What Is The Internet? 
(Considering Partial Connectivity)

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ABSTRACT
After 50 years, the Internet is still defined as "a collection of interconnected networks". Yet desires of countries for "their own internet" (Internet secession?), country-level firewalling, and persistent peering disputes all challenge the idea of a single set of "interconnected networks". We show that the Internet today has peninsulas of persistent, partial connectivity, and that some outages cause islands where the Internet at the site is up, but partitioned from the main Internet. We propose a new definition of the Internet defining a single, global network while helping us to reason about peninsulas and islands and their relationship to Internet outages. We provide algorithms to detect peninsulas and islands, find that peninsulas are more common than outages, with thousands of /24s IPv4 blocks that are part of peninsulas lasting a month or more. Root causes of most peninsula events (45%) are transient routing problems. However, a few long-lived peninsulas events (7%) account for 90% of all peninsula time, and they suggest root causes in country- or AS-level policy choices. We also show that islands occur. Our definition shows that no single country can unilaterally claim to be "the Internet", and helps clarify the spectrum from partial reachability to outages in prior work.

KEYWORDS
Internet, Internet reliability, Network outages, Active measurements

1 INTRODUCTION
What is the Internet?

The term was first used to specify an early version of TCP, but without definition [12]. The first definition was "A collection of interconnected networks is an internet" in a paper comparing X.25 and the ARPANet as two examples of internets [46]. The Federal Networking Council (FNC) added a common address space, with "an agreement between networks to interconnect under an evolving set of protocols, in a globally unique address space to enable universal data delivery" [27]. More recent work considered namespace (DNS) and IPv6. Many laypeople do not consider such technical details and blur the Internet with applications: the World-Wide Web or even Facebook is their Internet.

Yet the notion of a globally unique "Internet" today faces new challenges. IPv6 was proposed as a replacement for IPv4, and after 20 years of development, it is coming into its own network (as of May 2021, 33% of Google’s users access it over IPv6 [30]). Others have proposed separate networks for political reasons: In 2019, Russia suggested they were going to demonstrate a Russian Internet that can operate independently of outside influence [55]. China has had strong views on what is allowed on their domestic Internet, protected by the Great Firewall [2, 3]. In 2020, Huawei suggested a "new Internet" as a set of protocols [26]. We expand about these challenges in subsection 2.1

But such grand changes aside, what is the Internet today? Most users access the Internet from mobile phones, with most behind Network Address Translation (NAT) devices [54], so they use IP but without a public address. Typical security recommendations mandate firewalls, preventing general addressing. And efforts such as the Interplanetary Internet [9, 37] and the Internet-of-Things seek to bring "the Internet" into space or into embedded devices.

If the Internet is networks that interconnect, then persistent failures in such interconnection are a flaw. Today’s Internet consists of many public and private companies that agree to exchange traffic through peering, either as a customer buying service from a provider, or without cost through a settlement-free peering. Yet disputes over peering have sometimes resulted in serious congestion [5], and even long-term partial unreachability [39]. This unevenness has been recognized and detected experimentally [20] and other systems detect and route around partial unreachability [1, 38].

The primary contribution of this paper is to provide a definition of “the Internet”: the Internet is the connected component of public IP addresses that can reach more than 50% of the active, public IP addresses (section 2). Prior definitions [12, 27, 46] helped distinguish the Internet from alternatives at the time, but don’t address today’s challenges. We define an Internet that can answer questions about who “keeps” the name Internet if a nation or group secede. It also helps reason about fragmented reachability (a previous subject [1, 38]) that arises from routing trouble, and persistent peering disputes, large-scale firewalls, and carrier-grade network address translation. This definition captures the idea of a single, global Internet implicit in some prior definitions (actually...
two, one per v4 and v6 address space). Although theoretical (one cannot observe from all addresses) it is the asymptote of a technical realizable measurement from specific observers, and is not dependent on assertions of authority.

The second contribution of this paper is to develop two new algorithms (section 3) to identify two types of network fragmentation that underlie this definition. First, Taitao detects peninsulas, when a network can reach some parts of the Internet directly, but not others. Peninsulas result from peering disputes or long-term firewalls. Second, Chiloe detects islands, networks that have internal connectivity but are sometimes cut off from the Internet as a whole. Our algorithms do not require new active measurements, instead they provide a new interpretation of existing active measurement datasets that cover millions of IPv4 /24s blocks and several interesting events. To this data we add new algorithms, and new independent traceroutes to validate our results (section 4).

Our third contribution is to use these algorithms to understand to what degree the current IPv4 Internet suffers reachability problems (section 5). Partial reachability is important in prior work that routes through a third party [1, 38], but that work did not quantify how often these solutions are required. We find that peninsulas are more common than outages (as defined in the next paragraph), with thousands of /24s IPv4 blocks that are part of peninsulas lasting a month or more. Root causes of most peninsula events (45%) are transient routing problems. However, a few long-lived peninsula events (7%) account for 90% of all peninsula time, and they suggest root causes in country- or AS-level policy choices.

Finally, this understanding and definition of the Internet, partial connectivity, and outages (section 2) clarifies prior studies of Internet outages [31, 47, 49, 52, 53] in section 6. We show that operational systems converge on the conceptual definition, given that networks are not just “up” or “down”, but also partially reachable as peninsulas and sometimes disconnected islands.

All of the data used and created in this paper is available at no cost (subsection 3.1). Our work poses no ethical concerns: although we use data on individual IP addresses, we have no way of associating them with individuals. Our work was IRB reviewed and identified as non-human subjects research (USC IRB IIR00001648).

2 HOW DO WE DEFINE THE INTERNET?

When we define the Internet, we differentiate between conceptual and operational definitions [22]. Our conceptual definition in subsection 2.2 articulates what we would like to observe, while our operational definition in section 3 articulates how we can estimate this value. While our conceptual definition is intractable to fully realize, it provides an ideal to strive for.

2.1 Why is it Hard to Define the Internet?

The introduction gave classic but informal definitions of the Internet from 1974 to 1995, definition useful when the idea of connecting different media was research. However, the economic and political importance of the Internet since then has stressed these definitions in several ways.

Questions of Internet sovereignty have brought multiple governments to assert control over the Internet, or at least their portion. In 2009, some suggested the U.S. should have an Internet “kill switch” [51]. In 2019, Russia suggested they would experiment with an independent Russian Internet. Since the 2000s a number of countries have created and grown nation-level firewalls and access control, either for content moderation [2, 3] or to disconnect during political unrest [18]. What happens to the Internet if a major portion secedes and chooses to operate independently? Are there now two Internets? If not, which part is “the” Internet?

