Observing the Global IPv4 Internet: What IP Addresses Show

John Heidemann[1]

[1]U. of Southern California / Information Sciences Institute and CS Dept.
and [2]Swathmore and [3]The College of New Jersey

joint work with Guillermo Baltra[1], Asma Enayet[1], Yuri Pradkin[1], Xiao Song[1], Erica Stutz[2,1]

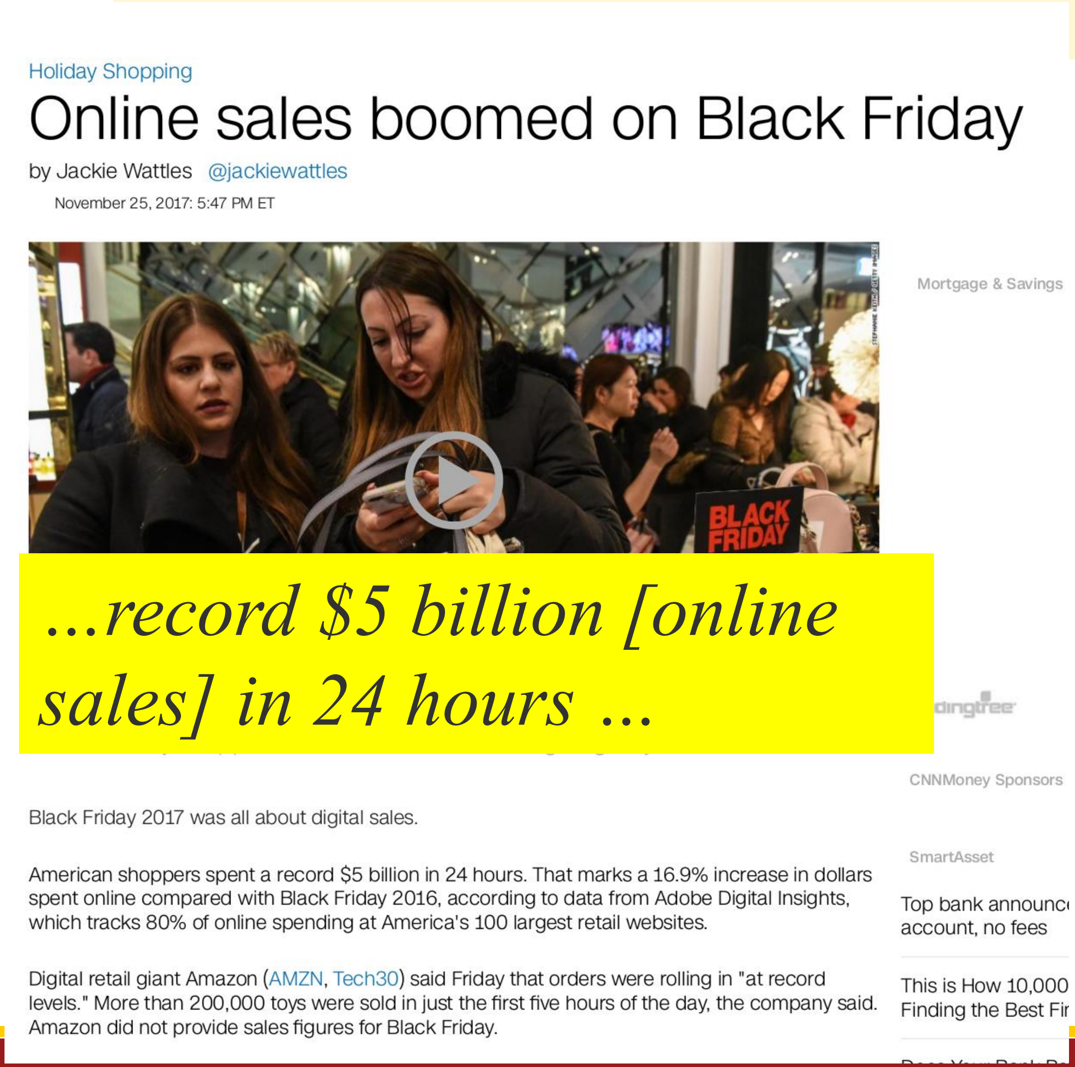
prior contributors: Abdulla Alwabel[1], Ryan Bogutz[3,1], Aqib Nisar[1], Lin Quan[1]

2021-07-20

This research is sponsored by NSF -2028279 (MINCEQ), CNS-2007106 (EIEIO), and NSF-1659886 (ISI REU). Prior work was supported by NSF and DHS HSAPRRPA Cyber Security Division. The views herein are those of the authors and do not necessarily represent those of DHS or the U.S. Gov't.

The Internet is Important…

The Internet is Important…



Holiday Shopping

Online sales boomed on Black Friday

by Jackie Wattles @jackiewattles

November 25, 2017: 5:47 PM ET

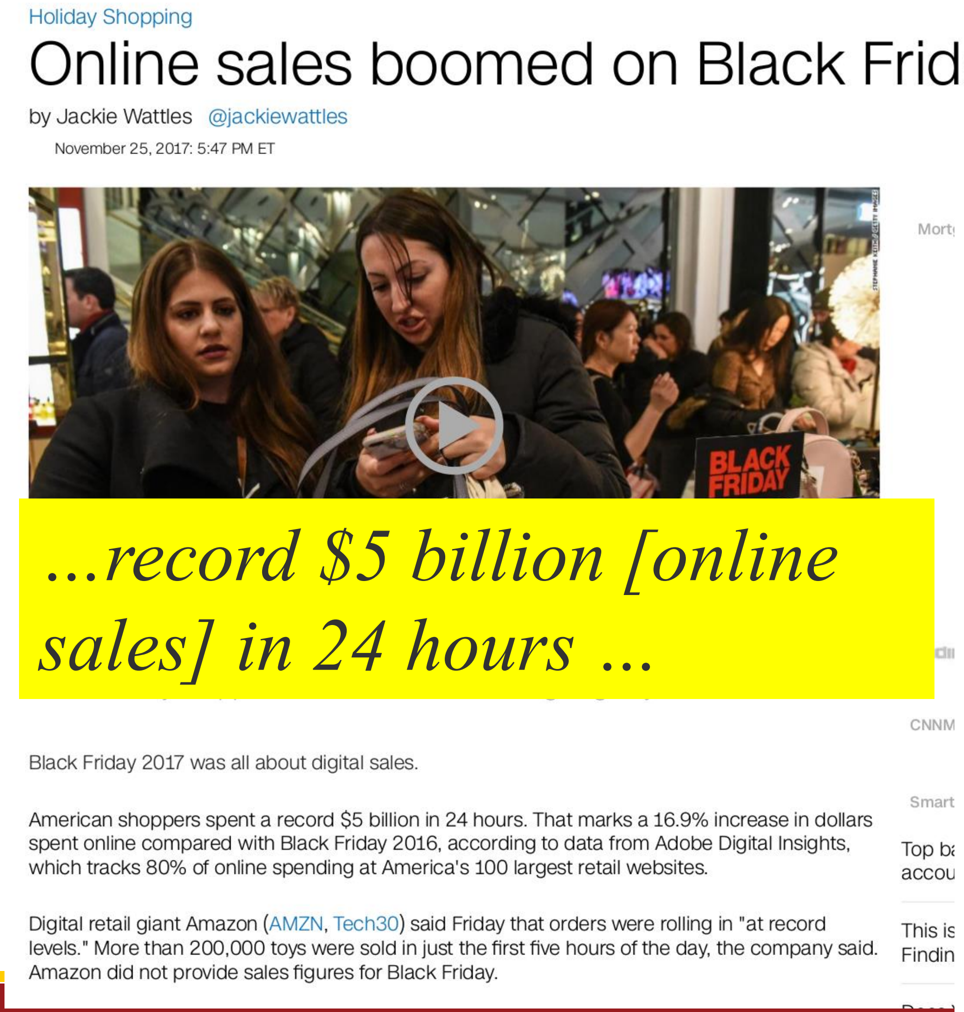
…record $5 billion [online sales] in 24 hours …

Black Friday 2017 was all about digital sales.

American shoppers spent a record $5 billion in 24 hours. That marks a 16.9% increase in dollars spent online compared with Black Friday 2016, according to data from Adobe Digital Insights, which tracks 80% of online spending at America's 100 largest retail websites.

Digital retail giant Amazon (AMZN, Tech30) said Friday that orders were rolling in "at record levels." More than 200,000 toys were sold in just the first five hours of the day, the company said. Amazon did not provide sales figures for Black Friday.

The Internet is Important…



Holiday Shopping

Online sales boomed on Black Friday

by Jackie Wattles @jackiewattles

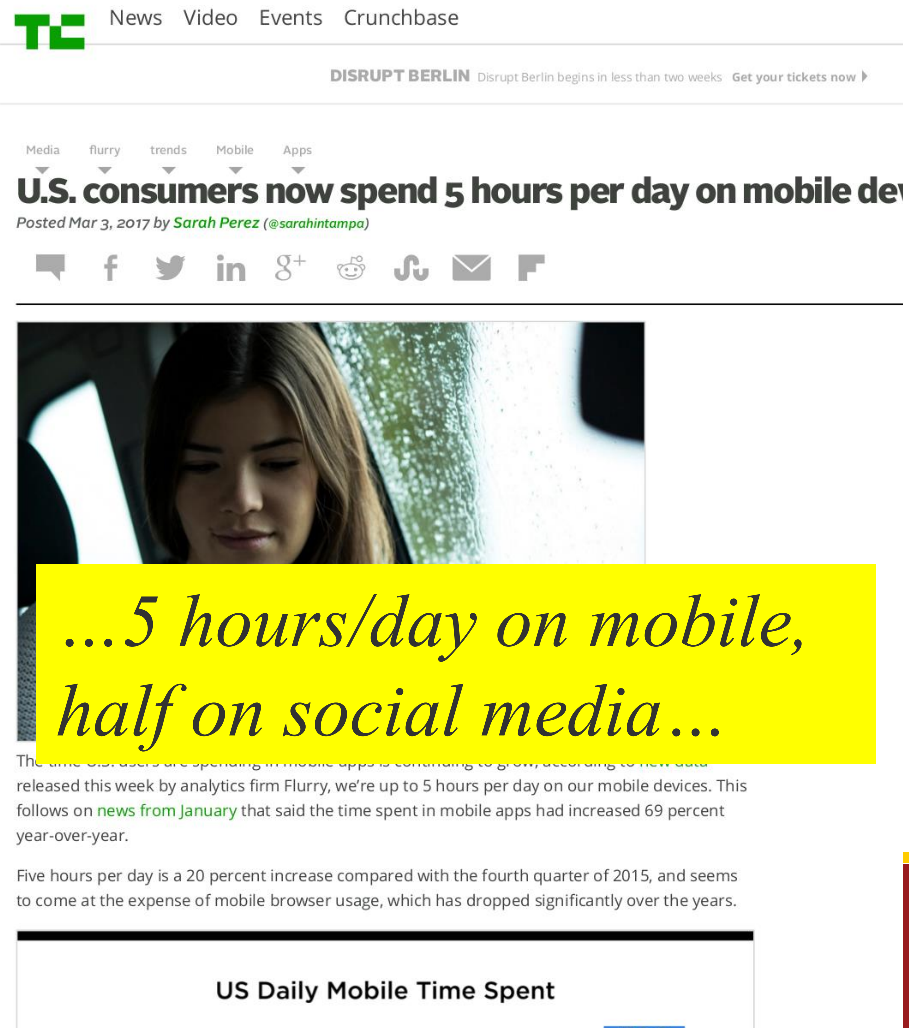
November 25, 2017: 5:47 PM ET

Black Friday 2017 was all about digital sales.

American shoppers spent a record $5 billion in 24 hours. That marks a 16.9% increase in dollars spent online compared with Black Friday 2016, according to data from Adobe Digital Insights, which tracks 80% of online spending at America's 100 largest retail websites.

Digital retail giant Amazon (AMZN, Tech30) said Friday that orders were rolling in "at record levels." More than 200,000 toys were sold in just the first five hours of the day, the company said. Amazon did not provide sales figures for Black Friday.

…record $5 billion [online sales] in 24 hours …



News Video Events Crunchbase
DISRUPT BERLIN Disrupt Berlin begins in less than two weeks Get your tickets now
Media flurry trends Mobile Apps

U.S. consumers now spend 5 hours per day on mobile dev

Posted Mar 3, 2017 by Sarah Perez (@sarahintampa)

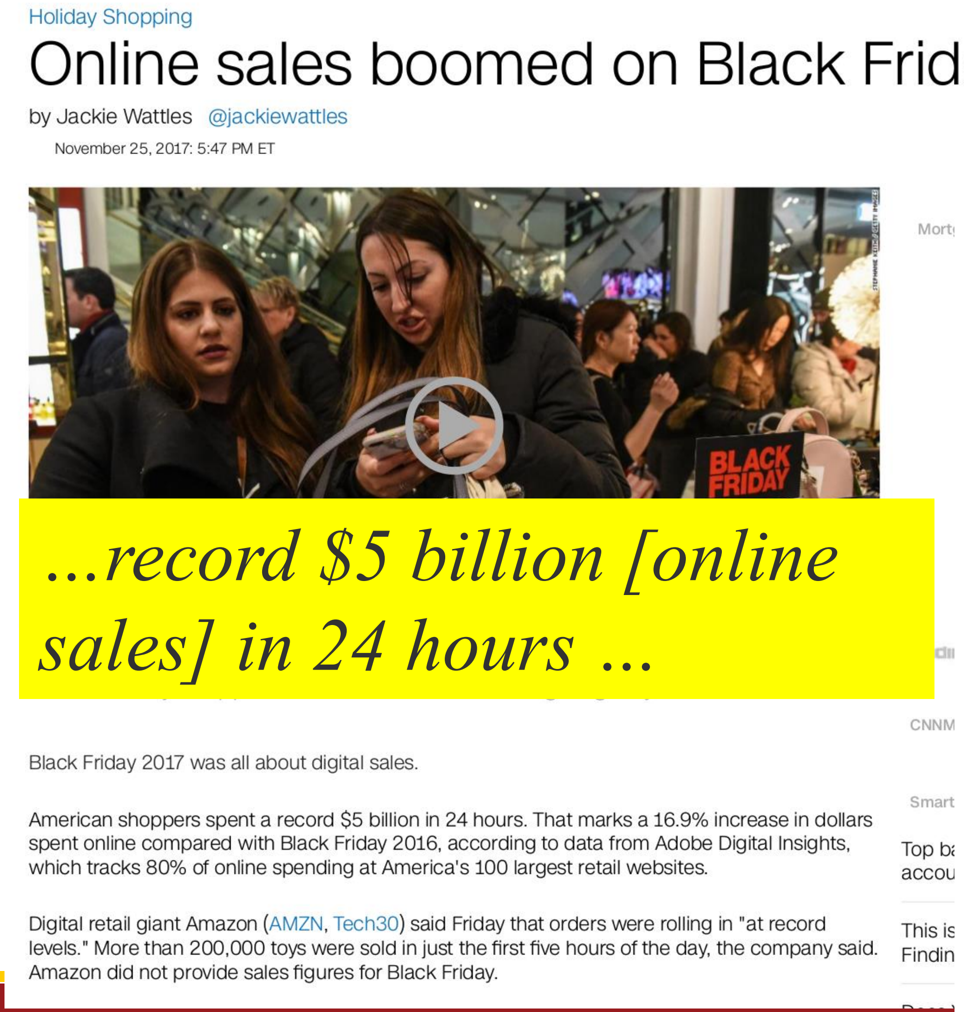
The time U.S. users are spending in mobile apps is continuing to grow, according to new data released this week by analytics firm Flurry, we're up to 5 hours per day on our mobile devices. This follows on news from January that said the time spent in mobile apps had increased 69 percent year-over-year.

Five hours per day is a 20 percent increase compared with the fourth quarter of 2015, and seems to come at the expense of mobile browser usage, which has dropped significantly over the years.

US Daily Mobile Time Spent

…5 hours/day on mobile, half on social media…

The Internet is Important…



Holiday Shopping

Online sales boomed on Black Friday

by Jackie Wattles @jackiewattles

November 25, 2017: 5:47 PM ET

Mort

CNNM

Smart

Top ba
accou

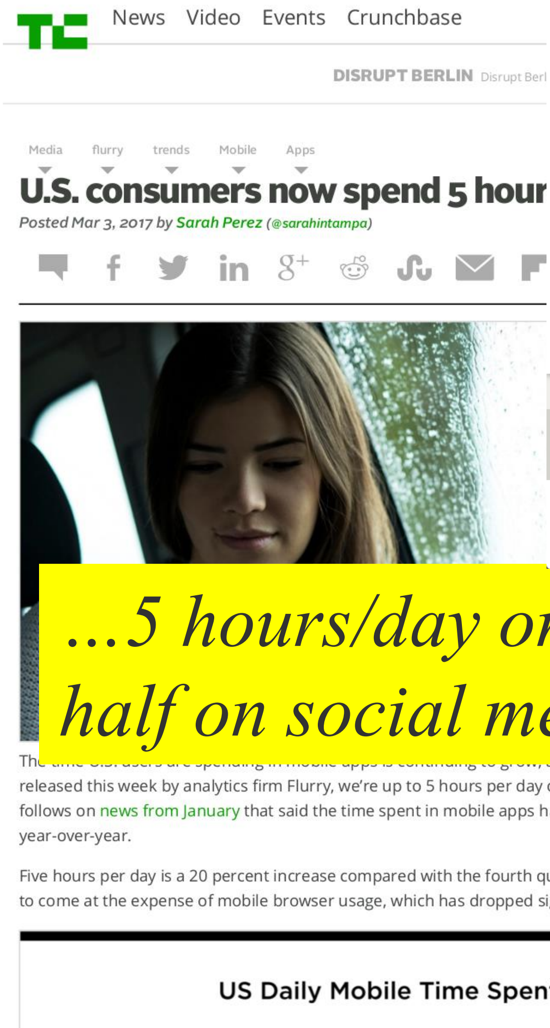
This is
Findin

Black Friday 2017 was all about digital sales.

American shoppers spent a record $5 billion in 24 hours. That marks a 16.9% increase in dollars spent online compared with Black Friday 2016, according to data from Adobe Digital Insights, which tracks 80% of online spending at America's 100 largest retail websites.

Digital retail giant Amazon (AMZN, Tech30) said Friday that orders were rolling in "at record levels." More than 200,000 toys were sold in just the first five hours of the day, the company said. Amazon did not provide sales figures for Black Friday.

…record $5 billion [online sales] in 24 hours …



TC
News Video Events Crunchbase
DISRUPT BERLIN Disrupt Berl
Media flurry trends Mobile Apps

U.S. consumers now spend 5 hour

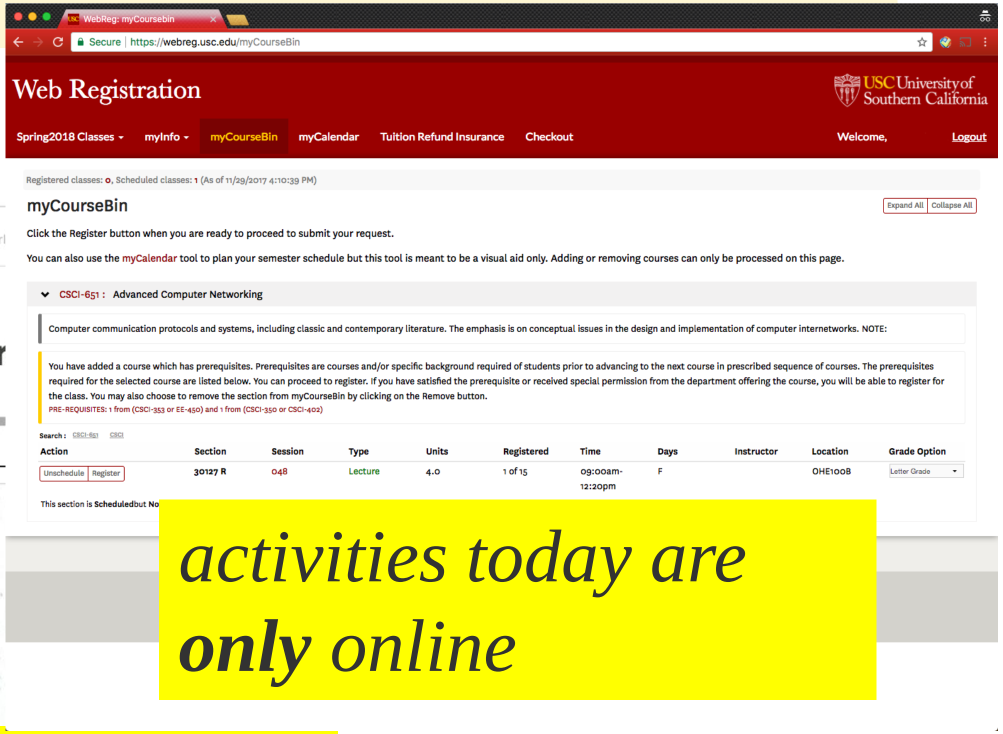
Posted Mar 3, 2017 by Sarah Perez (@sarahintampa)

The time U.S. users are spending in mobile apps is continuing to grow, according to new data released this week by analytics firm Flurry, we're up to 5 hours per day on our mobile devices. This follows on news from January that said the time spent in mobile apps had increased 69 percent year-over-year.

Five hours per day is a 20 percent increase compared with the fourth quarter of 2015, and seems to come at the expense of mobile browser usage, which has dropped significantly over the years.

US Daily Mobile Time Spent

…5 hours/day on mobile, half on social media…



Registered classes: 0, Scheduled classes: 1 (As of 11/29/2017 4:10:39 PM)

myCourseBin

Click the Register button when you are ready to proceed to submit your request.

You can also use the myCalendar tool to plan your semester schedule but this tool is meant to be a visual aid only. Adding or removing courses can only be processed on this page.

CSCI-651 : Advanced Computer Networking

Computer communication protocols and systems, including classic and contemporary literature. The emphasis is on conceptual issues in the design and implementation of computer internetworks. NOTE:

You have added a course which has prerequisites. Prerequisites are courses and/or specific background required of students prior to advancing to the next course in prescribed sequence of courses. The prerequisites required for the selected course are listed below. You can proceed to register. If you have satisfied the prerequisite or received special permission from the department offering the course, you will be able to register for the class. You may also choose to remove the section from myCourseBin by clicking on the Remove button.

PRE-REQUISITES: 1 from (CSCI-353 or EE-450) and 1 from (CSCI-350 or CSCI-402)

Search : CSCI-651 CSCI

Action	Section	Session	Type	Units	Registered	Time	Days	Instructor	Location	Grade Option
Unschedule Register	30127 R	048	Lecture	4.0	1 of 15	09:00am-12:20pm	F		OHE100B	Letter Grade

This section is Scheduledbut No

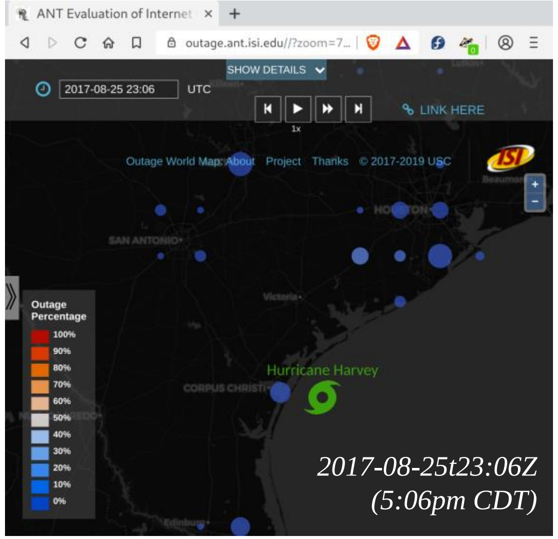
activities today are ***only*** *online*

The *World* Is Important

hurricanes, floods, fires, blizzards…

Hurricane Harvey,
August 2017

before landfall:
few outages



2017-08-25t23:06Z
(5:06pm CDT)

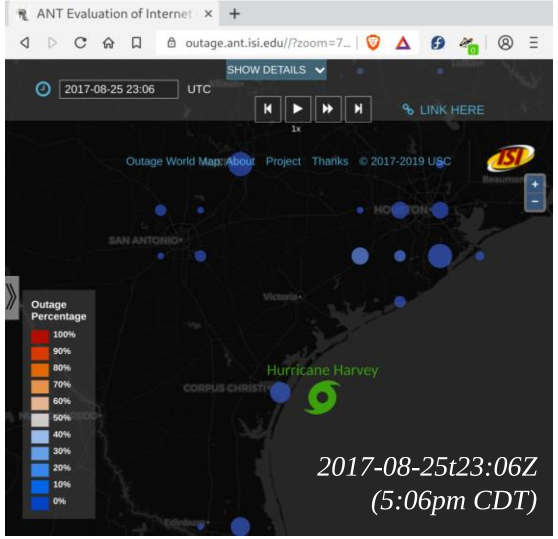
animation: (play)
https://ant.isi.edu/outage/ani/harvey/

The *World* Is Important

hurricanes, floods, fires, blizzards…

Hurricane Harvey,
August 2017

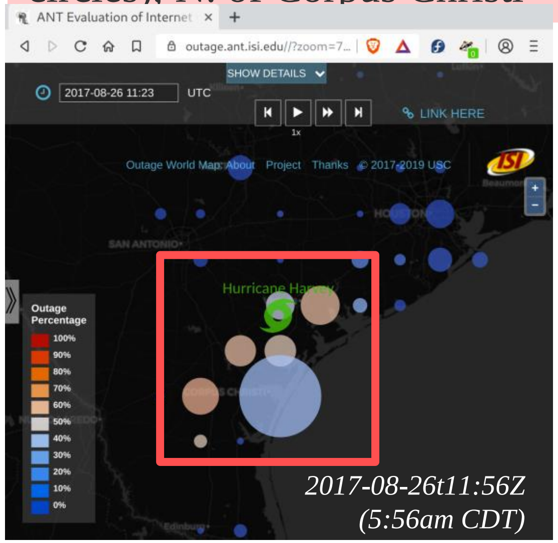
before landfall:
few outages



2017-08-25t23:06Z
(5:06pm CDT)

