

FOCI 2026

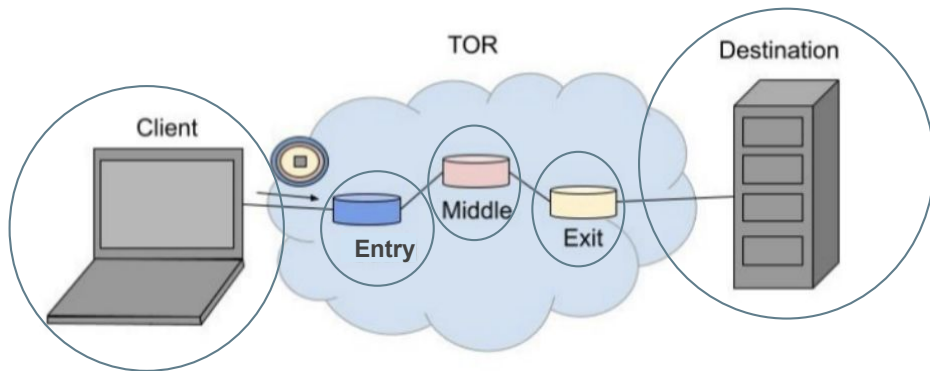
Who Carries Tor? Measuring Bandwidth-Weighted Transit Concentration



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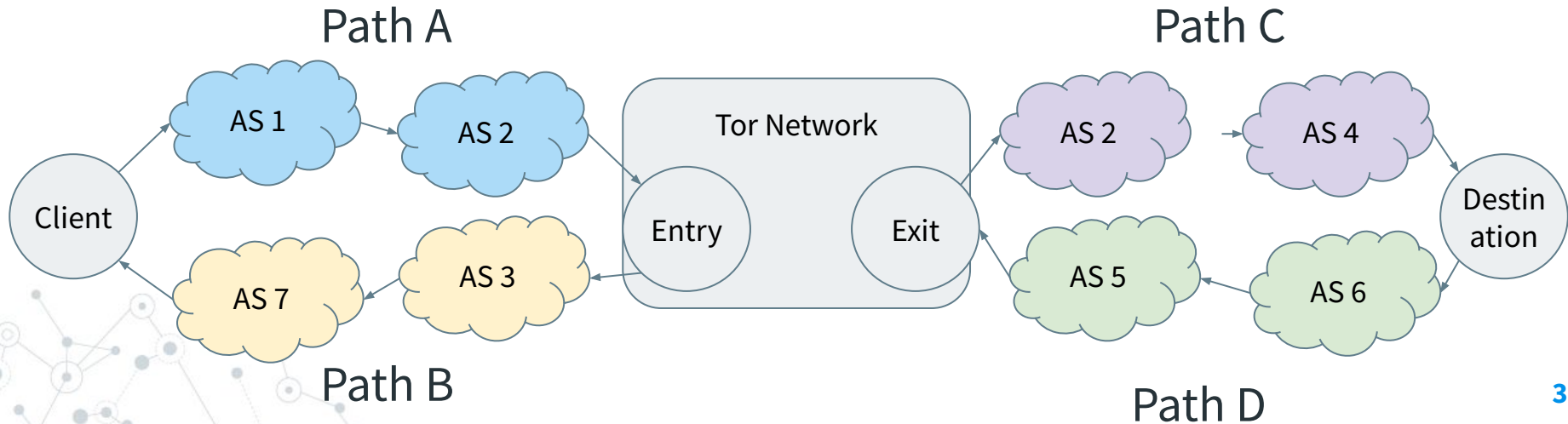
What is the Tor Network?

- ◎ **Anonymous Network** for Internet Communication
 - Up to **10 million users in 2026**
- ◎ **Relays:** Volunteer-Operated Servers
 - Types: Entry, Middle, Exit
- ◎ Each node knows the **IP address** of its immediate neighbors