Economic disputes between companies that operate the Internet have stressed a unified Internet with long-term peering disputes. On multiple occasions, peering disputes in the 2000s resulted in persistent congestion between parts of the Internet [5, 20]. Peering disputes between Tier-1 ISPs sometimes result in the long-term inability of parts of the Internet to reach to other parts [39]. If one defines a Tier-1 ISP as operating default-free routing, then any Tier-1 ISP must directly peer with all other Tier-1 ISPs. When two Tier-1 ISPs cannot reach a business agreement to exchange traffic (such as if they cannot agree on a price), then their customers cannot reach each other. While both ISPs are part of “the Internet”, what does it mean when portions of the Internet see persistent unreachability?

Full allocation of the IPv4 address space is a third stress. Many users access the public Internet only through network address translation, sometimes in multiple layers. Some private networks today exceed designated private address space [4]. Are computers that cannot reach each other part of “the Internet”?

The goal of this paper is to explore these new questions. We provide a definition of the Internet that accounts for Internet secession and Internet islands—groups of computers that can reach each other but not outside. We describe methods to detect long-term reachability problems, Internet peninsulas. We also relate these issues to localized Internet outages. We consider network address translation and take as an epistemological axiom that there should be one Internet, or a clear statement that a single Internet no longer exists.
2.2 The Internet: A Conceptual Definition

We define the Internet as the connected component of public IP addresses that can reach each other with at least 50% of active, public IP addresses. This conceptual definition gives two Internets, one for the IPv4 address space and one for IPv6. We give our reasoning for this definition below.

This definition follows from the informal terms of “interconnected networks”, “IP protocol” and “global address space”. Their defining commonality is the capacity of two computers connected to reach each other independent of their logical location—can traffic from IP address \( x \) reach \( y \), and can \( y \) reach \( x \).

We formalize “an agreement of networks to interconnect” by considering reachability over public IP addresses: addresses \( x \) and \( y \) are interconnected if traffic from \( x \) can reach \( y \) and vice versa (that is: \( x \) and \( y \) can reach each other). Networks are groups of addresses that can reach each other.

Why More than 50%? We require that the Internet includes more than 50% of active addresses to reflect the principle that there is one Internet. We believe there should be a clearly defined Internet even if a major nation (or group of nations) chose to secede. Since only one partition can include the majority of active addresses, this definition provides an unambiguous, unique definition.

This definition suggests that it is possible for the Internet to fragment: if the current Internet breaks into three disconnected components when none has a majority of active addresses. Such a result would end a single, global Internet.

Addresses, Protocols, and Firewalls: This conceptual definition of the Internet is intentionally vague about the addresses and protocols that define reachability. The Internet today uses both IPv4 and IPv6; our definition applies to both protocols, effectively defining two Internets. Reachability can be tested through measurements with specific protocols, such as ICMP echo request (pings), or TCP or UDP queries. Such a test will result in an operational realization of our conceptual definition. Such realizations will differ in detail and accuracy, but we suggest they may converge on the ideal.

Firewalls complicate this matter by blocking some protocols or sources for policy reasons, and stateful firewalls may admit traffic in one direction, or in both directions after it is opened in one direction. Thus different protocols or times might give different answers, and one could define broad reachability with any protocol in a firewall-friendly manner, or narrowly. Our measurements in subsection 3.1 use IPv4 and ICMP echo requests; prior studies have compared IPv4 and probing protocol [7, 23, 47]. Although, some routers may rate-limit ICMP, this is a rare practice [32].

Why all addresses? We consider all addresses equally, rather than favor old or important locations or addresses. The Internet is global, and was intentionally designed without a hierarchy [13]. Our definition should not create a hierarchy or designate “special” addresses. This goal is consistent with recent goals for Internet decentralization [21].

Why reachability and not applications? Users care about applications, and a current user-centric view might be designed around perhaps reachability of HTTP. We focus on reachability at the IP layer as a more fundamental concept and has changed only twice since 1969 (with IPv4 and IPv6). The dominant application on the Internet has changed multiple times, and many important applications to other networks outside the Internet. (E-mail has been transparently relayed to UUCP and FidoNet, and the web to pre-IP mobile devices with WAP.)

2.3 The Internet Landscape

Our definition of the Internet highlights the Internet’s “rough edges”—places where reachability is limited by intentional partitions, peering and policy disputes, and outages. We next identify three types of problems: outages, islands, and peninsulas, and how they relate to the Internet as a whole.

2.3.1 Outages. A number of groups have examined Internet outages [31, 47, 49, 52]. These systems observe the IPv4 Internet and identify networks that are no longer reachable—they have left the Internet. Often these systems define outages operationally (network \( x \) is out because none of our Vantage Points (VPs) can reach it).

Conceptually, an outage is when all computers in a block are off, such as due to a power outage. If the computers or their network are on but cannot reach the Internet, we consider them islands. This conceptual definition differs from prior operational definitions where an outage exists when external VPs cannot see the target network.

Based on our definition of the Internet, an address \( a \) is a host-island if it cannot reach any other address, and it is part of the Internet if it can reach at least half of all active addresses. When it is connected to fewer than half the addresses, it is part of an island or peninsula, defined below.

2.3.2 Islands: Isolated Networks. An island is a group of public IP addresses that are partitioned from the Internet, but can continue to communicate among themselves. Both outages and islands are unreachable from an external VP, but with islands the computers are still active and talking among themselves.

Islands occur when an organization that has a single connection to the Internet loses its router or link to its ISP. A single-office business may become an island after a router failure, yet staff may use a webserver with them in the office even though they are unable to surf the public web. In the smallest case, an island may be a single address that can only ping itself, that is, an address island.
We believe that most outages are actually temporary islands. The conditions are identical from the outside, but can be distinguished by an observer within.

A Small Island: Figure 1 shows an example of an island we have observed. In this graph, each strip shows a different VP’s view of the last 156 addresses from the same IPv4 /24 block over 12 hours, starting at 2017-06-03T23:06Z. In each strip, the darkest green dots show positive responses of that address to an ICMP echo request (a “ping”) from that observer, and medium gray dots indicate a non-response to a ping. We show inferred state as lighter green or lighter gray until the next probe. We show 3 of the 6 VPs, with probes intervals of about 11 minutes (for methodology, see subsection 3.1).

The island is indicated by the red bar in the middle of the graph, where VP E continues to get positive responses from several other addresses (the continuous green bars along the top). By contrast, the other 5 VPs (2 VPs here, others in Appendix B) show many non-responses during this period. For this whole hour, VP E and this network are part of an island, cut off from the rest of the Internet and the other VPs.

Country-size Islands: We would typically say that a company that loses Internet access experienced an Internet outage and not call it an island. (In fact, with many companies depending on cloud-hosted services, loss of Internet may well stop all work in the company.)

However, we have seen country-size islands. In 2017q3 we observed 8 events when it appears that most or all of China stopped responding to external pings. Figure 2 shows the number of /24 blocks that were down over time, each spike more than 200k /24s, between two to eight hours long. We found no problem reports on network operator mailing lists, so we believe these outages were ICMP-specific and likely did not affect web traffic. In addition, we assume the millions of computers inside China continued to operate. We consider these cases examples of China becoming an ICMP-island.

