Partial Reachability in the Internet Core: Definition, Measurement, and Application (Invited Talk)

Technical Report on arXiv, released 2025-11-24

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This work is the abstract and slides of an invited keynote talk presented at ACM AINTEC 2025, the Asian Internet Engineering Conference at the Dr. Andrew L. Tan Data Science Institute, De La Salle University, Bonifacio Global City, Taguig, Philippines, on 2025-11-25.

TALK ABSTRACT

Routing strives to connect the Internet, but failures can result in **partial reachability** in the Internet. This talk identifies partial reachability as an underappreciated area. We will show that partial reachability affects as many users as Internet outages, sometimes persisting for days or years.

We suggest three steps are critical to better understand partial reachability: We first present a **conceptual definition of the Internet core**, since, surprisingly, today there is *no clear definition of what the Internet is*. This definition is technical and neutral, based on connectivity, not authority. It enables us to understand *peninsulas* as persistent partial reachability, and *islands*, where networks are disconnected from the core.

Second, these definitions allow us to realize **algorithms that detect peninsulas and islands** reusing data from existing measurement systems that provide Internet-wide observations over years from thousands of observers.

Finally, we show **important practical applications of this work**. Our new analysis shows that partial reachability affects even more users than outages. We show how to improve RIPE Atlas sensitivity by removing measurement error and persistent reachability problems that otherwise that otherwise overwhelm individual events. Finally, we use our neutral definition to inform Internet policy, including questions about Internet sovereignty.

MORE INFORMATION

For more information, please see our technical reports "What Is The Internet? Partial Connectivity of the Internet Core" [1] and "Reasoning About Internet Connectivity" [2].

SPEAKER BIOGRAPHY

John Heidemann is the chief scientist for the Network and Cybersecurity Division of the University of Southern California/Information Sciences Institute (USC/ISI) and a research professor in the Thomas Lord Department of Computer Science at USC. At ISI he leads the ANT (Analysis of Network Traffic) Lab, developing privacy-aware methods to measure the Internet and improve network reliability, security, protocols, and critical services.

ACKNOWLEDGMENTS

This work was done in collaboration with Guillermo Baltra, Yuri Pradkin, and Tarang Saluja.

This work is supported in part by NSF contract PIMAWAT/CNS-2319409, BRIPOD/OAC-2530698, and DARPA contract AQUARIUS.

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REFERENCES

[1] Guillermo Baltra and John Heidemann. 2023. *Detecting Partial Reachability in the Internet Core.* Technical Report arXiv:2107.11439v4. USC/Information Sciences Institute. https://doi.org/10.48550/2107.11439v4

[2] Guillermo Baltra, Tarang Saluja, Yuri Pradkin, and John Heidemann. 2024. *Reasoning About Internet Connectivity.* Technical Report arXiv:2407.14427 [cs.NI]. arXiv. https://ant.isi.edu/%7ejohnh/PAPERS/Baltra24b.html

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U. of Southern California / Information Sciences Institute and Thomas Lord Dept. of CS

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USC Viterbi School of Engineering Information Sciences Institute

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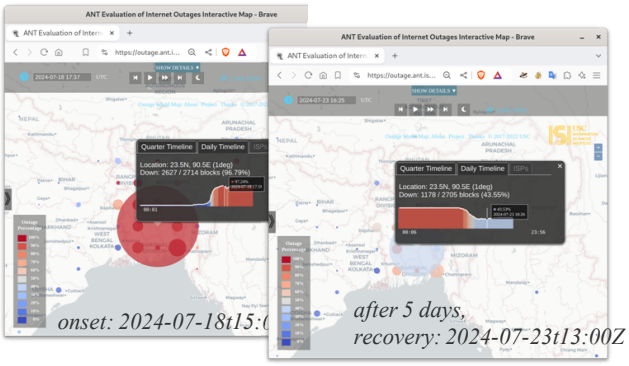
Outage detection finds things… Bangladesh's Civil Unrest, July 2024

In July 2024, a new law led to civil unrest and Bangladesh shut down their Internet *for five days.* In Aug., they did it again when the gov't resigned.



Outage detection finds things… Bangladesh's ~~Unrest~~ Change of Gov't, Aug. 2024