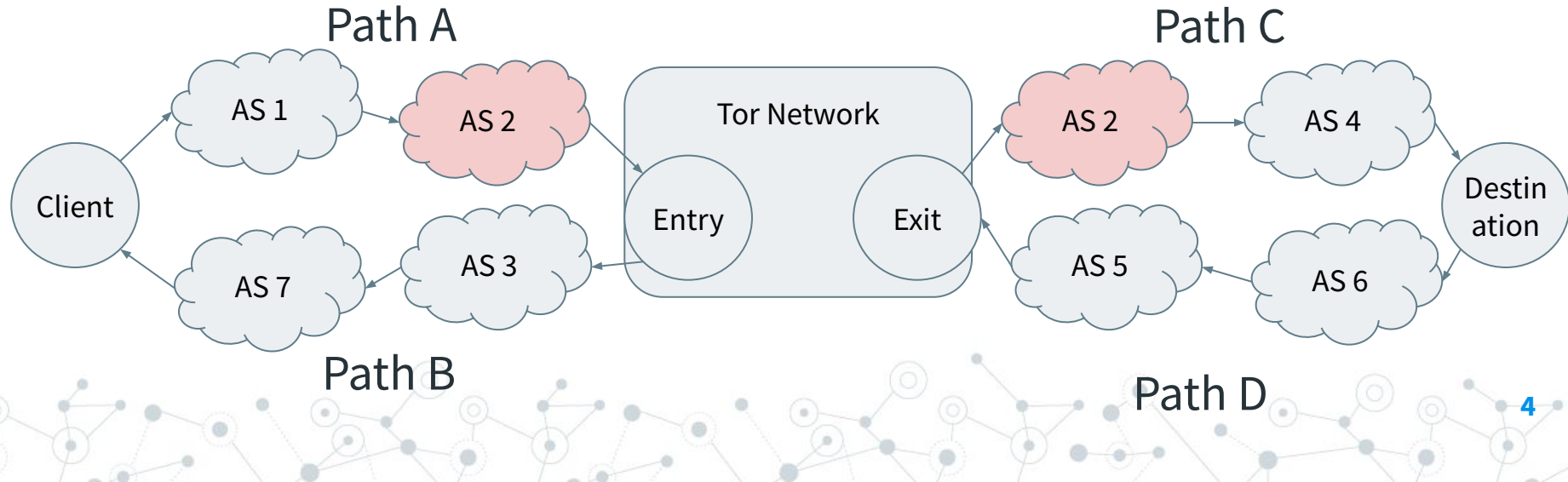
Autonomous Systems and Border Gateway Protocol

- ◎ **Autonomous Systems (ASes):** Internet networks (ISPs, companies, universities)
- ◎ **Border Gateway Protocol (BGP):** determines how traffic is routed between ASes
- ◎ **Routing is asymmetric:** forward and reverse paths may differ

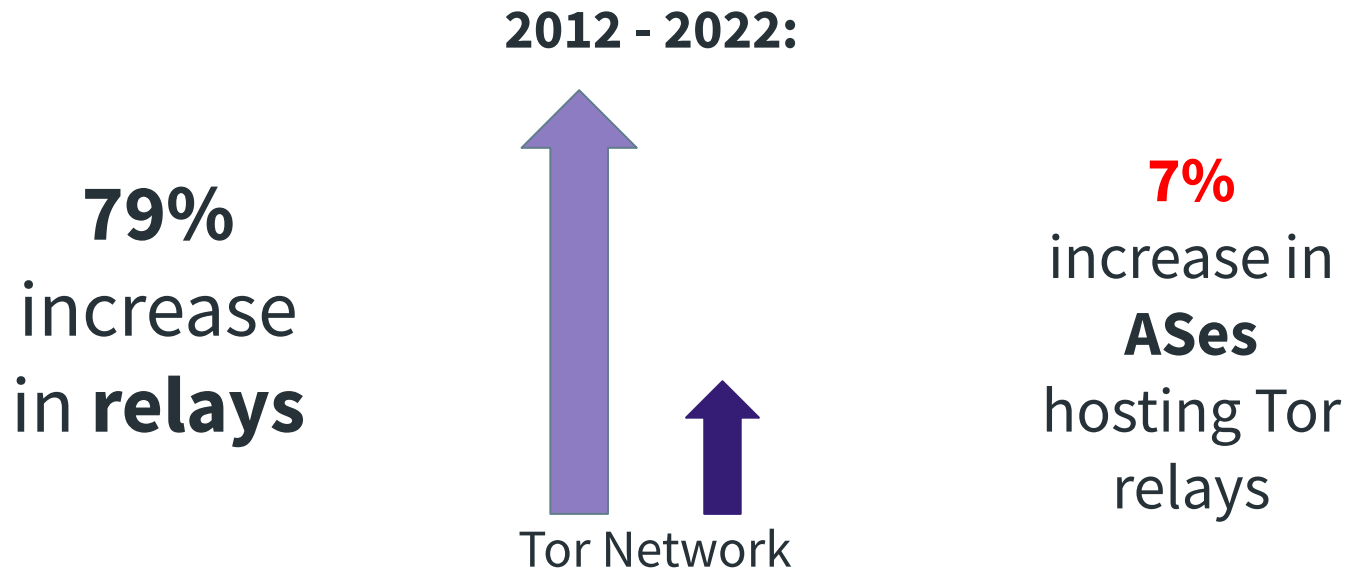


Traffic Correlation Attack

- ◎ Observes traffic entering and exiting an anonymity network
- ◎ Correlates flows using packet size, volume, and timing patterns
- ◎ Links a user to their destination without breaking encryption