2.3.3 Peninsulas: Partial Connectivity. While outages happen and create islands, a more pernicious problem is partial connectivity, when one can reach some destinations, but not others. We call a group of public IP addresses with partial connectivity with the Internet a peninsula. The presence of peninsulas have been recognized for nearly twenty years, with overlay networks demonstrated to route around them in RON [1] and later LIFEGUARD [38].

Peninsulas occur when a multi-homed network has outages or peering disputes upstream, or due to firewalls. Examples in IPv6: An example of a persistent peninsula is the IPv6 peering dispute between Hurricane Electric and Cogent. These two Tier-1 ISPs are unwilling to peer in IPv6 (presumably they cannot agree to business terms about settlements), and since they are both Tier-1 ISPs, they are also unwilling to send IPv6 to each other through another party (the “no valley” routing policy). This problem has existed since 2009 [39] and can be observed as of June 2020 in DNS-MON [50] as a small amount of persistent unreachability for IPv6 across most Root DNS letters.

We further confirm unreachability between Hurricane Electric and Cogent users in IPv6 by running traceroutes from their own looking glasses [15, 25] to the other’s DNS server (HE at 2001:470:20::2, and Cogent at 2001:550:1:a::d). While neither can reach their neighbor’s server, they do successfully reach their own. We do not see this problem on IPv4 (HE at 74.82.42.42, and Cogent at 66.28.0.14).

Other IPv6 dispute examples are Cogent with Google [48], and Cloudflare with Hurricane Electric [28]. Peering disputes are often the result of traffic imbalance and disagreements about a settlement-free or customer/provider relationship.

An Example in IPv4: We next explore a real-world example of partial reachability to several Polish ISPs that we found with our algorithms. On 2017-10-23, for a period of 3 hours starting at 22:02Z, five Polish Autonomous Systems (ASes) had 1716 blocks that were unreachable from five VPs while the same blocks remained reachable from a sixth VP.

Figure 3 shows the AS-level relationships at the time of the peninsula. Multimedia Polska (AS21021, or MP) provides service to the other 4 ISPs. MP has two Tier-1 providers:
We can confirm this peninsula with additional observations from CAIDA’s Ark traceroutes. During the event we see 94 unique Ark VPs attempted 345 traceroutes to the affected blocks. Of the 94 VPs, 21 VPs (22%) have their last responsive traceroute hop in the same AS as the target address, and 68 probes (73%) stopped before reaching that AS. The remaining 5 VPs were able to reach the destination AS for some probes, while not for others. (Sample traceroutes are in Appendix A.)

Although we do not have a root cause for this peninsula from network operators, large number of BGP Update messages suggests a routing problem. In subsection 5.4 we show peninsulas are mostly due to policy choices.

### 3 METHODOLOGY

To measure partial outages (islands and peninsulas) one must look for outages from multiple independent locations (see subsection 6.2). Most prior systems have focused on data from a single site (IODA [17], Chocolatine [31], Disco [53]), or have merged data from multiple sites to filter out partial outages (Thunderping [52], Trinocular [47], Wan et al. [58]). We now explicitly consider taking observations from multiple locations to detect partial outages and islands, following our definitions in section 2. We propose two new algorithms, Taitao to detect peninsulas, and Chiloe, to detect islands (named after a large Patagonian peninsula and island).

#### 3.1 Data Sources

Our algorithms use data from Trinocular [47] because it is available at no cost [57], is available since 2014, and covers most of the IPv4 Internet [6]. Briefly, Trinocular watches about 5M IPv4 /24 blocks. In each probing round of 11 minutes, it sends up to 15 ICMP echo requests (pings), stopping early if it proves the block is reachable. It interprets the results using Bayesian inference, and merges the results from six geographically distributed VPs. VPs are in Los Angeles (W), Colorado (C), Tokyo (J), Athens (G), Washington, DC (E), and Amsterdam (N). In principle our algorithms apply to other sources of active probing data as future work.

We validate our results using CAIDA’s Ark [10], and use AS numbers from Routeviews [43]. All data used in this paper is thus publicly available.

We use Trinocular measurements for 2017q4 because this time period had six active VPs, allowing us to make strong statements about how multiple perspectives help. (We use 2020q3 data in subsection 5.4 because Ark observed a very large number of loops in 2017q4.) Problems with different VPs reduced coverage for 2019 and 2020, but we verify and find quantitatively similar results for 2020 data in Appendix C.)
3.2 Taitao: a Peninsula Detector

Peninsulas occur when portions of the Internet are reachable from some locations and not others. Peninsulas can be observed when two VPs disagree on block reachability. With multiple VPs, any state other than all-up or all-down suggests a peninsula.

There are two challenges to detecting peninsulas. First, we don’t actually have VPs everywhere. If all VPs are on the same “side” of a peninsula, their reachability agree even though other potential VPs may disagree. Second, VPs observations are not synchronized and are spread over an 11-minute probing interval, so we expect that different VPs will make observations at slightly different times. Thus two correct observations may see before and after a network change, producing a false agreement or disagreement.

We identify peninsulas by detecting disagreements in block state by comparing valid VP observations that occur at about the same time. Since probing rounds occur every 11 minutes, we compare measurements within an 11-minute window. This approach will see peninsulas that last at least 11 minutes, but may miss briefer ones, or peninsulas where VPs are not on “both sides”.

Formally, $O_{i,b}$ is the set of observers with valid observations about block $b$ at round $i$. We look for disagreements in $O_{i,b}$. For that purpose, we define $O^u_{i,b} \subset O_{i,b}$ as the set of observers that measure block $b$ as up at round $i$. We detect a peninsula when:

$$0 < |O^u_{i,b}| < |O_{i,b}|$$

When only one VP reaches a block, that block can be either a peninsula or an island. We cannot distinguish between them without more information. In subsection 3.4 we add more information from what the positive VP sees about other blocks to determine islands.

3.3 Country-Level Peninsula Detection

Taitao detects peninsulas based on differences in observations. Long-lived peninsulas are likely intentional, from policy choices. One policy is filtering based on national boundaries, possibly to implement legal requirements about data sovereignty or economic boycotts.

We identify country-specific peninsulas as a special case of Taitao where a given destination block is reachable (or unreachable) from only one country, persistently for an extended period of time. (In practice, the ability to detect country-level peninsulas is somewhat limited because the only country with multiple VPs in our data is the United States. However, we augment non-U.S. observers with data from other non-U.S. sites such as Ark or RIPE Atlas.)

A country level peninsula occurs when all available VPs from the same country as the target block successfully reach the target block and all available VPs from different countries fail. Formally, we say there is a country peninsula when the set of observers claiming block $b$ is up at time $i$ is equal to $O^c_{i,b} \subset O_{i,b}$, the set of all available observers with valid observations at country $c$.

$$O^c_{i,b} = O_{i,b}$$

3.4 Chiloe: an Island Detector

According to our definition in subsubsection 2.3.2, islands occur when the Internet is partitioned, and the smaller component (that with less than half the active addresses) is the island. Typical islands are much, much smaller.