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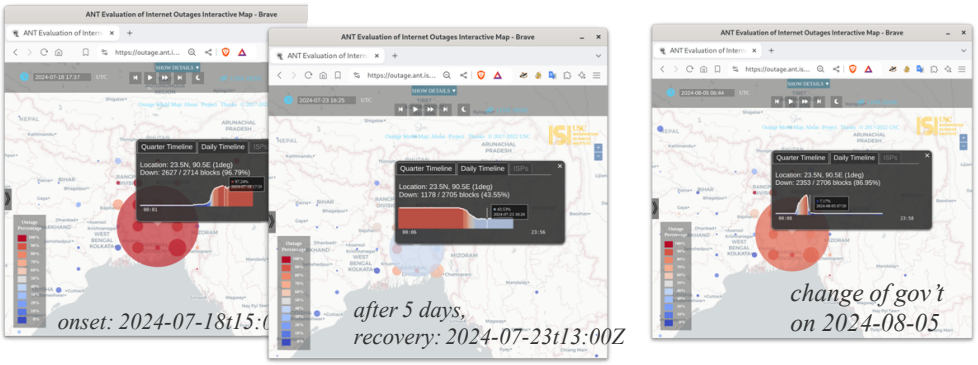
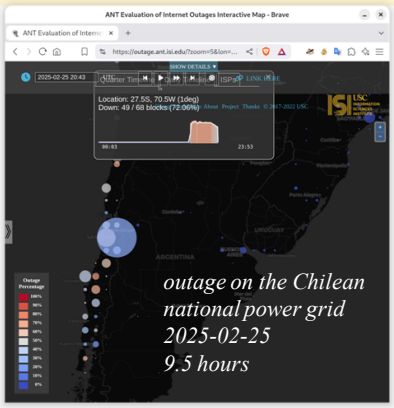
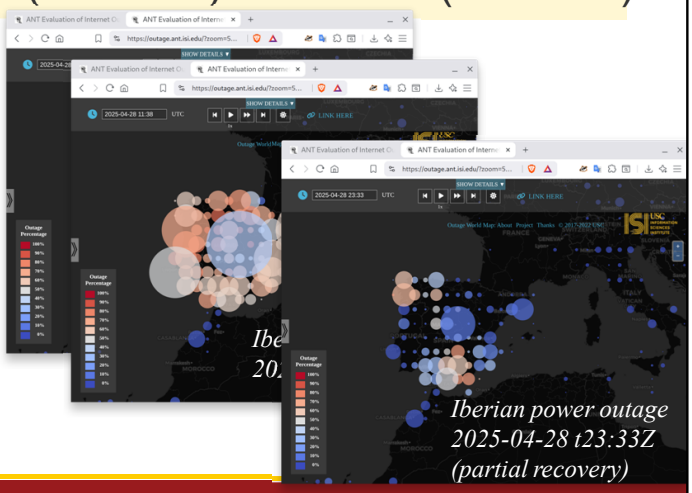


Outage detection finds things…
Power Outages in Chile (2025-02)and Iberia (2025-04)





Outage Detection (Un)Certainty

- this data is from **Trinocular**
  - 6 sites: LA, Denver, Washington/DC, Tokyo, Netherlands, Greece
- tested against several other systems
- and tested against *itself*… we compare the 6 sites
  - we vote to get **a single** answer
- but is it *correct*?

  …**but what about when our six sites *don't* agree?**
  - **measurement error? bugs?**
  - **or something else?**

We Need Better Theory to Explain Partial Outages

- outage detection has struggled with partial outages for years…
  - ThunderPing (2011) *hosed* state—some pings work and some don't'
  - Trinocular (2013): precision improvement small diffs are timing
  - CDN (Richter, 2018): maybe it's outages in *part* of the /24?
  - Trinocular (2019): majority voting for long disagreements
  - other systems ignore conflicting data
- common problem:
  no theory explaining disagreement in reachability observations

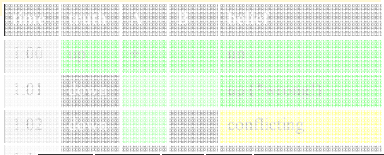
Premise 1: **Partial Reachability is Real**

- agreements are typical
- *some* disagreement is measurement error
  - ex: timing variation between sites (transient disagreement)

time	truth	A	B	belief
1:00	up	+		up
1:01	down			up (*wrong!)
1:02	down		-	conflicting
1:11	down	-		down (aggreeing)
1:13	down		-	down
1:22	down	-		down
1:24	down		-	down

Premise 1: **Partial Reachability is Real**

- agreements are typical
- *some* disagreement is measurement error
  - ex: timing variation between sites (transient disagreement)
- but **persistent disagreement is real: => partial reachability in the Internet**



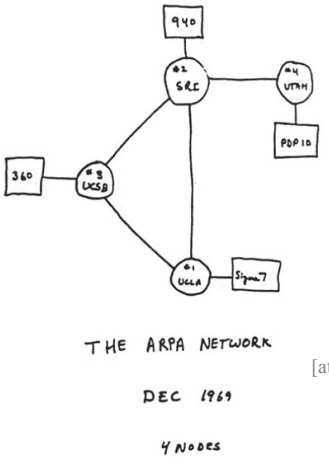
time	truth	A	B	belief
1:00	up	+		up
1:01	partial			true partial reach.
1:02	partial		+	
1:11	partial	-		**confirmed partial**
1:13	partial		+	
1:22	partial	-		
1:24	partial		+	

Outages Given Partial Reachaility

- **true outages** are disconnected from the Internet (or off)
- **partial outages are real**
  - disagreements observing reachability happen!
  - don't try to rationalize them away

If Outages are Disconnections, from What?

What is the Internet?

