Communication Networks

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Materials inspired from Scott Shenker & Jennifer Rexford

Last week on

Communication Networks

Internet routing

from here to there, and back

Intra-domain routing

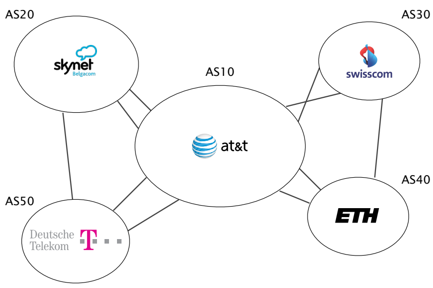
Link-state protocols

Distance-vector protocols

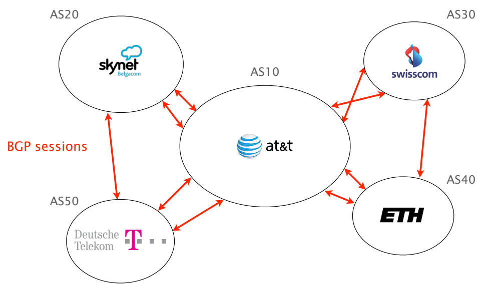
2 Inter-domain routing

Path-vector protocols

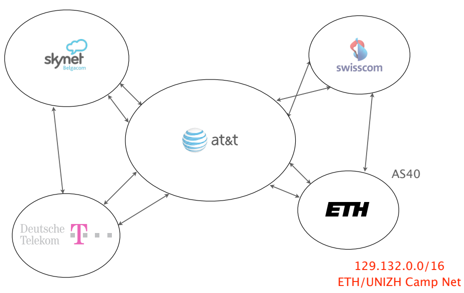
The Internet is a network of networks, referred to as Autonomous Systems (AS)



BGP is the routing protocol "glueing" the Internet together



Using BGP, ASes exchange information about the IP prefixes they can reach, directly or indirectly



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

There is a huge # of networks and prefixes

700k prefixes, >50,000 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

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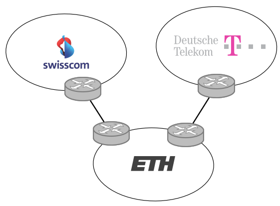
Unlike normal routing, policy routing does not guarantee reachability even if the graph is connected



Because of policies,
Swisscom cannot reach DT
even if the graph is connected

Problems
- Reachability
- Security
- Convergence
- Performance
- Anomalies
- Relevance

Many security considerations are simply absent from BGP specifications

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

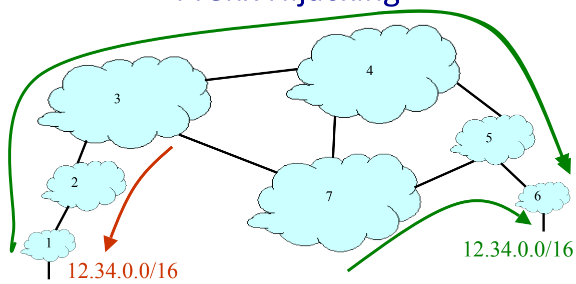
BGP (lack of) security

#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

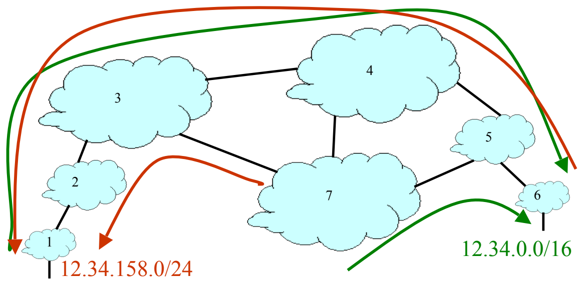


- Blackhole: data traffic is discarded
- Snooping: data traffic is inspected, then redirected
- Impersonation: traffic sent to bogus destinations

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

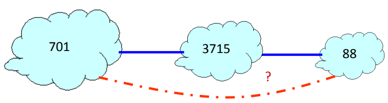
BGP (lack of) security

#1 BGP does not validate the origin of advertisements

#2 BGP does not validate the content of advertisements

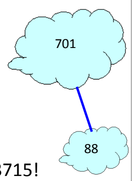
Bogus AS Paths

- 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



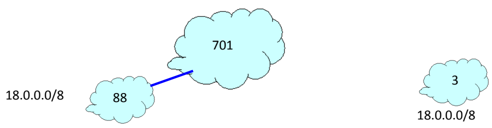
Bogus AS Paths

- 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?



