



When Consolidation is Not a Choice

Rashna Kumar

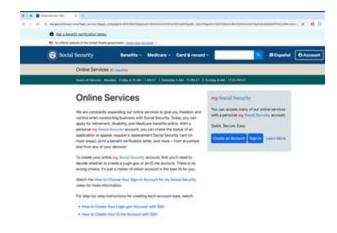
Research Fellow, Internet Society . PhD Candidate, Northwestern University

Mentors: Marinho Barcellos, Amreesh Phokeer, Fabián E. Bustamante





Websites Depend on Multiple Services



- Domain Name System (DNS)
 - Translate domain names to IP addresses



- Hosting
 - Serve content

 Often from CDN servers for faster, reliable access



HTTPS? Certificate Authority (CA)





Verify validity of SSL certificates to secure websites

These Services are Consolidating...



A few companies now operate much of the web's foundational infrastructure

Consolidation is a Problem for Resilience

Amazon reveals cause of AWS outage

that took everything from banks to smart beds offline

AWS explains in a lengthy post how a bug in automation software brought down thousands of sites and applications



Ca Signat, Snapchar, Robbox, Duolingo and Ring deorfields were some of the 2,000 comparation of the seed's AWS outage, according to Downdetector, Photograph: Anushree Fadnavis/Reuters

Cloudflare's CTO apologizes after error takes huge chunk of the internet offline — 'we failed our customers and the broader internet'

News By Luke James published November 18, 2025

CTO blames bot mitigation bug triggered by routine config change.





Druge credit: Getty / Smith Collection/Gadol

Cloudflare has confirmed that a bug in one of its core services caused a major outage on Tuesday, taking large portions of the internet offline and affecting traffic to services including X, CharGPT, and, Ironically, Downdetector, The company's CTO, Dane Knecht, posted a public apology shortly after services were restored, calling the incident "unacceptable" and attributing the disruption to a routine configuration change that triggered a crash in its bot mitigation layer.

Microsoft Azure Outage (Oct 29 2025): Root Cause, Impact and Technical Analysis



A deep technical breakdown of the Microsoft Azure outage on Oct 29 2025.

Learn how an Azure Front Door configuration change disrupted global services including Microsoft 365, Xbox Live and airline systems plus insights on root cause, mitigation and lessons for teams.



Prior Work on Consolidating Internet

Analyzing Third Party Service Dependencies in Modern Web Services: Have We Learned from the Mirai-Dyn Incident?

alcohalistanbox one ofer vindamijtandove opravda Many websites only on Ward parties for writing in p. 1965, CDW. in a., More Other intack (54) or consisting believe in a., Gelselligo constitut cone Titl's interrupted by each incolorie, we analyse the providence and impact of third mate dependencies. Forusing on these policial influencement species (ISO, 1706) and contilled processing checking by CA. We washed both direct in a. Twillian are Elect and malarest in g., Northis uses fermanter as C.A. which son Petrogo for 1965 deprechation. We also take two stupolate to blint and 1600 to and returned how the dependencies resired Our key Biologicare (E) 89% of the Alexa tige 186K websites cettable depend on third-party 2900, CDN, or CA providen i.e., of these provides go dove, these websites sould rather worker disruption of the san of third party services a consentrated, and the repprovides of CEW, SMS, or CA services can after tim fire of the op 1996 extentes, It's indirect dependencies amplify the impact of propositor CDW and 1980 providens by up to 208, and 10 ann that pure Assessment and concernment to make a particular Survivors, 2014 to 2020. Named on one Endings, we desire key ample