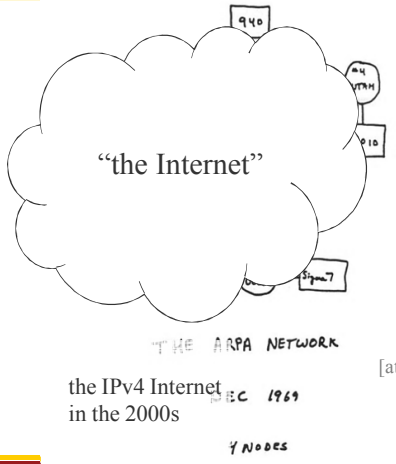


[attributed to Postel]

What is the Internet, Today?

What is the Internet?

What is the Internet, *today*?



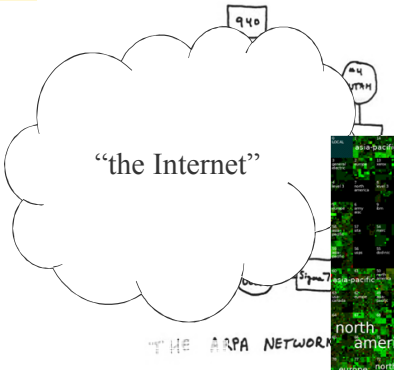
[attributed to Postel]

the IPv4 Internet in the 2000s

What is the Internet's *Edge*?

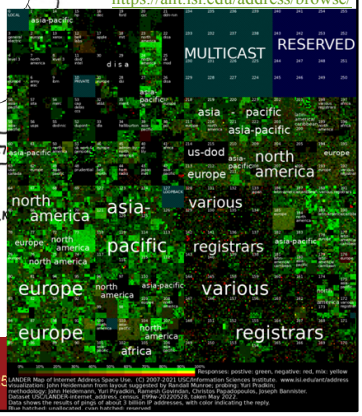
What is the Internet?

What is the Internet *edge* today?



the IPv4 Internet in the 2000s

An IPv4 census: all 2^{32} IPv4 addresses, on a Hilbert curve; brightness shows percent responding
https://ant.isi.edu/address/browse/



What is the Internet w/Cloud and NAT?

6 billion smart-phones (most behind CG-NAT)

1 billion home broadband (many with NAT)

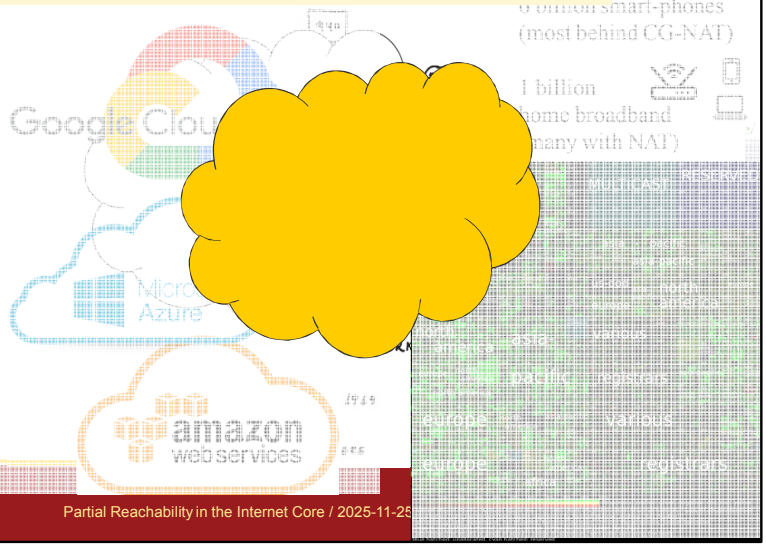
What is the Internet?

What is the Internet *edge and cloud* today?

What is the **Internet's Core**?

What is the
Internet Core?

the public,
shared fabric
that connects
everyone
(edge, cloud, you)

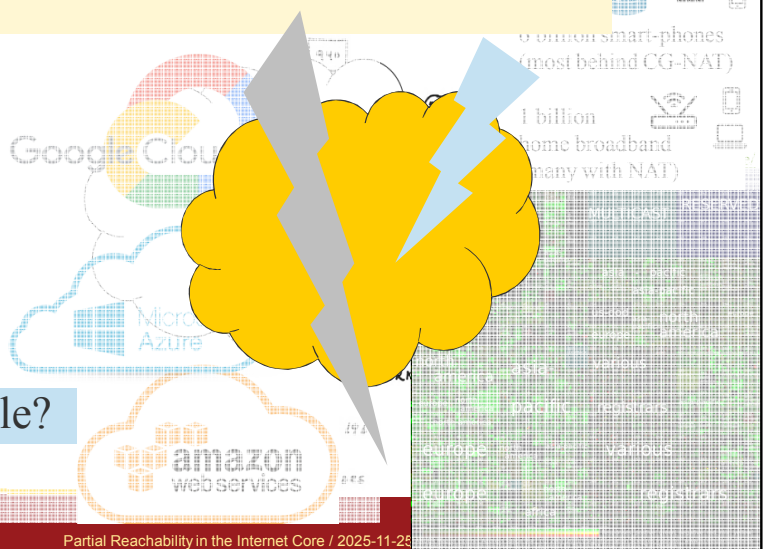


Premise 2: Define the *Internet Core*

What is the
Internet Core?