Problem: Lack of AS Diversity

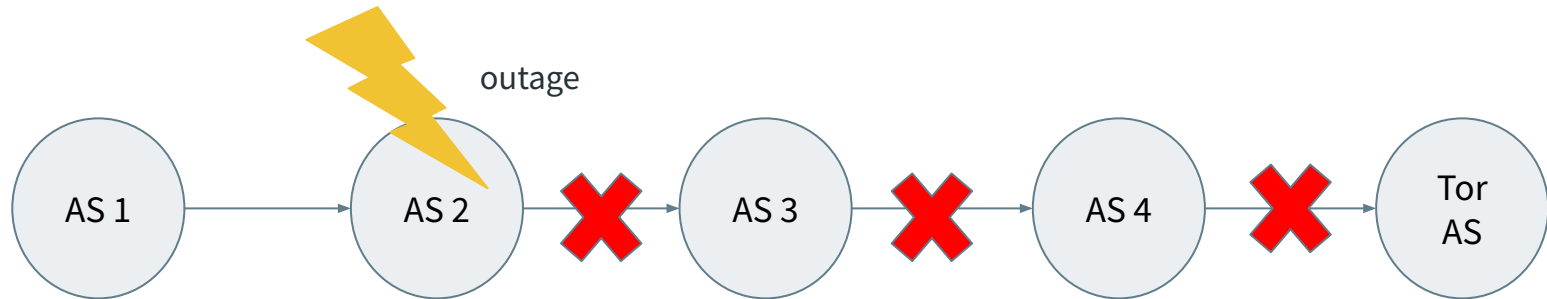


**Higher chance of same AS
appearing on both paths**

**Higher risk of traffic
correlation attacks**

Operational Risk of a Centralized AS

- ⦿ Traffic correlation attacks isn't the only concern
- ⦿ Centralization also increases operational risk
- ⦿ A single outage or BGP misconfiguration can result in the network being at risk

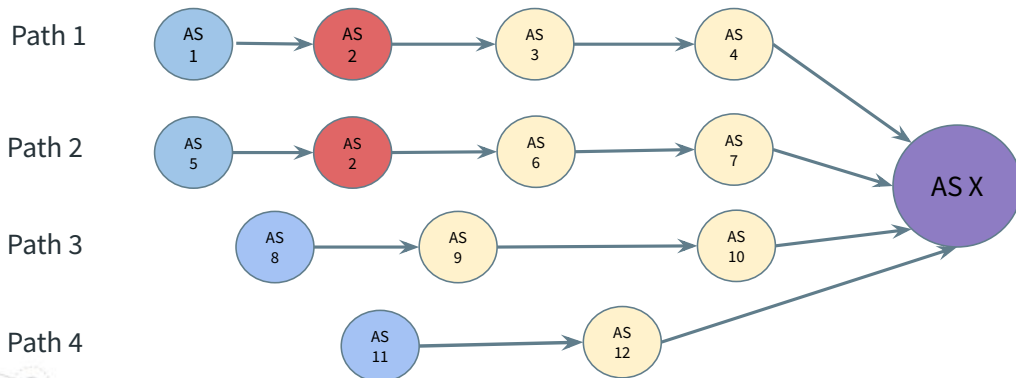


How concentrated is the Tor network?

Computing AS Hegemony: Betweenness Centrality

- ◎ **Betweenness-Centrality Score (BC Score):** measures the frequency an AS appears in a path
 - Note: Different BGP viewpoints may have biased views, creating biased scores
 - Leftmost ASes are viewpoint ASes