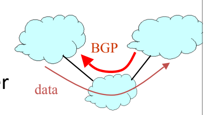
Bogus AS Paths

- 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



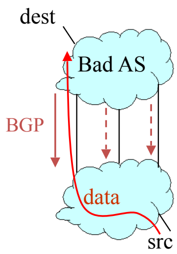
Invalid Paths

- 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

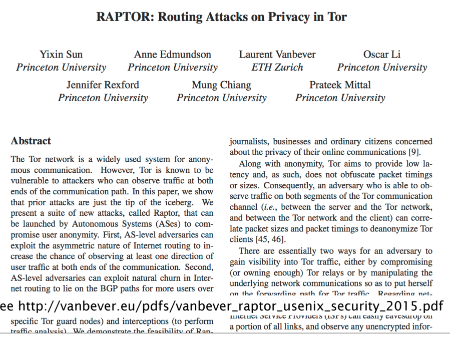
- Peers require consistent export
  - Prefix advertised at all peering points
  - Prefix advertised with same AS path length
- Reasons for violating the policy
  - Trick neighbor into "cold potato"
  - Configuration mistake
- Main defense
  - Analyzing BGP updates, or traffic,
  - … for signs of inconsistency



BGP Security Today

- Applying best common practices (BCPs)
  - Securing the session (authentication, encryption)
  - Filtering routes by prefix and AS path
  - Packet filters to block unexpected control traffic
- This is not good enough
  - Depends on vigilant application of BCPs
  - Doesn't address fundamental problems
    - Can't tell who owns the IP address block
    - Can't tell if the AS path is bogus or invalid
    - Can't be sure the data packets follow the chosen route

Routing attacks can be used to
de-anonymize Tor users



RAPTOR: Routing Attacks on Privacy in Tor

Yixin Sun, *Princeton University*; Anne Edmundson, *Princeton University*; Laurent Vanbever, *ETH Zurich*; Oscar Li, *Princeton University*
Jennifer Rexford, *Princeton University*; Mung Chiang, *Princeton University*; Prateek Mittal, *Princeton University*

Abstract

The Tor network is a widely used system for anonymous communication. However, Tor is known to be vulnerable to attackers who can observe traffic at both ends of the communication path. In this paper, we show that prior attacks are just the tip of the iceberg. We present a suite of new attacks, called Raptor, that can be launched by Autonomous Systems (ASes) to compromise user anonymity. First, AS-level adversaries can exploit the asymmetric nature of Internet routing to increase the chance of observing at least one direction of user traffic at both ends of the communication. Second, AS-level adversaries can exploit natural churn in Internet routing to lie on the BGP paths for more users over

specific Tor guard nodes) and interceptions (to perform

journalists, businesses and ordinary citizens concerned about the privacy of their online communications [9].

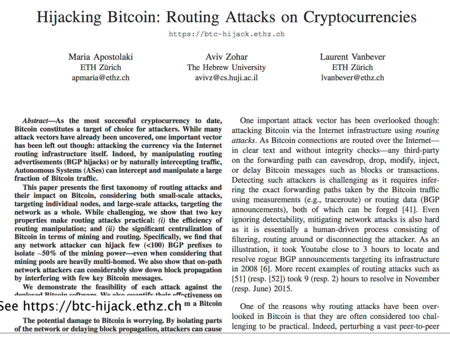
Along with anonymity, Tor aims to provide low latency and, as such, does not obfuscate packet timings or sizes. Consequently, an adversary who is able to observe traffic on both segments of the Tor communication channel (*i.e.*, between the server and the Tor network, and between the Tor network and the client) can correlate packet sizes and packet timings to deanonymize Tor clients [45, 46].