Can it fragment?

Can it be
partially reachable?



Prior Definitions of "Internet"

- TCP for an "internetwork" [Cerf and Khan, 1974]
- "A collection of interconnected networks is called an internet" [Postel, 1980]
  - examples were ARPAnet and X.25/X.75
- "an agreement to use an evolving set of protocols,
  in a globally unique address space,
  to enable universal data delivery" [Federal Networking Council, 1995]

Improving a Definition of "Internet"

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All good properties for the Internet!

But not *operationizable*.
(Measurable, quantifiable—what is and is not the Internet.)

Corner Cases of "the Internet": Bottom-Up

- 1 laptop with wifi (but not connected to anything)
  - it can run a webserver on a public IP
  - a web browser can connect to it(self)
- 2 laptops with wifi, connecting to each other
- 3 laptops, connecting over a layer-2 802.11s mesh
- 4 laptops, connecting with AODV multi-hop routing
- …and public IPs

"Corner" Case: the Cloud

- clouds have huge private address space
  - a full 10/8, with NATs to the Internet
    - reminder: 10/8 means 10.*.*.*, or 2^{24} = 16M IP addresses
  - actually, clouds have *dozens* of /8s
  - someday (today?) more *more private /8s than the public IPv4 net*

"Corner" Case: Cloud and Squatting

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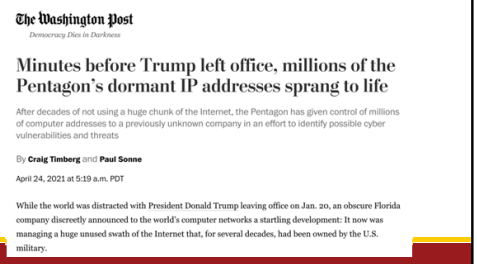
  - someday (today?) more *more private /8s than the public IPv4 net*

- DISA: 4 public /8s, since 1993
  - never publically routed
  - presumably active inside the U.S. DoD
  - and then routed in Jan. 2021



Political Threat: Countries

- a country disconnecting from the Internet
  - to prevent cheating on student exams (Iraq, Sudan)
  - because of protests and government instability (Egypt, Sudan)

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Political Threat: Countries

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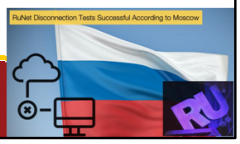
- a country disconnection for "Internet sovereignty"
  - (or claimed to disconnect)
- multiple countries sanction and de-peering



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Business Threat: ISPs Disputes

- two big ISPs with a peering dispute, won't exchange routes
- customers of those ISPs that cannot reach each other Internet

Our Contributions

- **recognizing partial reachability as fundamental** to network
- **defining the Internet Core**, a solution
- **algorithms to operationalize** the definition
- applications that show **this understand helps real systems**

Details: Baltra and Heidemann, "What is the Internet? Partial Connectivity at the Internet Core", arXiv:2107.11439v3

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Our Definition of the Internet Core

The Internet Core is all Active IP Addresses
that can Bidirectionally Route
to more than 50% of the public, Potentially Routable IP addresses

A *conceptual* definition
(no one can instantly measure
reachability between all IPs!)

A useful limit—
a goal for
operational algorithms.

And a basis
to reason about
corner cases.

Active IPs that can Bidirectionally Route to >50% of the public, Routable IPs

- why more than 50%?
  - 50% defines one, **unambiguous** component (a majority!)
- no central authority or special locations

- implications:
  - ⇒ there is only *one** Internet (* but wait two slides)
    - a lower threshold allows two groups to claim "the Internet" with a plurality
  - we can end the Internet by splitting into 3 pieces, each <50%
  - no one country or organization can unilaterally claim "the Internet"

Active IPs that can **Bidirectionally Route** to >50% of the public, Routable IPs

why **bidirectionally route**?

- can ping both ways
- captures "universal data delivery"

- implication: operationizable (we can measure it!)
  - alternatives to ping TCP or HTTP, but ping is most benign

Active IPs that can Bidirectionally Route to >50% of the **public, Routable IPs**

why the active and **public, (Potentially) Routable IPs?**

- captures "globally unique address space"
- public, potentially routable IPs: necessary for universal delivery

- implications
  - we actually define *two* Internets: IPv4 and IPv6
  - private addresses are second class

Active IPs that can Bidirectionally Route to >50% of the public, Routable IPs

why the **active?**

- allocated but not-routed doesn't "count"
- IPv6 is mostly unallocated!

- implications
  - use it if you have it!

A Engineering Definition to Be Useful

- users only want working ~~e-mail~~, ~~web~~, ~~Facebook~~, phone apps

- but…
  - policy makers enact laws and rulings
  - engineers design and operate protocols and networks
  - researchers design measurement systems

=> an operational definition can provide "facts on the ground", separate from politics or business

- users will benefit from these efforts!