Agea Kashaf

Carnegie Mirlion Distrereity

United Soldier Yerni Apeval Campgie Mellos Viscoentis Cannigle Mellon University

the Mine Date attack Stiff, Globalities introduction stone tockfoot in 2004 [16] and the Amuson SNO SColl attack to 2017 [16] affected a significant master of popular web services. These tecritoris care benefits assessment that the street of the authorization

yestelejen.com.nlu

- . An three singular recomments or an diese other types of their parts services that are also potential Achilles' back for affecting papalier with services? For example, as services and industrials is there a single promiter whose fallow will have a significant these set and other property property of the second
- a for fees hidden requires or malmor describes in homes exhalts and their third parts provides concerning concerns tion and the extent of third party dependencing e.g., feeding academia esta terralma a flund purity CDM Rour(DM, which to ture-depends on 1945 THO · E. and how, this websites alope, after the Den incolour? (his they
- relace their critical dependency on third party services? Did they become reductionly providently using prolingle third party We address those countries by ourseless out a measurement study using Alice's Ing. 1996, scholar [47]. No Suize on Hore sofration. hard services that next newbore websites critically rely on when

Hosting Industry Centralization and Consolidation

Laciane Zenbrucki", Raffiele Sommere", Lisandro Zanbrucketi Grancile", Arthur Selle Jacoby', Mattis Joskey', Govane C. M. Moure

Santow of Information (INF) Pederal University of Rin Grande do Sul (CPROS) Ports Airpre Bracel (Intelligable, sujacobs, gramille) Wird align by (Intercence, m.) relief) that weeks all

Design and Atalysis of Communication Systems (DACE) -University of Twenty Enrichedy. The Nytherlands

SIDN Labo Andrea, The Ninherlands giovate savora@sida.al

water and contradization of internet infrastructure, for this work, the DNS traffic towards the country-code Top-Level Donains or acraffalor the busting industry on the laterary he using arrive nests, covering 19 Top-Lorel Dunates (TLDs). We show have the market is bearily reterratested. 1/3 of the domains are hasted by only 8 hasting providers, all US-based companion. For the country-code PLDs to CRLSts, becomes, busing in primarile. Allous (195) studied pulsorisative DNS (205 survive influstrustime by local, national busing providers and and by the large transcrimentant. Controllation cut also be assembled to baseling chief and compat proothers. We show how should languages tand burders; shape the booting market - Gorman ling companies have a notable presume in Assirian and Swiss markets, given they all shore German as official tangenge. While Sorting concentration has been relatively high and stable over highlight different expects of locerant controllation. The part floor react, we see that Associate healthy companies. In control with the electronic and officer, in a related to high traffer, popular domains within or TLDs -- recept

Attenues. There have been growing concerns about the concern to spores controllication (e.g., Minute et al. [7] found that 1/7 of (scTLDs) of the Notherlands and New Zealand originated from 5 large. American companion) or quantited controlication in terms of infrarranter concentration (Kadul et al. (8) and some of any how or morest share. Facebook for example has 2.98 monthly active more that NOT (211); In present, all their consolidation assessments completeness one another and

In contrast with the absormancement offerts, in this work we focus on analyzing consolidation in the Web Assimp industry (22), which is a market organist dedicated to hosting websites and services that use HTTPS (23) as application

Each at its Own Pace: Third-Party Dependency and Centralization Around the World

RASHNA KUMAR, Northwestern University, USA SANA ASIF, Northwestern University, USA ELISE LEE, Northwestern University, USA.

FABIÁN E. BUSTAMANTE, Northwestern University, USA

We describe the results of a large scale study of third-party dependencies around the world based on regional top-500 popular websites accessed from vantage points in 50 countries, together covering all inhabited continents. This broad perspective shows that dependencies on a third-party DNS, CDN or CA provider vary widely around the world, ranging from 19% to as much as 36% of websites, across all countries. The critical dependencies of websites - where the site depends on a single third-party provider - are equally spread ranging from VS to 60% ICDN in Costs Rica and DNS in China, respectively). Interestingly, despite this high variability, our results suggest a highly concentrated market of third-party providers: three providers across all countries serve an average of 92% and Google, by itself, serves an average of 20% of the nurveyed websites Even more concerning, these differences persist a year later with increasing dependencies, particularly for DNS and CDNs. We briefly explore various factors that may help explain the differences and similarities in degrees of third-party dependency across countries, including economic conditions, Internet development, economic trading partners, categories, home countries, and traffic skewness of the country's top-501 sites. CCS Concepts - Natyorks -- Location based services Network measurement Public Internet

