Defining The Internet Core: Partial Connectivity and Internet Fragmentation

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What is the Internet?
What is the Internet, today?
What is the Internet edge, today?

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 edge and cloud?
What is the Internet Core?

the public, shared fabric that connects everyone (edge, cloud, you)
What is the Internet Core?

Can it fragment?

what does that mean?
how would we tell?
Today’s Internet Stressors

- political pressure
  - Russia’s “sovereign network”
  - a US or Chinese “off switch”?  
  - countries have turned off their Internet

- business and technical pressures
  - persistent unreachability from peering disputes

- quantifying Internet reliability
  - we and others measure outages  
  - but all the corner cases?

- existing stressors linger
  - NAT
  - IPv4 / IPv6 transition,  
  - IP squat space and IPv4 full allocation
Stressors … and Our Response

- **political pressure**
  - Russia’s “sovereign network”
  - a US or Chinese “off switch”?
  - many countries have turned the Internet off

- **technical pressures**
  - persistent unreachability from peering disputes

- **quantifying Internet reliability—measuring outages**
  - we measure outages, but all these corner cases?

- **existing stressors linger**
  - NAT, IPv4 / IPv6 transition, IP squat space

- **a technical definition, ahead of time, to illuminate political challenges**
  - explaining to an MP the technical limits of a legal “kill switch”
  - the Internet is collaborative—no single control controls it

- **define persistent unreachability**
  - enable measurements of reliability
    (so sunlight can help motivate resolution of private disputes)

- defining outages (ISI has outage data since 2014)
  - must understand **partial connectivity**—it not just binary
  - enable robust comparisons of ISP reliability

- **a new definition helps clarify old disputes**
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”

- TCP for an “internetwork” [Cerf and Khan, 1974]

- “A collection of interconnected networks is called an internet” [Postel, 1980]
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- “an agreement to use an evolving set of protocols, in a globally unique address space, to enable universal data delivery” [Federal Networking Council, 1995]

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
Corner Cases: 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

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

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

• a country with 24 IPv4 /8s and an aggressive national firewall

• a country disconnecting to proclaim “Internet sovereignty”
  – (or claimed to disconnect)

• multiple countries de-peering with country X due to sanctions
Our Contributions

• defining the Internet Core, conceptually
• algorithms to operationalize the definition
  – Taitao: detecting peninsulas—persistent, partial connectivity
  – Chiloe: detecting islands—fully disconnected parts
• measurements from today’s Internet

Details: Baltra and Heidemann, “What is the Internet? Partial Connectivity at the Internet Core”, arXiv:2107.11439v3
Our Definition of the Internet Core

The Internet Core is the connected component of active, public IP addresses that can reach 50% of each other.

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.
Connected Component of Active, Public IP Addresses Reaching >50%

- why more than 50%?
  - 50% defines one, unambiguous component (a majority!)

- no central authority or special locations

- implications:
  - there is only one* Internet
    - 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”
Connected Component of Active, Public IP Addresses Reaching >50% reachability?

- 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
Connected Component of Active, Public IP Addresses Reaching >50%

who: the active, public IPs

why?

- captures “globally unique address space”
- public IPs: necessary for universal delivery
- active: what’s in use, not “dark space”

implications

- we actually define two Internets: IPv4 and IPv6
- private addresses are second class
A Engineering Definition to Inform Policy

- 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 guide them and help promote an open Internet

- users will benefit from these efforts!
Observing the (IPv4) Internet

- 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

data: [https://outage.ant.isi.edu](https://outage.ant.isi.edu)
Defining the Internet Clarifies Partial Connectivity

When no VPs can reach the target:

- **Outages**: computers are off
- **Islands**: computers on, but unreachable

- **Peninsulas**: when *some VPs, but not all* can reach
  - partial connectivity in the Internet!
Islands

- when computers are not reachable
  – more common than “computers off” outages!
- happen anytime we have a disconnected part of the IP space

CenturyLink backbone outage
2020-08-30T11:35Z
customers 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
- common transient event as routes converge
  - see “Internet Optometry” by Bush et al, ACM IMC 2009
- sometimes persistent
  - peering disputes: like Cogent/HE peering dispute around IPv6
  - routing misconfiguration
  - firewalls
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

Before: two upstreams to Polska.

Others blackhole traffic.

L3’s old path still OK.
Contributions

- defining the Internet (a conceptual definition)
- algorithms that operationalize the definition
  - Taitao: detecting peninsulas—persistent, partial connectivity
  - Chiloe: detecting islands—fully disconnected parts
- data from today’s Internet

Taitao: Detecting 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

<table>
<thead>
<tr>
<th></th>
<th>Peninsula</th>
<th>Non Peninsula</th>
</tr>
</thead>
<tbody>
<tr>
<td>Taitao Peninsula</td>
<td>184</td>
<td>12</td>
</tr>
<tr>
<td>Non Peninsula</td>
<td>251 (strict)</td>
<td>1,976,701</td>
</tr>
</tbody>
</table>

False Positive (loose criteria):
- Requires >1 VP down
  (strict criteria => lower precision, likely due to firewalls)

<table>
<thead>
<tr>
<th></th>
<th>strict</th>
<th>loose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precision</td>
<td>0.42</td>
<td>0.82</td>
</tr>
<tr>
<td>Recall</td>
<td>0.94</td>
<td>0.94</td>
</tr>
<tr>
<td>F score</td>
<td>0.58</td>
<td>0.88</td>
</tr>
</tbody>
</table>

False Negative:
- Trinocular (all down) => firewalled
  
  high recall => we see most peninsulas
  high loose precision => most are loose peninsulas
Outages from $N$ Vantage Points

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

- VPs all up: normal
- VPs all down: outage

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.

- VPs all up: normal
- VPs disagree: peninsula
- VPs all down: outage

As many peninsulas as outages (each ~0.075% of time) ⇒ peninsulas matter!
How Long Do Peninsulas Last?

Methodology:
Taitao for 2017q4 (90 days)

Count events (solid lines) and cumulative duration (dashed line).

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).
Secession and the Internet

- q: can any single country or region “take over” the Internet?
- a: no

<table>
<thead>
<tr>
<th>RIR</th>
<th>IPv4 hosts</th>
<th>IPv6 /32s</th>
</tr>
</thead>
<tbody>
<tr>
<td>AFRINIC</td>
<td>121M</td>
<td>9,661</td>
</tr>
<tr>
<td>APNIC</td>
<td>892M</td>
<td>88,614</td>
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<tr>
<td>China</td>
<td>345M</td>
<td>54,849</td>
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<tr>
<td>ARIN</td>
<td>1673M</td>
<td>56,172</td>
</tr>
<tr>
<td>U.S.</td>
<td>1617M</td>
<td>55,026</td>
</tr>
<tr>
<td>LACNIC</td>
<td>191M</td>
<td>15,298</td>
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<tr>
<td>RIPE NCC</td>
<td>826M</td>
<td>148,881</td>
</tr>
<tr>
<td>Germany</td>
<td>124M</td>
<td>22,075</td>
</tr>
<tr>
<td>Allocated</td>
<td>221</td>
<td>318,626</td>
</tr>
</tbody>
</table>

What Is the Internet Core / 2023-07-26
Conclusions

- defining the Internet: >50% reachability of active, public IPs
- new algorithms: Taitao for peninsulas, Chiloe for islands
- data about Internet partial connectivity
  - peninsulas are as common as outages
  - no single country can claim “the Internet”
- does this definition help clarify questions in your Internet?

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