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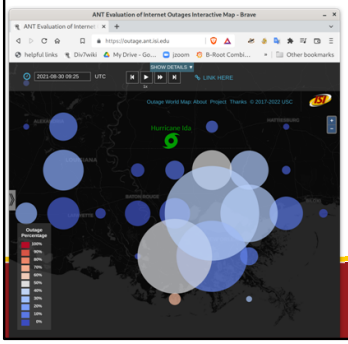
Observing the (IPv4) Internet

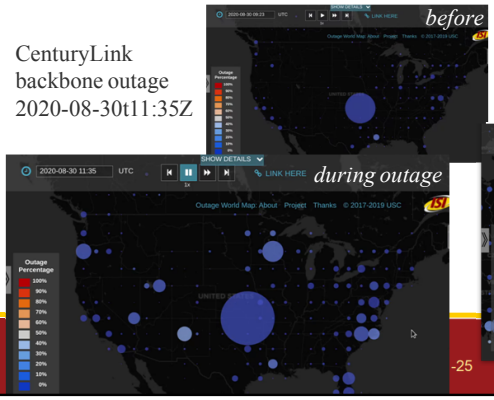
data: https://outage.ant.isi.edu

- we've studied **Internet Outages** since 2013 with Trinocular
  - ping 5.1M IPv4 blocks every 11 minutes
  - from 6 vantage points (VPs): Los Angeles, Washington DC, Colorado, Tokyo, Amsterdam, Athens
- but what does it mean when VPs disagree?

Hurricane Ida in Louisiana, 2021-08-29

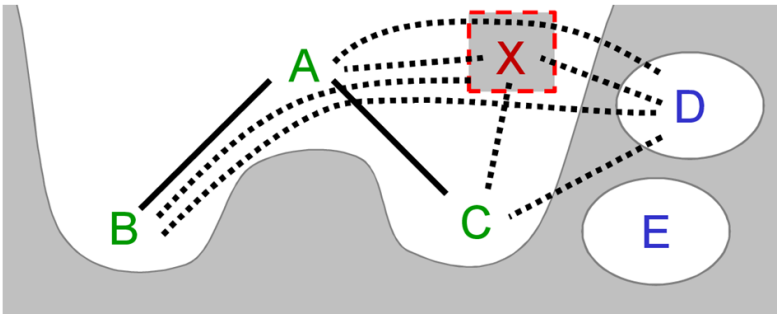


CenturyLink backbone outage 2020-08-30t11:35Z



Ukraine, 2022-03-09

Defining the Internet Clarifies Partial Connectivity



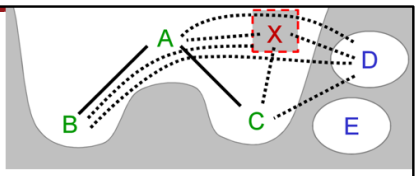
here letters are ASes,
routes are lines (working: solid, failed: dotted)

outage
powered off!

islands
disconnected
never connected

peninsulas
two that cannot reach, each other, but can reach many

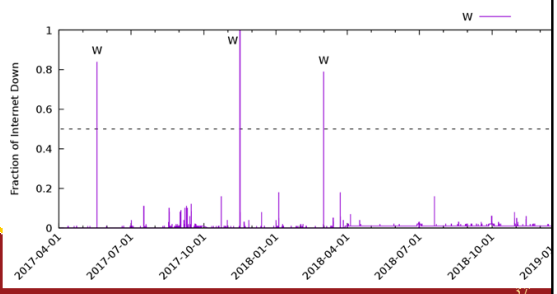
Islands



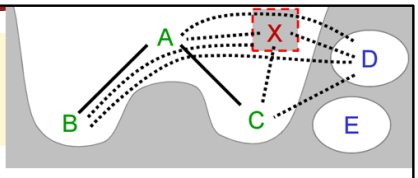
- when computers are not reachable (D & E)
  - more common than "computers off" outages (X)!
- happen anytime we have a disconnected part of the IP space

CenturyLink
backbone outage
2020-08-30t11:35Z
computers on customer
LANs could talk to each other

Near-total outages observed from ISI (W).
=> *islands at the observer (confirmed network problems)*



Peninsulas



- two locations cannot reach each other, but *can* reach others (B-C)

- routing transients make many short-lived peninsulas
  - see "Internet Optometry" by Bush et al, ACM IMC 2009
- sometimes persistent
  - peering disputes: like Cogent/HE peering dispute around IPv6
  - routing misconfiguration
  - firewalls