We can find islands by looking for networks that are only reachable from less than half of the Internet. However, to classify such networks as an island and not merely a peninsula, we need to show that it is partitioned. Without global knowledge, it is difficult to prove disconnection. In addition, if islands are partitioned from VPs, we cannot tell an island, where a part of the Internet is disconnected but still active inside, from an outage, where a part of the Internet is disconnected and also cannot communicate internally.

For these reasons, rather than looking for islands in the Internet, we instead look for islands that include VPs in their partition. Because we know the VP is active and scanning we can determine how much of the Internet is in its partition, ruling out an outage, and we can confirm the Internet is not reachable to rule out a peninsula.

Formally, we say that $B$ is the set of all blocks on the Internet that responded in the last week. $B^u_{i,o}$ is the set of observers with valid observations about block $b$ at round $i$. We detect a peninsula when:

$$0 < |B^u_{i,o}| < |B_{i,o}|$$

This method is limited to detecting islands that contain VPs. Also, because observation is not instantaneous, we must avoid confusing short-lived islands with long-lived peninsulas. For islands lasting longer than an observation period, we also require $|B^u_{i,o}| \rightarrow 0$. When $|B^u_{i,o}| = 0$, then we have an address island.

3.5 Determining Who Has the Internet

The U.S. [51], China [2, 3], and Russia [14] have all proposed unplugging from the Internet. Egypt disconnected during Arab spring [16], and several countries partially disconnected during exams [19, 24, 29, 34].

When the Internet partitions, which part is still “the Internet”? When a business disconnects, or a small country leaves, the answer is clear. What if a group of countries leave, splitting the Internet into huge islands of similar sizes?
Our definition of the Internet in subsection 2.2 defines the Internet as the majority of the active, public IP addresses. Majority uniquely provides an unambiguous, externally evaluatable decision—the partition exceeding 50% is the Internet.

An implication is that if there are multiple partitions and none keeps a majority, than the global Internet has ended. (A plurality is insufficient.)

4 VALIDATING OUR APPROACH

We next validate detection with Taitao and Chiloe. We compare Taitao peninsulas against independent data (subsection 4.1) and examine persistent country level peninsulas (subsection 4.2). We then compare Chiloe’s single-observer island detection against external observers (subsection 4.3).

4.1 Can Taitao Detect Peninsulas?

We compare Taitao detections from 6 VPs to independent observations taken from more than 100 VPs in CAIDA’s Ark [10]. This comparison is challenging, because both Taitao and Ark are operational systems with imperfect results, and because they differ in details such as probing frequency, targets, and method. It would be incorrect to declare one as perfect ground truth; instead we note agreement as likely truth, and discuss the likely cause of disagreements.

Although Ark data to the target is much less frequent than Trinocular, Ark makes observations from 171 global locations, so it provides a fresh perspective, and Ark collects traceroute data to the target, so it allows us to assess the where peninsulas begin. We expect to see a strong correlation between Taitao peninsulas and Ark observations. (We considered RIPE Atlas as another external dataset, but use Ark because it systematically traceroutes all /24 blocks.)

Identifying comparable blocks: We study 21 days of Ark observations from 2017-10-10 to -31. Ark provides coverage of all networks in two ways. With Ark team probing, 40 VPs traceroute to every routed /24 about once per day. For Ark prefix probing, about 35 VPs send traceroutes to .1 addresses of all routed /24s every day. We use both types of data: all three teams and all available prefix probing VPs, and we group results by /24 block of the traceroute’s target address.

Ark differs from Taitao’s input (Trinocular) in three ways: the target is a random address or the .1 address in each block; it uses traceroute, not ping; and it probes each block once per day, not every 11 minutes. We must account for these differences when comparing the datasets—Ark traceroutes will sometimes fail when a simple ping might succeed. First, Ark targets a random address or the .1 address, while Trinocular targets addresses known to respond, so Trinocular has a higher response rate. Second, Ark’s traceroutes terminate due to four reasons: success in reaching target address, ICMP unreachable message to the target address, loop in the path, or gap limit exceeded. We discard traceroutes halting because of a gap, since gaps indicate problems on the path, and may hide an endpoint that would be reachable if it were directly pinging.

To correct for differences in target addresses, we must avoid misinterpreting a block as unreachable when the block is online but Ark’s target address is not, we discard traces sent to non-ever-active addresses (not in “E(b)” observed from 16 IPv4 censuses [47]), and blocks for which Ark did not get a single successful response. (Even with this filtering, dynamic addressing means Ark still sometimes sees unreachables.)

To correct for Ark’s less frequent probing, we compare Trinocular down events that last 5 hours or more. Ark measurements are much less frequent (once every 24 hours) than Trinocular’s 11-minute reporting, so short Trinocular events often have no overlapping Ark observations. To confirm agreements or conflicting reports from Ark, we require at least 3 Ark observations within the peninsula’s span of time.

We filter out blocks that show frequent transient changes or show signs of network-level filtering. We define the “reliable” blocks that we keep as blocks that report as up at least 85% of the quarter from each of the 6 Trinocular VPs. We also discard as flaky blocks with frequently inconsistent responses across VPs. (We consider more than 10 combinations of VP as frequently inconsistent.)

The total number of blocks available for study matching our criteria for both Ark and Taitao is 2M.

Results of comparison: Table 1 shows detailed results, and Table 2 summarizes our interpretation. In this table, dark green indicates true positives (TP): when (a) either both Taitao and Ark show mixed results, both indicating a peninsula, or when (b) Taitao indicates a peninsula (1 to 5 sites up but at least one down), Ark shows all down during the event and up before and after. We treat Ark in case (b) as a positive because Ark probing is infrequent enough (only one probe per team every 24 hours is guaranteed, further this considers non-E(b) addresses which we discard) that we cannot guarantee VPs within the peninsula probing available target addresses. Because peninsulas are fairly rare, so too are true positives, but we see 184 TPs.

We show true negatives as light green and neither bold nor italic. In almost all of these cases (1.4M) both Taitao and Ark show the block up with no conflicting observations. Because of dynamic addressing [45], many Ark traceroutes end in a failure at the last hop (even after we discard never-reachable). We therefore count this second most-common result (491k cases) as a true negative. For the same reason, we include the small number (97) of cases where Ark reports conflicting results and Taitao is all-up, assuming Ark terminates at an empty address. We include in this category, the 90 events...
where Ark is all-down and Trinocular is all-up. We attribute Ark’s failure to reach its targets to infrequent probing.

We mark false negatives as red and bold. For these few cases (only 12), all Trinocular VPs are down, but Ark reports all or some responding. We believe these cases indicate blocks that have chosen to drop Trinocular traffic.