Harvey Landfall: 2017-08-26t03:00Z (10pm CDT)

serious outages (red circles), N. of Corpus Christi



2017-08-26t11:56Z
(5:56am CDT)

animation: (play)
https://ant.isi.edu/outage/ani/harvey/

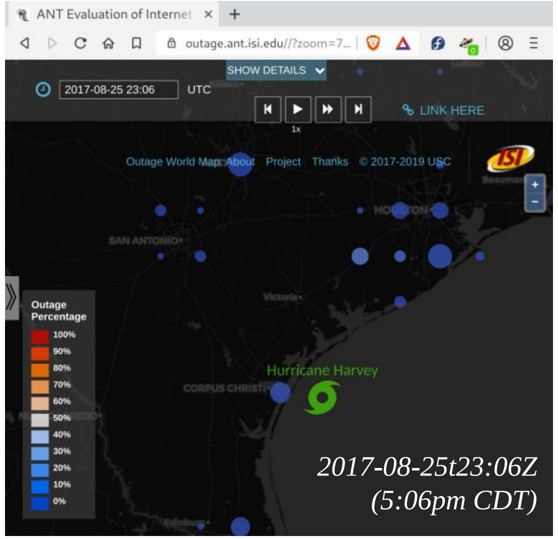
The *World* Is Important

hurricanes, floods, fires, blizzards…

Hurricane Harvey,
August 2017

animation: (play)
https://ant.isi.edu/outage/ani/harvey/

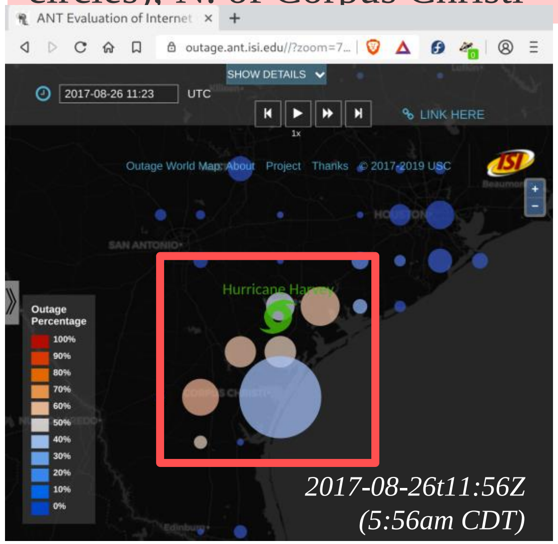
before landfall:
few outages



2017-08-25t23:06Z
(5:06pm CDT)

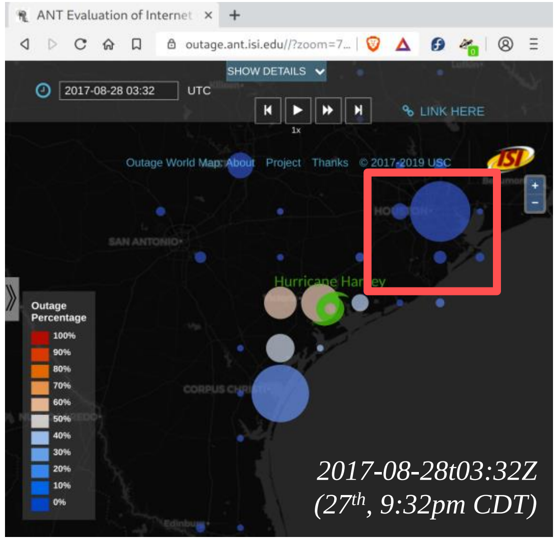
Harvey Landfall: 2017-08-26t03:00Z (10pm CDT)

serious outages (red circles), N. of Corpus Christi



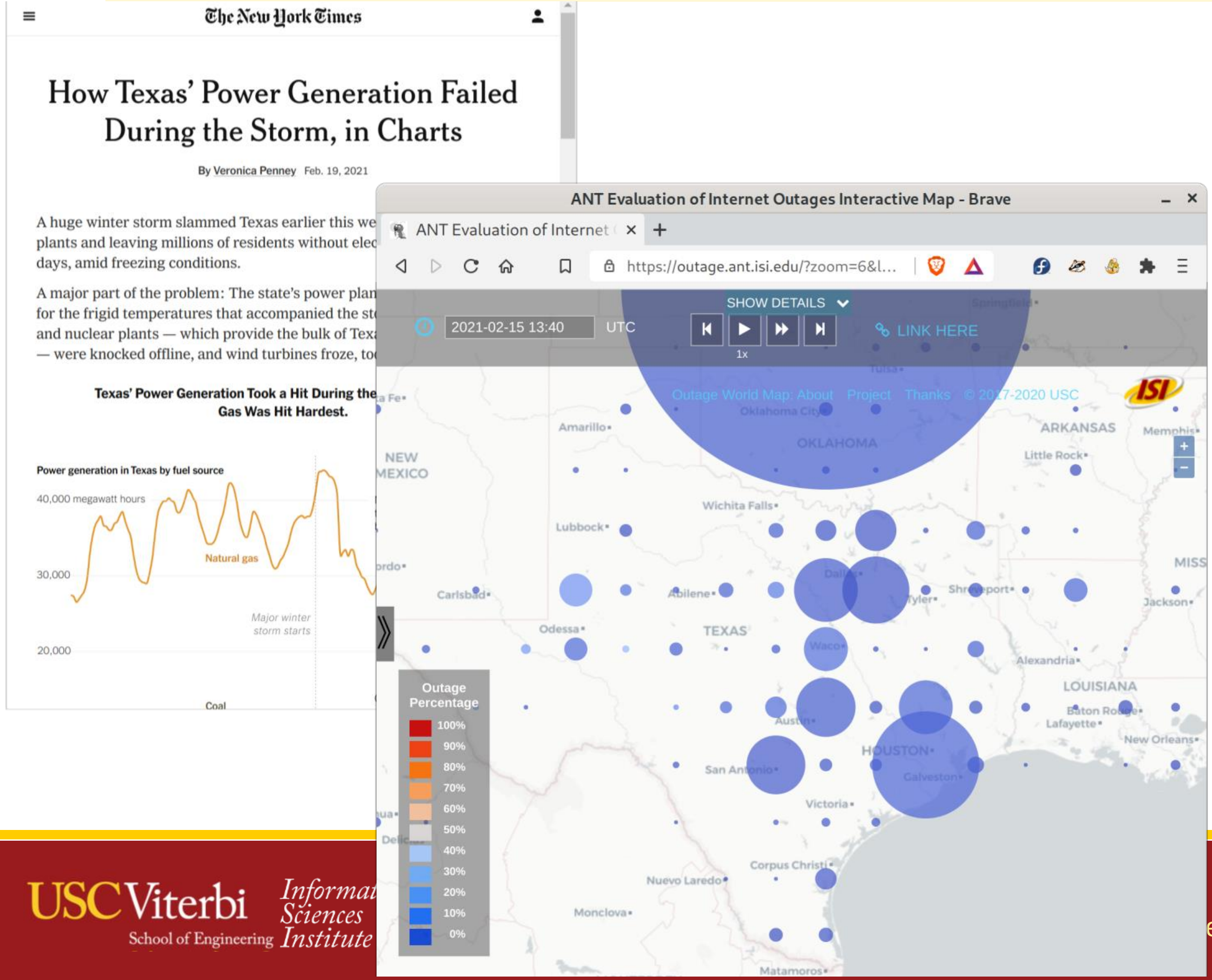
2017-08-26t11:56Z
(5:56am CDT)

many outages (large circles), in Houston-flooding



2017-08-28t03:32Z
(27th, 9:32pm CDT)

Events are Changing the World



The New York Times

How Texas' Power Generation Failed During the Storm, in Charts

By Veronica Penney Feb. 19, 2021

A huge winter storm slammed Texas earlier this we
plants and leaving millions of residents without elec
days, amid freezing conditions.

A major part of the problem: The state's power plan
for the frigid temperatures that accompanied the st
and nuclear plants — which provide the bulk of Tex
— were knocked offline, and wind turbines froze, to

Texas' Power Generation Took a Hit During the
Gas Was Hit Hardest.

Power generation in Texas by fuel source
40,000 megawatt hours
30,000
20,000
Natural gas
Major winter storm starts
Coal

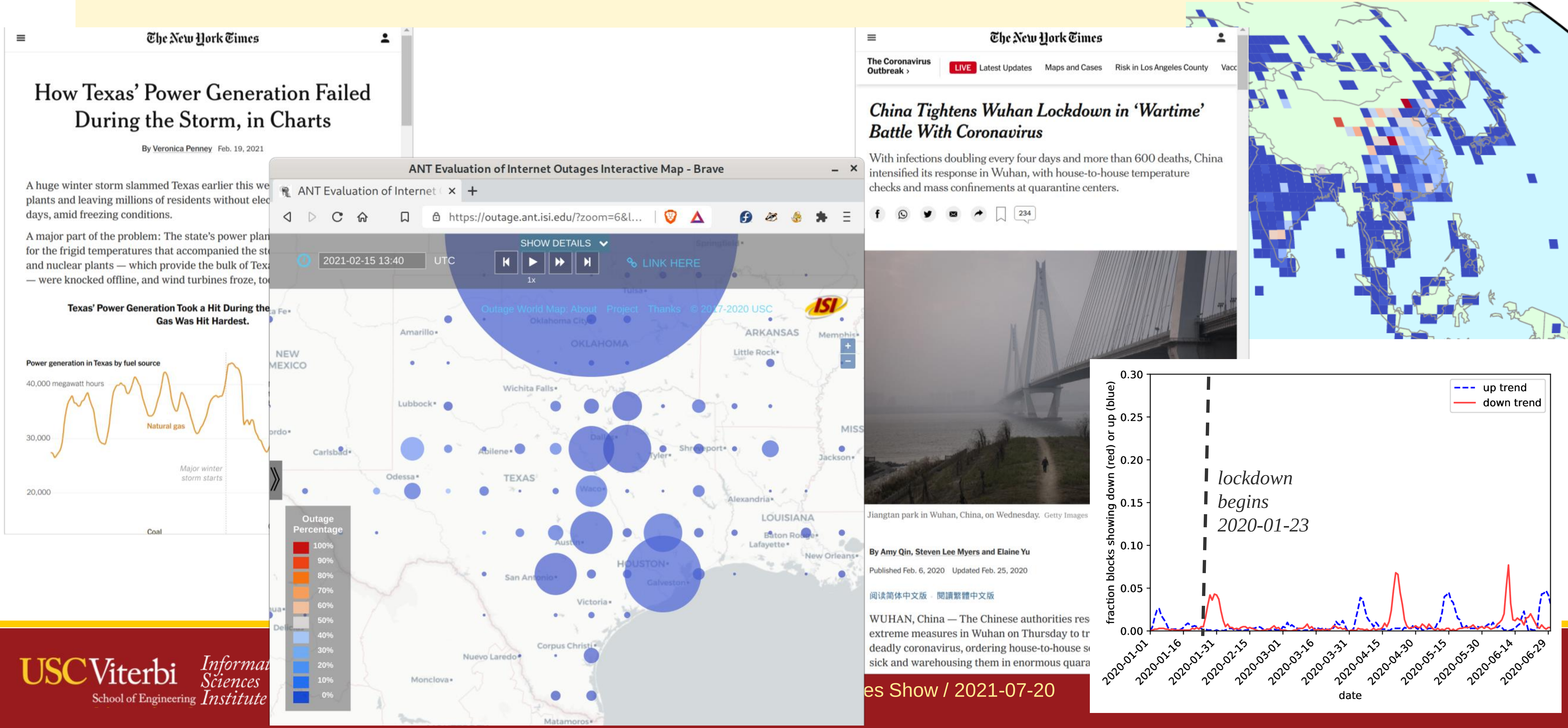
ANT Evaluation of Internet Outages Interactive Map - Brave

ANT Evaluation of Internet

https://outage.ant.isi.edu/?zoom=6&l...

2021-02-15 13:40 UTC

Events are Changing the World



The New York Times

How Texas' Power Generation Failed During the Storm, in Charts

By Veronica Penney Feb. 19, 2021

A huge winter storm slammed Texas earlier this we plants and leaving millions of residents without elec days, amid freezing conditions.

A major part of the problem: The state's power plan for the frigid temperatures that accompanied the st and nuclear plants — which provide the bulk of Texa — were knocked offline, and wind turbines froze, to

Texas' Power Generation Took a Hit During the Gas Was Hit Hardest.

Power generation in Texas by fuel source
40,000 megawatt hours
30,000
20,000
Natural gas
Major winter storm starts
Coal

ANT Evaluation of Internet Outages Interactive Map - Brave

The New York Times

The Coronavirus Outbreak › LIVE Latest Updates Maps and Cases Risk in Los Angeles County Vacc

China Tightens Wuhan Lockdown in 'Wartime' Battle With Coronavirus

With infections doubling every four days and more than 600 deaths, China intensified its response in Wuhan, with house-to-house temperature checks and mass confinements at quarantine centers.

Jiangtan park in Wuhan, China, on Wednesday. Getty Images

By Amy Qin, Steven Lee Myers and Elaine Yu

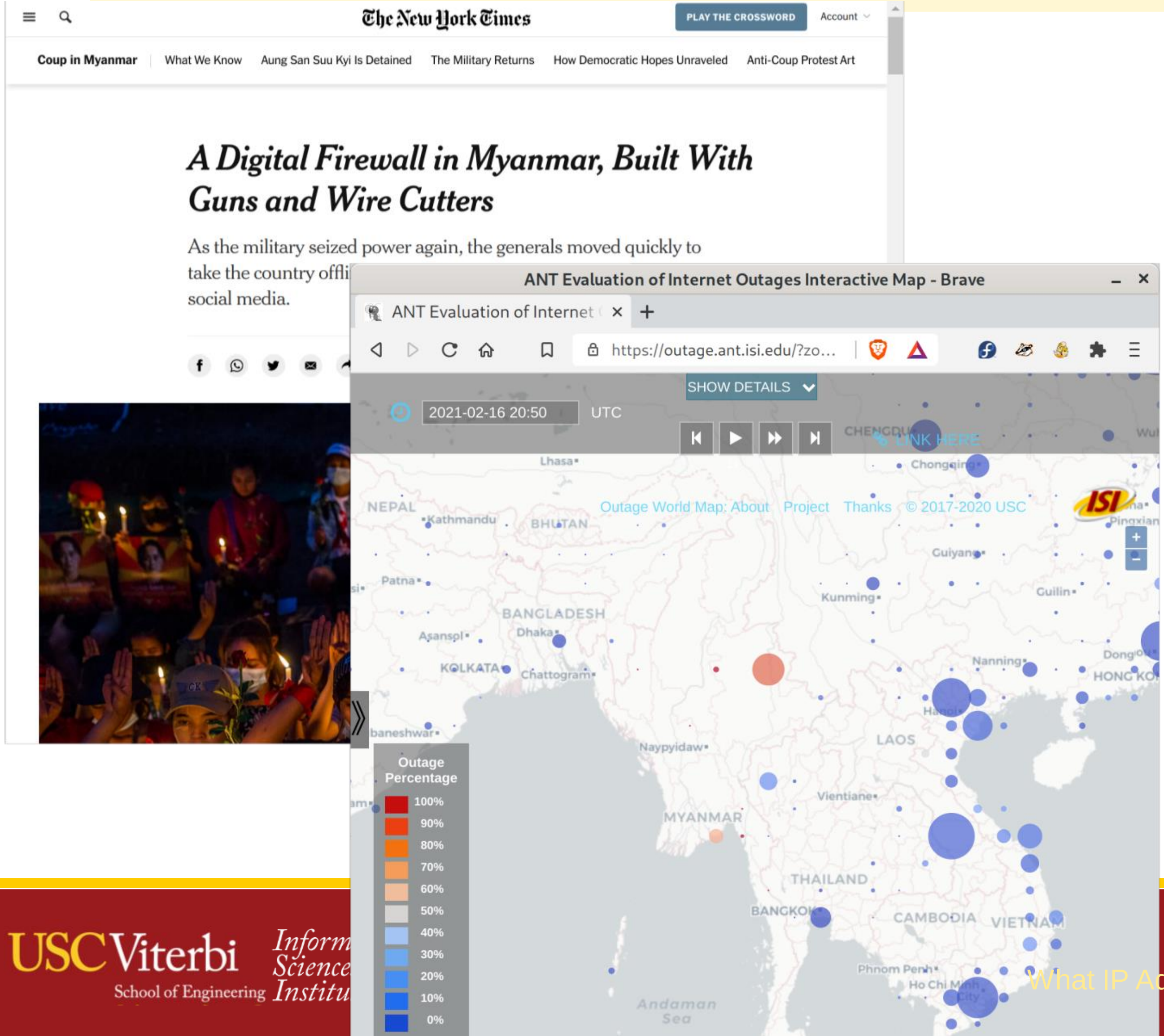
Published Feb. 6, 2020 Updated Feb. 25, 2020

阅读简体中文版 閱讀繁體中文版

WUHAN, China — The Chinese authorities res extreme measures in Wuhan on Thursday to tr deadly coronavirus, ordering house-to-house s sick and warehousing them in enormous quara

Countries Are Changing the World

Countries Are Changing the World



The New York Times

PLAY THE CROSSWORD

Account

Coup in Myanmar | What We Know | Aung San Suu Kyi Is Detained | The Military Returns | How Democratic Hopes Unraveled | Anti-Coup Protest Art

A Digital Firewall in Myanmar, Built With Guns and Wire Cutters

As the military seized power again, the generals moved quickly to take the country offli
social media.

ANT Evaluation of Internet Outages Interactive Map - Brave

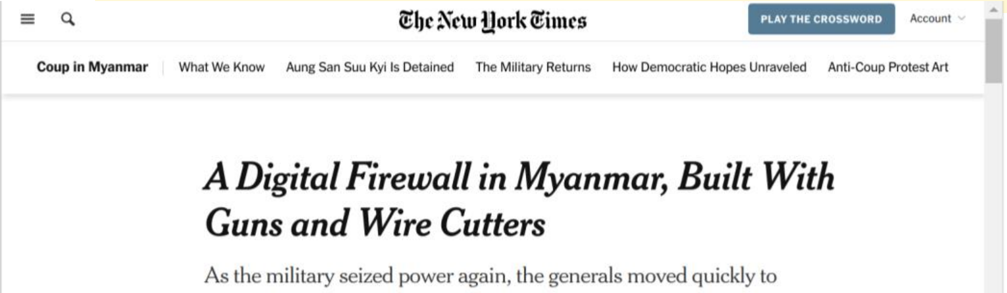
https://outage.ant.isi.edu/?zo…

SHOW DETAILS

2021-02-16 20:50 UTC

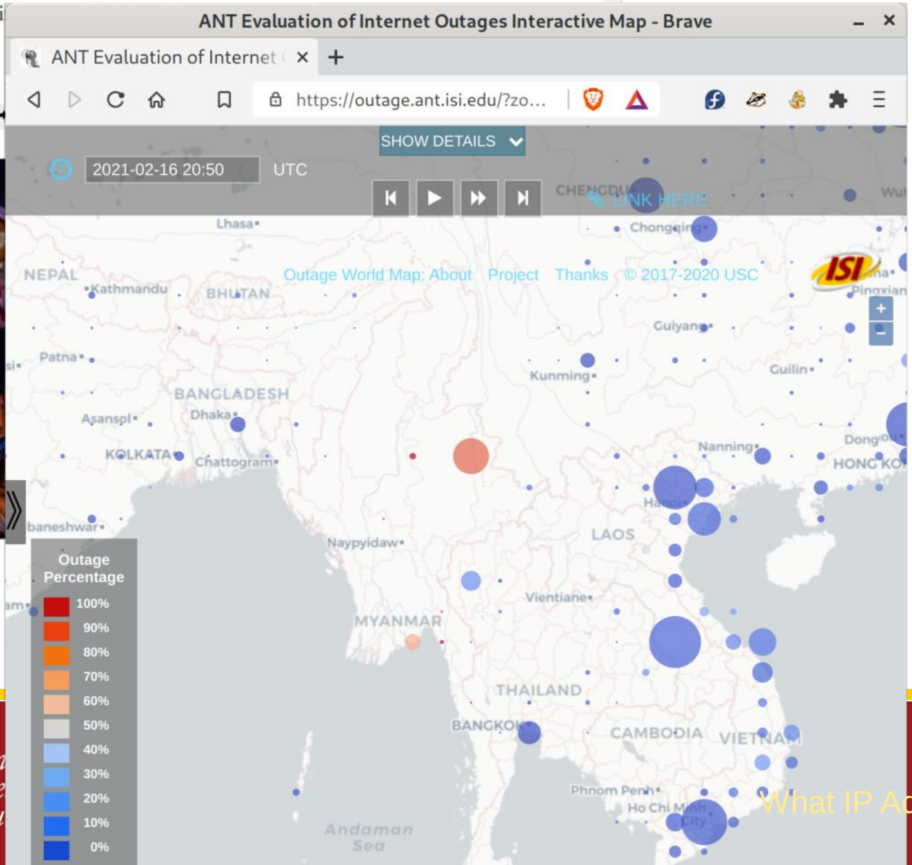
Outage World Map: About Project Thanks © 2017-2020 USC

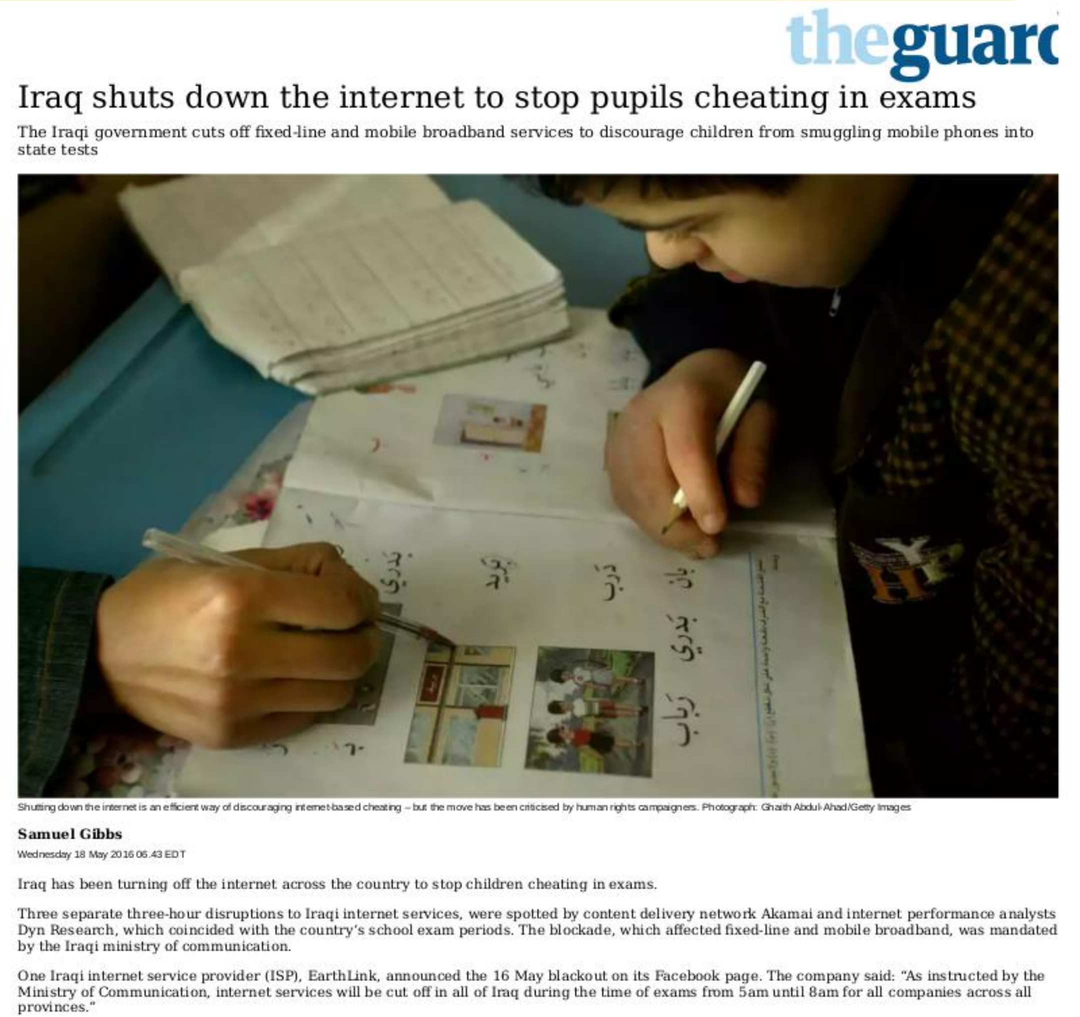
Countries Are Changing the World



A Digital Firewall in Myanmar, Built With Guns and Wire Cutters

As the military seized power again, the generals moved quickly to take the country offli… social media.





Iraq shuts down the internet to stop pupils cheating in exams

The Iraqi government cuts off fixed-line and mobile broadband services to discourage children from smuggling mobile phones into state tests

Shutting down the internet is an efficient way of discouraging internet-based cheating – but the move has been criticised by human rights campaigners. Photograph: Ghaith Abdul-Ahad/Getty Images

Samuel Gibbs

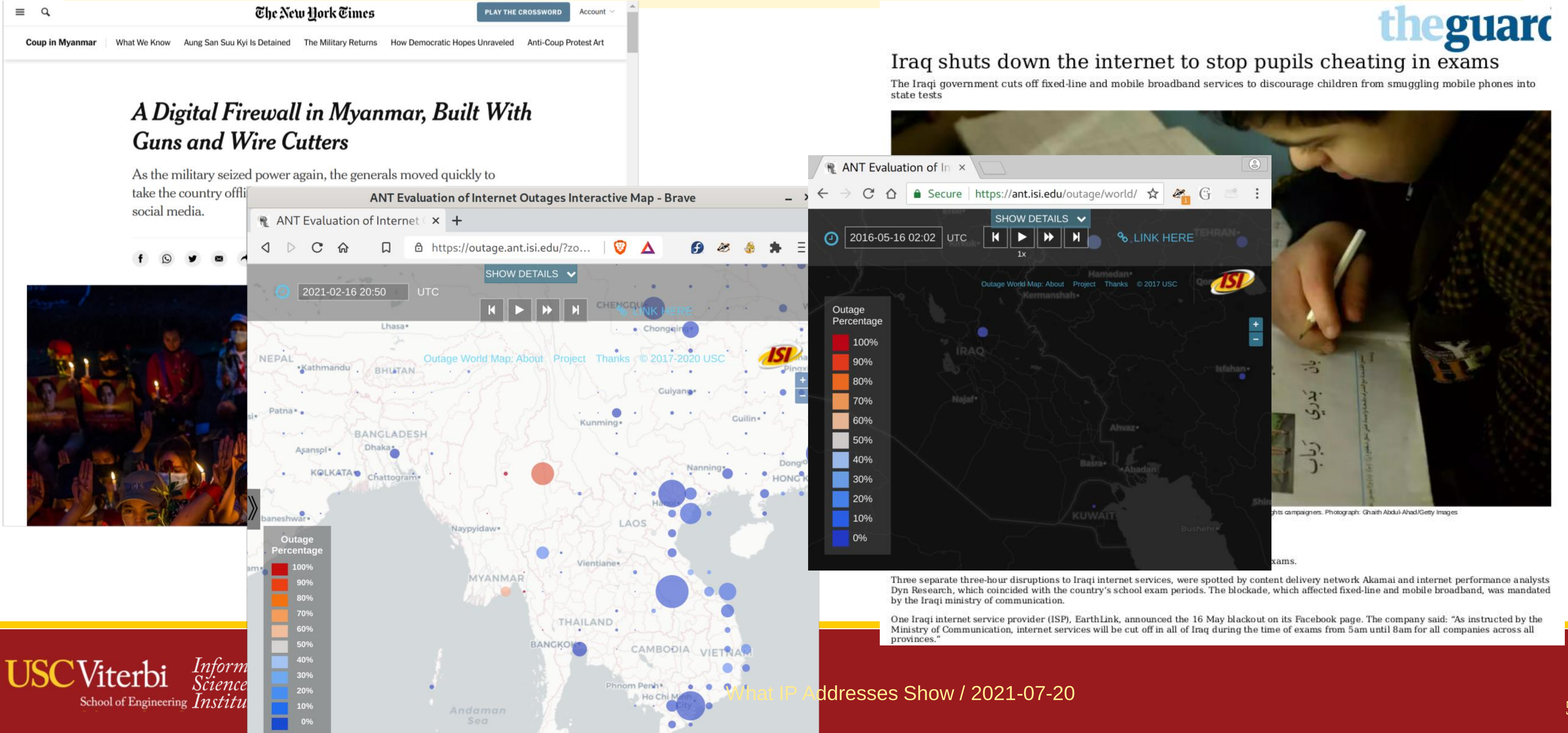
Wednesday 18 May 2016 06.43 EDT

Iraq has been turning off the internet across the country to stop children cheating in exams.