There are essentially two ways for an adversary to gain visibility into Tor traffic, either by compromising (or owning enough) Tor relays or by manipulating the underlying network communications so as to put herself

a portion of all links, and observe any unencrypted infor-

See http://vanbever.eu/pdfs/vanbever_raptor_usenix_security_2015.pdf

Routing attacks can be used to
partition the Bitcoin network



Hijacking Bitcoin: Routing Attacks on Cryptocurrencies

https://btc-hijack.ethz.ch

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***Abstract*—As the most successful cryptocurrency to date, Bitcoin constitutes a target of choice for attackers. While many attack vectors have already been uncovered, one important vector has been left out though: attacking the currency via the Internet routing infrastructure itself. Indeed, by manipulating routing advertisements (BGP hijacks) or by naturally intercepting traffic, Autonomous Systems (ASes) can intercept and manipulate a large fraction of Bitcoin traffic.**

This paper presents the first taxonomy of routing attacks and their impact on Bitcoin, considering both small-scale attacks, targeting individual nodes, and large-scale attacks, targeting the network as a whole. While challenging, we show that two key properties make routing attacks practical: *(i)* the efficiency of routing manipulation; and *(ii)* the significant centralization of Bitcoin in terms of mining and routing. Specifically, we find that any network attacker can hijack few (<100) BGP prefixes to isolate ~50% of the mining power—even when considering that mining pools are heavily multi-homed. We also show that on-path network attackers can considerably slow down block propagation by interfering with few key Bitcoin messages.

We demonstrate the feasibility of each attack against the

The potential damage to Bitcoin is worrying. By isolating parts of the network or delaying block propagation, attackers can cause

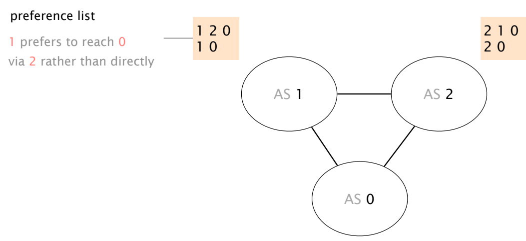
One important attack vector has been overlooked though: attacking Bitcoin via the Internet infrastructure using *routing attacks*. As Bitcoin connections are routed over the Internet—in clear text and without integrity checks—any third-party on the forwarding path can eavesdrop, drop, modify, inject, or delay Bitcoin messages such as blocks or transactions. Detecting such attackers is challenging as it requires inferring the exact forwarding paths taken by the Bitcoin traffic using measurements (e.g., traceroute) or routing data (BGP announcements), both of which can be forged [41]. Even ignoring detectability, mitigating network attacks is also hard as it is essentially a human-driven process consisting of filtering, routing around or disconnecting the attacker. As an illustration, it took Youtube close to 3 hours to locate and resolve rogue BGP announcements targeting its infrastructure in 2008 [6]. More recent examples of routing attacks such as [51] (resp. [52]) took 9 (resp. 2) hours to resolve in November (resp. June) 2015.

One of the reasons why routing attacks have been overlooked in Bitcoin is that they are often considered too challenging to be practical. Indeed, perturbing a vast peer-to-peer

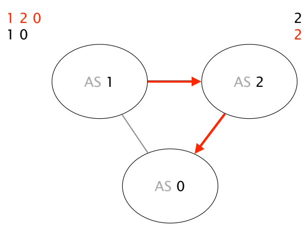
See https://btc-hijack.ethz.ch

Problems	Reachability
	Security
	Convergence
	Performance
	Anomalies
	Relevance

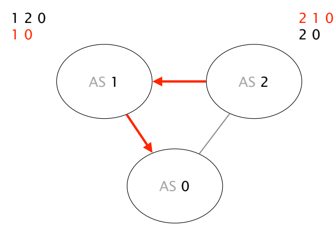
With arbitrary policies,
BGP may have multiple stable states