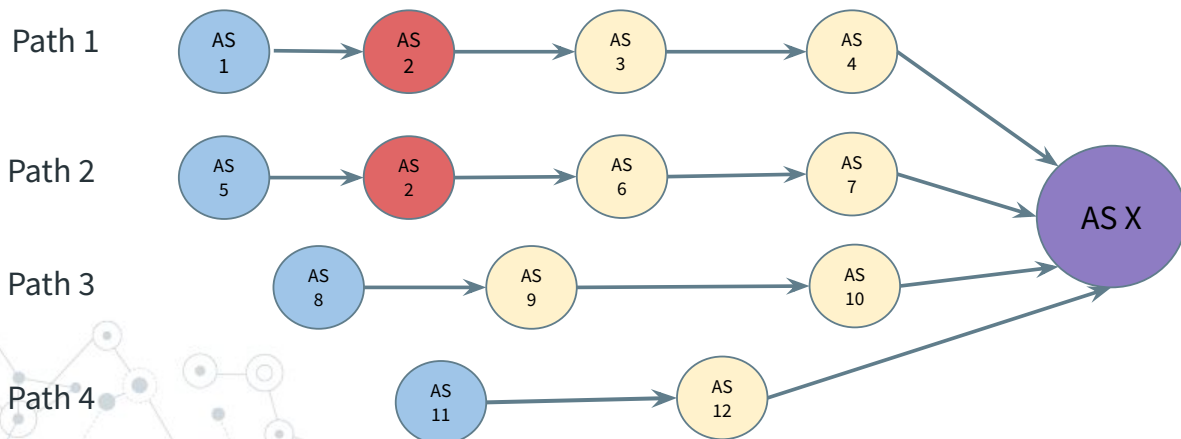
Viewpoint ASes



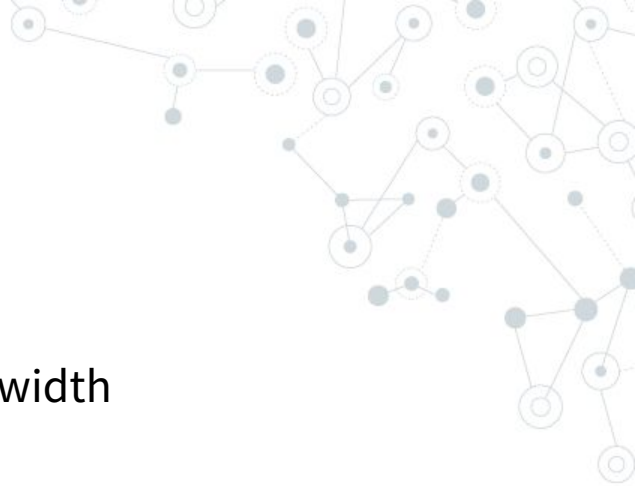
AS Hegemony Score

- ◎ **AS Hegemony:** Apply trimmed mean across BGP viewpoints, discarding outliers to reduce sampling bias
 - Scale from 0 (low) to 1 (high)

Viewpoint ASes



**Hegemony score of
AS 2: 0.5**
(trimmed mean across
viewpoints' BC)



Our Contributions

◎ **Bandwidth Weighting**

- Weighted AS paths by Tor relay consensus bandwidth

◎ **Symbolic AS**

- Appended a symbolic Tor AS as the logical destination

◎ **Country-level Tor Hegemony**

- Computed country-level Tor hegemony using geolocated BGP viewpoints

◎ **Relay Deployment**

- Proposed relay placement to reduce transit concentration
- 

Tor Hegemony Pipeline



Input:
BGP Data
(2015-2025)



Input:
Tor
Consensus
Dataset
(2015-2025)



Input:
CAIDA Dataset
(2015-2025)

Extract
AS Paths,
relay IPs,
relay bandwidth

Map relay
IPs to
hosting
ASes

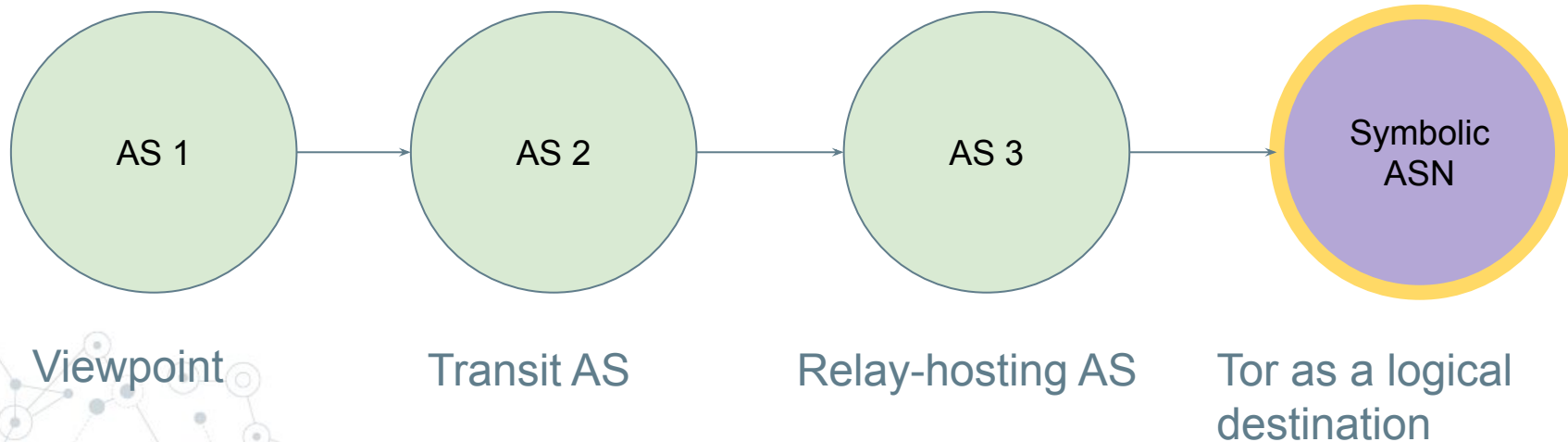
Append Symbolic ASN after each Tor
relay AS