Finally, yellow italics shows cases where a Taitao peninsula is a false positive, since all Ark probes reached target block. This scenario occurs when either some Trinocular VPs have their traffic filtered, or all Ark VPs are “inside” the peninsula. Light yellow (strict) shows all the 251 cases that Taitao detects. For most of these cases (201), Trinocular has 5 responding VPs and 1 non-responsive, suggesting network problems are near one of the Trinocular VPs. Discarding these cases we get 40 (orange), a loose estimate.

The strict scenario sees precision 0.42, recall 0.94, and $F_1$ score 0.58, and in the loose scenario, precision improves to 0.82 and $F_1$ score to 0.88. We consider these results good, but with some room for improvement.

### 4.2 Can We Detect Country-Level Peninsulas?

Next, we verify our ability to detect country level peninsulas (subsection 3.3). Our hypothesis is that national borders sometimes result in long-term network unreachability. For example, rather than complying with external legal requirements (such as the EU’s GDPR [56]), an organization may prohibit access from those countries. Alternatively, a country’s military or government websites may limit access to foreign users.

Distinguishing country-level peninsulas from simple outages requires multiple VPs in the same country. Unfortunately the source data we use only has multiple VPs for the United States. We therefore look for U.S.-specific peninsulas where only these VPs can reach the target and the non-U.S.-VPs cannot, or vice versa. We begin by considering the 501 cases where Taitao reports that only U.S. VPs can see the target, and compare that to how Ark VPs respond.

We validate our observations against Ark, following subsection 4.1, except retaining blocks with less than 85% uptime.

We only consider Ark VPs that are able to reach the destination (that halt with “success”). We note blocks that can only be reached by Ark VPs within the same country as domestic, and blocks that can be reached from VPs located in other countries as foreign.

In Table 3 we show the number of blocks that uniquely responded to all U.S. VP combinations during the quarter. We contrast these results against Ark reachability.

We first examine true positives, when Taitao shows a peninsula responsive only to U.S. VPs and nearly all Ark VPs confirm this result. We see 211 targets are U.S.-only, and another 171 are available to only a few non-U.S. countries. The specific combinations vary: sometimes allowing access from the U.K., or Mexico and Canada. Together these make 382 true positives, most of the 501 cases.

In yellow italics we show 47 cases of false positives where more than five non-U.S. countries are allowed access. In many cases these include many European countries.

In light green we show true negatives. Here we include blocks that filter one or more U.S. VPs, and are reachable from Ark VPs in multiple countries, amounting to a total of 69 blocks. There are other categories involving non-U.S. sites, along with other millions of true negatives, however, we only concentrate in these few.

In red and bold we show three false negatives. These three blocks seem to have strict filtering policies, as they were reached only by W and not C or E in the 21 days period.

### 4.3 Can Chiloe Detect Islands?

Chiloe (subsection 3.4) detects islands when a VP within the island can reach less than half the rest of the world. When less than 50% of the network replies, it means that the VP is either in an island (for brief events, or when replies drop near zero) or a peninsula (long-lived partial replies).
To validate Chiloe’s correctness, we compare when a single VP believes to be in an island, against what the rest of the world believes about that VP.

We establish ground truth at a block level granularity—if VP x can reach its own block when x believes to be in an island, while other external VPs can’t reach x’s block, then x’s island is confirmed. On the other hand, if an external VP can reach x’s block, then x is not in island, but in a peninsula. In subsection 6.2 we show that Trinocular VPs are independent, and therefore no two VPs live within the same island.

We take 3 years worth of data from each of the six Trinocular VPs. Since Trinocular measures block asynchronously every 11 minutes, we use 11 minute timebins as our snapshot of the Internet. We ignore cases where the VP can access 95% or more of the Internet.

In Table 5 we show that Chiloe detects 23 islands across three years. In 2 of these events, the block is unreachable from other VPs, confirming the island with our ground-truth methodology. Manual inspection confirms that the remaining 19 events are islands too, but at the address level—the VP was unable to reach anything but did not lose power, and other addresses in its block were reachable from VPs at other locations. Finally, for 2 events, the prober’s block was reachable during the event by every site including the prober itself which suggests partial connectivity (a peninsula), and therefore a false positive.

The 566 non-island events (true negatives) are when more than 5% but less than 50% of the Internet was inaccessible from a single VP. In each of these cases, one or more other VPs were able to reach the affected VP’s block, showing they were not an island (although perhaps a peninsula). We omit the very frequent events when less than 5% of the network is unavailable from the VP from the table, although they too are true negatives.

Bold red shows 8 false negatives. These are events that last about 2 Trinocular rounds or less (22 min), often not enough time for Trinocular to change its belief on block state.

<table>
<thead>
<tr>
<th>Country Specific</th>
<th>Ark</th>
<th>Country Pen</th>
<th>Non Country Pen</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>382</td>
<td>47</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>98</td>
</tr>
</tbody>
</table>

Table 4: Country specific peninsula detection confusion matrix. Dataset A30, 2017q4.

<table>
<thead>
<tr>
<th>Trinocular</th>
<th>Island</th>
<th>Add Island</th>
<th>Peninsula</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2</td>
<td>19</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>8</td>
<td>566</td>
</tr>
</tbody>
</table>

Table 5: Chiloe confusion matrix, events between 2017-01-04 and 2020-03-31. Datasets A28 through A39.

<table>
<thead>
<tr>
<th>Target Prefix</th>
<th>Sites Up</th>
<th>Target AS At Before</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>21,765</td>
<td>32,489</td>
</tr>
<tr>
<td>1</td>
<td>587</td>
<td>1,197</td>
</tr>
<tr>
<td>2</td>
<td>2,981</td>
<td>4,199</td>
</tr>
<tr>
<td>3</td>
<td>12,709</td>
<td>11,802</td>
</tr>
<tr>
<td>4</td>
<td>117,377</td>
<td>62,881</td>
</tr>
<tr>
<td>5</td>
<td>101,516</td>
<td>53,649</td>
</tr>
<tr>
<td>6</td>
<td>235,170</td>
<td>133,728</td>
</tr>
<tr>
<td>7</td>
<td>61,392</td>
<td>6,864</td>
</tr>
<tr>
<td>8</td>
<td>31,211</td>
<td>2,981</td>
</tr>
<tr>
<td>9</td>
<td>2,981</td>
<td>101,516</td>
</tr>
<tr>
<td>10</td>
<td>149,047</td>
<td>113</td>
</tr>
<tr>
<td>11</td>
<td>127,867</td>
<td>31,211</td>
</tr>
<tr>
<td>12</td>
<td>307,506</td>
<td>1,197</td>
</tr>
<tr>
<td>13</td>
<td>119,778</td>
<td>117,377</td>
</tr>
<tr>
<td>14</td>
<td>52,479</td>
<td>587</td>
</tr>
<tr>
<td>15</td>
<td>117,377</td>
<td>127,867</td>
</tr>
<tr>
<td>16</td>
<td>307,506</td>
<td>31,211</td>
</tr>
<tr>
<td>17</td>
<td>119,778</td>
<td>113</td>
</tr>
<tr>
<td>18</td>
<td>52,479</td>
<td>31,211</td>
</tr>
<tr>
<td>19</td>
<td>117,377</td>
<td>113</td>
</tr>
<tr>
<td>20</td>
<td>307,506</td>
<td>113</td>
</tr>
<tr>
<td>21</td>
<td>119,778</td>
<td>113</td>
</tr>
<tr>
<td>22</td>
<td>52,479</td>
<td>31,211</td>
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<tr>
<td>23</td>
<td>117,377</td>
<td>113</td>
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<tr>
<td>24</td>
<td>307,506</td>
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<td>25</td>
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</tr>
<tr>
<td>26</td>
<td>52,479</td>
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<td>27</td>
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<tr>
<td>29</td>
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<td>113</td>
</tr>
<tr>
<td>30</td>
<td>52,479</td>
<td>31,211</td>
</tr>
</tbody>
</table>

