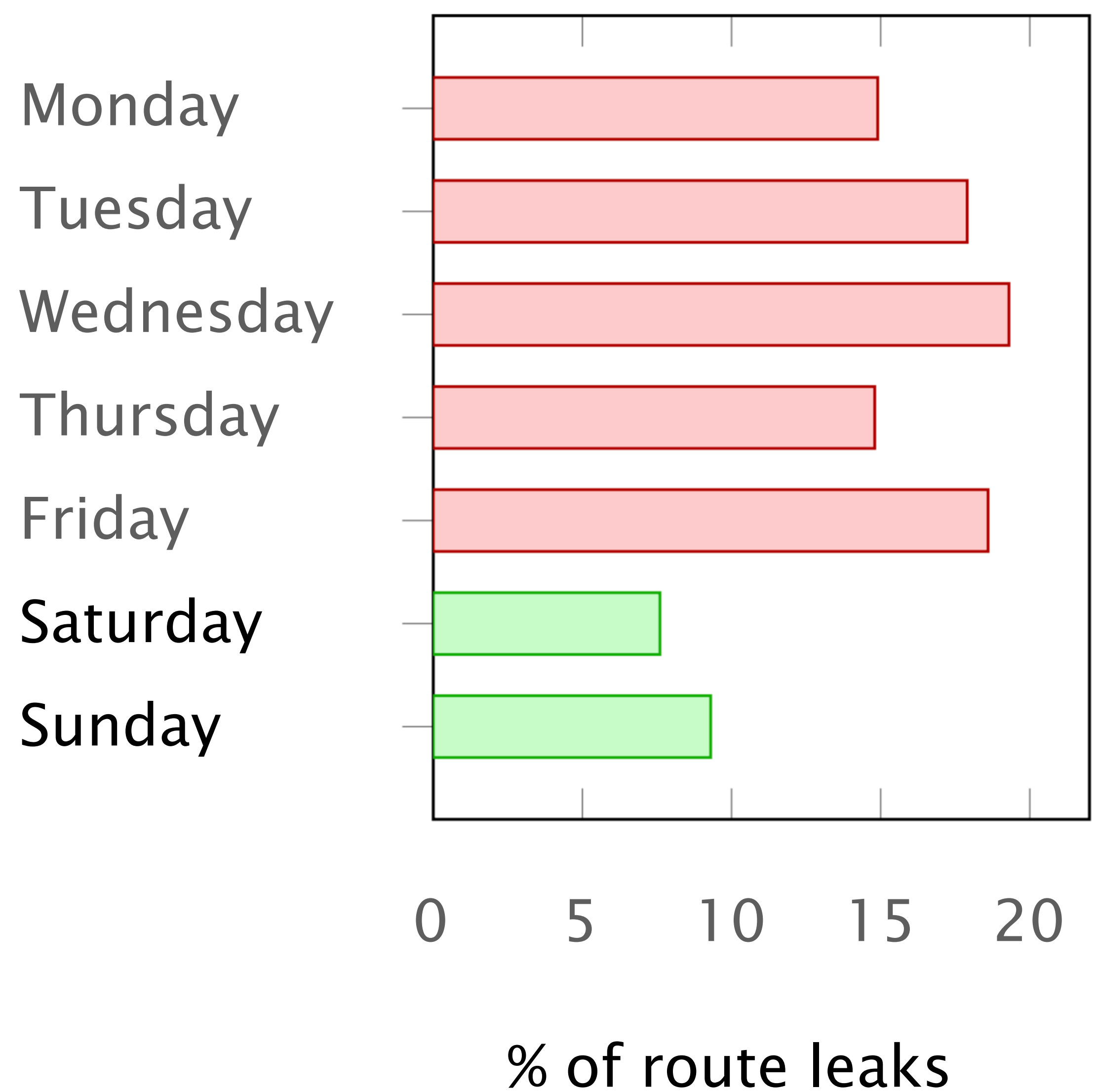
The cause was yet another BGP routing leak, a router misconfiguration directing Internet traffic from its intended path to somewhere else.