Calculate
bandwidth-weighted
BC

Calculate Tor
hegemony

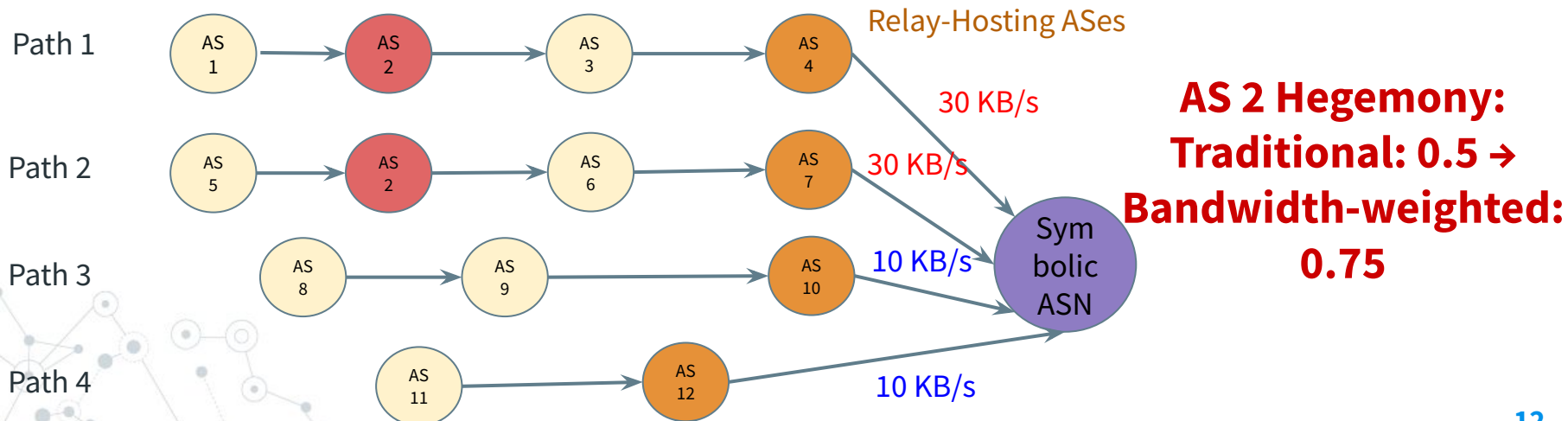
Symbolic ASN: Tor as a logical destination

- ◎ Tor has no natural destination AS
- ◎ We append a Symbolic ASN after each relay-hosting AS