Table 6: Halt location of failed traceroutes for peninsulas longer than 5 hours. Dataset A41, 2020q3.

5 QUANTIFYING ISLANDS AND PENINSULAS

We next apply our approach to the Internet. For peninsulas: how often do they occur (subsection 5.1), how long do they last (subsection 5.2), and how big are they (subsection 5.3)? These evaluations characterize how effective systems using overlay routing [1, 38] are. We also look at peninsula location by ISP (subsection 5.4) and country (subsection 5.5). Finally, we look at island frequency (subsection 5.6) and the implications of country-level internet secession (subsection 5.7).

5.1 How Common are Peninsulas?

Our goal is to quantify how big the problem of peninsulas is. Outages have brought large attention by researchers both in Academia and Industry given the dire effects down time has over network services [59].

Our approach is to measure the duration of peninsulas across the Internet. We also vary the number of VP used to identify whether peninsula down time converges in a diminishing returns curve.

We consider three types of events: all up, all down, and disagreement. In the first two cases, all available VPs agree that the target block is either up or down. In the last case, VPs disagree on block state, that is, a peninsula.

We run Taitao over Trinocular data for 2017q4 [57] to determine duration in each state. Figure 5 shows the distribution of peninsulas measured as a fraction of block-time for an increasing number of sites. We consider all possible combinations of the six sites.

With more VPs we get a better view of the Internet’s overall state. As more reporting sites are added, more peninsulas are discovered. That is, previously block states erroneously inferred as all up or all down, are corrected to peninsulas. All-down (left) decreases from an average of 0.00082 with 2 VPs to 0.00074 for 6 VPs. All-up (right) goes down a relative decrease from 0.0029 to 0.00045. Outages (left) converge after 3 sites, as shown by the fitted curve and decreasing variance. Peninsulas and all-up converge more slowly.
5.2 How Long Do Peninsulas Last?
Peninsulas have multiple root causes: some are short-lived routing misconfigurations while others may be long-term disagreements in routing policy. In this section we determine the distribution of peninsulas in terms of their duration to determine the prevalence of persistent peninsulas. We will show that there are millions of brief peninsulas, likely to routing transients, but that 90% of peninsula-time is in long-lived events (5 h or more).

To characterize peninsula duration we use Taitao to detect peninsulas that occurred during 2017q4. For all peninsulas, we see 23.6M peninsulas affecting 3.8M unique blocks. If instead we look at long-lived peninsulas (at least 5 h), we see 4.5M peninsulas in 338k unique blocks. Figure 6a examines the duration of these peninsulas in three ways: the cumulative distribution of the number of peninsulas of each size for all events (left, solid, purple line), the cumulative distribution of the number of peninsulas of each size for VP down events longer than 5 hours (middle, solid green line), and the cumulative size of peninsulas for VP down events longer than 5 hours (right, dashed green line).

We see that there are many very brief peninsulas (purple line): about 33% last from 20 to 60 minutes (about 2 to 6 measurement rounds). Such events are not just one-off loss, since they last at least two observation periods. These results suggest that while the Internet is robust, there are many small connectivity glitches (7.8M events).

In addition, we see some events that are two rounds (20 minutes) or shorter. Such events could be BGP transients or failures due to random packet loss.

The number of day-long or multi-day peninsulas is small, only 1.7M events (7%, the purple line). However, about 90% of all peninsula-time is in such longer-lived events (the right, dashed line), and 50% of time is in events lasting 10 days or more, even when longer than 5 hours events are less numerous (compare the middle, green line to the left, purple line). Events lasting a day are long-enough that can be debugged by human network operators, and events lasting longer than a week are long-enough that they may represent policy disputes. Together, these long-lived events suggest that there is benefit to identifying non-transient peninsulas and addressing the underlying routing problem.

5.3 What Is the Size of Peninsulas?
When network issues cause connectivity problems like peninsulas, the size of those problems may vary, from country-size (see subsection 5.5), to AS-size, and also for routable prefixes or fractions of prefixes. We next examine peninsula sizes.

We begin with Taitao peninsula detection at a /24 block level. We match peninsulas across blocks within the same prefix by start time and duration, both measured in one hour timebins. This match implies that the Trinocular VPs observing the blocks as up are also the same.

We compare peninsulas to routable prefixes from Routeviews [43]. We perform longest prefix match between /24 blocks and prefixes.

Routable prefixes consist of many blocks, some of which may not be measurable. We therefore define the peninsula-prefix fraction for each routed prefix as fraction of blocks in the peninsula that are Trinocular-measurable blocks. To reduce noise provided by single block peninsulas, we only consider peninsulas covering 2 or more blocks in a prefix.

Figure 6b shows the number of peninsulas for different prefix lengths and the fraction of the prefix affected by the peninsula as a heat-map, where we group them into bins.

We see that about 10% of peninsulas are likely due to routing problems or policies, since 40k peninsulas affect the
whole routable prefix. However, a third of peninsulas (101k, at the bottom of the plot) affect only a very small fraction of the prefix. These low prefix-fraction peninsulas suggest that more than half of peninsulas happen inside an ISP and are not due to interdomain routing.

Finally, we show that longer-lived peninsulas are likely due to routing or policy choices. Figure 6c shows the same data source, but weighted by fraction of time each peninsula contributes to the total peninsula time during 2017q4. Here the larger fraction of weight are peninsulas covering full routable prefixes—20% of all peninsula time during the quarter (see left margin).

5.4 Where Do Peninsulas Occur?

Firewalls, link failures, and routing problems cause peninsulas on the Internet. These can either occur inside a given AS, or in upstream providers.

To detect where the Internet breaks into peninsulas, we look at traceroutes that failed to reach their target address, either due to a loop or an ICMP unreachable message. Then, we find where these traces halt, and take note whether halting occurs at the target AS and target prefix, or before the target AS and target prefix.