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



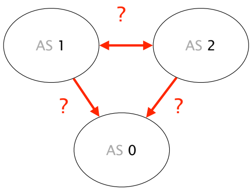
If AS1 is the first one to advertise 1 0,
the system stabilizes in a state where AS 2 is happy



The actual assignment depends on the ordering between the messages

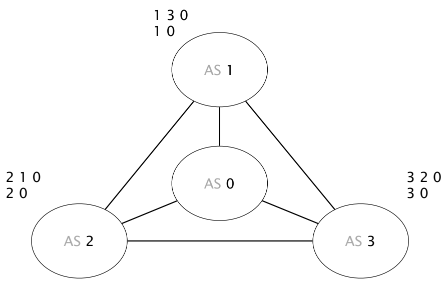
Note that AS1/AS2 could change the outcome by manual intervention

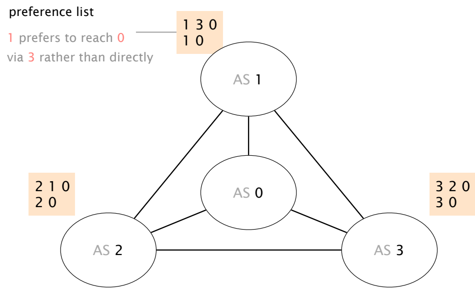
… this is not always possible *



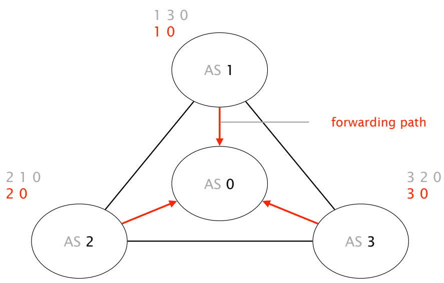
* https://www.nanog.org/meetings/nanog31/presentations/griffin.pdf

With arbitrary policies,
BGP may fail to converge

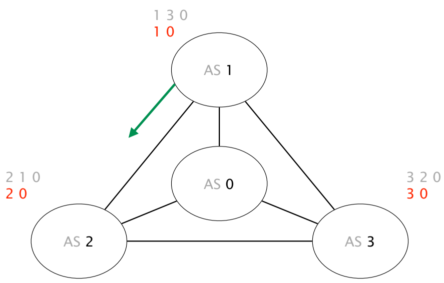




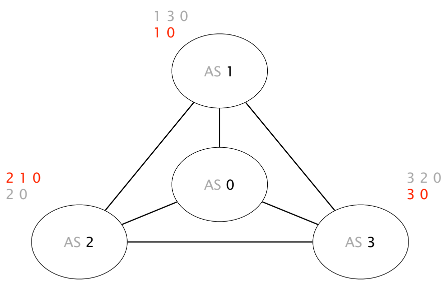
Initially, all ASes only know the direct route to 0



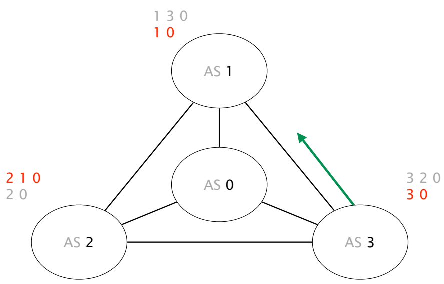
AS 1 advertises its path to AS 2



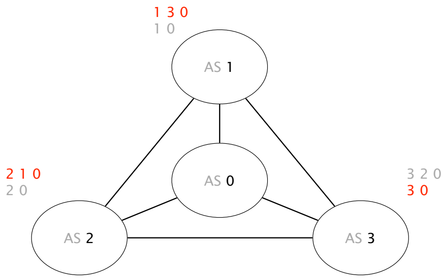
Upon reception,
AS 2 switches to 2 1 0 (preferred)