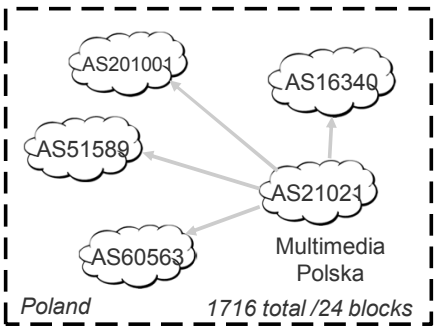
A Peninsula in Poland

On 2017-10-23,
for 3 hours from 22:02Z

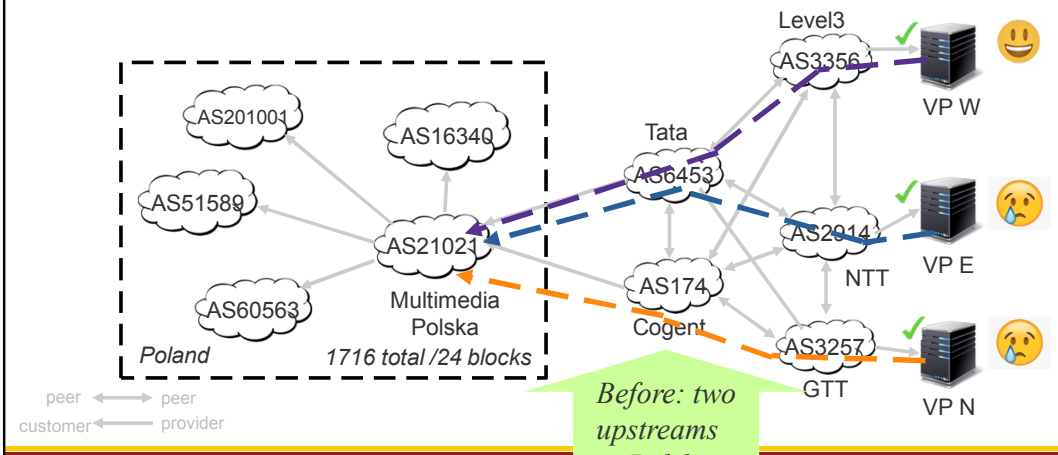
one VP (W)
could reach 5 Polish ISPs

but 5 others could not.

=> A peninsula! *Why?*

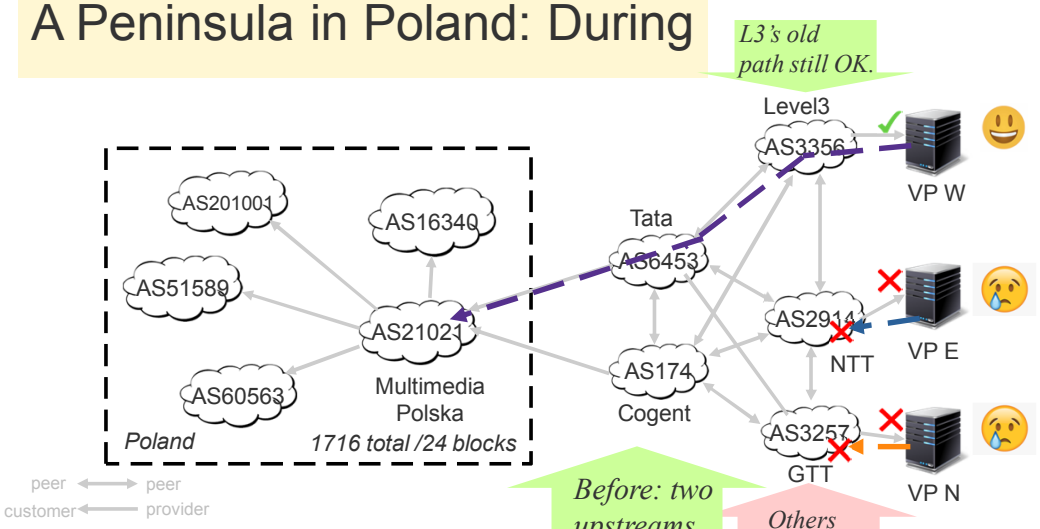


A Peninsula in Poland: Before



Before: two upstreams to Polska.

A Peninsula in Poland: During



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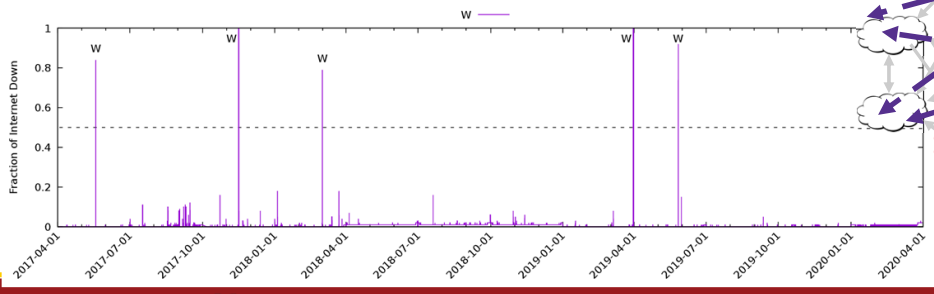
- **algorithms to operationalize** the definition
  - Chiloe: an algorihtm to detect islands
  - Taitao: an alogrithm to detect peninsulas
- applications that show this understand helps real systems