Of Choices and Control - A Comparative Analysis of Government

Radina Kamar	Embas Carisino	Lakes De Angelis Res
nahnakana (Krajin auritmenten ole	anthe consequent source ofe	Managelogië ste ei
Naritmenne Fanoriti)	Nortecone Conseque	Camunalel & Banco An
Krasma, R., USA	France, S, UAA	Bunco Ann, regentes
Mauricio Bussone	Publish E. Bustamante	Bream Approb Quali
advancespituleuse	Stransporter Services	Bream garrightens order pla
Enterended de Busson Assa	Surfacestes Conventy	(1974)
Busson Asson, Augustina	Stransport, E., USA	Labores, Palamon
	Mantane G. Brieff	

CCS Concepts

Formalizing Dependence of Web Infrastructure

Kimberly Ruth Stanford Claimmen Studied Chiversity Studied CA USA Stundard, CA, CSA

ABSTRACT

Over the past decade, become controllectors and its implications the privacy, resilience, and inservation have become a topic of artise Attack. While the parteciping community informally agrees on the definition of controllustres, we link a fireful metric for quantifying it, which has limited in depth analysis. In this work, we introduce a represent their street is a between the between the anticulations, to diving the we also assured how regionalisations geopolitical dependence on the lateract the land control of the control output. We argue that controllection and regionalization are interested forms of depris Since that both affect the Soul reportunion of sacre and should be printly studied. We develop a naite of statistical book, which we use to farter understand dependence across flow layers of web infrastructure - boring providers, DNS infrastructure, cartificate authorities in 100 countries. We look that this partitional toolking can serve up that Englishmen for Sature applicate of Internet before the **Gastam Akiwate** Stanford University Stanford University Stanford CA 15th Stanford CA 175A

native and have warned that contradication can lead bearington. rest respettion, and pose privary resource [34, 43, 52]. Pennits increased attention to the tonic our community below Egonom metrics to recurrent and mesons about controllecture. Prior work conceptually agrees that controllutions is the the concess of an increase function on a small marrier of previation (18, 56, 43, 46 15. TLI but, without a motive the directly measuring concentration investigations have received to reporting invariants like the pre-cratings of piece booked by the top ten providers and amplicating the market place of well-known beyone given. While these stud have conquestionably shed light on interest behavior, the last of a Discourse marrier markes if conferences to common controllection arreses constition, indicating/time lacress, and pursue in time. Distring descriptive resources also extra distributional transces. For distance sating the held drain of websites limited by the top providers show not account the the distribution among these providers, which can shanatically affect resiliency and erivary

Clouding up the Internet: how centralized is DNS traffic becoming?

Greene C. M. Moora co. Sebastion Costeo co. Was Harbidge of Maarten Walledon - Cristian Streetman p. o. 6 SENS Labor 25 Sension DEC 6 CROSS 6 STationary of Toronto

the live last power is consolidated of traffic basic indicate prices ann the books of a fire resolved physics. We necessar 2000 and computing controllution by studying 2000 reading collected at a THE cost we've and two counts only top tool domains to fill to one in Europe and the office in Counts — and place or detect of complements. Heavy there that of all provide to both or Talls, as artifices I large stend permittee. We compare the about incoder solvaniracinam and highlight a Macropium; in Solvanium same climal provides fewerly stepling Prin, (1993)07, and (190) over TVT, while others among the same server little areas LDF areas Bred. We about a security feature - such as QNAVE assessment - 4 specific breadly a large reactor of succe

at in Automorphisms

rate Sealow (60 Finding of the bound has perceived in the safe because in a females because he blade of the Atle Street Steel, Std. Atle, Nov. Sell. 65, 550, 5 page Table to Closed commet previous and their Africa