Three separate three-hour disruptions to Iraqi internet services, were spotted by content delivery network Akamai and internet performance analysts Dyn Research, which coincided with the country's school exam periods. The blockade, which affected fixed-line and mobile broadband, was mandated by the Iraqi ministry of communication.

One Iraqi internet service provider (ISP), EarthLink, announced the 16 May blackout on its Facebook page. The company said: "As instructed by the Ministry of Communication, internet services will be cut off in all of Iraq during the time of exams from 5am until 8am for all companies across all provinces."

Countries Are Changing the World



The New York Times

PLAY THE CROSSWORD

Account

Coup in Myanmar | What We Know | Aung San Suu Kyi Is Detained | The Military Returns | How Democratic Hopes Unraveled | Anti-Coup Protest Art

A Digital Firewall in Myanmar, Built With Guns and Wire Cutters

As the military seized power again, the generals moved quickly to take the country offli social media.

ANT Evaluation of Internet Outages Interactive Map - Brave

https://outage.ant.isi.edu/?zo…

2021-02-16 20:50 UTC

theguardian

Iraq shuts down the internet to stop pupils cheating in exams

The Iraqi government cuts off fixed-line and mobile broadband services to discourage children from smuggling mobile phones into state tests

ANT Evaluation of In

Secure https://ant.isi.edu/outage/world/

2016-05-16 02:02 UTC

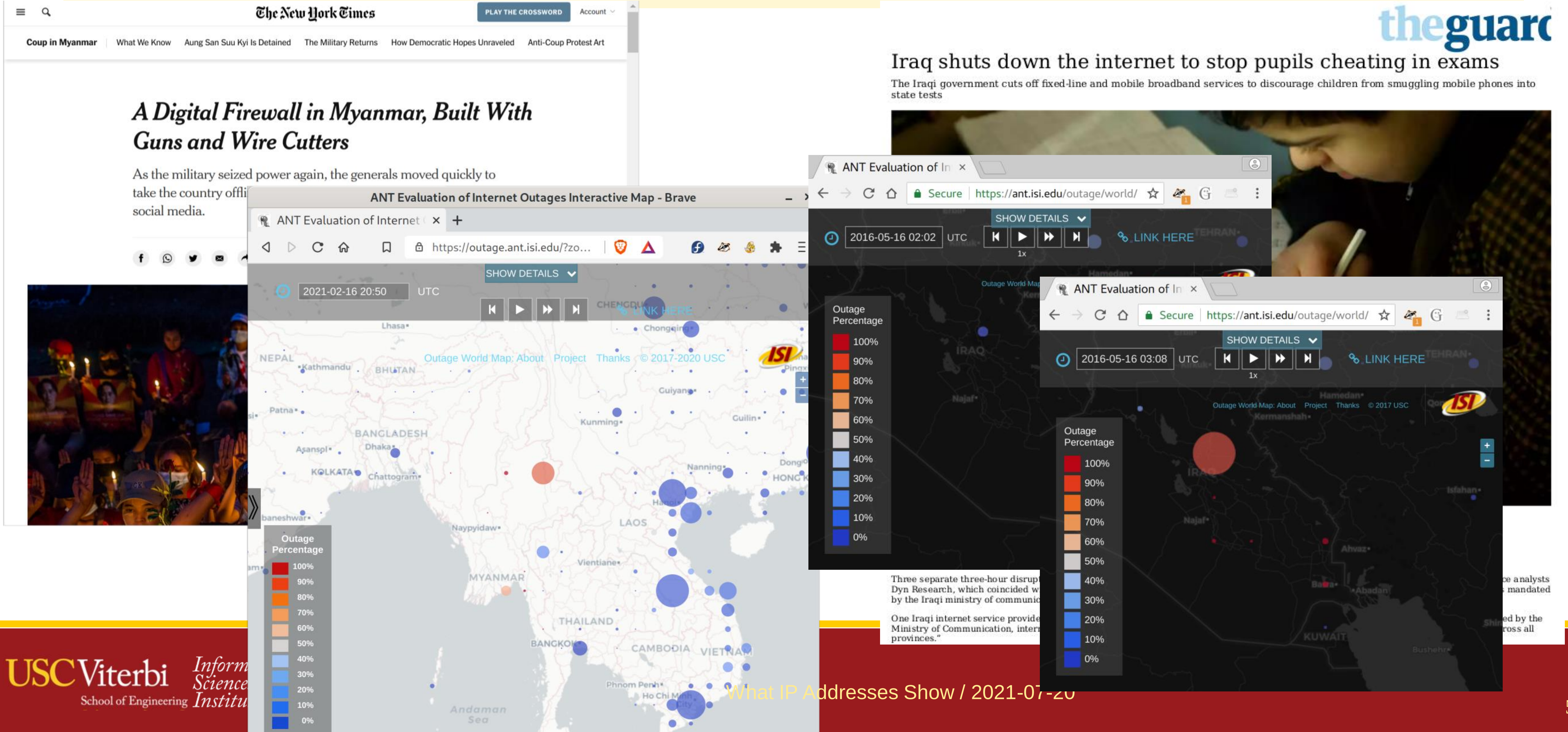
hts campaigners. Photograph: Ghaith Abdul-Ahad/Getty Images

xams.

Three separate three-hour disruptions to Iraqi internet services, were spotted by content delivery network Akamai and internet performance analysts Dyn Research, which coincided with the country's school exam periods. The blockade, which affected fixed-line and mobile broadband, was mandated by the Iraqi ministry of communication.

One Iraqi internet service provider (ISP), EarthLink, announced the 16 May blackout on its Facebook page. The company said: "As instructed by the Ministry of Communication, internet services will be cut off in all of Iraq during the time of exams from 5am until 8am for all companies across all provinces."

Countries Are Changing the World



The New York Times

PLAY THE CROSSWORD

Account

Coup in Myanmar | What We Know | Aung San Suu Kyi Is Detained | The Military Returns | How Democratic Hopes Unraveled | Anti-Coup Protest Art

A Digital Firewall in Myanmar, Built With Guns and Wire Cutters

As the military seized power again, the generals moved quickly to take the country offli social media.

theguard

Iraq shuts down the internet to stop pupils cheating in exams

The Iraqi government cuts off fixed-line and mobile broadband services to discourage children from smuggling mobile phones into state tests

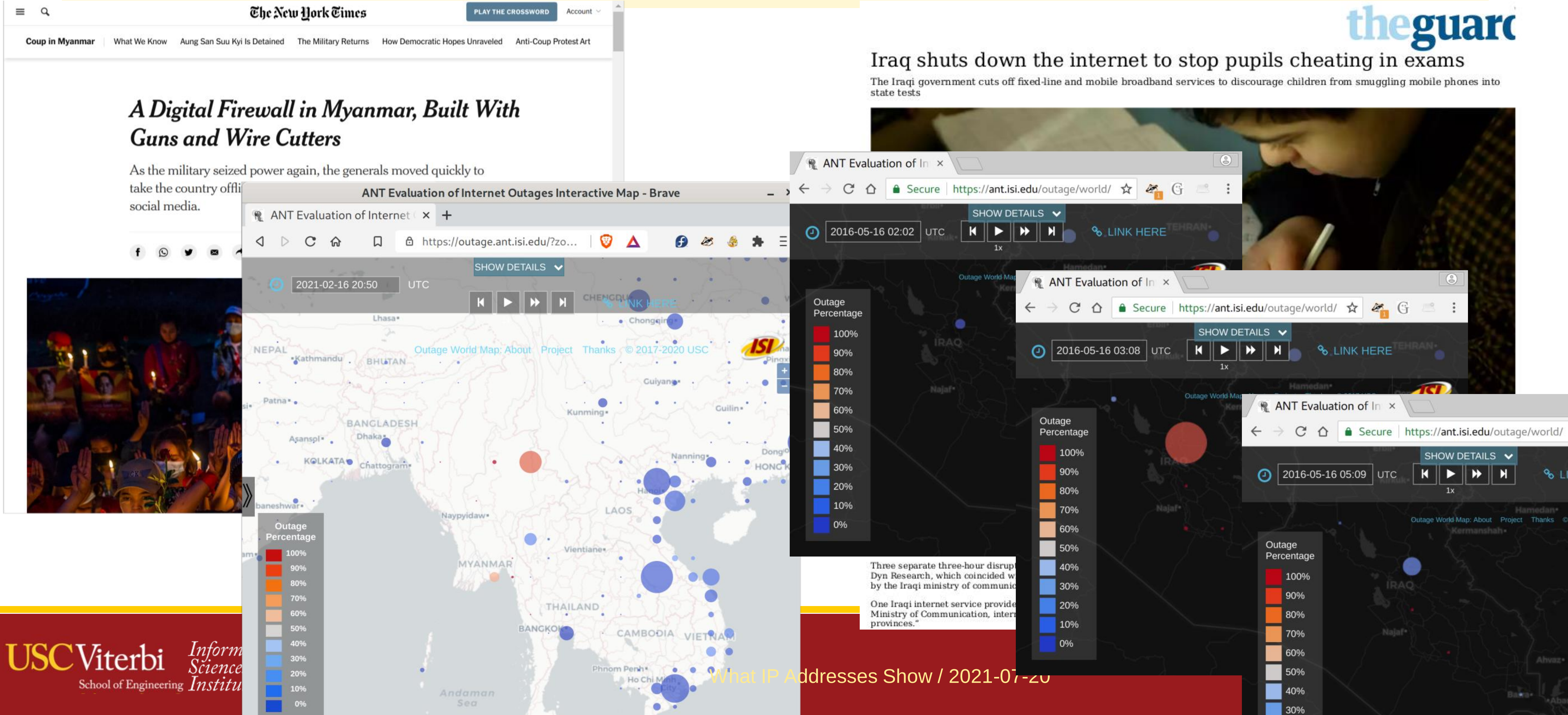
Three separate three-hour disrup Dyn Research, which coincided w by the Iraqi ministry of communic

One Iraqi internet service provide Ministry of Communication, intern provinces."

ce analysts mandated

ed by the ross all

Countries Are Changing the World



The New York Times

PLAY THE CROSSWORD | Account

Coup in Myanmar | What We Know | Aung San Suu Kyi Is Detained | The Military Returns | How Democratic Hopes Unraveled | Anti-Coup Protest Art

A Digital Firewall in Myanmar, Built With Guns and Wire Cutters

As the military seized power again, the generals moved quickly to take the country offli… social media.

theguard…

Iraq shuts down the internet to stop pupils cheating in exams

The Iraqi government cuts off fixed-line and mobile broadband services to discourage children from smuggling mobile phones into state tests

Three separate three-hour disrup… Dyn Research, which coincided w… by the Iraqi ministry of communic…

One Iraqi internet service provide… Ministry of Communication, intern… provinces."

ANT Evaluation of Internet Outages Interactive Map - Brave

https://outage.ant.isi.edu/?zo…

2021-02-16 20:50 UTC

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

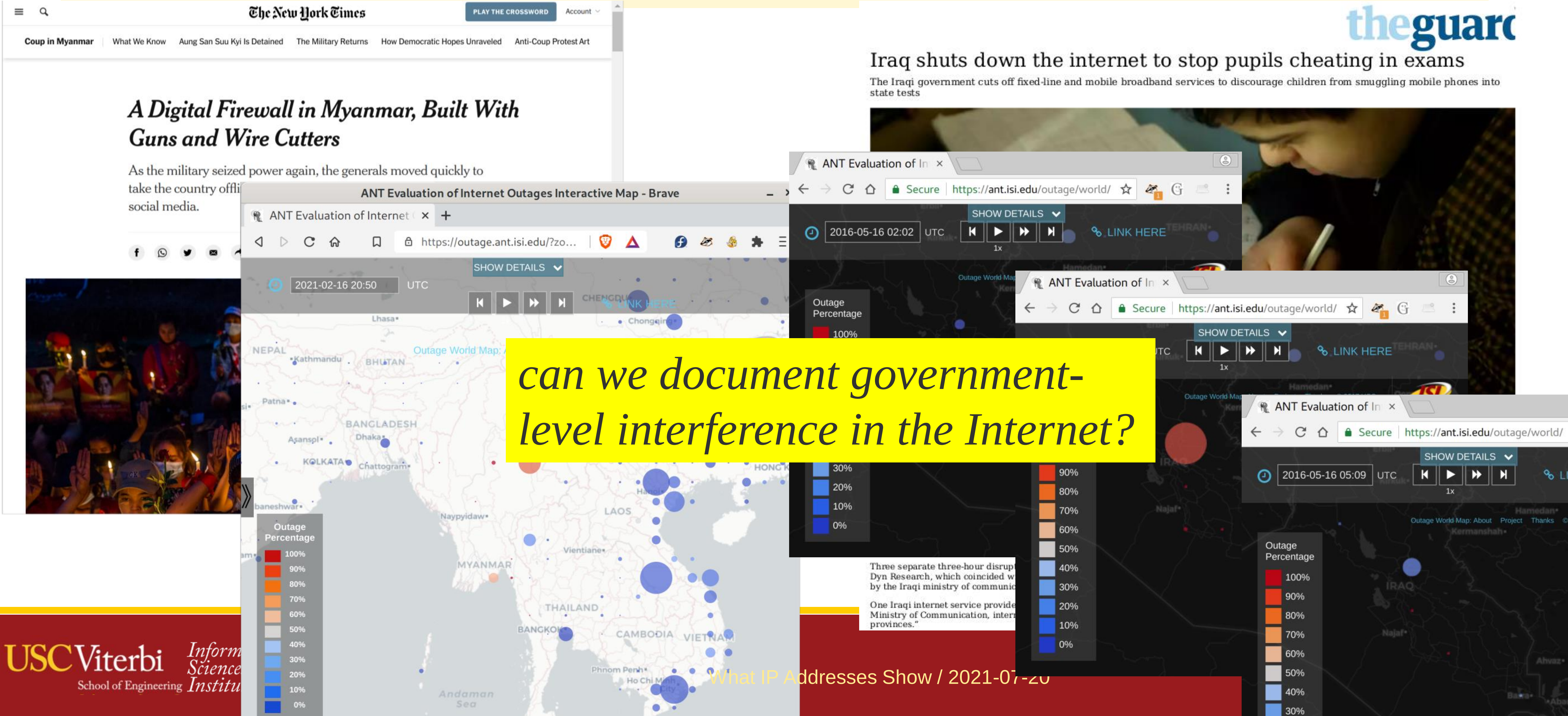
2016-05-16 02:02 UTC

2016-05-16 03:08 UTC

2016-05-16 05:09 UTC

Outage World Map: About Project Thanks © 2017-2020 USC

Countries Are Changing the World



The New York Times

A Digital Firewall in Myanmar, Built With Guns and Wire Cutters

As the military seized power again, the generals moved quickly to take the country offli social media.

theguard

Iraq shuts down the internet to stop pupils cheating in exams

The Iraqi government cuts off fixed-line and mobile broadband services to discourage children from smuggling mobile phones into state tests

Three separate three-hour disrup Dyn Research, which coincided w by the Iraqi ministry of communic

One Iraqi internet service provide Ministry of Communication, interr provinces."

can we document government-level interference in the Internet?

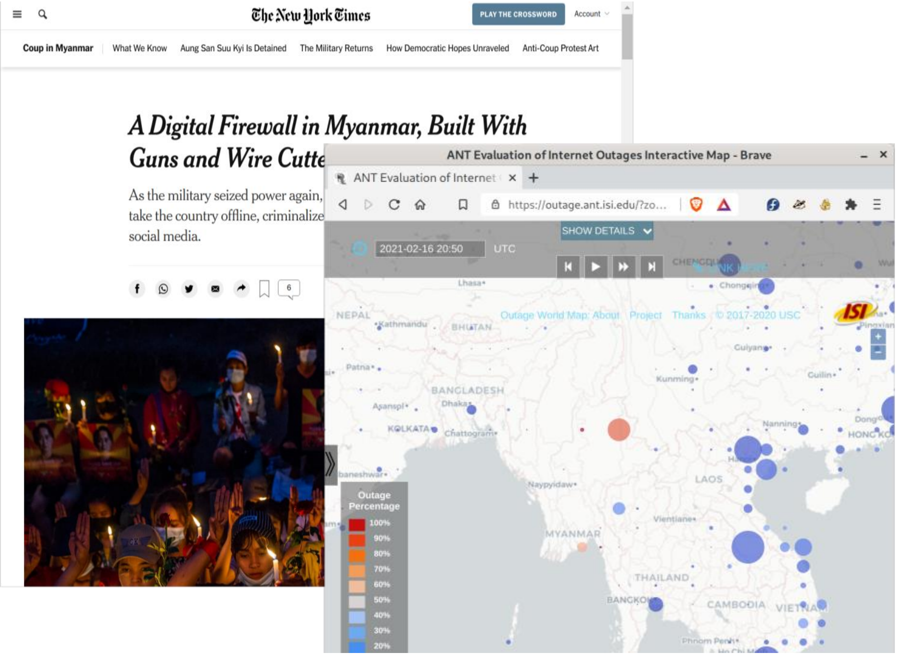
USC Viterbi School of Engineering
Information Sciences Institute

Network Reliability Matters *Now*

in the Internet, in the world, and how they connect…

Network Reliability Matters *Now*

in the Internet, in the world, and how they connect…



The New York Times

Coup in Myanmar | What We Know | Aung San Suu Kyi Is Detained | The Military Returns | How Democratic Hopes Unraveled | Anti-Coup Protest Art

A Digital Firewall in Myanmar, Built With Guns and Wire Cutte

As the military seized power again, take the country offline, criminalize social media.

ANT Evaluation of Internet Outages Interactive Map - Brave

https://outage.ant.isi.edu/?zo…

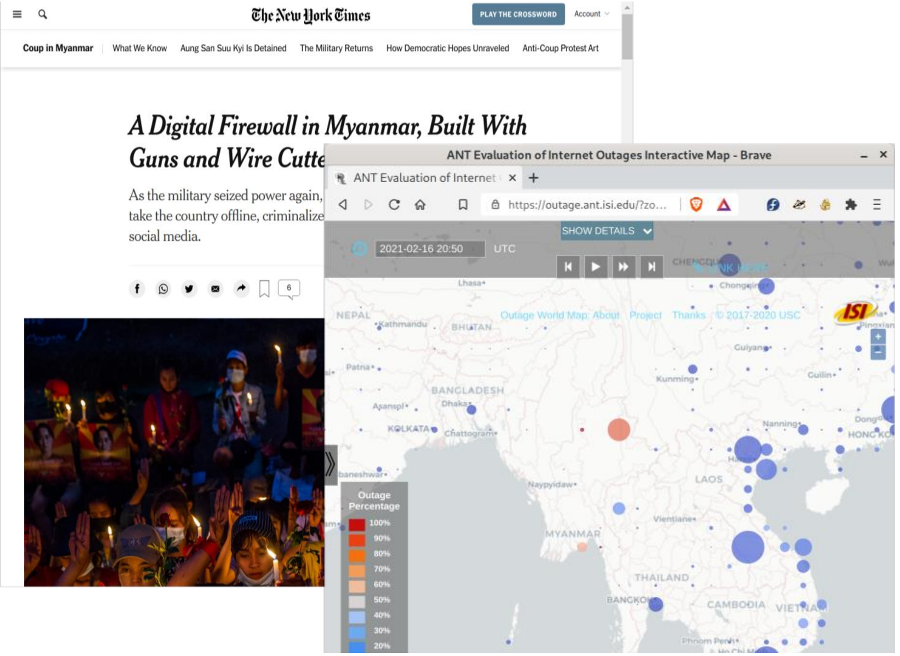
2021-02-16 20:50 UTC

Outage World Map: About Project Thanks © 2017-2020 USC

communication without
intentional network interference

Network Reliability Matters *Now*

in the Internet, in the world, and how they connect…



The New York Times

Coup in Myanmar | What We Know | Aung San Suu Kyi Is Detained | The Military Returns | How Democratic Hopes Unraveled | Anti-Coup Protest Art

A Digital Firewall in Myanmar, Built With Guns and Wire Cutte

As the military seized power again, … take the country offline, criminalize … social media.

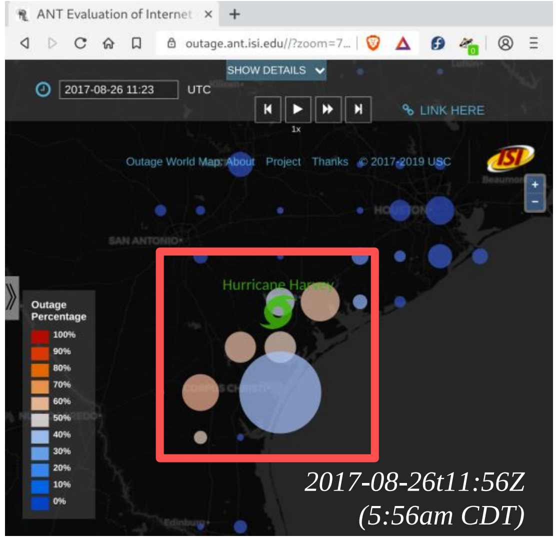
ANT Evaluation of Internet Outages Interactive Map - Brave

https://outage.ant.isi.edu/?zo…

2021-02-16 20:50 UTC

communication without
intentional network interference

Harvey Landfall: 2017-08-26t03:00Z (10pm CDT)



ANT Evaluation of Internet

outage.ant.isi.edu/?zoom=7…

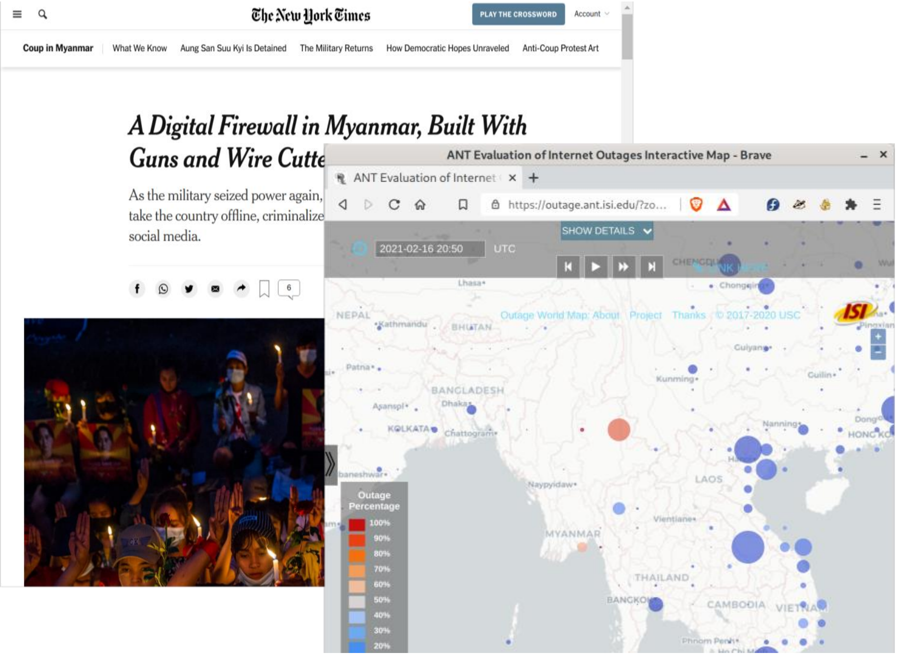
2017-08-26 11:23 UTC

2017-08-26t11:56Z
(5:56am CDT)

speedy **physical recovery to natural disasters**

Network Reliability Matters *Now*

in the Internet, in the world, and how they connect…



The New York Times

Coup in Myanmar | What We Know | Aung San Suu Kyi Is Detained | The Military Returns | How Democratic Hopes Unraveled | Anti-Coup Protest Art

A Digital Firewall in Myanmar, Built With Guns and Wire Cutte

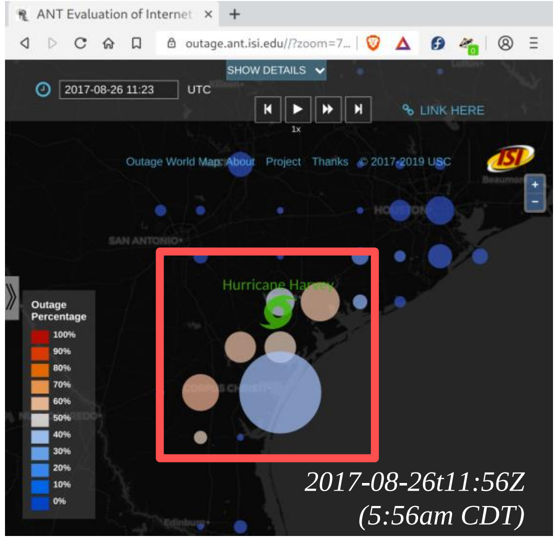
As the military seized power again, take the country offline, criminalize social media.

ANT Evaluation of Internet Outages Interactive Map - Brave

https://outage.ant.isi.edu/?zo…

2021-02-16 20:50 UTC

Harvey Landfall: 2017-08-26t03:00Z (10pm CDT)

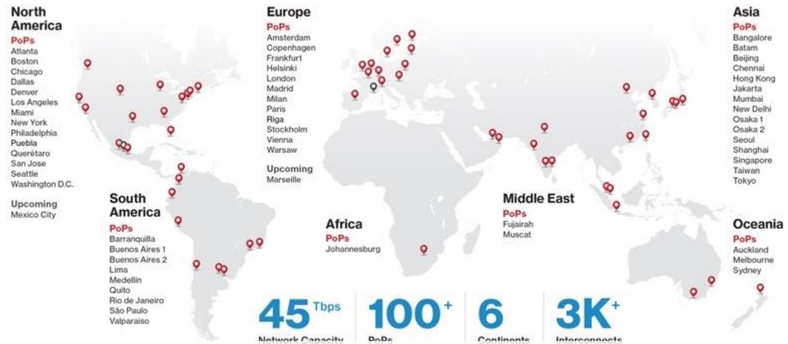


ANT Evaluation of Internet

outage.ant.isi.edu/?zoom=7…

2017-08-26 11:23 UTC

2017-08-26t11:56Z (5:56am CDT)



communication without **intentional network interference**

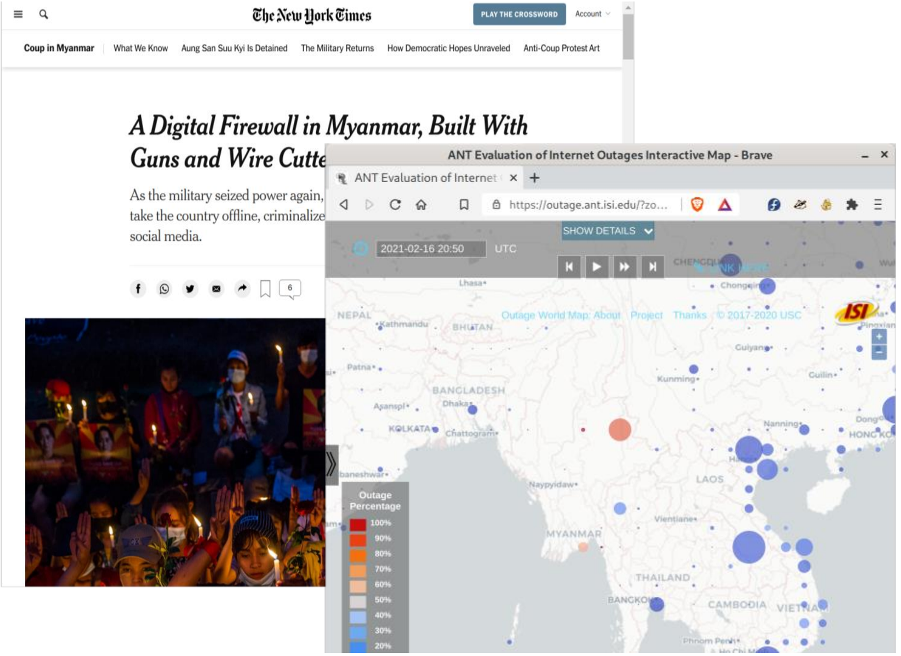
speedy **physical recovery to natural disasters**

CDNs with **choices where to serve customers**

Network Reliability Matters *Now*

in the Internet, in the world, and how they connect…

can we provide near-real-time results to help response?