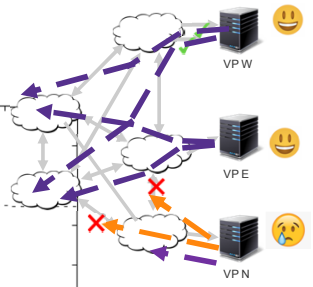
Details: Baltra and Heidemann, "What is the Internet? Partial Connectivity at the Internet Core", arXiv:2107.11439v3

Chiloe: an Algorithm to Detect Islands

- idea: when a VP is up, but can't see most or all of the Internet
  => an island

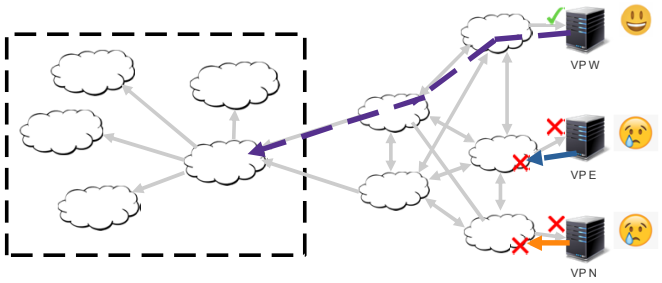
Near-total outages observed from ISI (W).
=> islands at the observer (confirmed network problems)





Taitao: An Algorithm to Detect Peninsulas

- idea: probe a target network from several independent VPs
- if they disagree (some reach and others don't)
  => peninsula



Applying Taitao: Detecting Peninsulas

- data source: reanalysis of Trinocular
  - from: LA, Denver, Washington (DC), Amsterdam, Athens, Tokyo
  - to: 5M IPv4 /24s, pinging every 11 minutes
  - reanalyze 21 days starting 2017-10-10
- validate against traceroutes from CAIDA's Ark
  - 171 VPs, tracerouting every /24 once a day

Validating Taitao Peninsulas: Precision and Recall

True Positive and True Negatives
- both systems usually agree => high recall

False Positive (loose criteria):
- => good precision

(strict criteria => lower precision, likely due to firewalls)

Taitao \ Ark	Peninsula	Non Peninsula	
Peninsula	184	*251 (strict)*	*40 (loose)*
Non Peninsula	12	1,976,701	

	strict	*loose*
Precision	0.42	0.82
Recall	0.94	0.94
F score	0.58	0.88

False Negative:
- Trinocular (all down) => firewalled

⇒ high recall (0.94):
what we see is true
⇒ ok to good precision (0.42 to 0.82)
we see a lot (w/ flexible comparison)

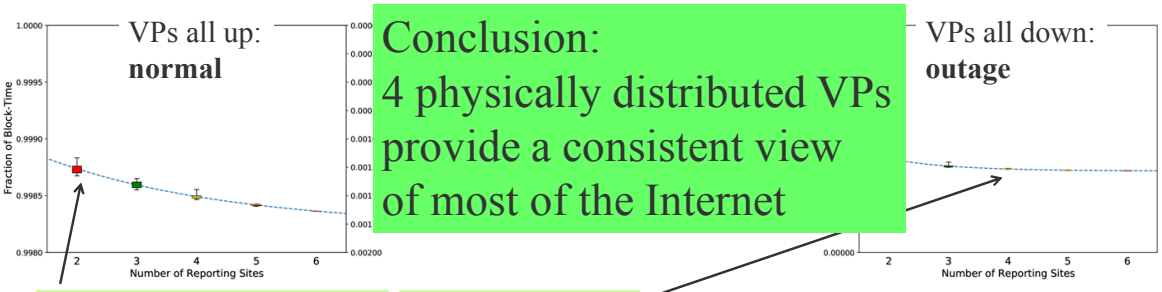
Our Contributions

- recognizing partial reachability as fundamental to network
- defining the Internet Core, conceptually
- algorithms to operationalize the definition
- applications that show **this understand helps real systems**

Details: Baltra and Heidemann, "What is the Internet? Partial Connectivity at the Internet Core", arXiv:2107.11439v3

Outages from *N* Vantage Points

Compare: Taitao for 40 days (start 2017-10-06), compare all combinations of 2 to 6 VPs.



Conclusion:
4 physically distributed VPs provide a consistent view of most of the Internet

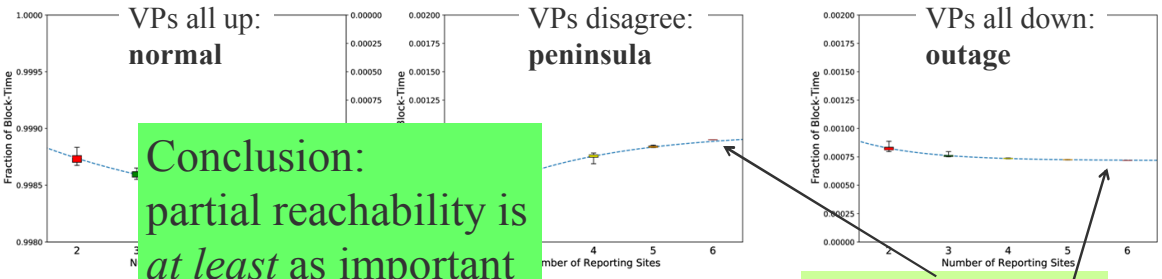
variance is small:
⇒VPs are *independent*
(any 2 give the same result)

values converge
(4 VPs ≈ 6 VPs)
⇒VPs are *enough*

How Common Are Peninsulas?