Among the large active possible, he are a handful of companion becausing the third companing industry, effecting on debated services such an insinger and then processing. Given their market Decision is the paper or arrest per for the works dressure al first large chinal reserve promition (Table 1) manufairs (see, 1946 right Essinates. We analyse the three begans alread provider Personal Desgle, and Municelli and Cleraffler (given three care hope public OHI service (12). For competines, we also said the Roper-giant Facebook, for longe the largest crotal extensions of State are other-land permitter, we became the calculations from the

The research community has been tracking this growing consolidation for years yet it keeps accelerating

Governments are Increasingly Relying on E-Services



Importance of digital government:

- Federal websites in the US draw nearly two billion visits every month
- In the Asia-Pacific region, 77 percent of citizens primarily access government services through digital platforms

Prior Work Shows Governments are Shaped by Same Consolidation Trends

Hosting markets are already consolidated for government services:

- Cloudflare hosts e-services for 49 governments
- And serves up to 72% of all government web bytes for one country



But Do Governments Have a Choice? Are They Opting to Be Consolidated?

Constraint-Driven (Structural)



Choice-Driven (Strategic)



Potential reasons:

Few or no domestic infrastructure options

Potential reasons:

Perceived reliability, cost, procurement rules, vendor ties

Consequence:

Shared dependency across government and commercial web

Consequence:

Government chooses consolidation, where commercial web shows options

How We Determine Whether Consolidation Is a Choice

To distinguish what the environment forces from what governments choose

Block by country (structural baseline)

- Each country forms a block with shared infrastructure, regulation, market conditions
- This fixes the structural environment.

Within-block groups

- Treated: Government domains
- Reference: Commercial domains from the same country, stratified by popularity:
 - Top-1k: large/global actors
 - Mid-1k: mid-tier actors
 - Bottom-1k: small/local actors

Inference: Compare consolidation vs. decentralization across groups within a block

- Similar patterns → structural forces
- Divergent patterns → strategic choices by governments

Measurement Design: Collecting Data

Scope and Inputs

Countries: 61, spanning every continent (over 82% of the world's Internet population)

Domains Per Country:

- All Government sites
- 3K Commercial sites (CrUX)

Building Dataset

Government domains: Collected from official sources

Commercial Domains:

- Split CrUX domains per country into Top / Middle / Bottom stratas
- From each strata, collect 1K sites using systematic step sampling (uniform +popularity-aware coverage)

Service Extraction

Connect to country-local VPN and collect for each landing page:

- All resources and their hosting orgs
- Authoritative DNS nameservers
- Certificate Authorities from TLS handshake

Measurement Design: Analyzing Data

Provider Concentration (HHI)

For each strata:

- Resample domains with replacement (same sample size)
- Repeat 5,000 bootstrap iterations

For each country × service × strata:

Obtain distribution of HHI values

Compare Consolidation within blocks

For each bootstrap iteration, compute ΔHHI

ΔHHI = HHI_{commercial} – HHI {government}

Produce bootstrap distribution of Δ HHI per (country × service × strata)

Check statistical significance of ΔHHI (p-values)

Compare Patterns across blocks

Structural Consolidation: ΔHHI not significant (and Government provider diversity resembles commercial sites)

Strategic Consolidation: ΔHHI significant (Clear separation between government and commercial sites)

Government Consolidation Across Services

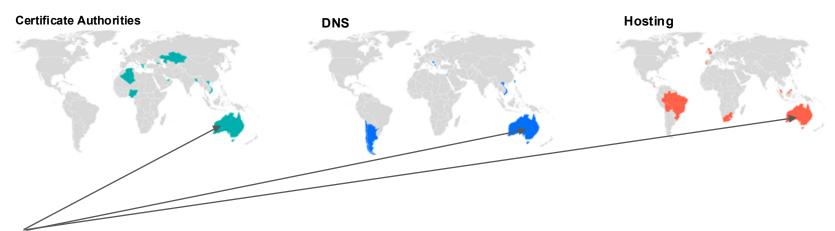
These maps show how consolidated government web infrastructure is across services. Colors reflect HHI thresholds commonly used in antitrust