The New York Times

PLAY THE CROSSWORD

Account

Coup in Myanmar | What We Know | Aung San Suu Kyi Is Detained | The Military Returns | How Democratic Hopes Unraveled | Anti-Coup Protest Art

A Digital Firewall in Myanmar, Built With Guns and Wire Cutte

As the military seized power again, take the country offline, criminalize social media.

ANT Evaluation of Internet Outages Interactive Map - Brave

https://outage.ant.isi.edu/?zo…

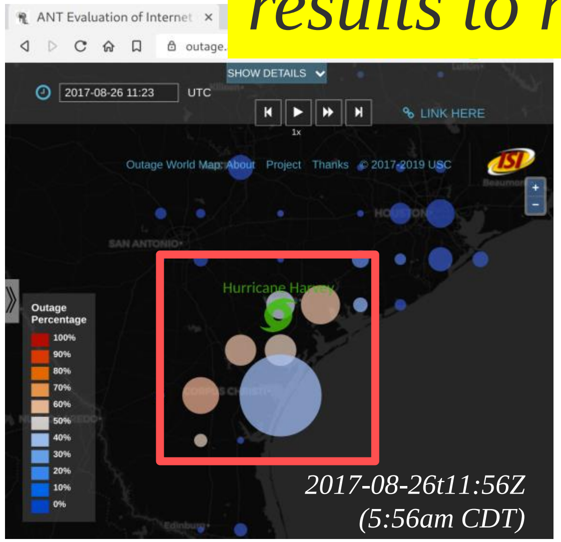
SHOW DETAILS

2021-02-16 20:50 UTC

Outage World Map: About | Project | Thanks | © 2017-2020 USC

communication without **intentional network interference**

Harvey Landfall: 2017-08-26t03:00Z (10pm CDT)



ANT Evaluation of Internet

SHOW DETAILS

2017-08-26 11:23 UTC

LINK HERE

Outage World Map: About | Project | Thanks | © 2017-2019 USC

2017-08-26t11:56Z (5:56am CDT)

speedy **physical recovery to natural disasters**

North America
PoPs
Atlanta
Boston
Chicago
Dallas
Denver
Los Angeles
Miami
New York
Philadelphia
Puebla
Querétaro
San Jose
Seattle
Washington D.C.

Upcoming
Mexico City

South America
PoPs
Barranquilla
Buenos Aires 1
Buenos Aires 2
Lima
Medellin
Quito
Rio de Janeiro
São Paulo
Valparaiso

Europe
PoPs
Amsterdam
Copenhagen
Frankfurt
Helsinki
London
Madrid
Milan
Paris
Riga
Stockholm
Vienna
Warsaw

Upcoming
Marseille

Africa
PoPs
Johannesburg

Middle East
PoPs
Fujairah
Muscat

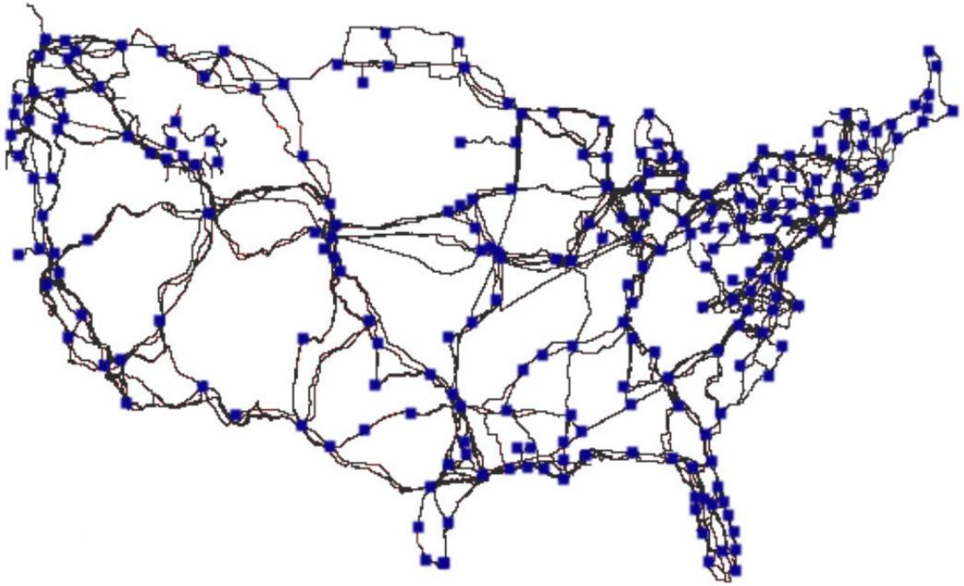
Asia
PoPs
Bangalore
Batam
Beijing
Chennai
Hong Kong
Jakarta
Mumbai
New Delhi
Osaka 1
Osaka 2
Seoul
Shanghai
Singapore
Taiwan
Tokyo

Oceania
PoPs
Auckland
Melbourne
Sydney

45 Tbps Network Capacity | 100+ PoPs | 6 Continents | 3K+ Interconnects

CDNs with **choices where to serve customers**

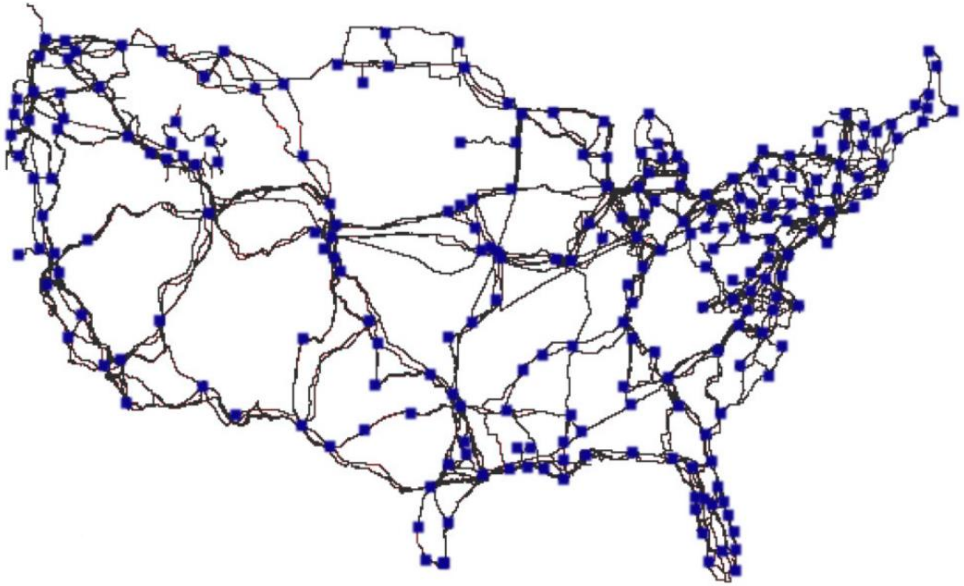
Network Reliability Can Improve *Tomorrow*



Physical conduits used by the U.S. Internet.

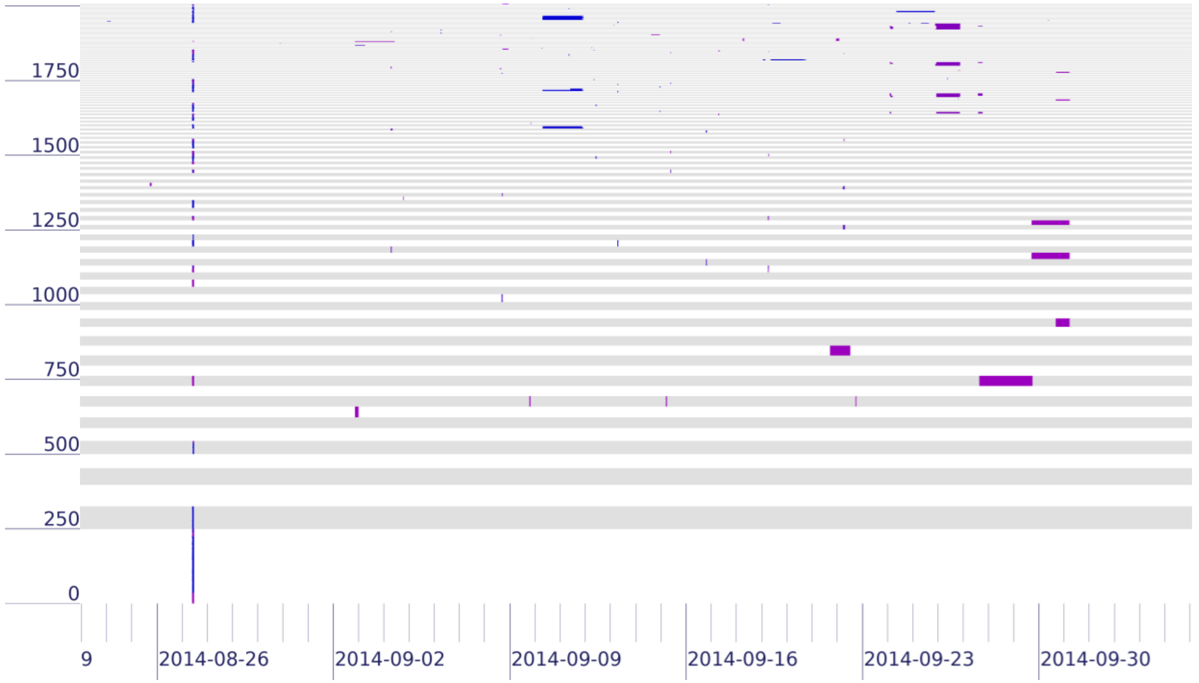
From “InterTubes: A Study of the US Long-Haul Fiber-optic Infrastructure” by Durairajan, Barford, Sommers, and Willinger, ACM SIGCOMM, Aug. 2015

Network Reliability Can Improve *Tomorrow*



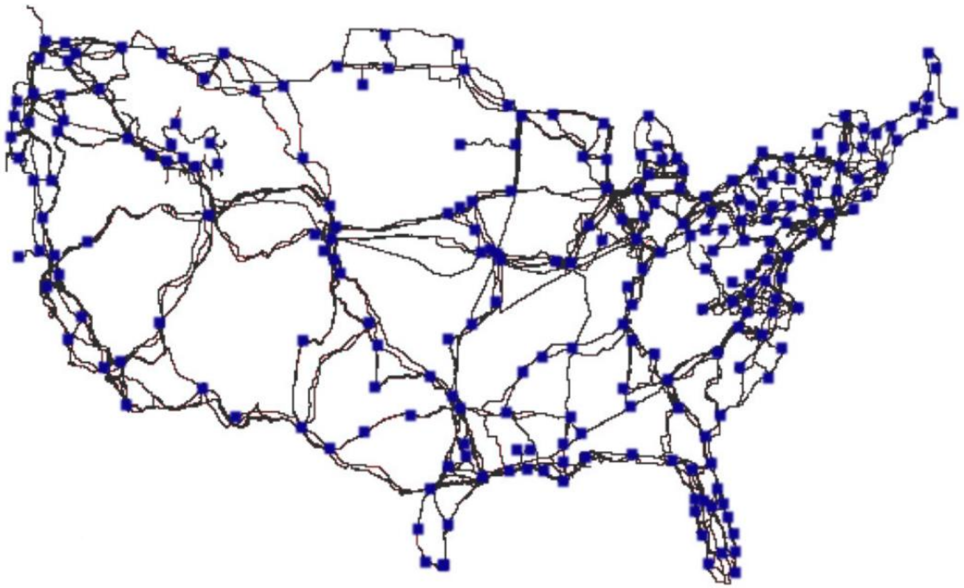
Physical conduits used by the U.S. Internet.

From “InterTubes: A Study of the US Long-Haul Fiber-optic Infrastructure” by Durairajan, Barford, Sommers, and Willinger, ACM SIGCOMM, Aug. 2015



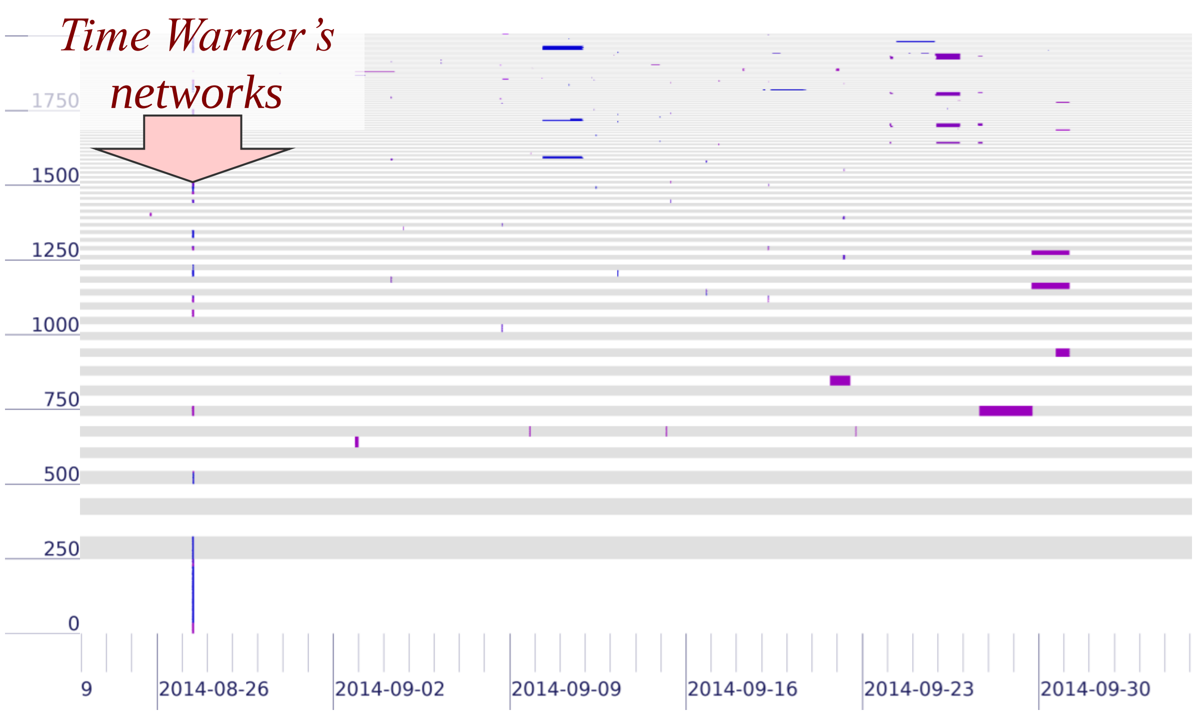
Clustering algorithms discovering Time Warner’s network from their Sept. 2014 outage.

Network Reliability Can Improve *Tomorrow*



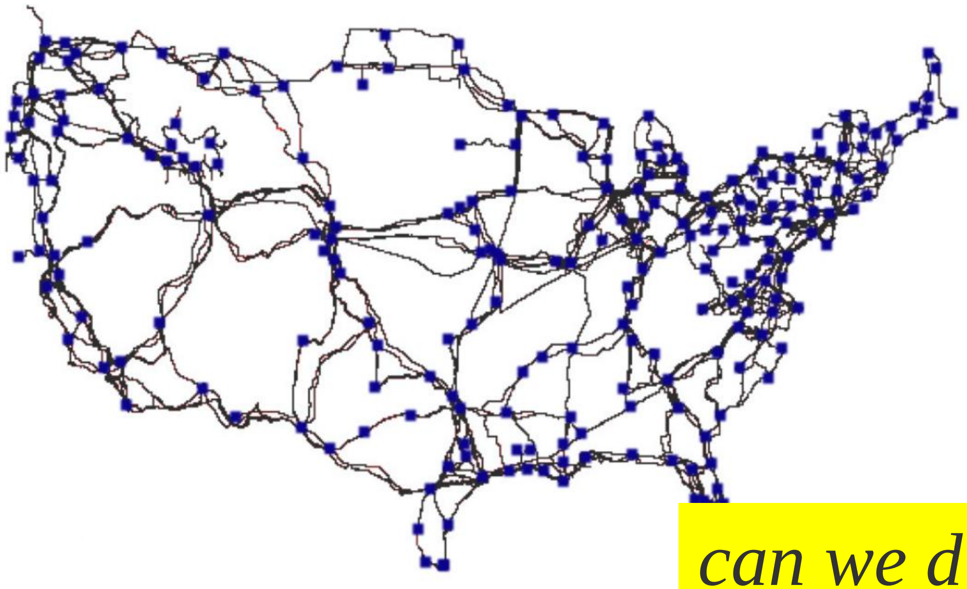
Physical conduits used by the U.S. Internet.

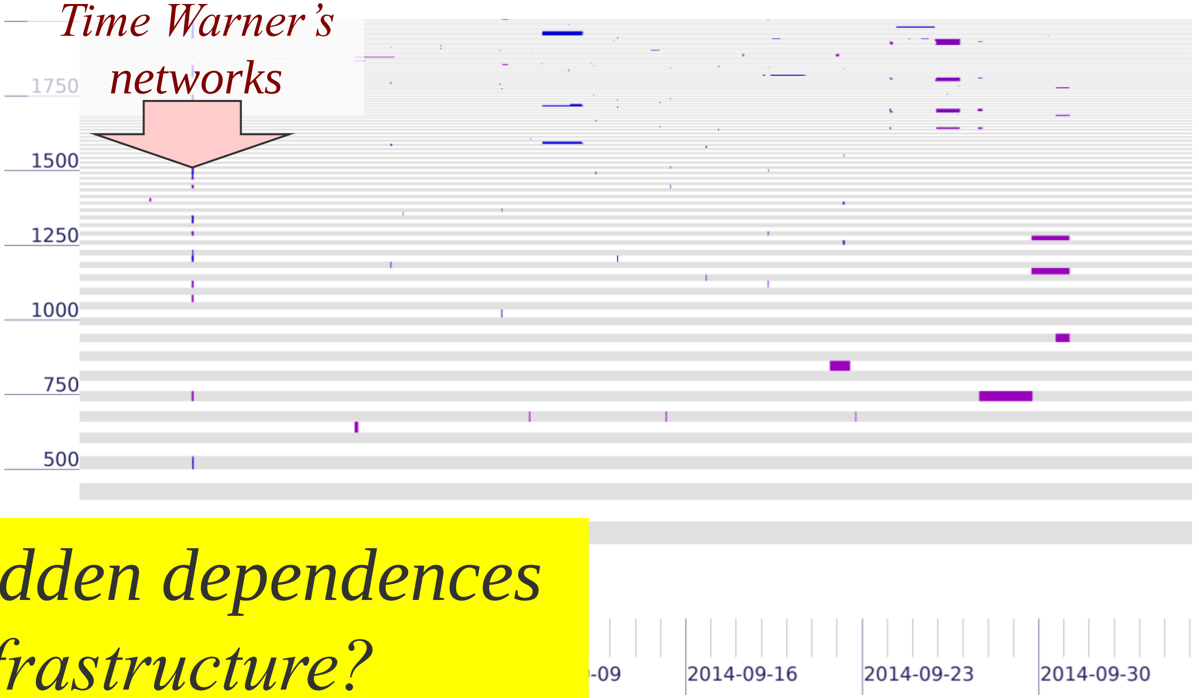
From “InterTubes: A Study of the US Long-Haul Fiber-optic Infrastructure” by Durairajan, Barford, Sommers, and Willinger, ACM SIGCOMM, Aug. 2015



Clustering algorithms discovering Time Warner’s network from their Sept. 2014 outage.

Network Reliability Can Improve *Tomorrow*





Time Warner's networks

can we discover hidden dependences in the Internet's infrastructure?

Physical conduits used by the U.S. I

From "InterTubes: A Study of the US Long-Haul Fiber-optic Infrastructure" by Durairajan, Barford, Sommers, and Willinger, ACM SIGCOMM, Aug. 2015

Clustering algorithms discovering Time Warner's network from their Sept. 2014 outage.

Understanding Internet Reliability

- opportunities observing Internet reliability
- **from scanning to outages**
- from outages to clusters: hidden dependencies
- finding work-from-home

The IPv4 Internet

we scan the IPv4 Internet (since 2006!)

2^{32} addresses (~4 billion)

usually written: 4 parts, each 8-bits

192.0.2.1 (from 0.0.0.0 to 255.255.255.255)

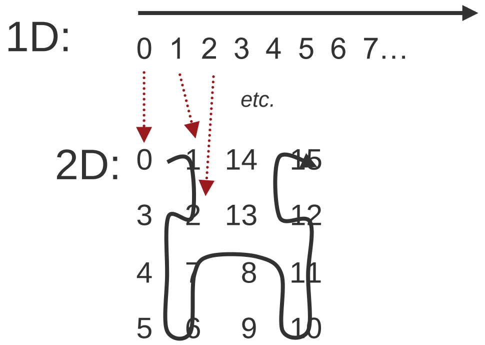
address **blocks:** adjacent addresses with same first *n* bits

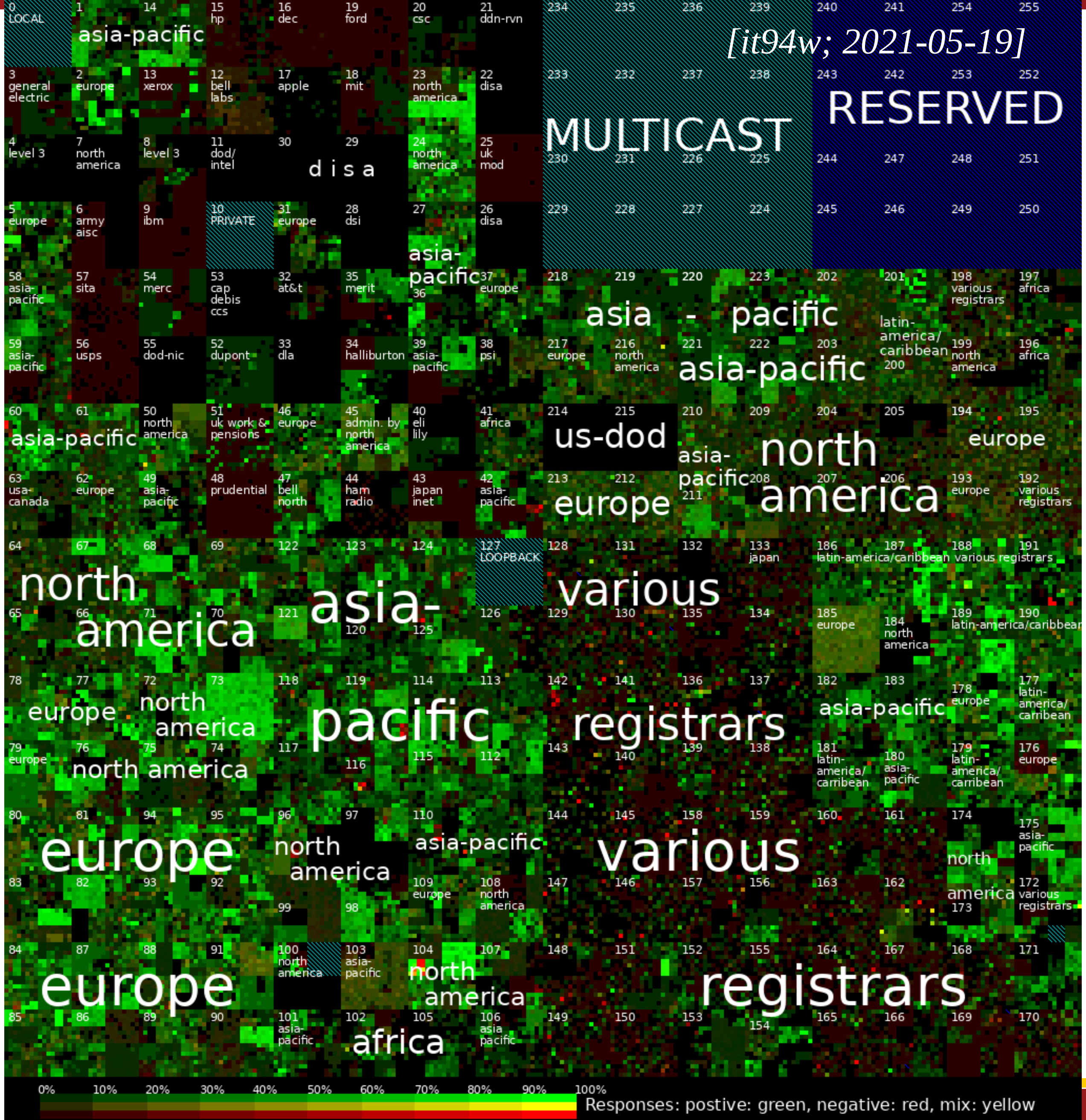
192.0.*.* /16

or just 192.0/16

(prefix=192.0, n=16)

squares on the map

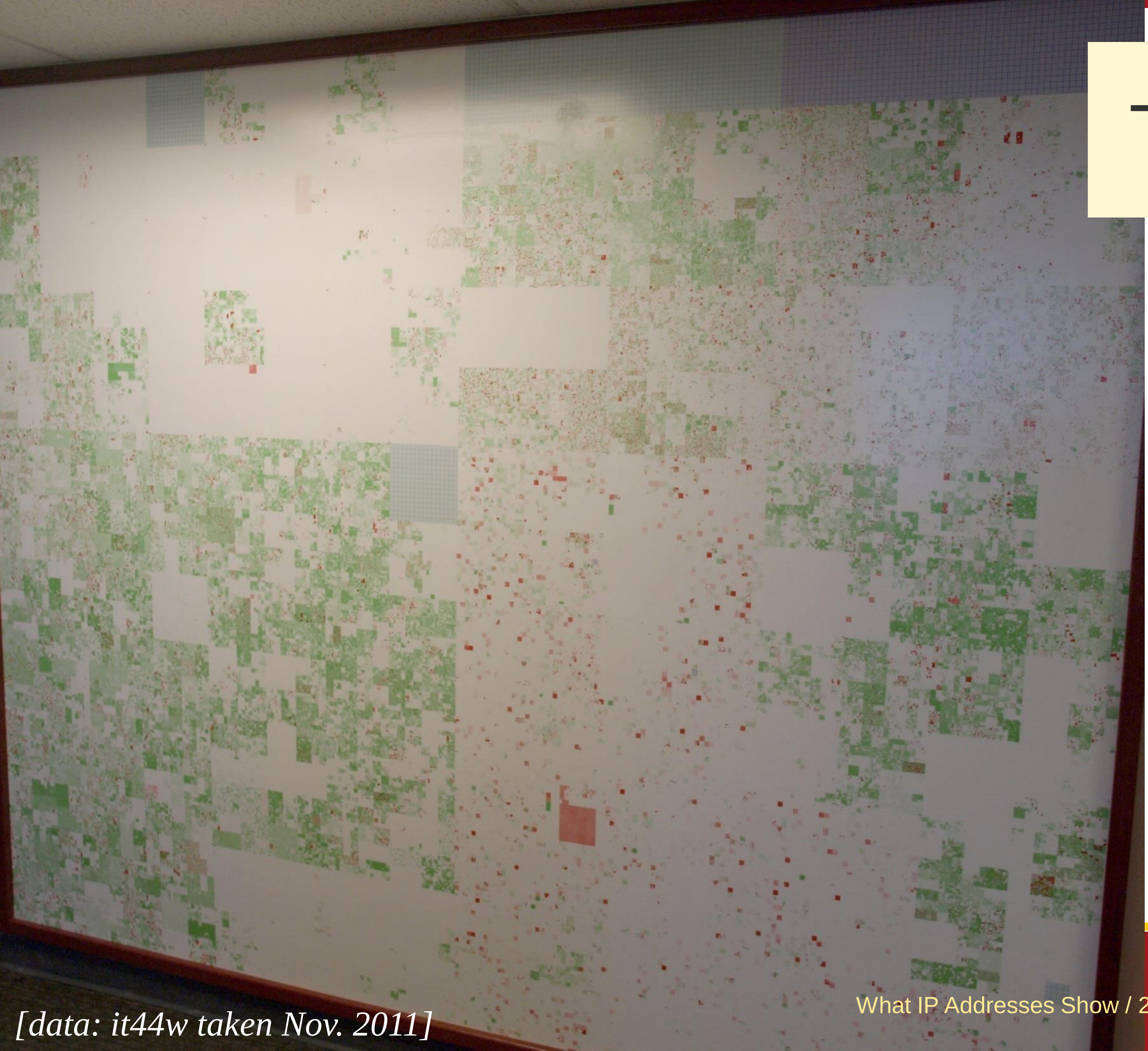




Responses: postive: green, negative: red, mix: yellow

LANDER Map of Internet Address Space Use. (C) 2007-2021 USC/Information Sciences Institute. www.isi.edu/ant/address
visualization: John Heidemann from layout suggested by Randall Munroe; probing: Yuri Pradkin;
methodology: John Heidemann, Yuri Pryadkin, Ramesh Govindan, Christos Papadopoulos, Joseph Bannister.
Dataset USC/LANDER-internet_address_census_it94w-20210519, taken May 2021.
Data shows the results of pings of about 3 billion IP addresses, with color indicating the reply.
Blue hatched: unallocated, cyan hatched: reserved