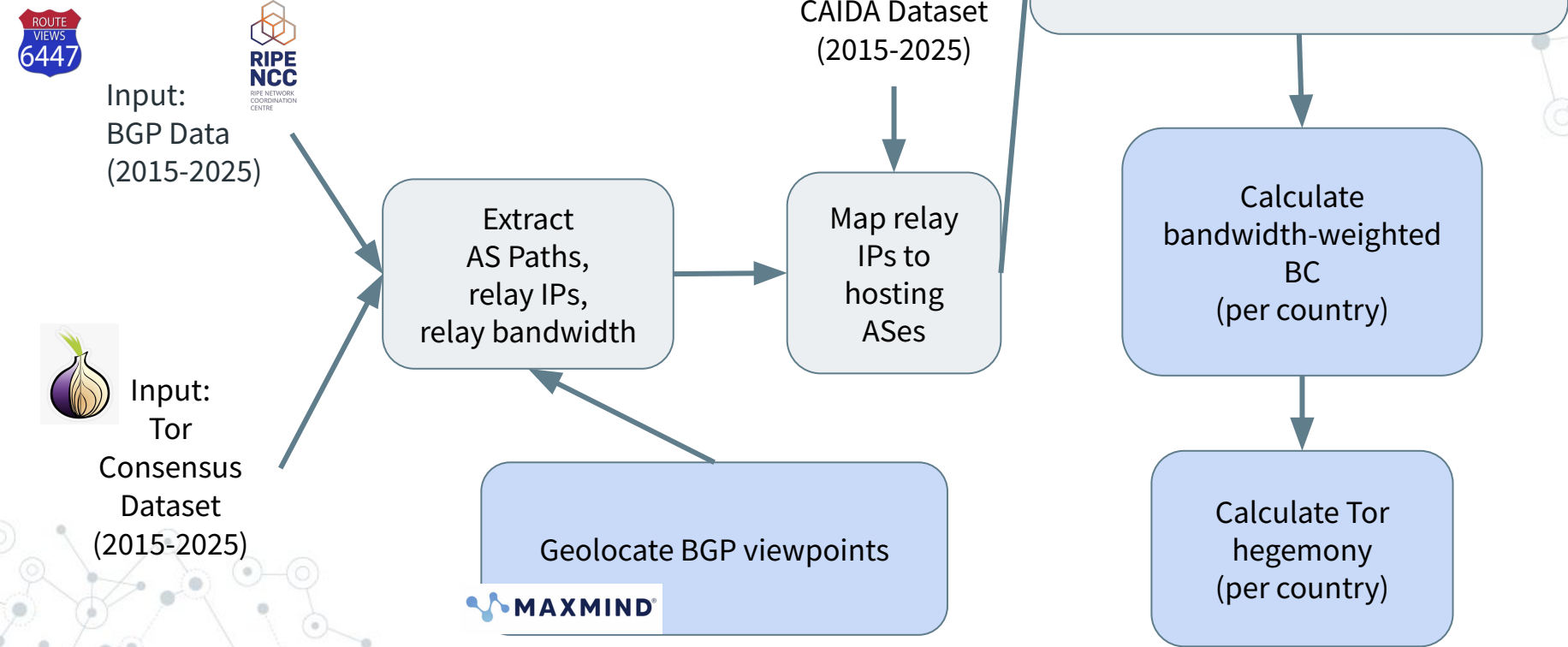


Bandwidth-Weighted Hegemony Scores

- Traditional: All paths contribute equally
- Our approach: Weigh paths by relay consensus bandwidth
 - Higher-bandwidth paths contribute more to Hegemony

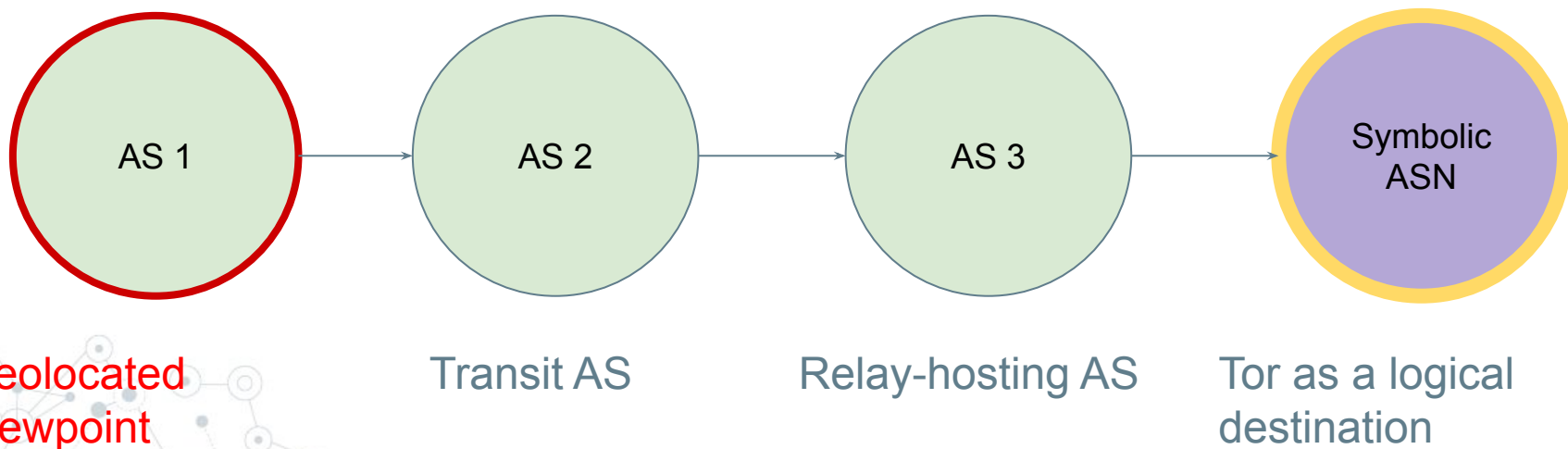


Country-Level Tor Hegemony Pipeline



Country Tor Hegemony Scores

- ◎ Start from the Tor Hegemony pipeline
- ◎ Geolocate BGP viewpoints (MaxMind)
- ◎ Calculate Tor Hegemony per viewpoint country