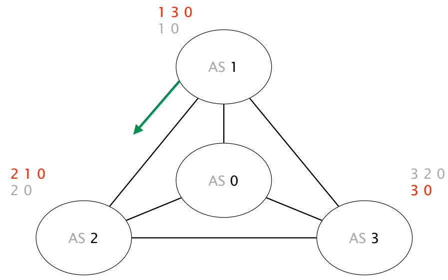
AS 3 advertises its path to AS 1



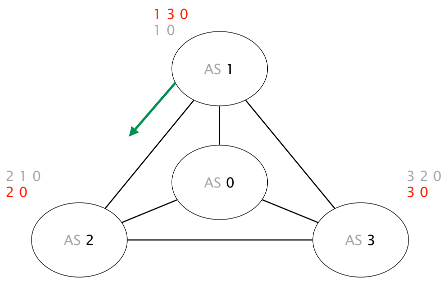
Upon reception,
AS 1 switches to 1 3 0 (preferred)



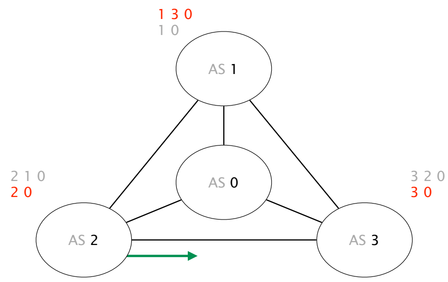
AS 1 advertises its new path 1 3 0 to AS 2



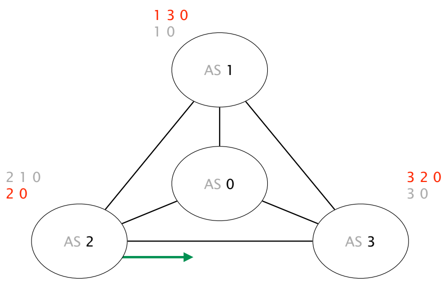
Upon reception,
AS 2 reverts back to its initial path 2 0



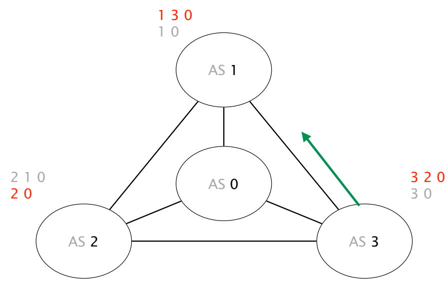
AS 2 advertises its path 2 0 to AS 3



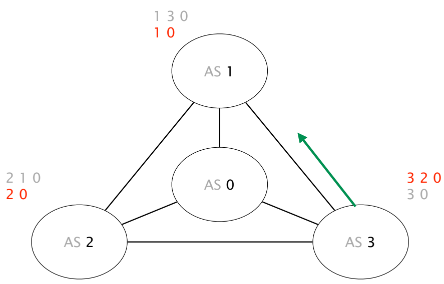
Upon reception,
AS 3 switches to 3 2 0 (preferred)



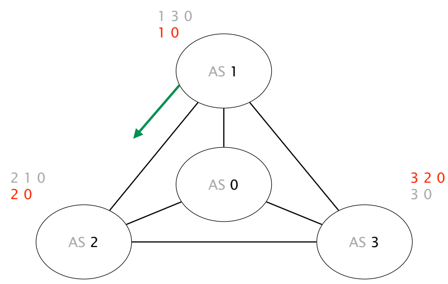
AS 3 advertises its new path 3 2 0 to AS 1



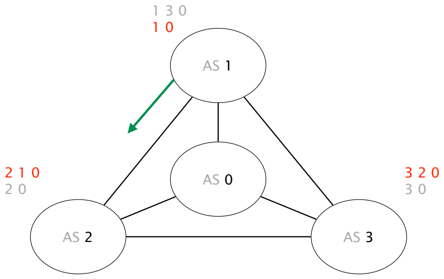
Upon reception,
AS 1 reverts back to 1 0 (initial path)