The *Whole* Internet



[data: it44w taken Nov. 2011]

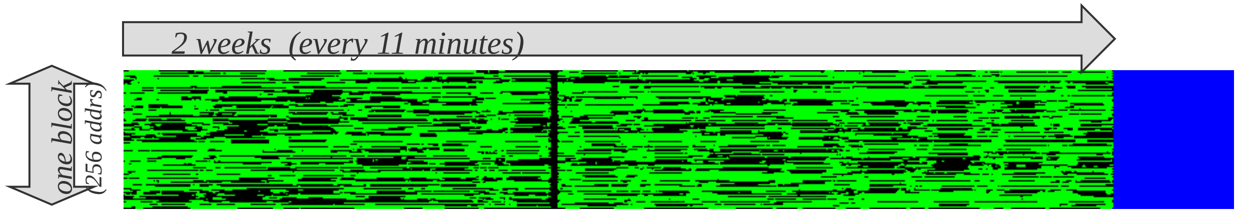
- here, 1 pixel is 1 address
- 2.8x2.8m (9x9’) at 600dpi
- green: positive, red: negative; white: no resp.
- this data is from 2011

From Pings to Network Outages

another view:

over **2 weeks**

one block
(256 addrs)

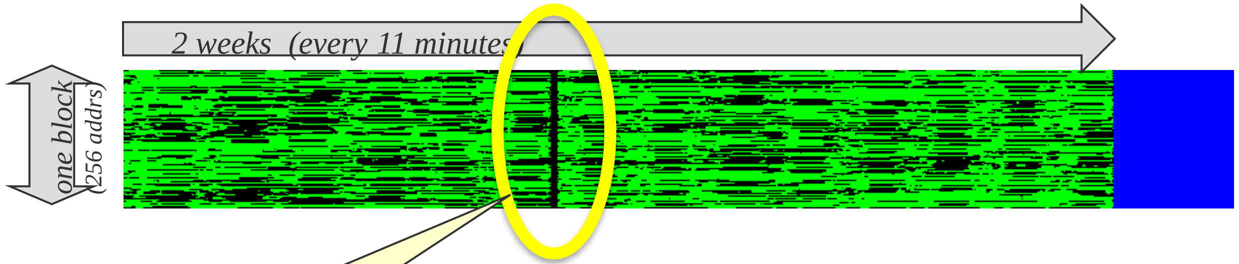


From Pings to Network Outages

another view:

over **2 weeks**

one block
(256 addrs)



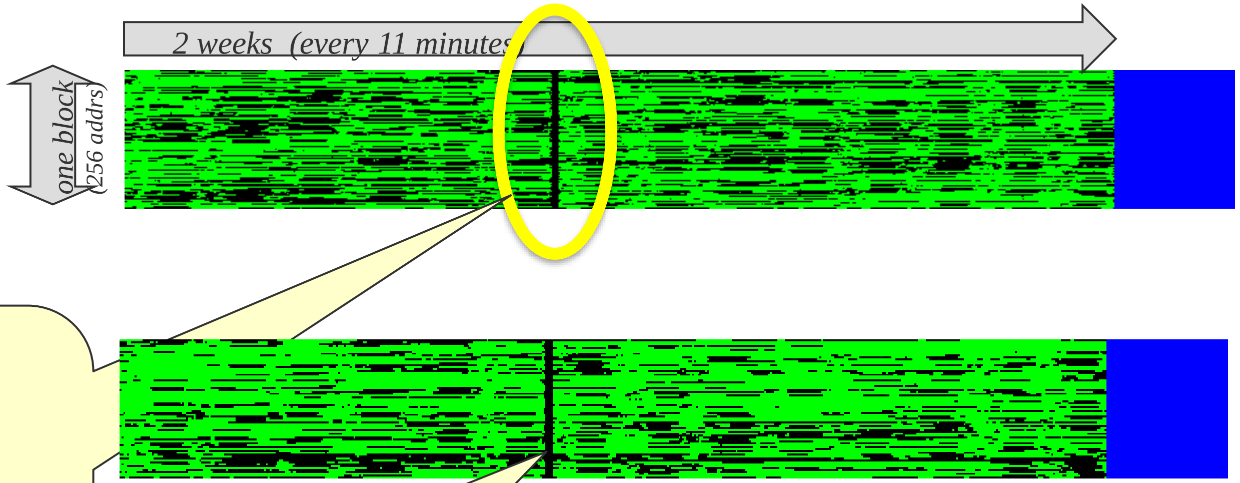
but what's this glitch? (the vertical bar of black)

From Pings to Network Outages

another view:

over **2 weeks**

one block
(256 addrs)



but what's this glitch? (the vertical bar of black)

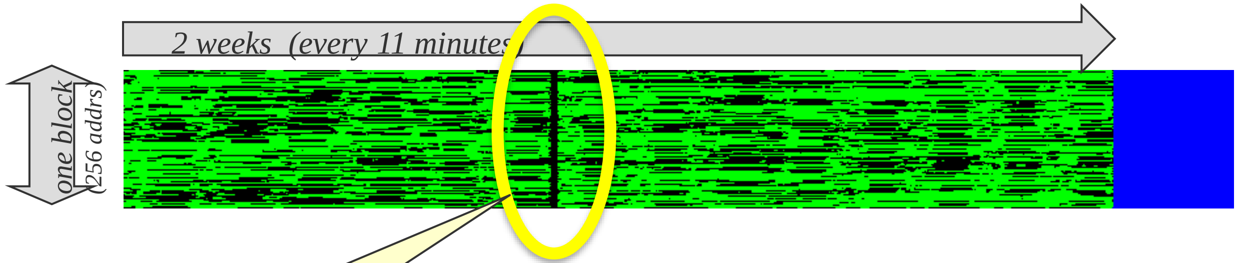
(in more than one block)

From Pings to Network Outages

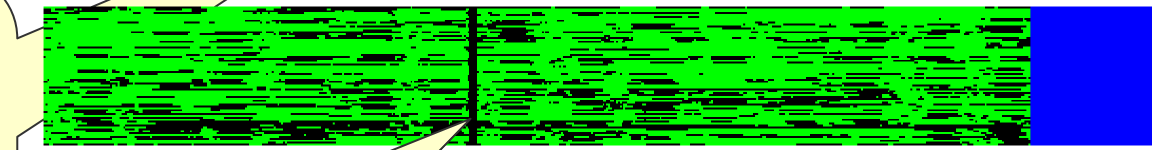
another view:

over **2 weeks**

one block
(256 addrs)

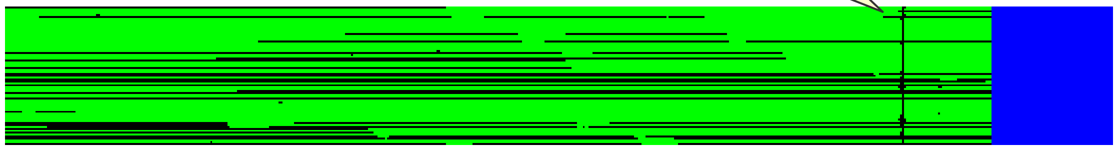


but what's this glitch? (the vertical bar of black)



(in more than one block)

(at different times, too)

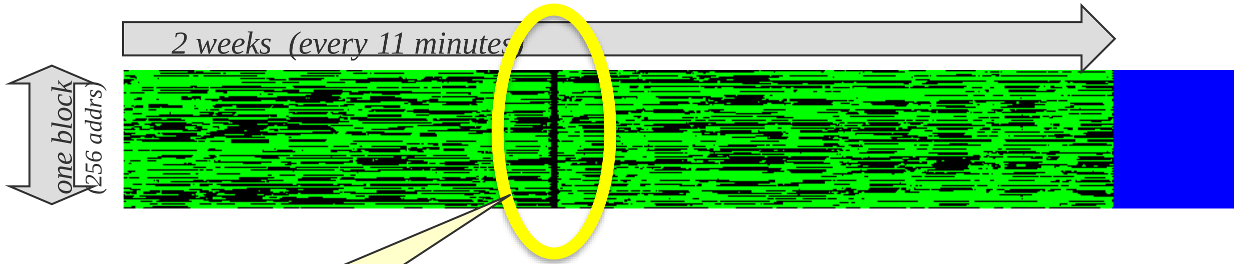


From Pings to Network Outages

another view:

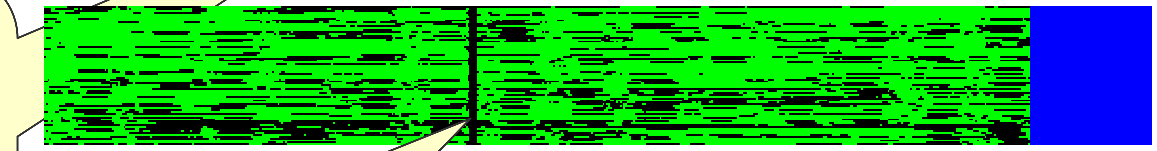
over **2 weeks**

one block
(256 addrs)



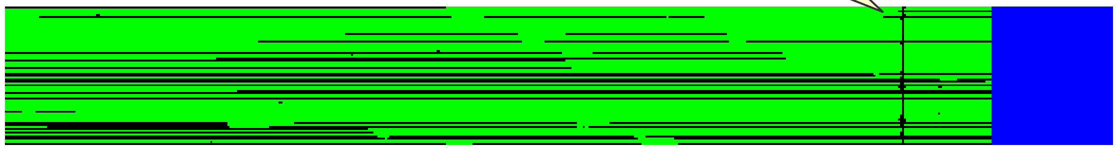
these bars are network outages

but what's this glitch? (the vertical bar of black)



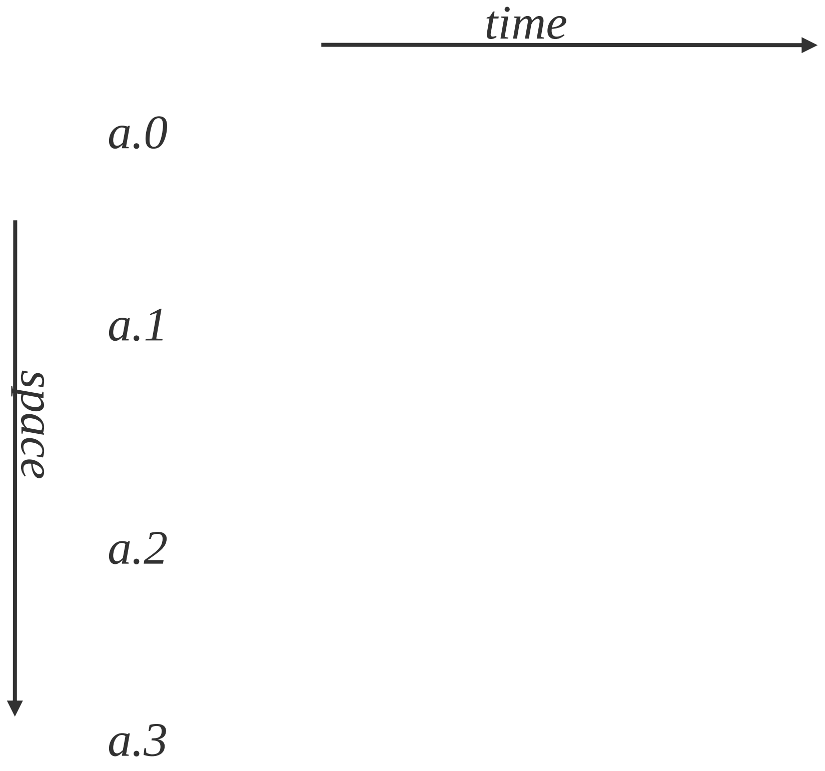
(in more than one block)

(at different times, too)



Outages from Ambiguous Signals

challenge: a ping is ambiguous


time

space

a.0

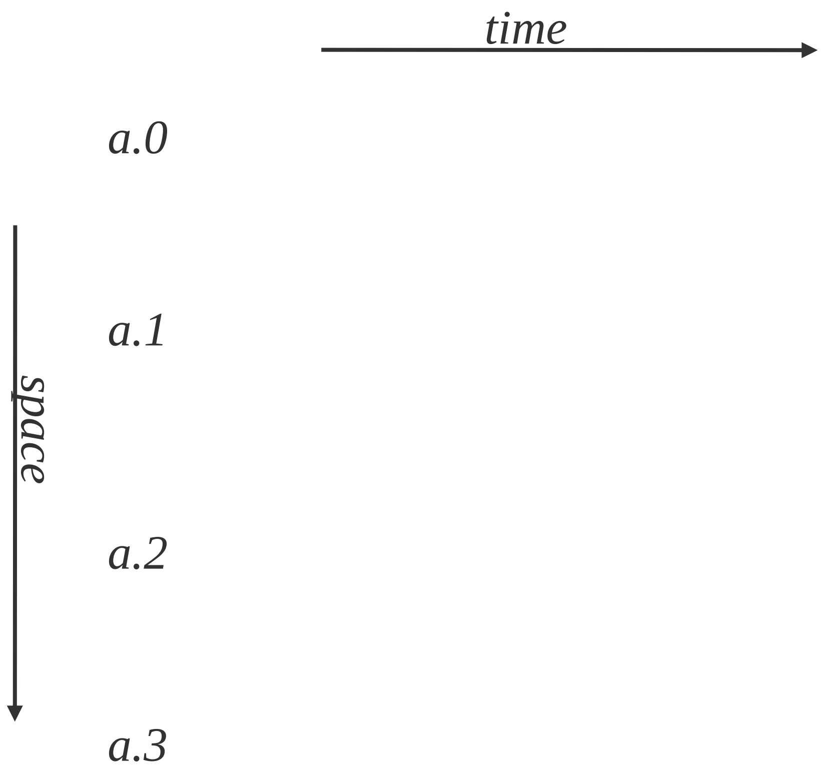
a.1

a.2

a.3

(blocks: really have 256 addresses, we show 4 here)

Outages from Ambiguous Signals

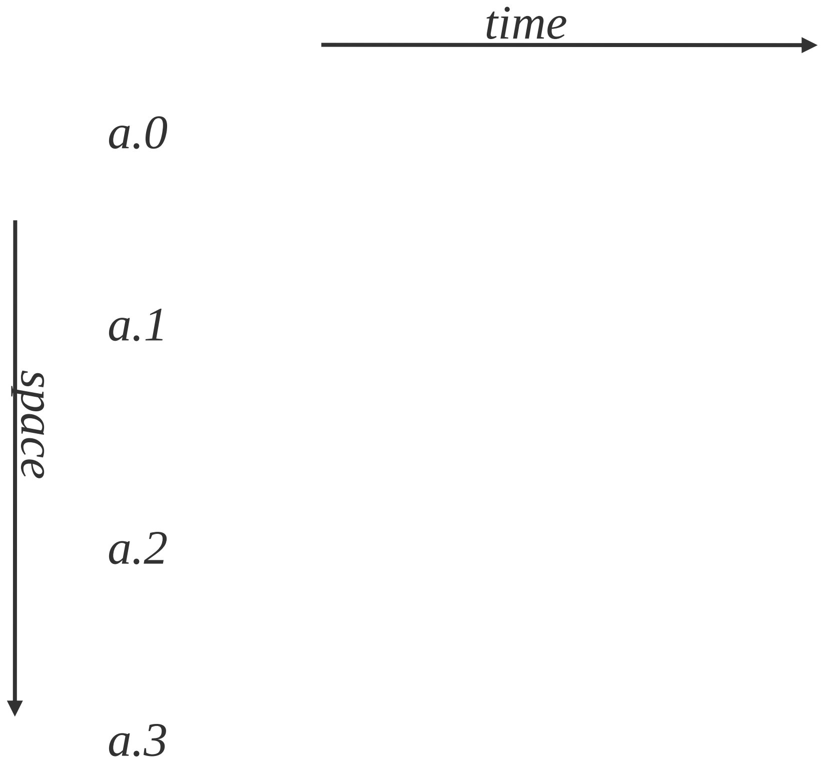


challenge: a ping is ambiguous

single negative:
address is down

(blocks: really have
256 addresses, we show 4 here)

Outages from Ambiguous Signals



(blocks: really have
256 addresses, we show 4 here)

challenge: a ping is ambiguous

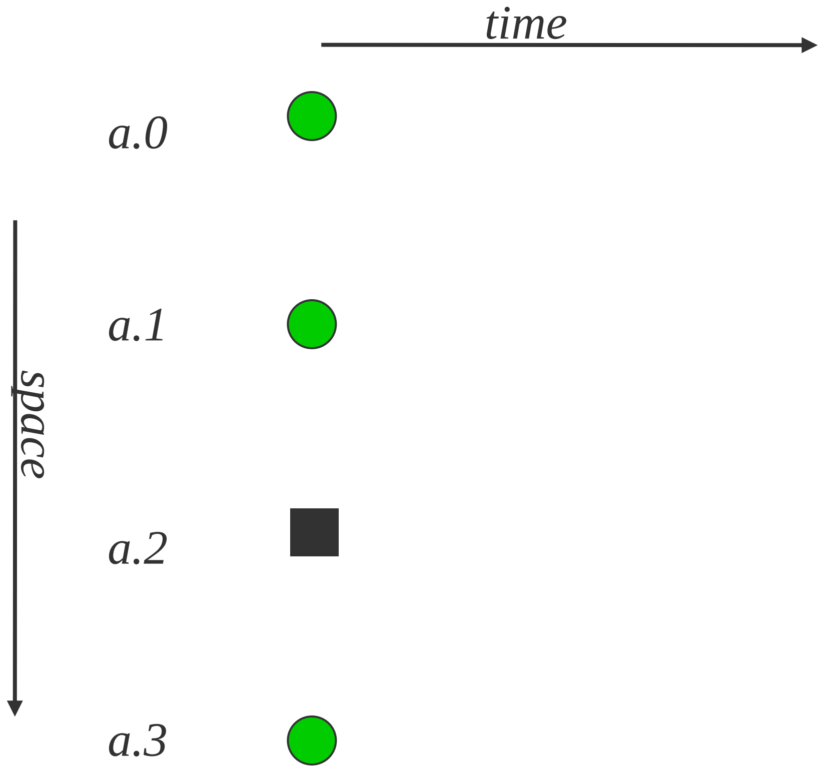
single negative:
address is down

or

computer crashed
laptop suspended

computer address reassigned
probe or reply lost
firewall enabled

Outages from Ambiguous Signals



(blocks: really have 256 addresses, we show 4 here)

challenge: a ping is ambiguous

single negative: address is down

or

computer crashed

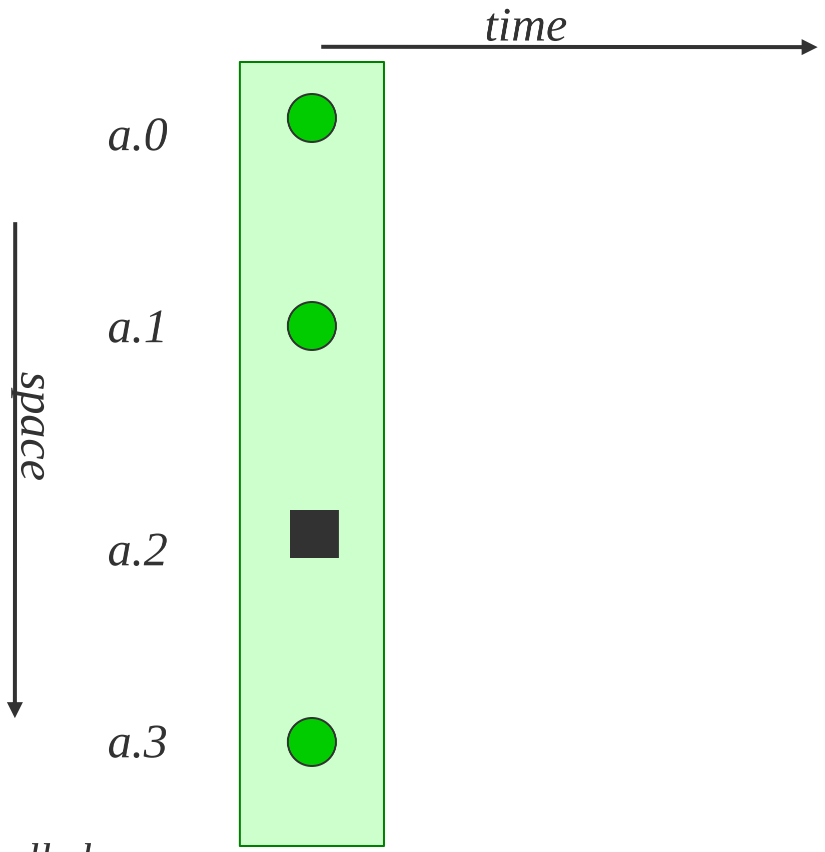
laptop suspended

computer address reassigned

probe or reply lost

firewall enabled

Outages from Ambiguous Signals



(blocks: really have 256 addresses, we show 4 here)

challenge: a ping is ambiguous

single negative: address is down

or

computer crashed

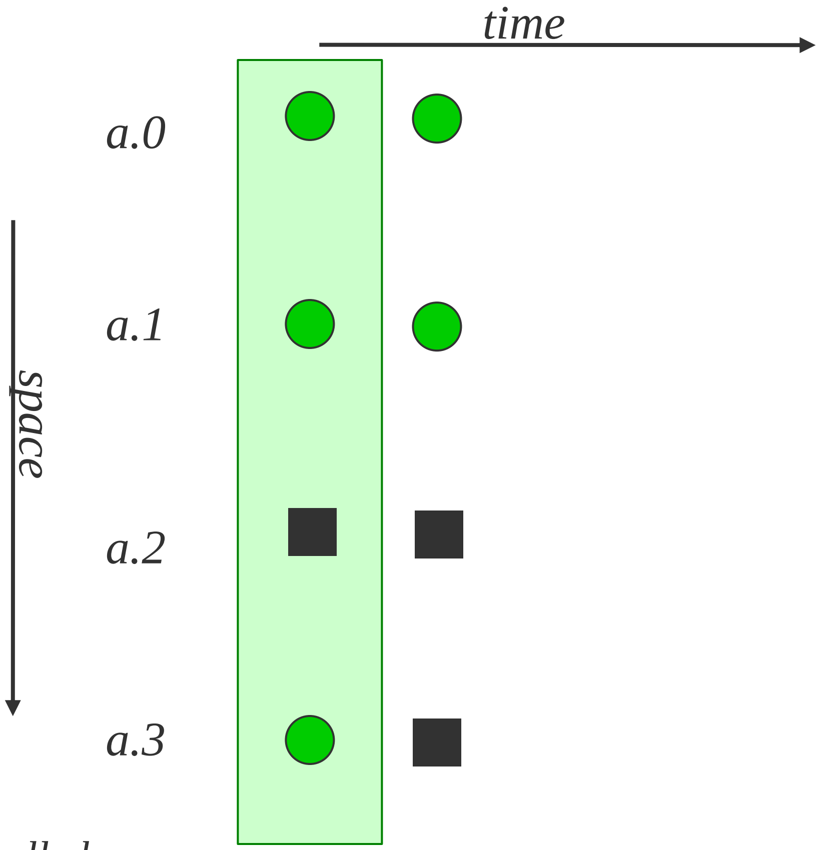
laptop suspended

computer address reassigned

probe or reply lost

firewall enabled

Outages from Ambiguous Signals



(blocks: really have 256 addresses, we show 4 here)