Governments worldwide are highly consolidated on Certificate Authorities Hosting is overall more moderate, with a fewer cases of high consolidation

Structural Government Consolidation Across Services

These countries show similar moderate-to-high consolidation across government and commercial strata



Australia's consolidation patterns reflect structural forces rather than strategic choices

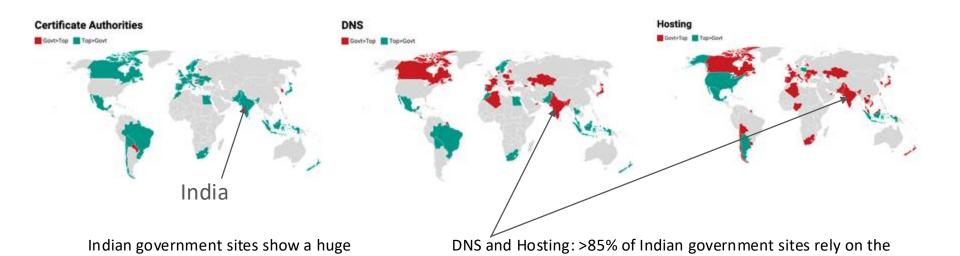
- Government and commercial sites rely on a similar set of certified providers across all services
- Australian government follows a Cloud First strategy and a multi-vendor model, avoiding reliance on a single national provider

Strategic Government Consolidation Across Services

reliance on a domestic CA eMudhra,

reducing reliance on global CAs

These maps show where government consolidation departs from commercial patterns



National Informatics Centre (NIC)

Strategic Government Consolidation Across Services

These maps show where government consolidation departs from commercial patterns

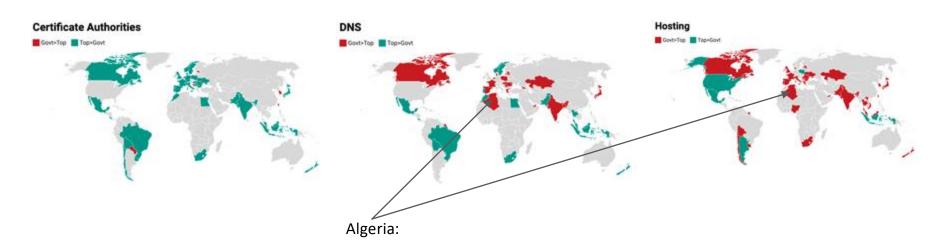


DNS: Dominated by Hoster.kz and state-linked providers

Hosting: Strong reliance on Kazakhtelecom and domestic infrastructure

Strategic Government Consolidation Across Services

These maps show where government consolidation departs from commercial patterns



DNS: All Government sites rely on Cloudflare DNS

Hosting: Government sites highly consolidated under Telecom Algeria (>80%)

Our Framework Reveals

When constraints drive outcomes and when choices create threats to resilience



Our framework separates what governments *must* do from what they *choose* to do

Building a More Resilient Internet



Support where consolidation is structural

Invest to build local DNS, hosting and CA capacity



Intervene where consolidation is strategic

Policy nudges can reduce unnecessary dependency



Can help strengthen Internet Resilience

By local infrastructure development and policy engagement

Ongoing Work

- Clustering countries by regulatory and market characteristics
- Assessing implications of strategic consolidation for resilience and sovereignty
- Analyzing on-path dependencies

More insights to come as we deepen the analysis!

Thank you!

Happy to get in touch for any questions:

rashnakumar 2024@u.northwestern.edu

https://sites.northwestern.edu/rashnakumar/