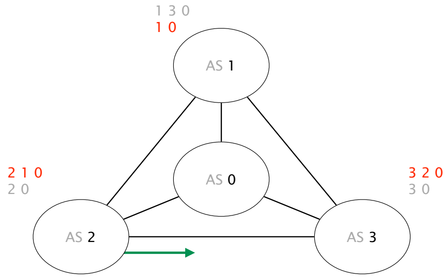
AS 1 advertises its new path 1 0 to AS 2



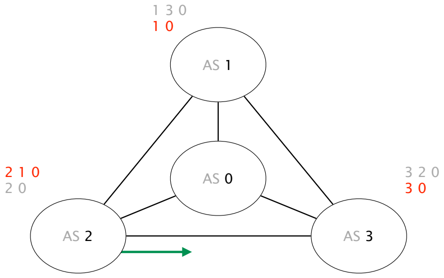
Upon reception,
AS 2 switches to 2 1 0 (preferred)



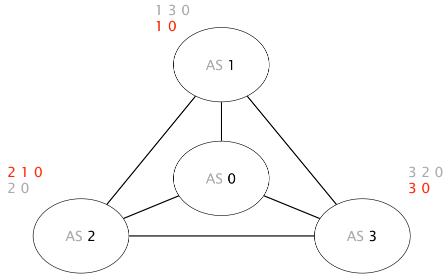
AS 2 advertises its new path 2 1 0 to AS 3



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

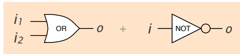
see "Using Routers to Build Logic Circuits: How Powerful is BGP?"

How do you prove such a thing?

How do you prove such a thing?

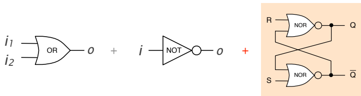
Easy, you build a computer using BGP…

Logic gates



Logic gates

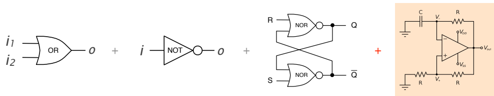
Memory



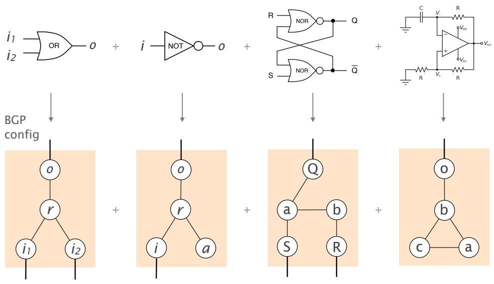
Logic gates

Memory

Clock



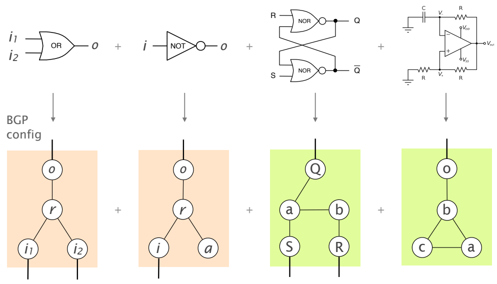
BGP has it all!



BGP has it all!

Memory

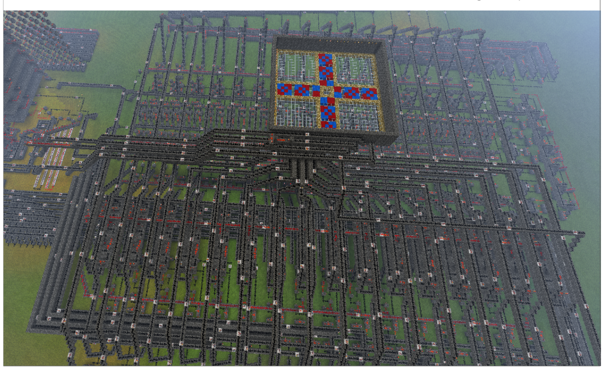
Clock



famous incorrect BGP configurations (Griffin et al.)