challenge: a ping is ambiguous

single negative: address is down

or

computer crashed

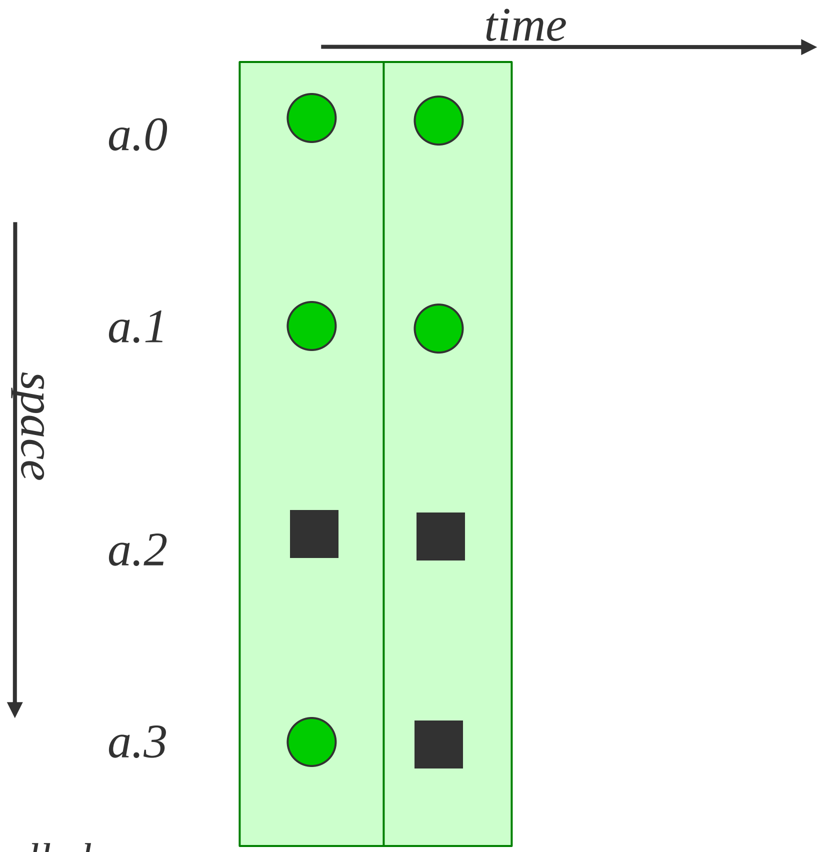
laptop suspended

computer address reassigned

probe or reply lost

firewall enabled

Outages from Ambiguous Signals



(blocks: really have
256 addresses, we show 4 here)

challenge: a ping is ambiguous

single negative:
address is down

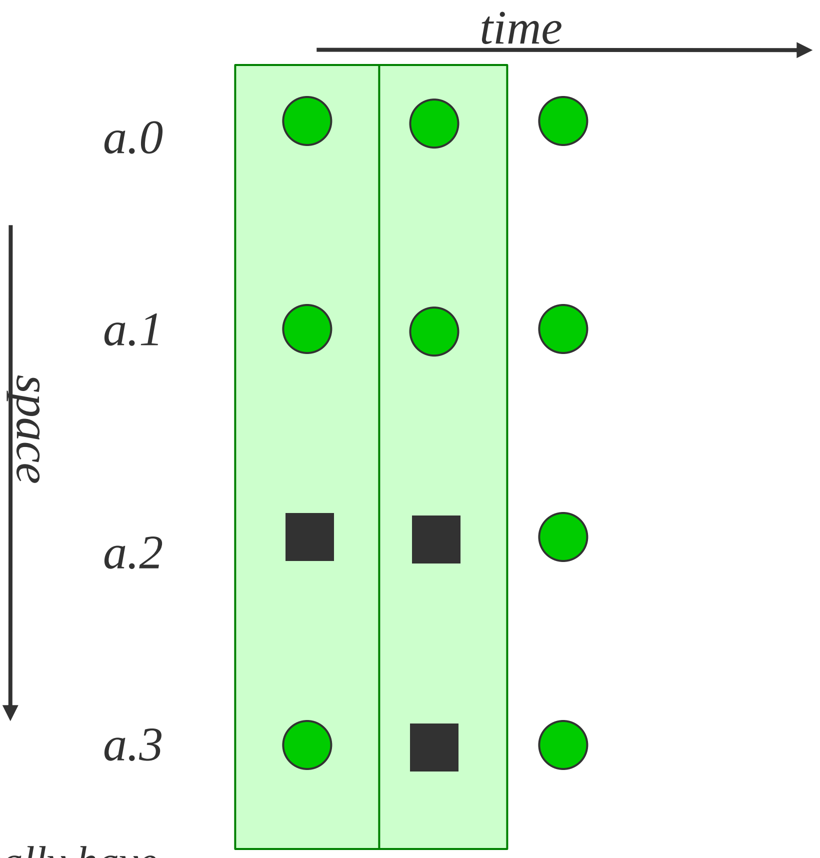
or

computer crashed
laptop suspended

computer address reassigned

probe or reply lost
firewall enabled

Outages from Ambiguous Signals



(blocks: really have 256 addresses, we show 4 here)

challenge: a ping is ambiguous

single negative: address is down

or

computer crashed

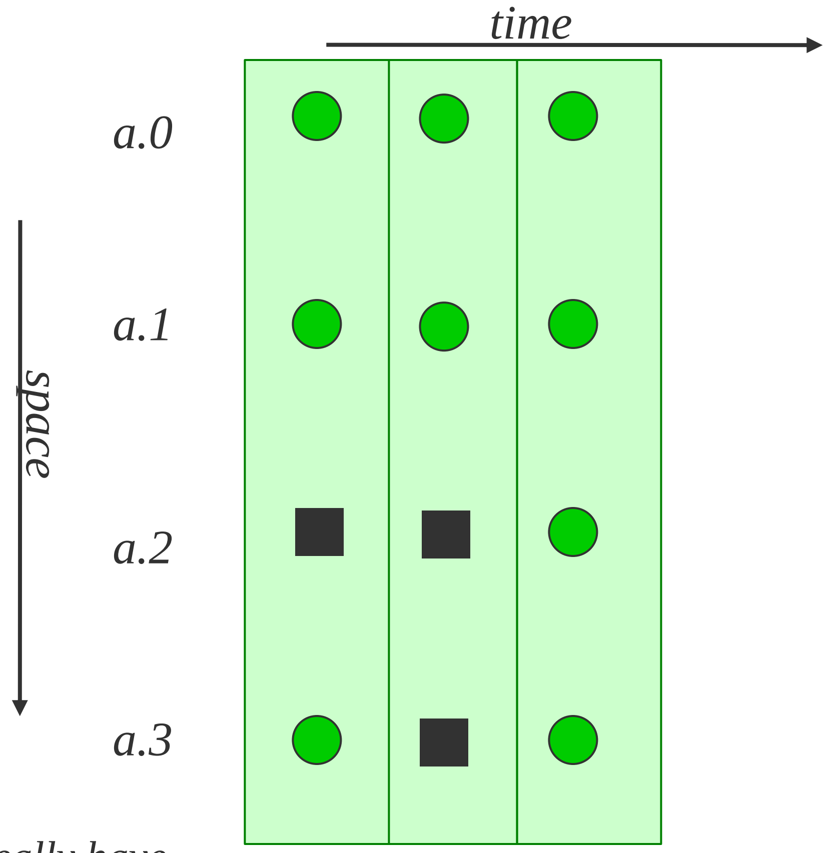
laptop suspended

computer address reassigned

probe or reply lost

firewall enabled

Outages from Ambiguous Signals



(blocks: really have 256 addresses, we show 4 here)

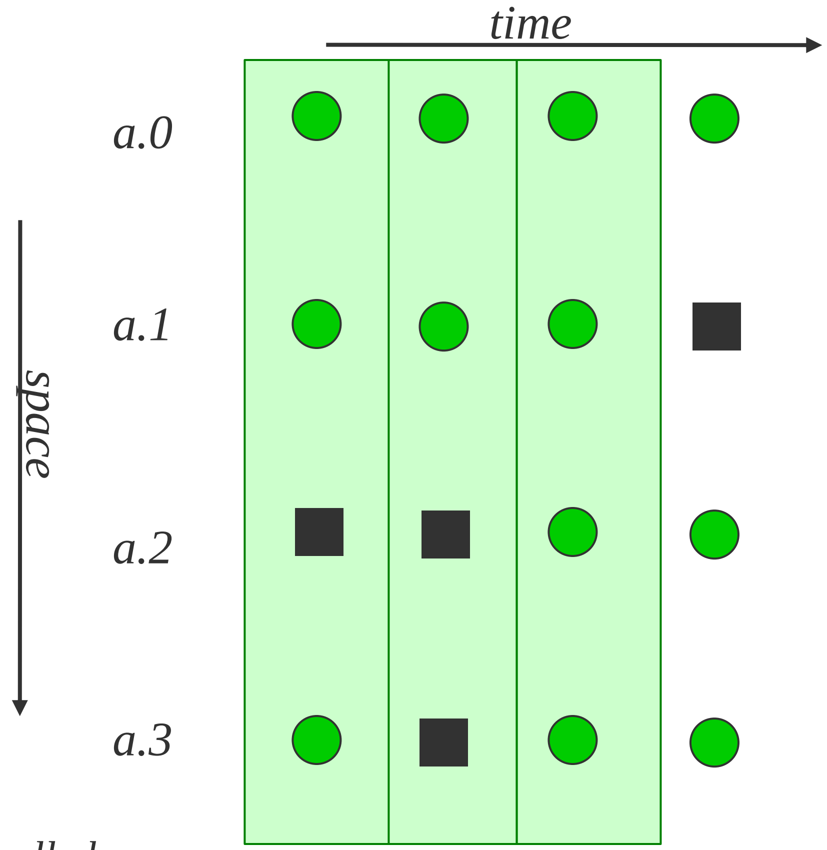
challenge: a ping is ambiguous

single negative:
address is down

or
computer crashed
laptop suspended

computer address reassigned
probe or reply lost
firewall enabled

Outages from Ambiguous Signals

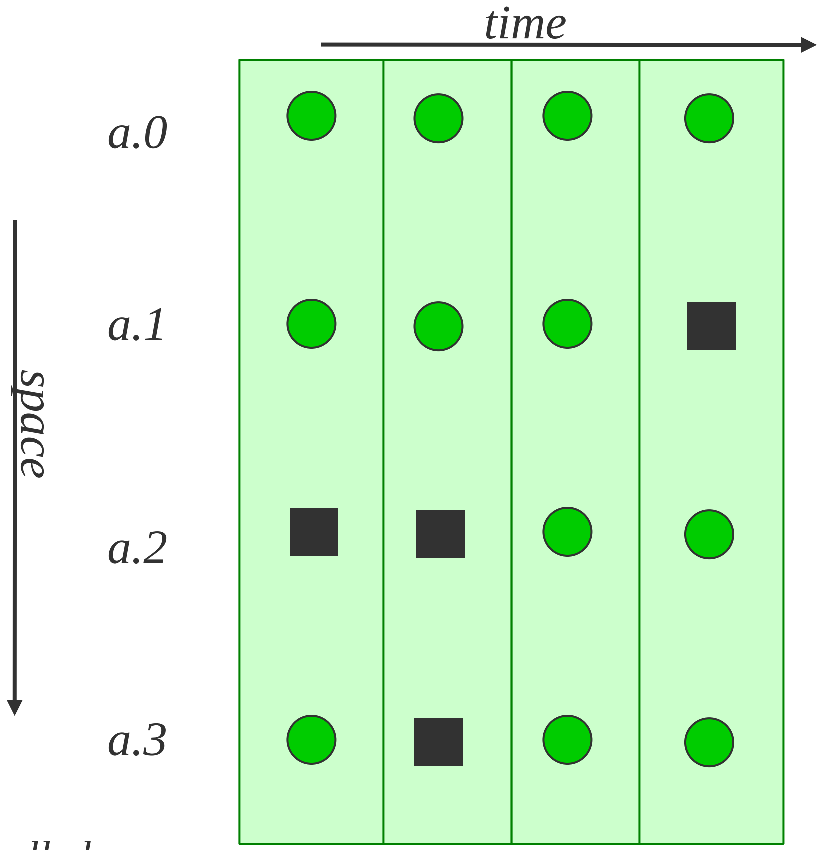


(blocks: really have 256 addresses, we show 4 here)

challenge: a ping is ambiguous

single negative:
address is down
or
computer crashed
laptop suspended
computer address reassigned
probe or reply lost
firewall enabled

Outages from Ambiguous Signals



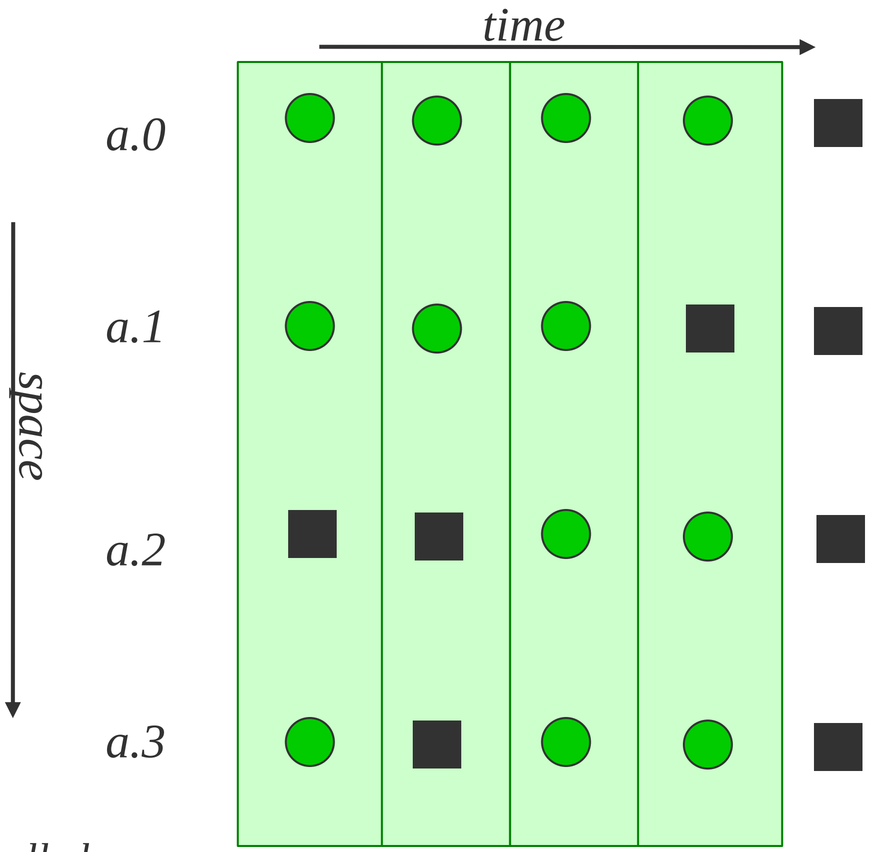
a.0	●	●	●	●
a.1	●	●	●	■
a.2	■	■	●	●
a.3	●	■	●	●

(blocks: really have 256 addresses, we show 4 here)

challenge: a ping is ambiguous

single negative:
address is down
or
computer crashed
laptop suspended
computer address reassigned
probe or reply lost
firewall enabled

Outages from Ambiguous Signals



(blocks: really have
256 addresses, we show 4 here)

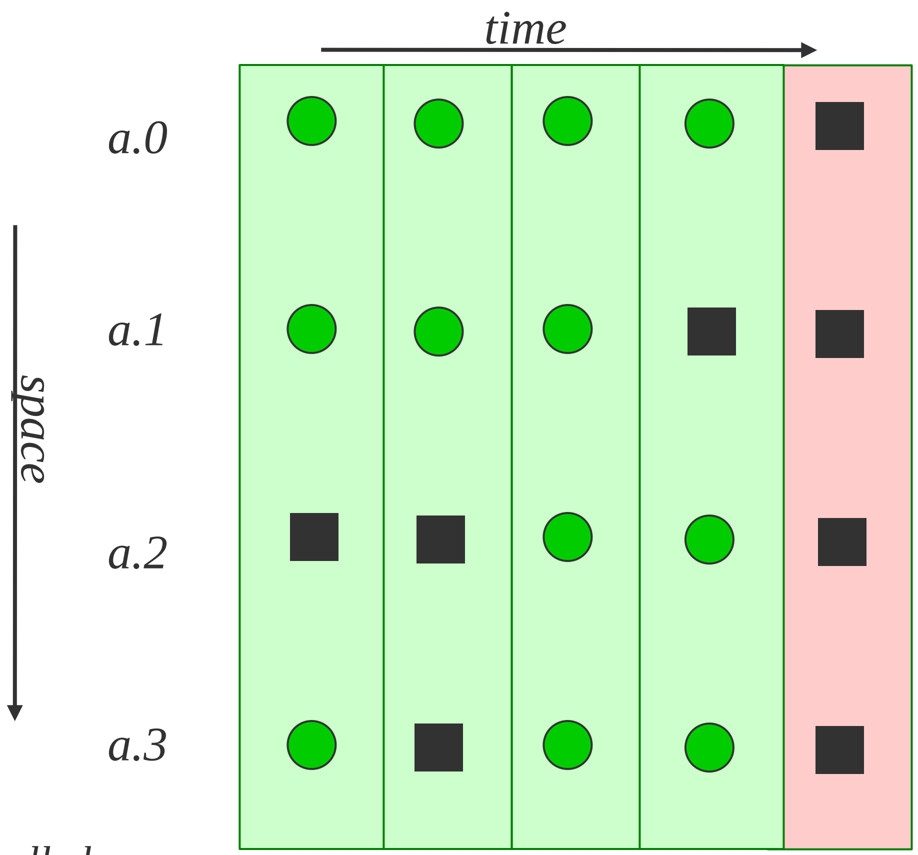
challenge: a ping is ambiguous

single negative:
address is down

or

computer crashed
laptop suspended
computer address reassigned
probe or reply lost
firewall enabled

Outages from Ambiguous Signals



(blocks: really have
256 addresses, we show 4 here)

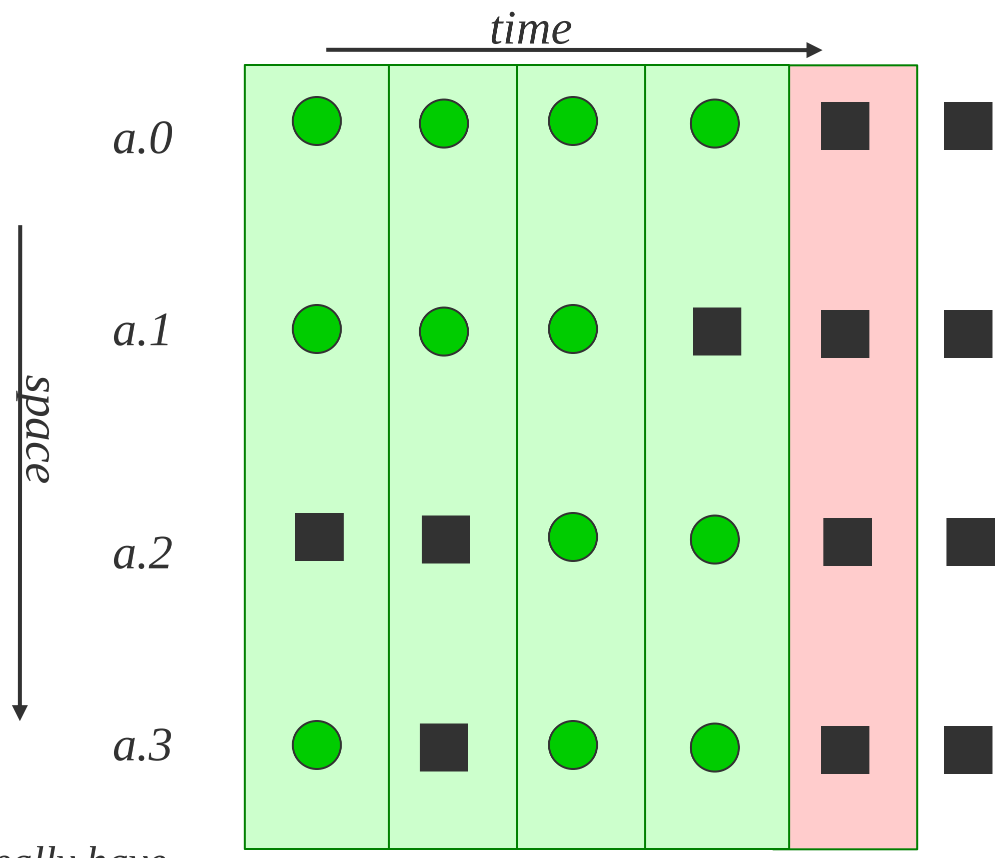
challenge: a ping is ambiguous

single negative:
address is down

or
computer crashed
laptop suspended

computer address reassigned
probe or reply lost
firewall enabled

Outages from Ambiguous Signals



(blocks: really have 256 addresses, we show 4 here)

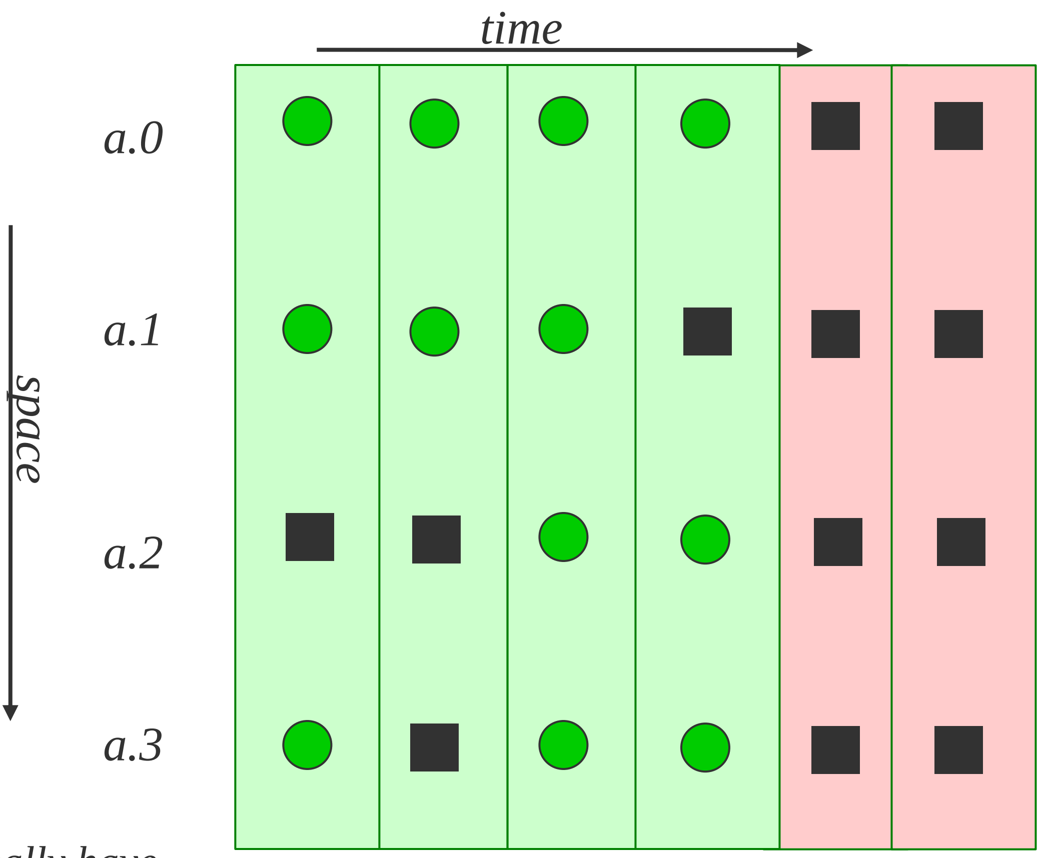
challenge: a ping is ambiguous

single negative:
address is down

or
computer crashed
laptop suspended

computer address reassigned
probe or reply lost
firewall enabled

Outages from Ambiguous Signals



(blocks: really have 256 addresses, we show 4 here)

challenge: a ping is ambiguous

single negative: address is down

or

computer crashed

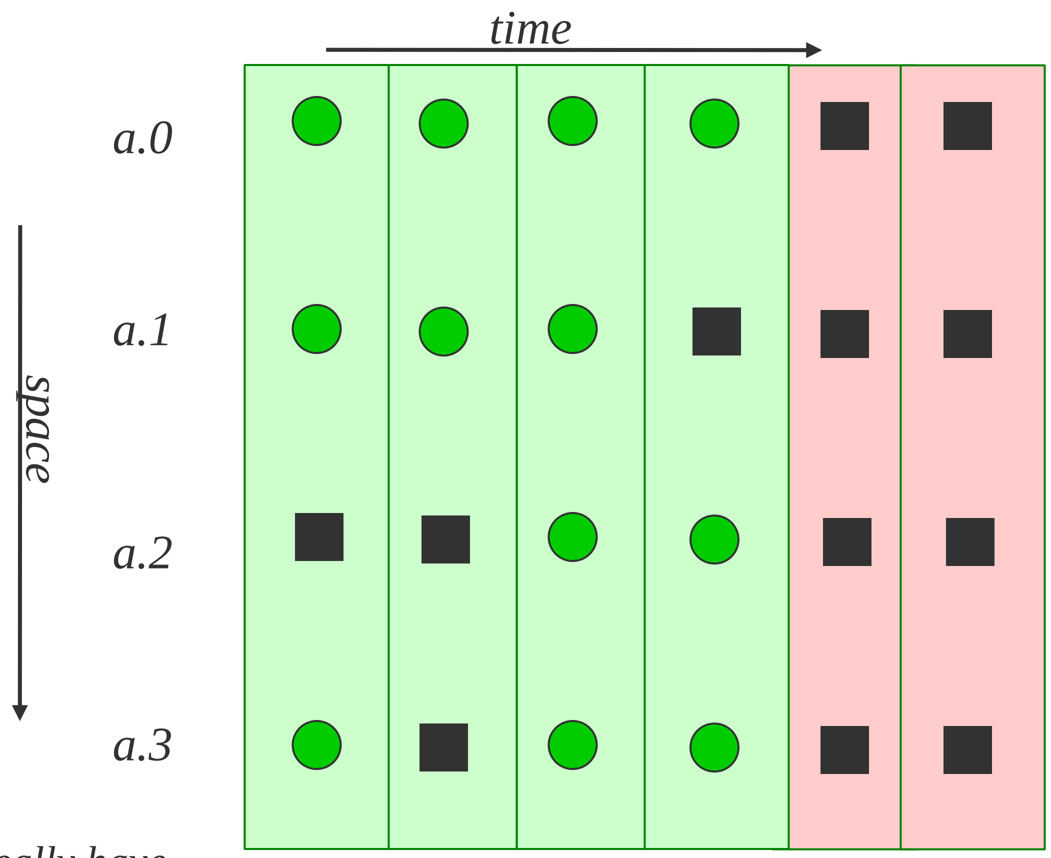
laptop suspended

computer address reassigned

probe or reply lost

firewall enabled

Outages from Ambiguous Signals



a.0	●	●	●	●	■	■
a.1	●	●	●	■	■	■
a.2	■	■	●	●	■	■
a.3	●	■	●	●	■	■

(blocks: really have 256 addresses, we show 4 here)

challenge: a ping is ambiguous

single negative: address is down

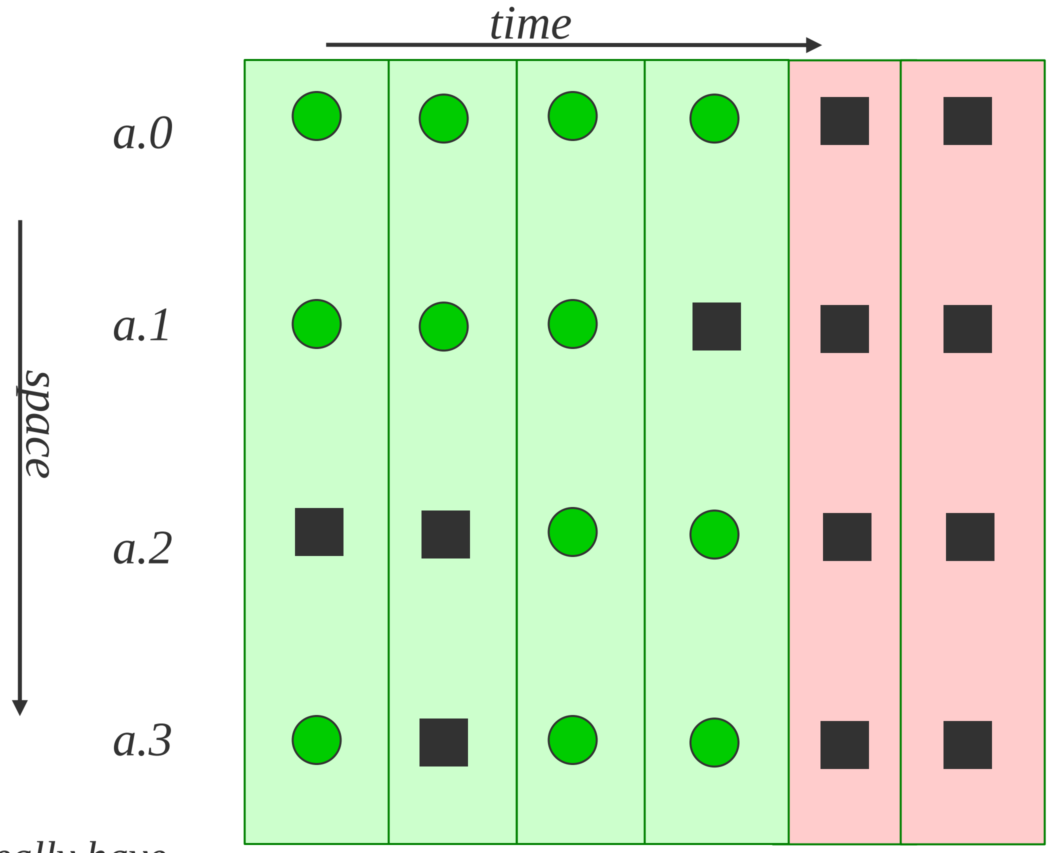
or
computer crashed
laptop suspended

computer address reassigned
probe or reply lost
firewall enabled

***all** negative:*
block is down

!!!