“Human factors are responsible

for 50% to 80% of network outages”

Juniper Networks, *What’s Behind Network Downtime?*, 2008

Ironically, this means that the Internet works better during the week-ends…



source: Job Snijders (NTT)

Problems

Reachability

Security

Convergence

Performance

Anomalies

Relevance

The world of BGP policies is rapidly changing

ISPs are now eyeballs talking to content networks

e.g., Swisscom and Netflix/Spotify/YouTube

Transit becomes less important and less profitable

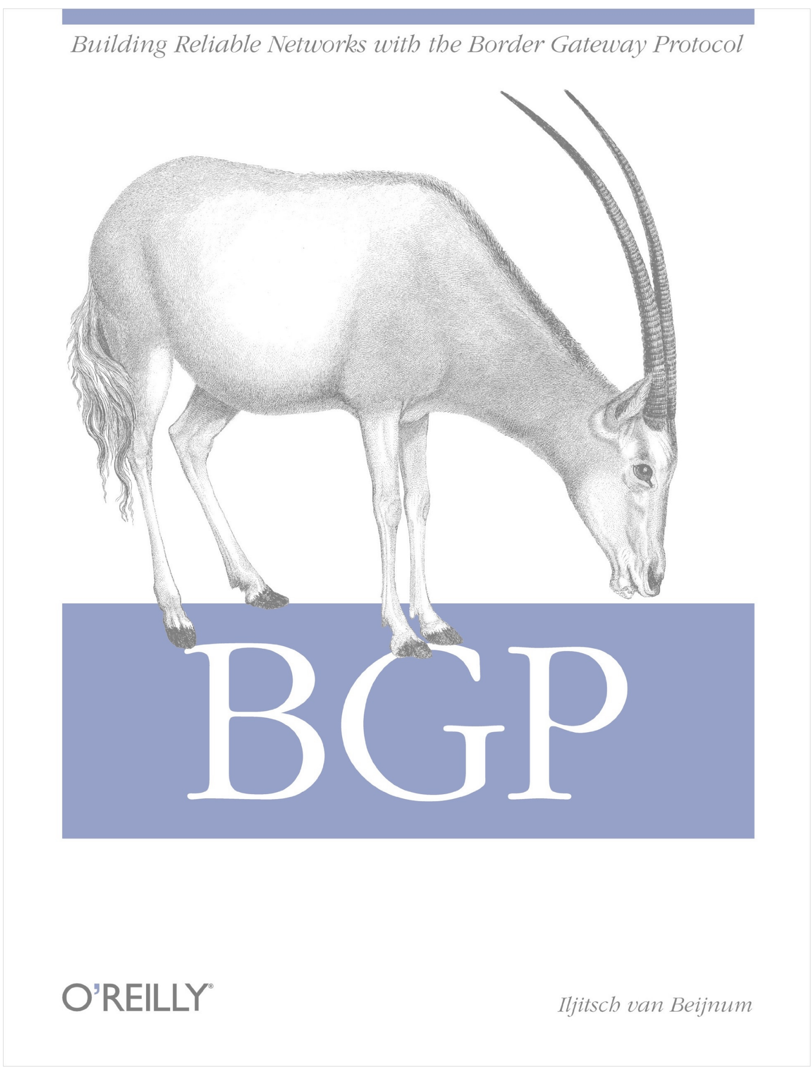
traffic move more and more to interconnection points

No systematic practices, yet

details of peering arrangements are private anyway

Border Gateway Protocol

policies and more



BGP Policies

Follow the Money

Protocol

How does it work?

Problems

security, performance, …

Communication Networks

Spring 2022

Laurent Vanbever

nsg.ee.ethz.ch

ETH Zürich (D-ITET)

April 11 2022