For our experiment we run Taitao to detect peninsulas at target blocks over Trinocular VPs, we use Ark’s traceroutes [11] to find last IP address before halt, and we get target and halting ASNs and prefixes using RouteViews.

In Table 6 we show how many traces halt at or before the target network. The center, gray rows show peninsulas (disagreement between VPs) with their total sum in bold. For all peninsulas (the bold row), more traceroutes halt at or inside the target AS (235k vs. 134k, the left columns), but they more often terminate before reaching the target prefix (308k vs. 61k, the right columns). This difference suggests policy is implemented at or inside ASes, but not at routable prefixes. By contrast, outages (agreement with 0 sites up) more often terminate before reaching the target AS. Because peninsulas are more often at or in an AS, while outages occur in many places, it suggests that peninsulas are policy choices.

5.5 Country-Level Peninsulas

Country-specific filtering is a routing policy made by networks to restrict traffic they receive. We next look into what type of organizations actively block overseas traffic. For example, good candidates to restrain who can reach them for security purposes are government related organizations. We test for country-specific filtering (subsection 3.3) over 2017q4 and find 429 unique U.S.-only blocks in 95 distinct ASes. We then manually verify each AS categorized by industry in Table 7. It is surprising how many universities filter by country. While not common, country specific blocks do occur.

5.6 How Common Are Islands?

Multiple groups have shown that there are many network outages in the Internet [31, 47, 49, 52, 53]. We have described (section 2) two kinds of outages: full outages where all computers at a site are down (perhaps due loss of power), and islands, where the site is cut off from the Internet but computers at the site can talk between themselves. We next use Chiloe to determine how often islands occur. Chiloe provides a very limited viewpoint—we can only confirm islands that are around one of the six VPs, but examination of three years of data allows us to confirm islands.

Figure 7 shows the fraction of the Internet that is reachable from 6 VPs for each 11 minutes, over three years, from 2017-04-01 to 2020-04-01, with a dotted line at the 50% threshold that Chiloe uses to detect an island (subsection 3.4). We run Chiloe across each VP for this period.

Table 9 shows the number of islands per VP over this period. Over the 3 years, all six VPs see from 1 to 5 islands. In addition, we see that islands do not always cause the
entire Internet to be unreachable, and there are a number of cases where from 20% to 50% of the Internet is inaccessible. We believe these cases represent brief islands, since islands shorter than an 11 minute complete scan will only be partially observed. We find 12 in the 20% to 50% range, all are short, and 4 are less than 11 minutes.

We conclude that islands do happen, but they are rare, and at irregular times. This finding is consistent with importance of the Internet at the locations where we run VPs.

5.7 Can the Internet Partition?

In subsection 3.5 we discussed threats to secede from the Internet, and suggested that connection to more than half the addresses defines “the Internet” in the face of partition. Most threats to secede have been by countries or groups of countries. If a country were to exert control over their allocated addresses would result in a country level island or peninsulas. We next use our reachability definition of more than 50% to reason about control of the IP address space.

We therefore next look at address allocation by country to see if any country or group has enough addresses to secede and claim to be “the Internet” with a majority of addresses.

To evaluate the power of any country or RIR to control the Internet, Table 8 shows how many IPv4 hosts and IPv6 /32s are allocated to each Regional Internet Registry (RIR) [35, 36]. In IPv4, some address ranges have special purposes and therefore not allocatable: like Multicast, Class E blocks reserved for future use. Additionally, IANA reserves 0/8, 10/8, and 127/8 for local network usage.

We see that no individual RIR or country can secede and take “the Internet”, because none controls the majority of IPv4 addresses. ARIN has the largest amount with 1673M allocated, that is, 45.2%. Inside ARIN, the United States has the majority of hosts (1617M).

This claim also applies to IPv6, where no RIR or country surpasses a 50% allocation. RIPE (an RIR) is close with 46.7%, and China and the U.S. have high country allocations. With most of IPv6 unallocated, these fractions may change.

We conclude that no individual country can declare itself “the Internet” without reallocating addresses or colluding with other countries. Suggesting, that the Internet today is an international creation.
6 OUTAGES REVISITED

6.1 Observed Outage and External Data

To evaluate outage classification with conflicting information, we consider Trinocular reports and compare to external information in traceroutes from CAIDA Ark.

Figure 8 compares Trinocular with 21 days of Ark topology data, from 2017-10-10 to -31 from all 3 probing teams. For each Trinocular outage we classify the Ark result as success or three types of failure: unreachable, loop, or gap.

Trinocular’s 6-site-up case suggests a working network, and we consider this case as typical. However, we see that about 25% of Ark traceroutes are “gap”, where several hops fail to reply. We also see about 2% of traceroutes are unreachable (after we discard traceroutes to never reachable addresses). Ark probes a random address in each block; many addresses are non-responsive, explaining these.

With 1 to 5 sites up, Trinocular is reporting disagreement. We see that the number of Ark success cases (the green, with each other, they are dissimilar. We quantify similarity with the majority, the pair shows similarity. If they disagree with the convergence we see in Figure 5.

Trinocular VPs. (We show only half of the symmetric matrix.)

As Table 10(a) shows similarity values for each pair of the 6 Trinocular VPs. (We show only half of the symmetric matrix.) No two sites have a similarity more than 0.14, and most pairs are under 0.08. This result shows that no two sites are particularly correlated.

7 RELATED WORK

A number of works have previously tried to define the Internet [12, 26, 27, 46]. As discussed in subsection 2.1, they distinguish the Internet from other networks of their time, but do not address today’s network disputes and secession threats.

Previous work has looked into the problem of partial outages. RON provides alternate-path routing around failures for a mesh of sites [1]. LIFEGUARD, proposes a route failure remediation system by generating BGP messages to reroute traffic through a working path [38]. While both solve the problem of partial outages, neither quantifies the amount, duration, or scope of partial outages.

Internet scanners have examined bias by location [33], more recently looking for policy-based filtering [58]. We measure policies with our country specific algorithm, and we extend those ideas to defining the Internet.

Outage detection systems have encountered partial outages. Thunderping recognizes the “hosed” state of partial replies as something that occurs, but leaves its study to future work [52]. Trinocular discards partial outages by reporting the target block “up” if any VP can reach it [47]. To the best of our knowledge, prior outage detection systems have not both explained and reported partial outages as part of the Internet, nor studied their extent.

We use the idea of majority to define the Internet in the face of secession. That idea is fundamental in many algorithms for distributed consensus [41, 42, 44], with applications for example to certificate authorities [8].

8 CONCLUSIONS

This paper provided a new definition of the Internet to reason about partial connectivity and secession. We developed the algorithm Taitao, to find peninsulas of partial connectivity, and Chiloe, to find islands. We showed that partial connectivity events are more common than simple outages, and used these definitions to clarify outages and the Internet.