Outages from Ambiguous Signals



(blocks: really have 256 addresses, we show 4 here)

challenge: a ping is ambiguous

single negative: address is down

or

computer crashed
laptop suspended

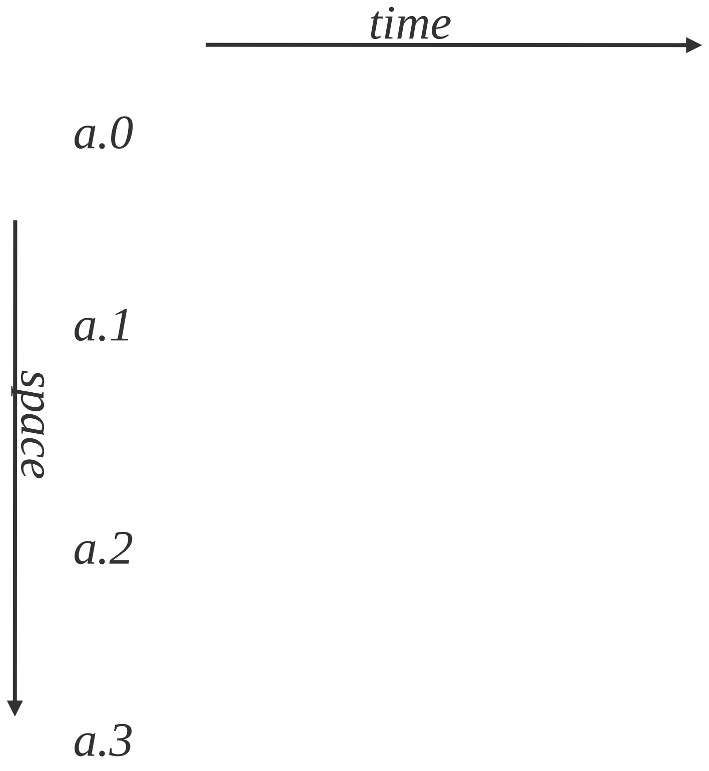
computer address reassigned
probe or reply lost
firewall enabled

multiple probes for reliable block-level signal

***all** negative: block is down*

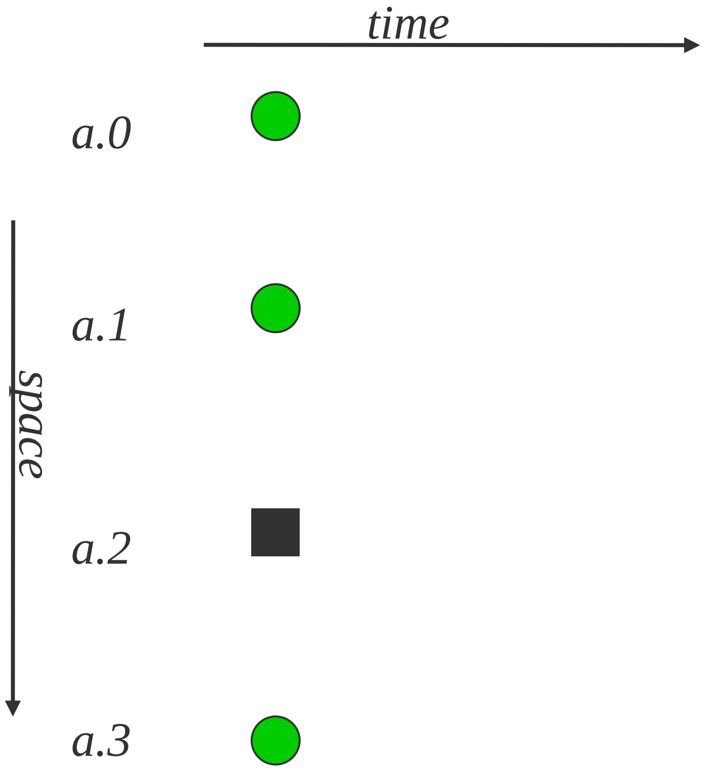
!!!

Probing Politely: *Just Enough*



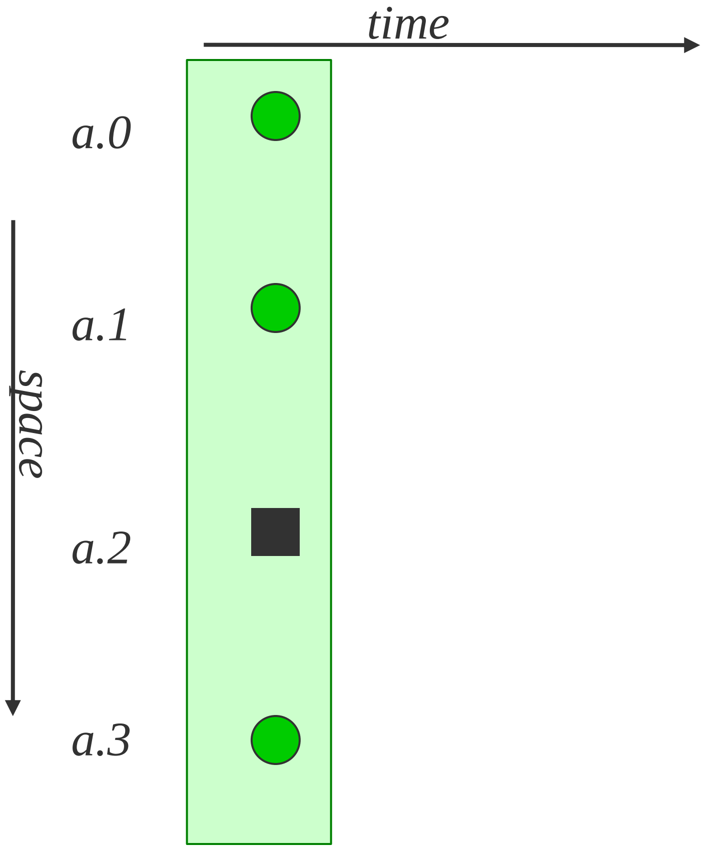
polite: minimal traffic to your net

Probing Politely: *Just Enough*



polite: minimal traffic to your net

Probing Politely: *Just Enough*

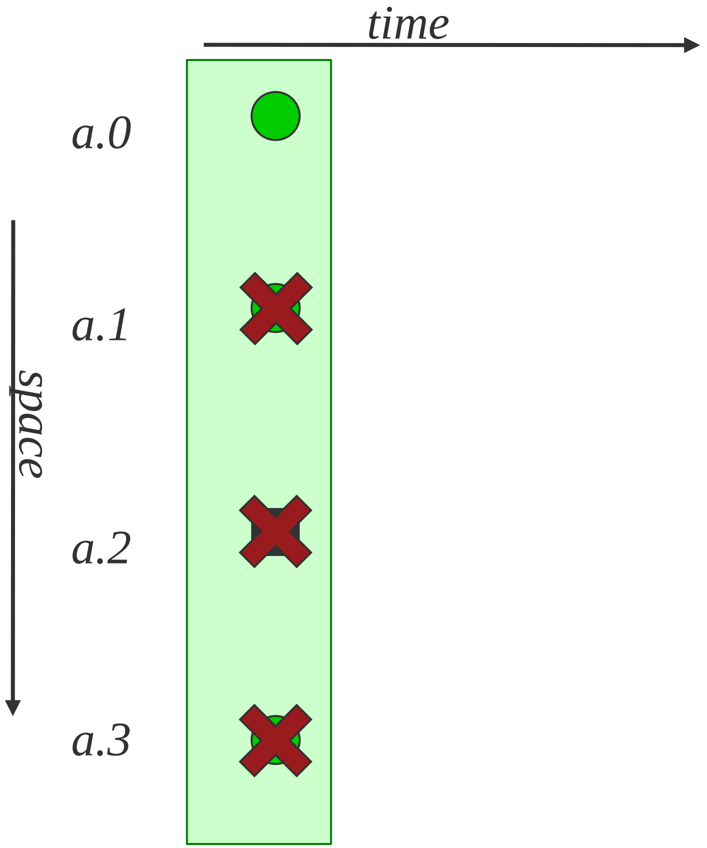


polite: minimal traffic to your net

positive responses => block is up

but don't need all 4 to learn

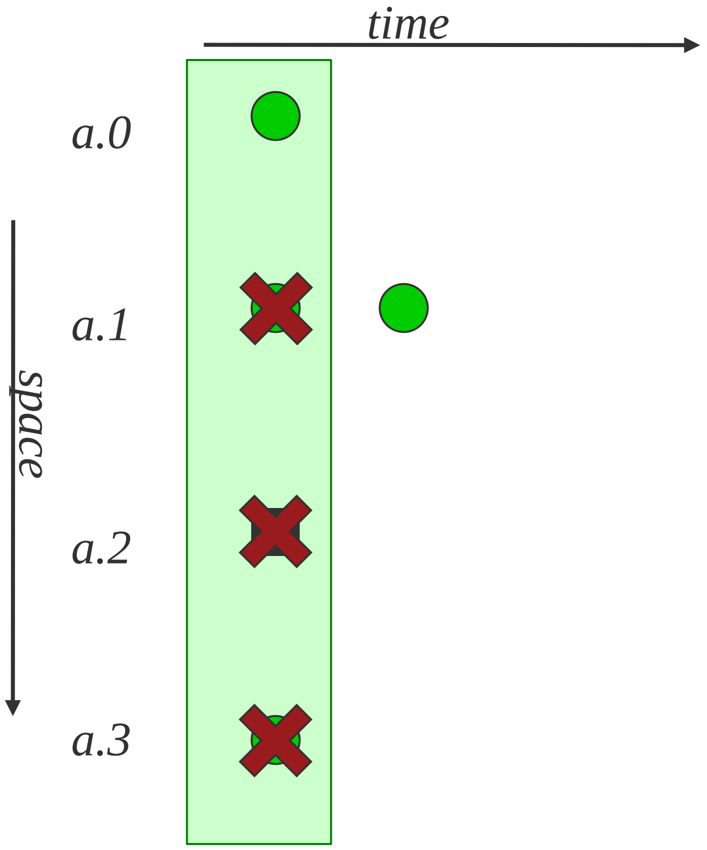
Probing Politely: *Just Enough*



polite: minimal traffic to your net

positive responses => block is up
but don't need all 4 to learn

Probing Politely: *Just Enough*

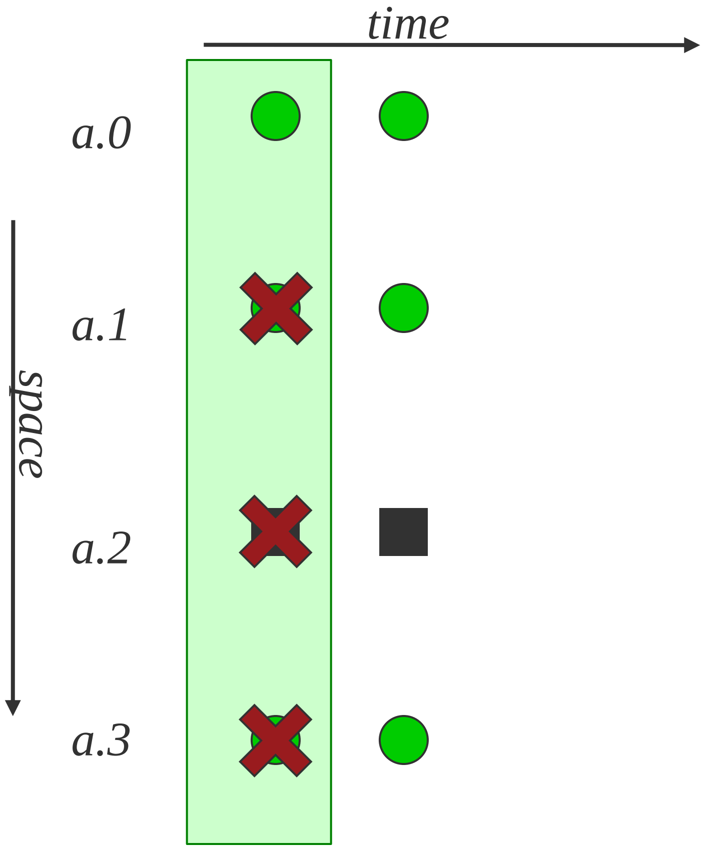


polite: minimal traffic to your net

positive responses => block is up
but don't need all 4 to learn

1. instead: probe one by one
2. find **one is up**

Probing Politely: *Just Enough*

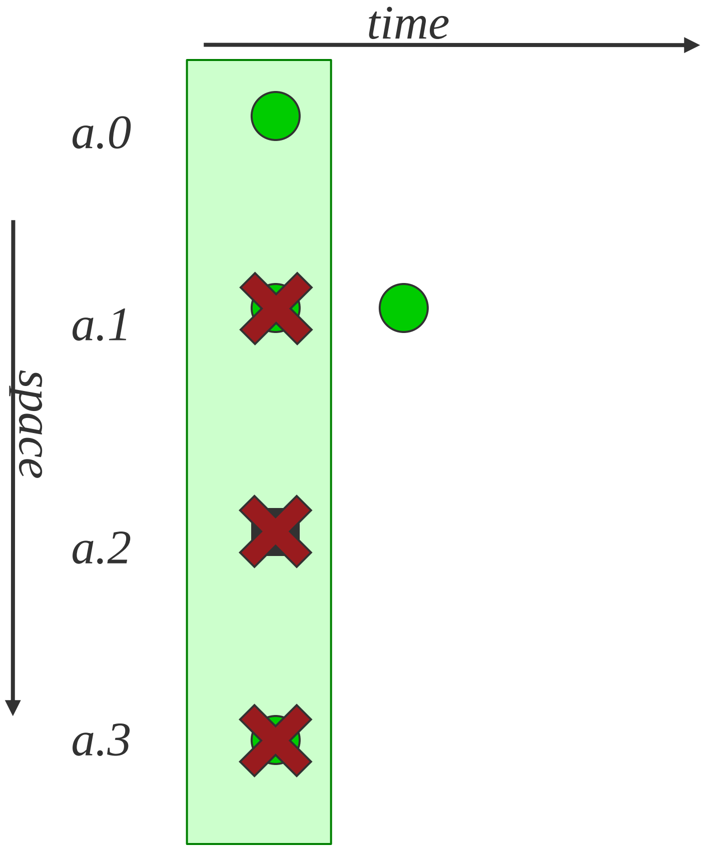


polite: minimal traffic to your net

positive responses => block is up
but don't need all 4 to learn

1. instead: probe one by one
2. find **one is up**

Probing Politely: *Just Enough*

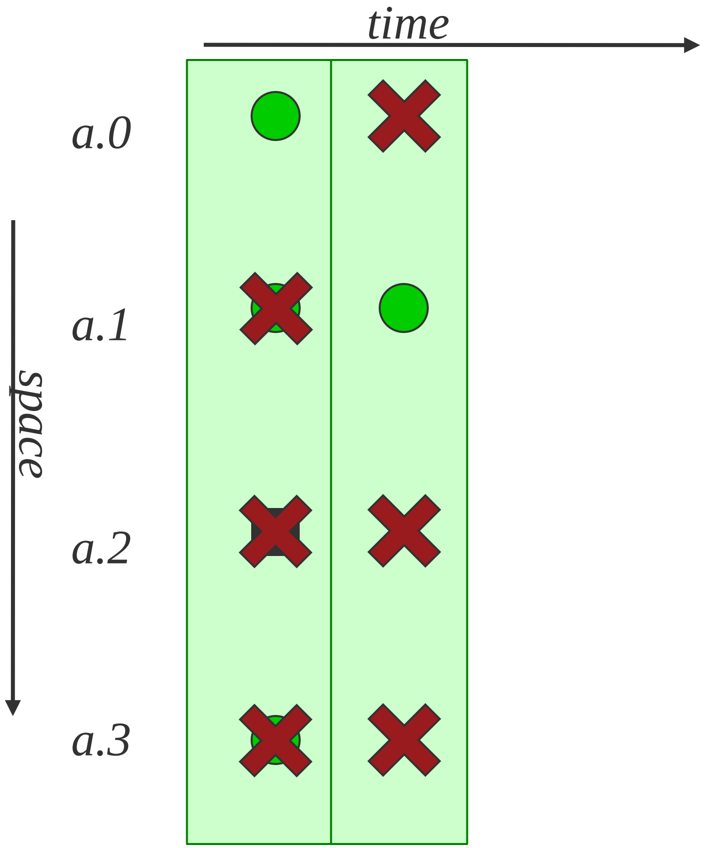


polite: minimal traffic to your net

positive responses => block is up
but don't need all 4 to learn

1. instead: probe one by one
2. find **one is up**

Probing Politely: *Just Enough*

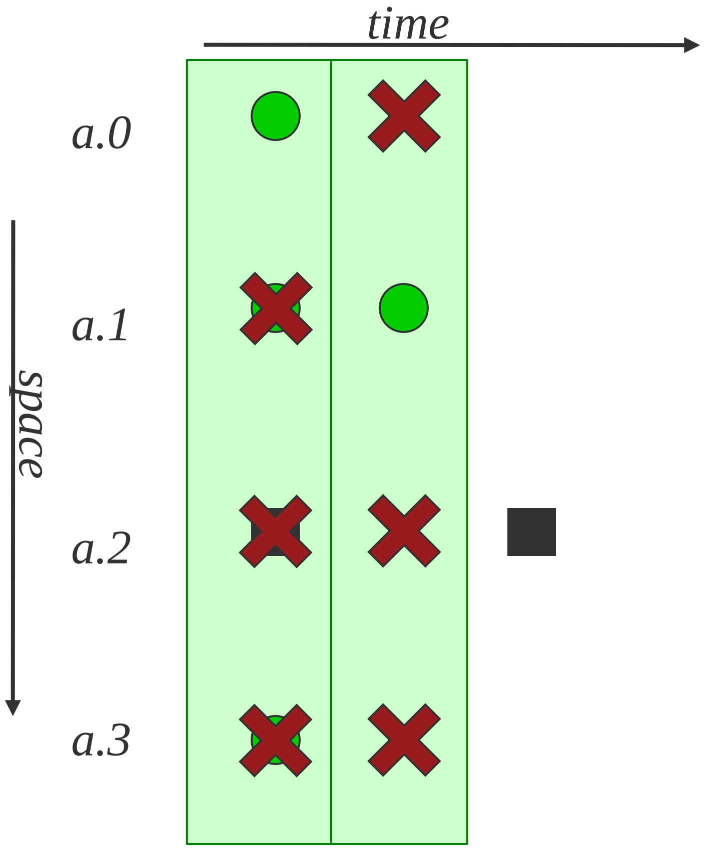


polite: minimal traffic to your net

positive responses => block is up
but don't need all 4 to learn

1. instead: probe one by one
2. find **one is up** => **stop early**

Probing Politely: *Just Enough*

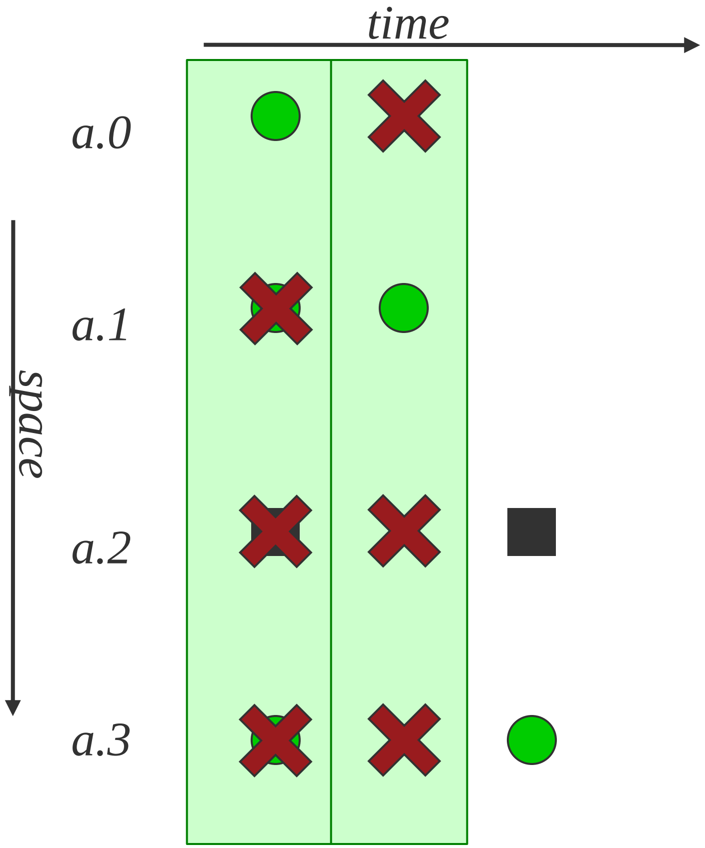


polite: minimal traffic to your net

positive responses => block is up
but don't need all 4 to learn

1. instead: probe one by one
2. find **one is up** => **stop early**
3. if **try is down**

Probing Politely: *Just Enough*

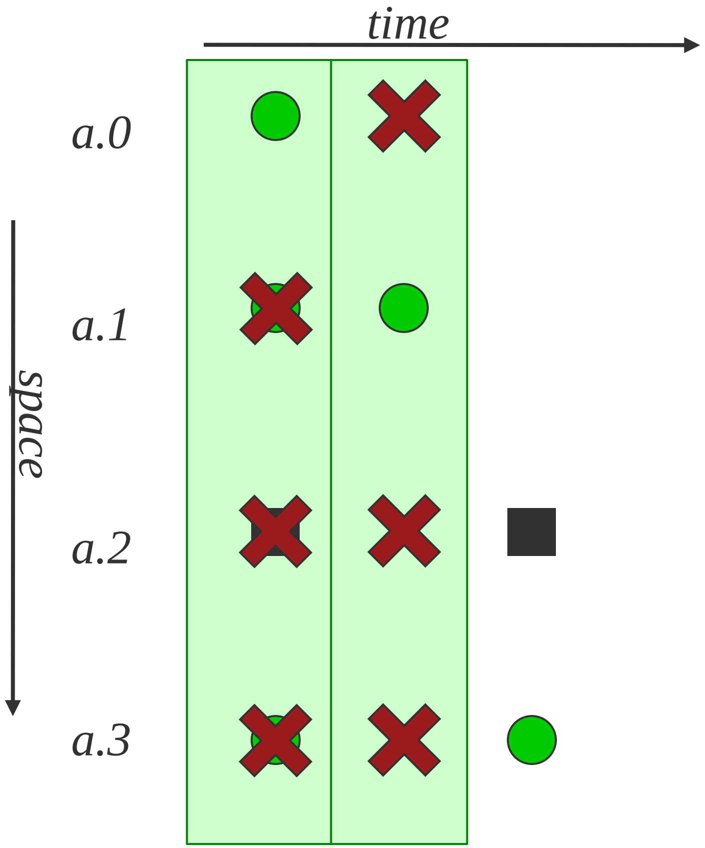


polite: minimal traffic to your net

positive responses => block is up
but don't need all 4 to learn

1. instead: probe one by one
2. find **one is up** => **stop early**
3. if **try is down** => **try again**

Probing Politely: *Just Enough*



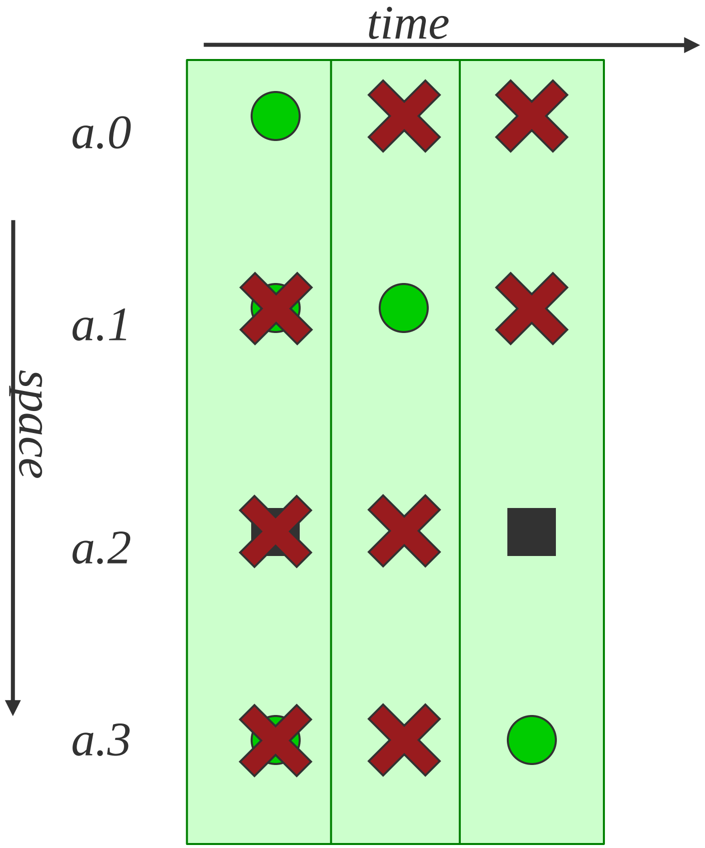
polite: minimal traffic to your net

positive responses => block is up
but don't need all 4 to learn

1. instead: probe one by one
2. find **one is up** => **stop early**
3. if **try is down** => **try again**