Backbone Infrastructure Shapes AS Hegemony

© 2015 - 2017: **Level3/CenturyLink/Lumen (AS 3356)**

- Dominant transit AS

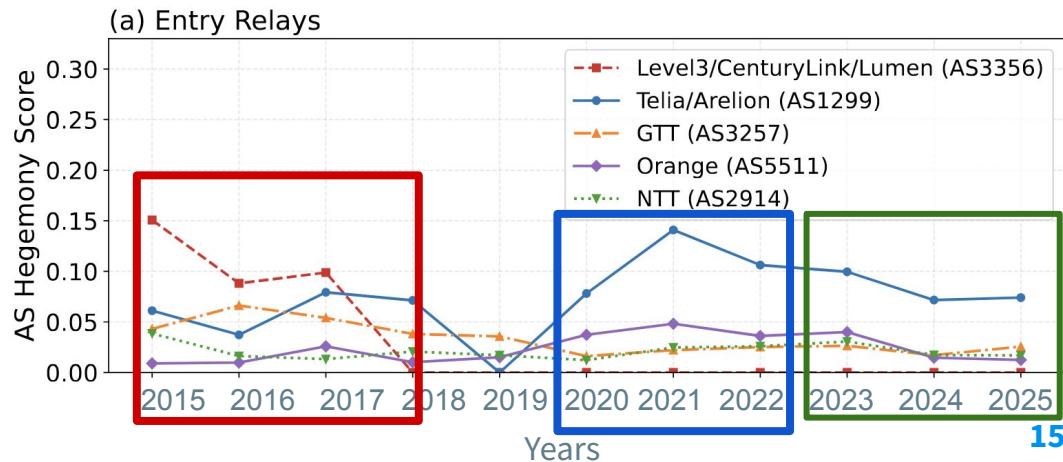
© 2020 - 2022: **Telia/Arelion (AS 1299)**

- Became the dominant transit AS

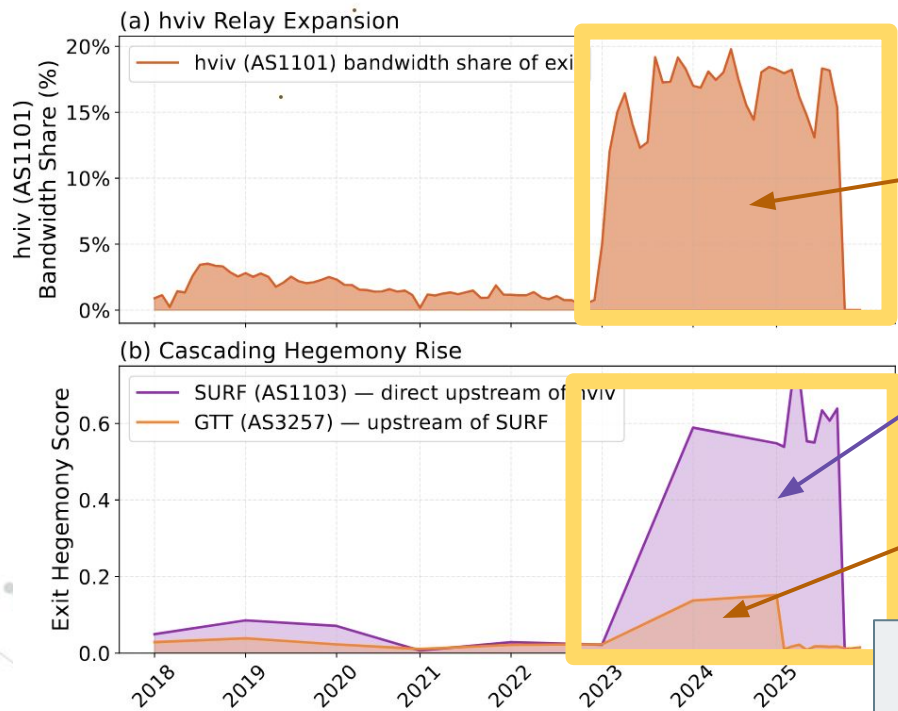
© 2023: **No single AS dominants**

- All scores < 0.08

Backbone infrastructure decisions can substantially reshape AS concentration



Relay Expansion Propagates Upstream



AS Path: **hviv** -> **SURF** -> **GTT**

Hviv (Relay-hosting AS)

Relays: 20 → 300

SURF

Hegemony: 0.0 to 0.59

GTT

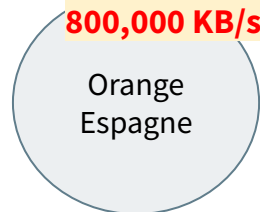
Hegemony: 0.0 to 0.15

Increasing relay capacity in one AS also increases the hegemony of its upstream providers