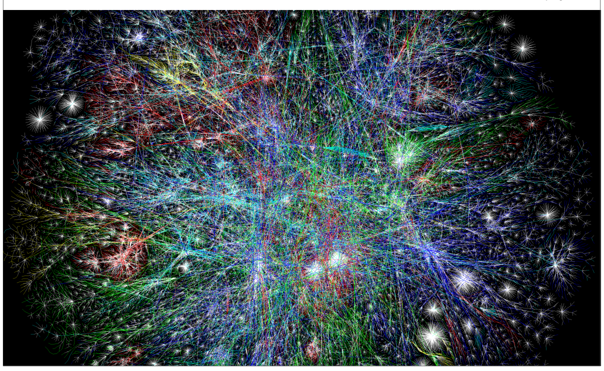
Instead of using Minecraft
for building a computer… use BGP!

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



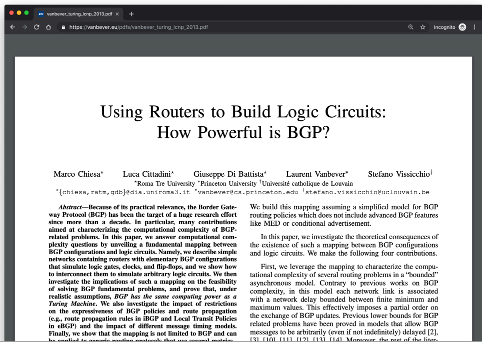
Checking BGP correctness is as hard as checking the termination of a general program

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


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

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

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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

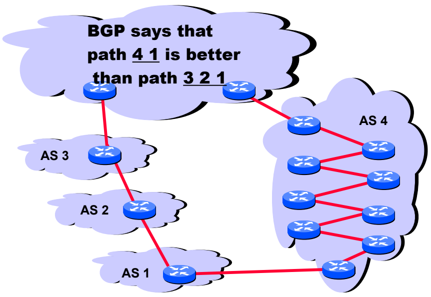
known as "Gao-Rexford" rules

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
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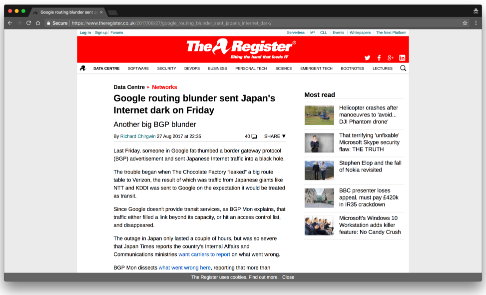
- Relevance

BGP configuration is hard to get right, you'll understand that very soon

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


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

The Register — Biting the hand that feeds IT

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

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

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In August 2017

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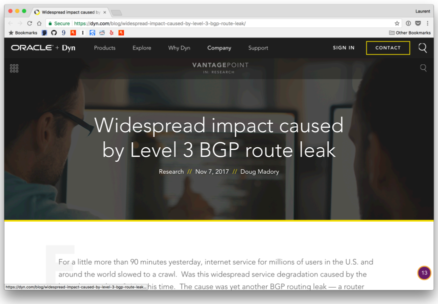
The outage in Japan only lasted a couple of hours
but was so severe that [...] the country's
Internal Affairs and Communications ministries
want carriers to report on what went wrong.

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 [...],

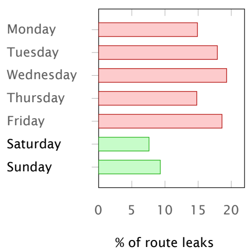
Internet service for millions of users in the U.S.
and around the world slowed to a crawl.

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

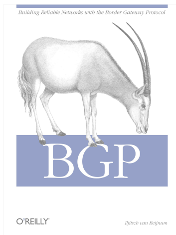
The world of BGP policies is rapidly changing

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 2021

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nsg.ee.ethz.ch

ETH Zürich (D-ITET)
April 26 2021