ACKNOWLEDGMENTS

The authors would like to thank John Wroclawski for his input on an early version of the paper.
### Table 8: RIR IPv4 hosts and IPv6 /32 allocation [35, 36]

<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>3.3%</td>
</tr>
<tr>
<td>APNIC</td>
<td>892M</td>
<td>24.0%</td>
</tr>
<tr>
<td>China</td>
<td>345M</td>
<td>9.3%</td>
</tr>
<tr>
<td>ARIN</td>
<td>1673M</td>
<td>45.2%</td>
</tr>
<tr>
<td>U.S.</td>
<td>1617M</td>
<td>43.7%</td>
</tr>
<tr>
<td>LACNIC</td>
<td>191M</td>
<td>5.2%</td>
</tr>
<tr>
<td>RIPE NCC</td>
<td>826M</td>
<td>22.3%</td>
</tr>
<tr>
<td>Germany</td>
<td>124M</td>
<td>3.3%</td>
</tr>
</tbody>
</table>

Allocated: 221 100% 318,626 100%

### Table 9: Islands detected from 2017-04-01 to 2020-04-01

<table>
<thead>
<tr>
<th>Sites Events /Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>W 5 1.67</td>
</tr>
<tr>
<td>C 2 0.67</td>
</tr>
<tr>
<td>J 1 0.33</td>
</tr>
<tr>
<td>G 1 0.33</td>
</tr>
<tr>
<td>E 3 1.00</td>
</tr>
<tr>
<td>N 2 0.67</td>
</tr>
</tbody>
</table>

All 14 4.67

### Table 10: Similarities between sites relative to all six. Dataset: A30, 2017q4.

<table>
<thead>
<tr>
<th>C</th>
<th>J</th>
<th>G</th>
<th>E</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>W</td>
<td>0.017</td>
<td>0.031</td>
<td>0.019</td>
<td>0.035</td>
</tr>
<tr>
<td>C</td>
<td>0.077</td>
<td>0.143</td>
<td>0.067</td>
<td>0.049</td>
</tr>
<tr>
<td>J</td>
<td>0.044</td>
<td>0.036</td>
<td>0.046</td>
<td></td>
</tr>
<tr>
<td>G</td>
<td>0.050</td>
<td>0.100</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>0.058</td>
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</table>

The work is supported in part by the National Science Foundation, CISE Directorate, award CNS-2007106 and NSF-2028279. The U.S. Government is authorized to reproduce and distribute reprints for Governmental purposes notwithstanding any copyright notation thereon.

**REFERENCES**


A VALIDATION OF THE POLISH PENINSULA

In subsubsection 2.3.3 we reported a peninsula covering 5 polish ASes that lasted for three hours. Figure 3 shows the AS level map and the relationship between ASes at the time of the peninsula. Multimedia Polska (AS21021) is the provider of the other 4 ISPs. Similarly, Multimedia Polska has two main providers, Cogent (AS174) and Tata (AS6453). Before the peninsula, we find that most traffic to Multimedia Polska from our probers is routed through Cogent.

Using Taitao we detect that the event starts on 2017-10-23t20:00Z. About the same time, we observe a high number (20,275) of BGP update messages announcing and withdrawing routes to the affected blocks (see Figure 9). These updates correspond to Tata announcing Multimedia Polska’s prefixes. Probably either due to Multimedia Polska changing its peering relationships, and making Tata more prominent over Cogent, or a failure in the Multimedia Polska - Cogent link.

Initially, traffic routed through Cogent is not successful at shifting to Tata, except Level3, which keeps Multimedia Polska reachable from prober W during the whole time. The event ends after 3 hours, where we see a peak of 23,487 BGP messages updating routes to the affected prefixes. (see Figure 9).

In Figure 10 we provide data from our 6 external VPs, where W is uniquely capable of reaching the target block, thus living in the same peninsula.

We further verify this event by looking at traceroutes. During the event we see 94 uniqueArk VPs attempted 345 traceroutes to the affected blocks. Of the 94 VPs, 21 VPs (22%) have their last responsive traceroute hop in the same AS as the target address, and 68 probes (73%) stopped before reaching that AS. Table 11 shows traceroute data from a single CAIDA Ark VP before and during the peninsula described in subsubsection 2.3.3 and Figure 4. This data confirms the block was reachable from some locations and not others. During the event, this trace breaks at the last hop within the source AS.

B VALIDATION OF THE SAMPLE ISLAND

In subsubsection 2.3.2 we reported an island affecting a /24 block where VP E lives. During the time of the event, E was able to successfully probe addresses within the same block, however, unable to reach external addresses. This event started at 2017-06-03t23:06Z, and can be observed in Figure 7.

Furthermore, no other VP was able to reach the affected block for the time of the island as shown in Figure 11.
C ADDITIONAL RESULTS

We use Trinocular measurements for 2017q4 because this time period had six active VPs, allowing us to make strong statements about how multiple perspectives help.

In this section, we verify our results using additional datasets, and find quantitatively similar results.

C.1 Additional Confirmation of the Number of Peninsulas

Similarly, as in subsection 5.1, we quantify how big the problem of peninsulas is, this time using Trinocular 2018q4 data.

In Figure 12 we confirm, that with more VPs more peninsulas are discovered, providing a better view of the Internet’s overall state.

Outages (left) converge after 3 sites, as shown by the fitted curve and decreasing variance. Peninsulas and all-up converge more slowly.

At six VPs, here we find and even higher difference between all down and disagreements. Confirming that peninsulas are a more pervasive problem than outages.

C.2 Additional Confirmation of Peninsula Duration

In subsection 5.2 we characterize peninsula duration for 2017q4, to determine peninsula root causes. To confirm our results, we repeat the analysis, but with 2020q3 data.

As Figure 13a shows, similarly, as in our 2017q4 results, we see that there are many very brief peninsulas (from 20 to 60 minutes). These results suggest that while the Internet is robust, there are many small connectivity glitches.

Events shorter than two rounds (22 minutes), may represent BGP transients or failures due to random packet loss.

The number of multi-day peninsulas is small. However, these represent about 90% of all peninsula-time. Events lasting a day are long-enough that can be debugged by human network operators, and events lasting longer than a week are long-enough that they may represent policy disputes. Together, these long-lived events suggest that there is benefit to identifying non-transient peninsulas and addressing the underlying routing problem.

C.3 Additional Confirmation of Size

In subsection 5.3 we discussed the size of peninsulas measured as a fraction of the affected routable prefix. In the latter section, we use 2017q4 data. Here we use 2020q3 to confirm our results.

Figure 13b shows the peninsulas per prefix fraction, and Figure 13c. Similarly, we find that while small prefix fraction peninsulas are more in numbers, most of the peninsula time is spent in peninsulas covering the whole prefix. This result is consistent with long lived peninsulas being caused by policy choices.
Figure 12: Distribution of block-time fraction over sites reporting all down (left), disagreement (center), and all up (right), for events longer than five hour. Dataset A34, 2018q4.

Figure 13: Peninsulas measured with per-site down events longer than 5 hours during 2020q3. Dataset A41.