(disagreement in reachability)

Compare: Taitao for 40 days (start 2017-10-06), compare all combinations of 2 to 6 VPs.



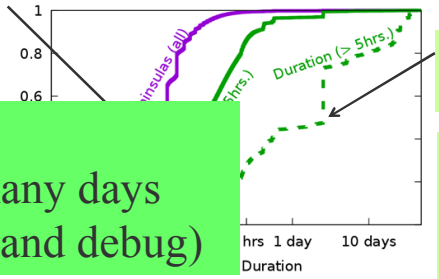
Conclusion:
partial reachability is *at least* as important as outages!

as many peninsulas as outages
(each ~0.075% of time)
⇒peninsulas matter!

How Long Do Peninsulas Last?

Methodology:
Taitao for 2017q4
(90 days)

Most peninsula events are short-lived (33% less than 60 minutes) => routing transients



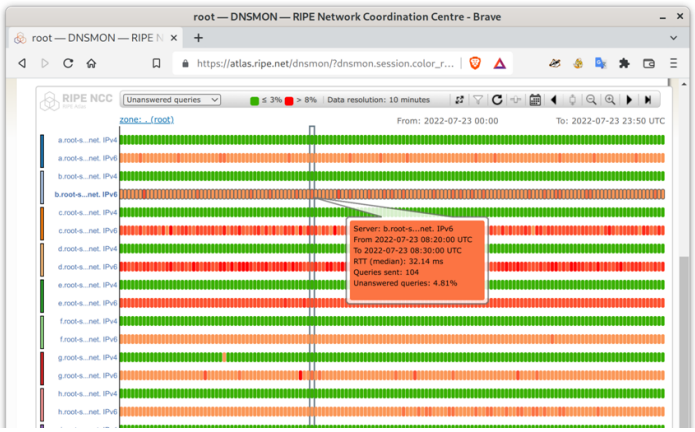
some last 2+ days => policy disagreement

Users that see peninsulas see long-lasting ones (60% are ~2+ days).

Conclusion:
some peninsulas last many days (enough time to detect and debug)

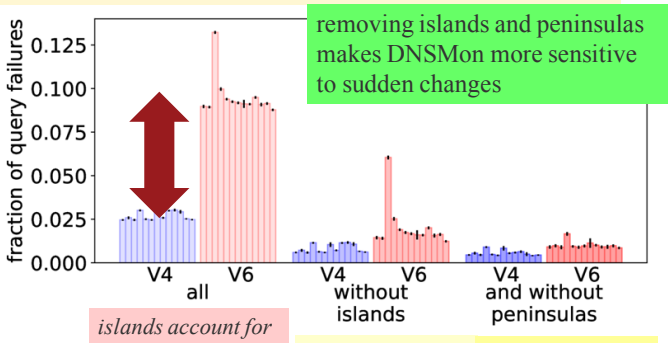
A Practical Application: Making RIPE DNSMon More Sensitive

- dnsmon.ripe.net: essential root DNS monitor
  - IPv4 and IPv6 reachability to the 13 root DNS letters
- problem: for *years* IPv6 reachability is bad (worse than IPv4)
- is this *real? fixable?*



Partial Outages and RIPE DNSMon

- the problem: DNSMon didn't really consider partial outages
  - Atlas probes were *islands*: cannot reach the outside*
  - one RSO is on a *peninsulas*: they cannot reach everywhere
- filtering these standing problems lets DNSMon *see daily change*



removing islands and peninsulas makes DNSMon more sensitive to sudden changes

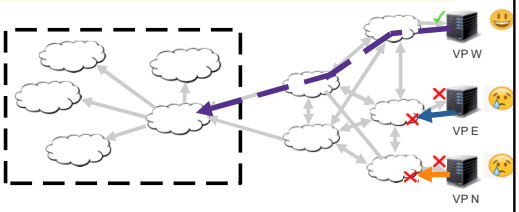
islands account for half of IPv4 and most IPv6 problems

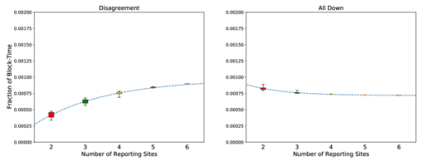
removing islands: one peninsula stand sout

removing both: v4 is really more reliable than v6

Conclusions

- **partial reachability is real**
- **defining the Internet** helps
  Active IPs that can Bidirectionally Route
  to >50% of the public, Routable IPs
- new algorithms **can measure peninsulas and islands**
- this perspective **improves**
  - **outage detection, RIPE DNSMon**
  - does this definition help clarify *your* Internet?





(more detail: our tech report:
arXiv:2107.11439 v3)