Singapore: Relay Bandwidth Shapes AS Hegemony

◎ ViewQwest rises to 0.5; NewMedia drops to 0.0

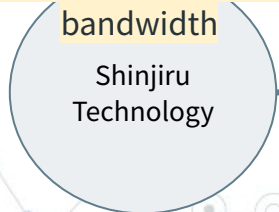
**Bandwidth increase to over
800,000 KB/s**



Score: 0.33 -> 0.5

ViewQwest

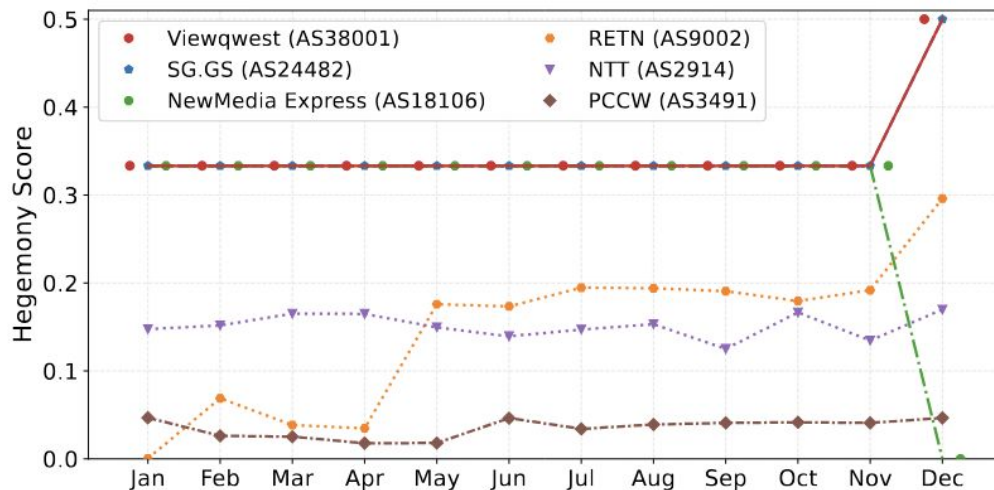
**200,000 KB/s drop in
bandwidth**



Score: 0.33 -> 0.0

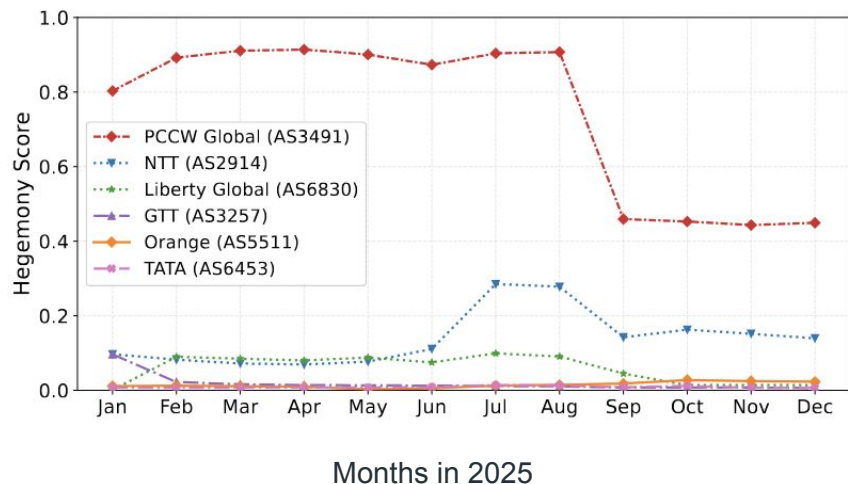
NewMedia

Relay bandwidth changes directly
reshape AS Hegemony



Months in 2025

Malaysia: Relay Loss Reshapes Transit Hegemony



- ◎ Relay-hosting ASes lose relays
 - FranTech: 175 → 81
 - British Telecommunications: 2 → 1
- ◎ Their upstream transit providers lose influence
 - PCCW, NTT, Liberty Global all carry these relays
- ◎ Result: All three transit ASes show a **drop** in Hegemony

Preliminary Relay Deployment Strategy

- ◎ Motivation
 - Relay placement can unintentionally increase transit AS concentration
- ◎ Key idea
 - Use AS hegemony to guide where new relays should be deployed
- ◎ Preliminary strategy
 - A simple greedy heuristic recommends relay placements that reduce transit AS hegemony.

Conclusion

- ◎ What shapes AS Hegemony?
 - **Backbone infrastructure:** acquisition and restructuring
 - **Relay placements:** bandwidth and relay capacity
- ◎ Relay deployment strategy
 - Suggest relay placements to reduce transit AS concentration

Thank you!