=> **stop less early**

Probing Politely: *Just Enough*



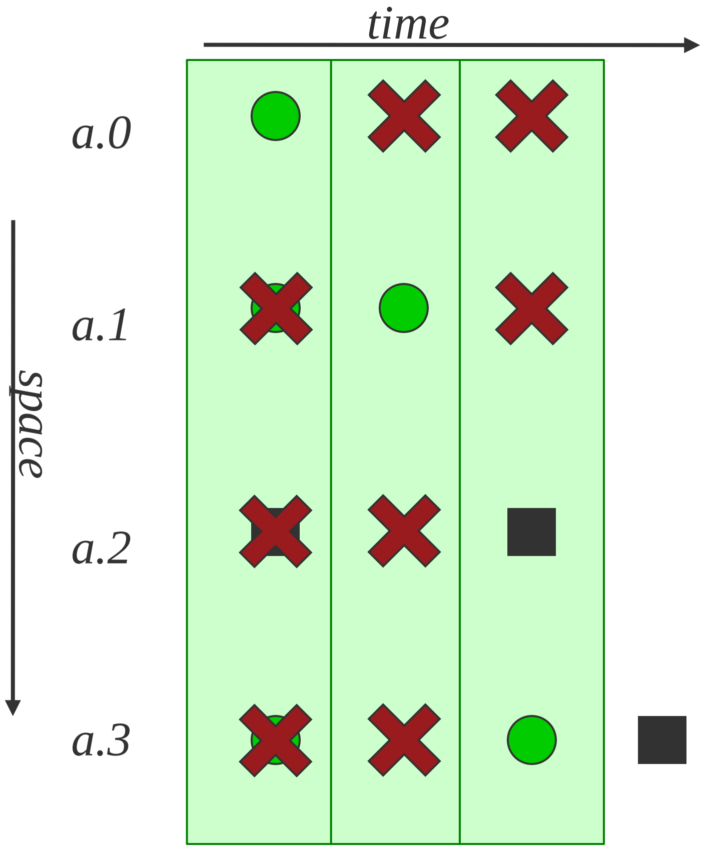
polite: minimal traffic to your net

positive responses => block is up
but don't need all 4 to learn

1. instead: probe one by one
2. find **one is up** => **stop early**
3. if **try is down** => **try again**

=> **stop less early**

Probing Politely: *Just Enough*

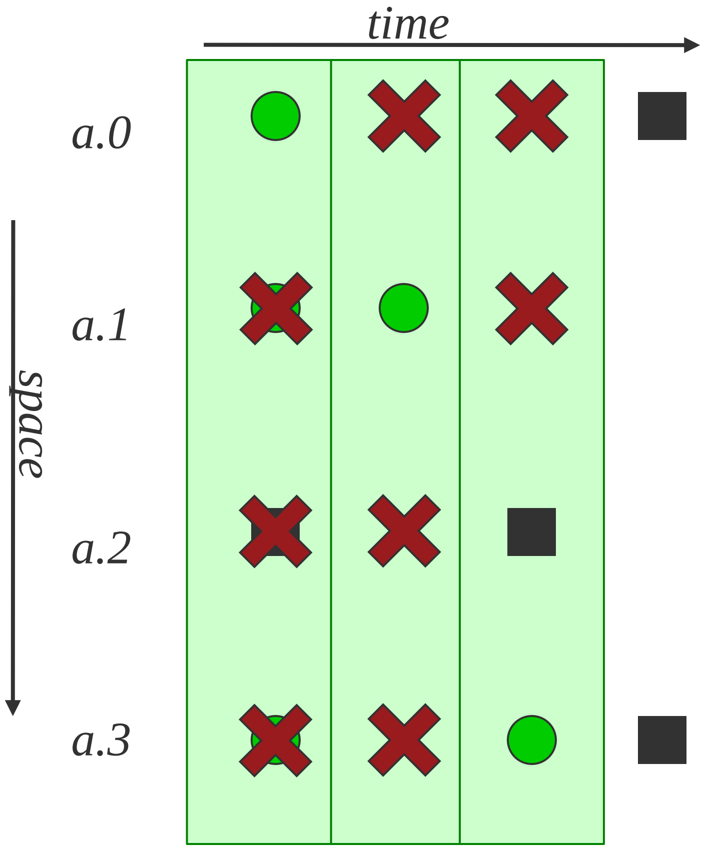


polite: minimal traffic to your net

positive responses => block is up
but don't need all 4 to learn

1. instead: probe one by one
2. find **one is up** => **stop early**
3. if **try is down** => **try again**
   => **stop less early**
4. **several fail**

Probing Politely: *Just Enough*

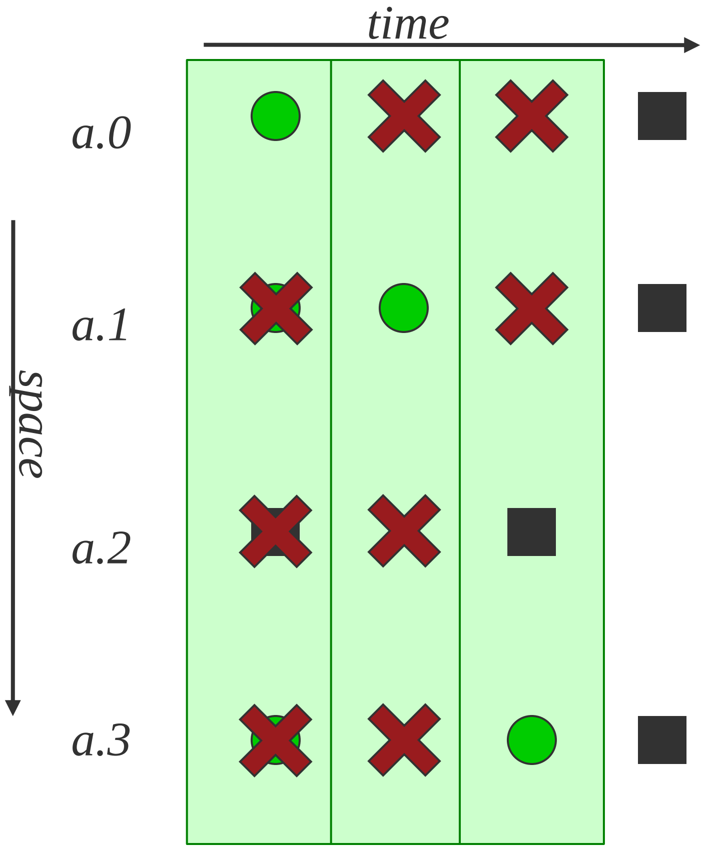


polite: minimal traffic to your net

positive responses => block is up
but don't need all 4 to learn

1. instead: probe one by one
2. find **one is up** => **stop early**
3. if **try is down** => **try again**
   => **stop less early**
4. **several fail**

Probing Politely: *Just Enough*

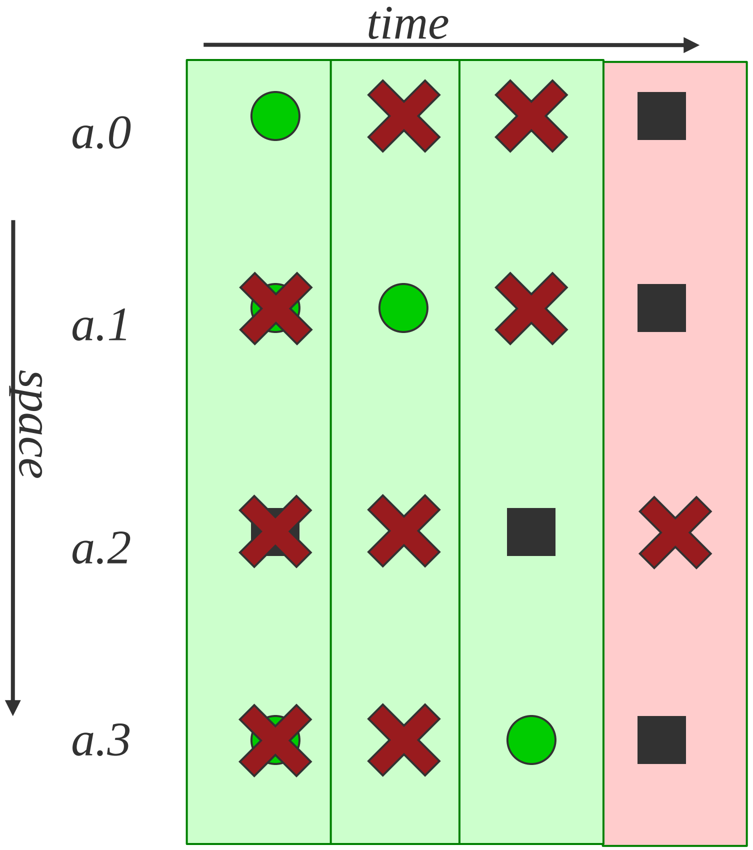


polite: minimal traffic to your net

positive responses => block is up
but don't need all 4 to learn

1. instead: probe one by one
2. find **one is up** => **stop early**
3. if **try is down** => **try again**
   => **stop less early**
4. **several fail**

Probing Politely: *Just Enough*

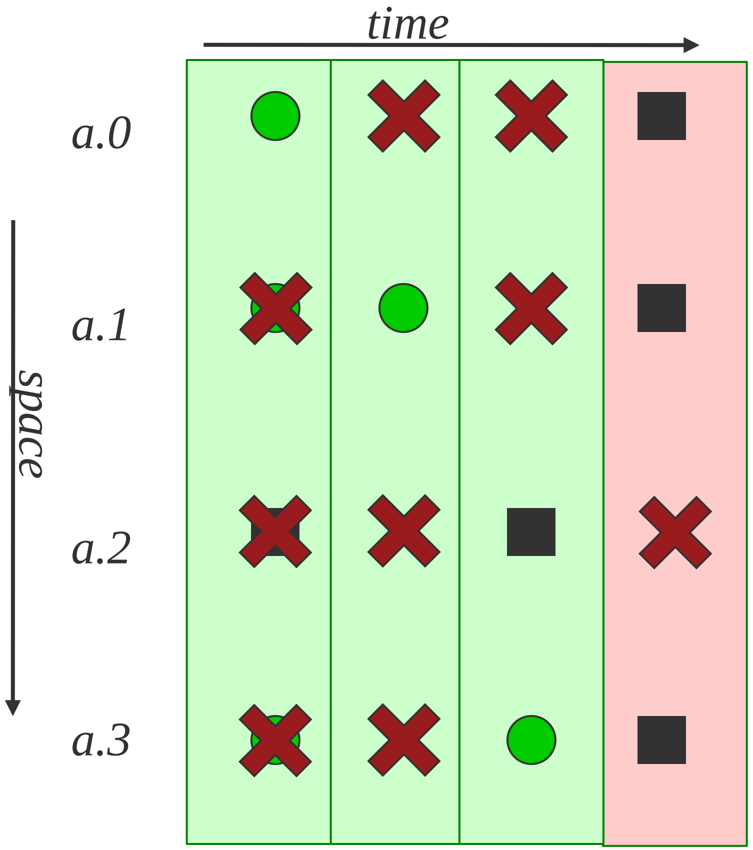


polite: minimal traffic to your net

positive responses => block is up
but don't need all 4 to learn

1. instead: probe one by one
2. find **one is up** => **stop early**
3. if **try is down** => **try again**
=> **stop less early**
4. **several fail** => **block down**

Probing Politely: *Just Enough*



polite: minimal traffic to your net

positive responses => block is up

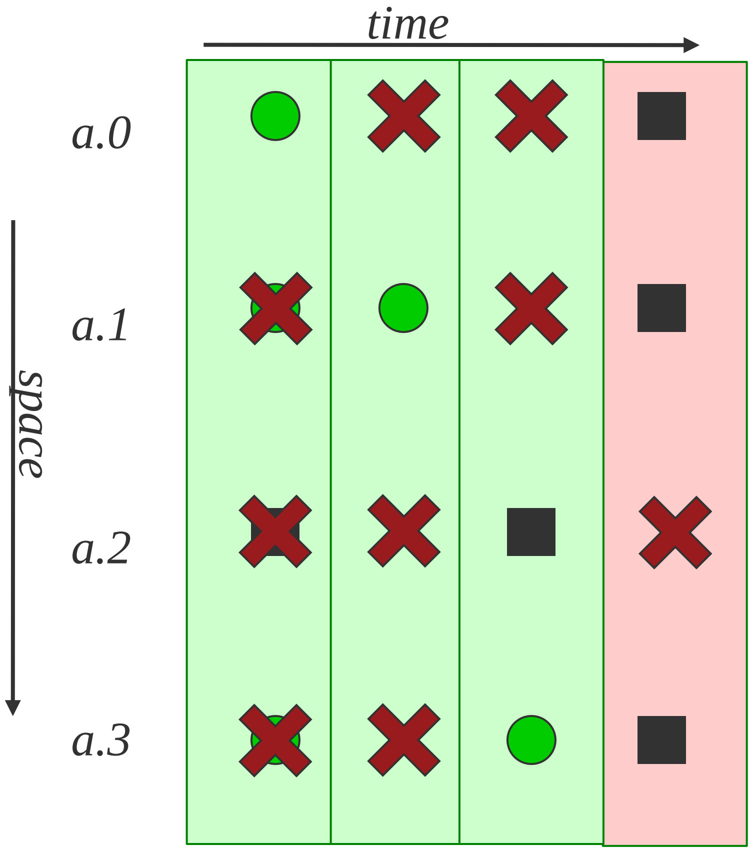
but don't need all 4 to learn

1. instead: probe one by one
2. find **one is up** => **stop early**
3. if **try is down** => **try again**

   => **stop less early**
4. **several fail** => **block down**

adaptive probing uses Bayesian inference informed by model of block response

Probing Politely: *Just Enough*



polite: minimal traffic to your net

positive responses => block is up
but don't need all 4 to learn

1. instead: probe one by one
2. find **one is up** => **stop early**
3. if **try is down** => **try again**
   => **stop less early**
4. **several fail** => **block down**

adaptive probing uses Bayesian inference informed by model of block response

probing politely => observing without harm

Trinocular Outage Detection: Key Properties

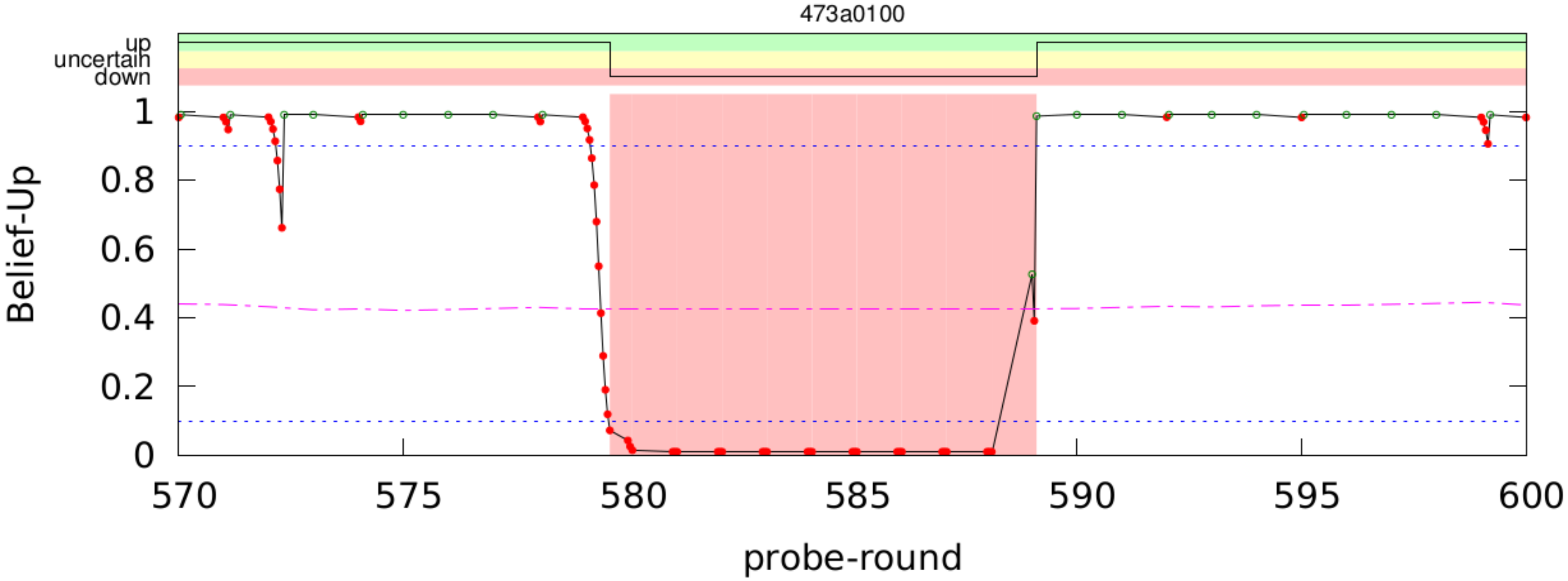
- Trinocular: active probing to detect Internet edge outages
  - **principled**: probe only when needed (informed by Bayesian inference)
  - **precise**: outage duration ±330s (half of probing interval)
  - **parsimonious**: only +0.7% background radiation (at target /24, per Trinocular instance)

(details: “Trinocular: Understanding Internet Reliability Through Adaptive Probing”, Quan, Heidemann, Pradkin, SIGCOMM Aug. 2013)

Principled: Bayesian Inference Interprets Probes

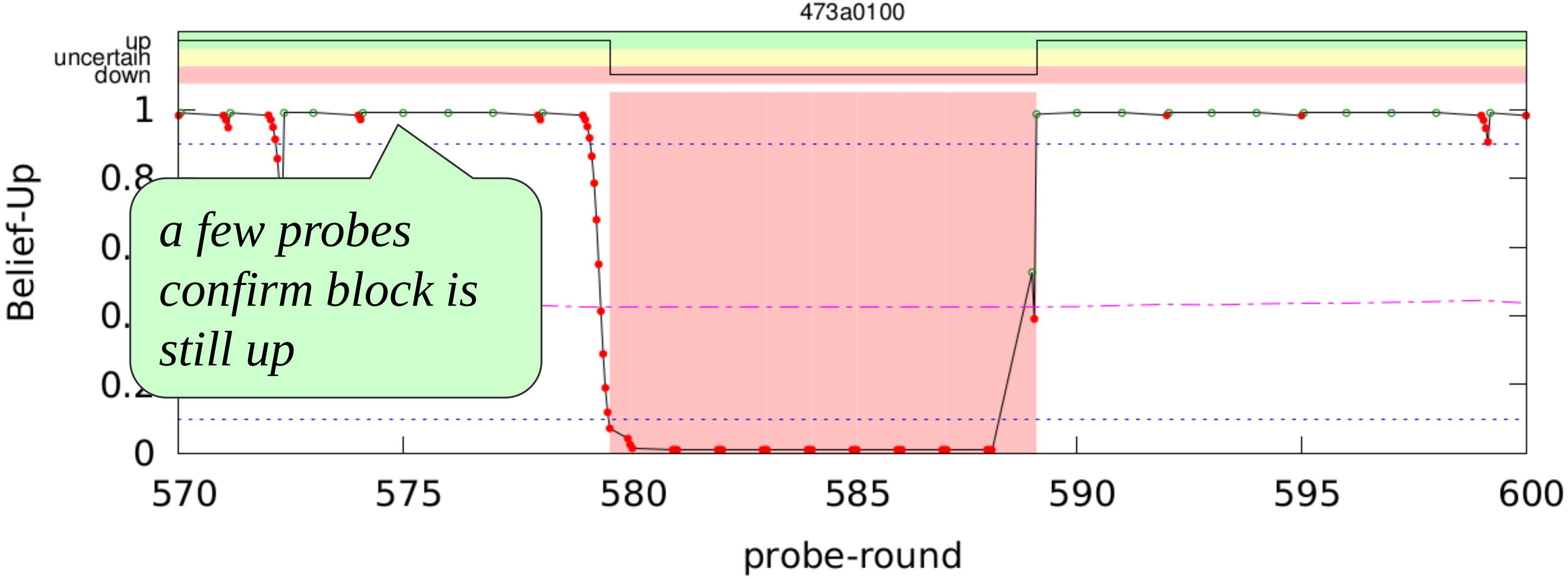
model: every responding |E(b)|=111, active A(E(b))=0.515

this block is sparse but consistent, so *only a few probes needed*



Principled: Bayesian Inference Interprets Probes

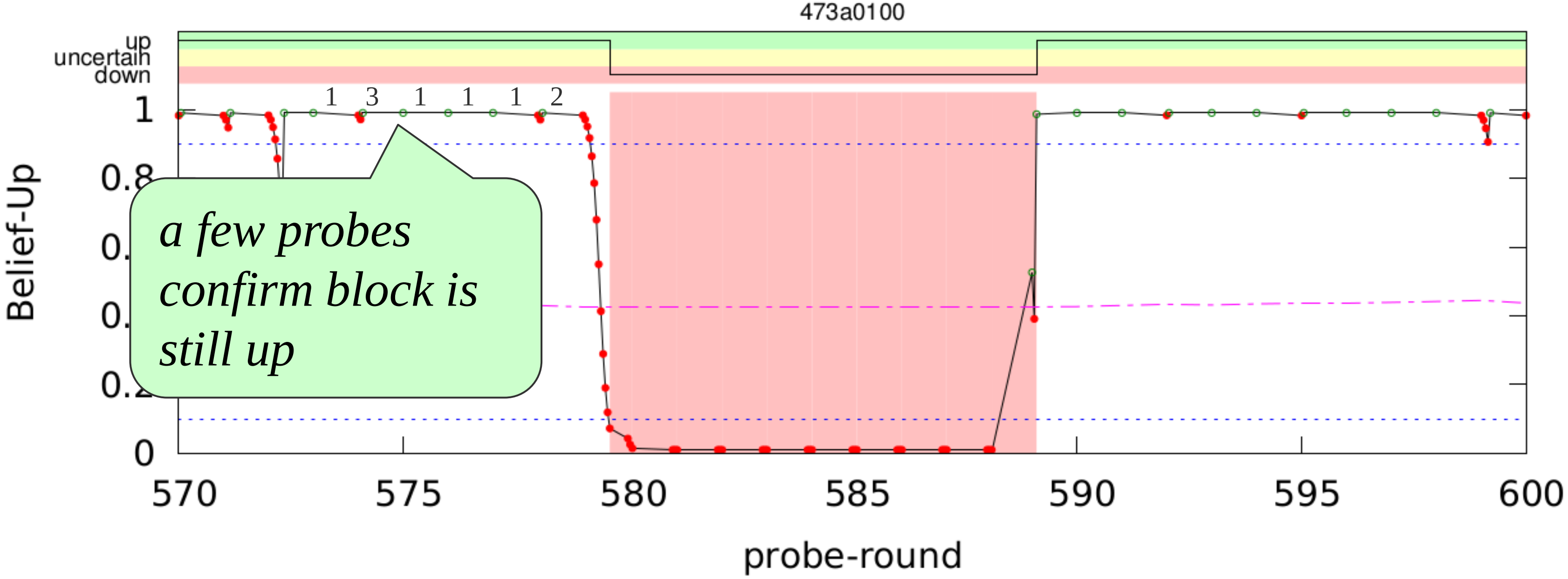
model: every responding |E(b)|=111, active A(E(b))=0.515
this block is sparse but consistent, so *only a few probes needed*



a few probes confirm block is still up

Principled: Bayesian Inference Interprets Probes

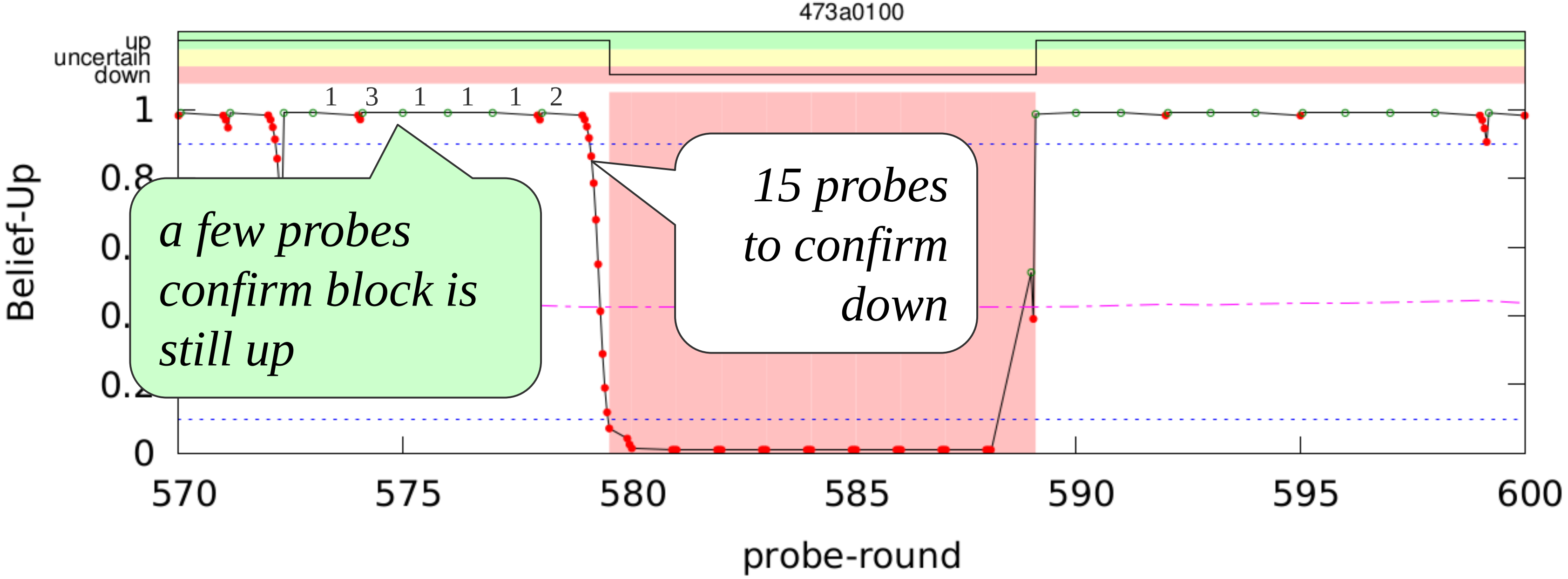
model: every responding |E(b)|=111, active A(E(b))=0.515
this block is sparse but consistent, so *only a few probes needed*



a few probes confirm block is still up

Principled: Bayesian Inference Interprets Probes

model: every responding |E(b)|=111, active A(E(b))=0.515
this block is sparse but consistent, so *only a few probes needed*



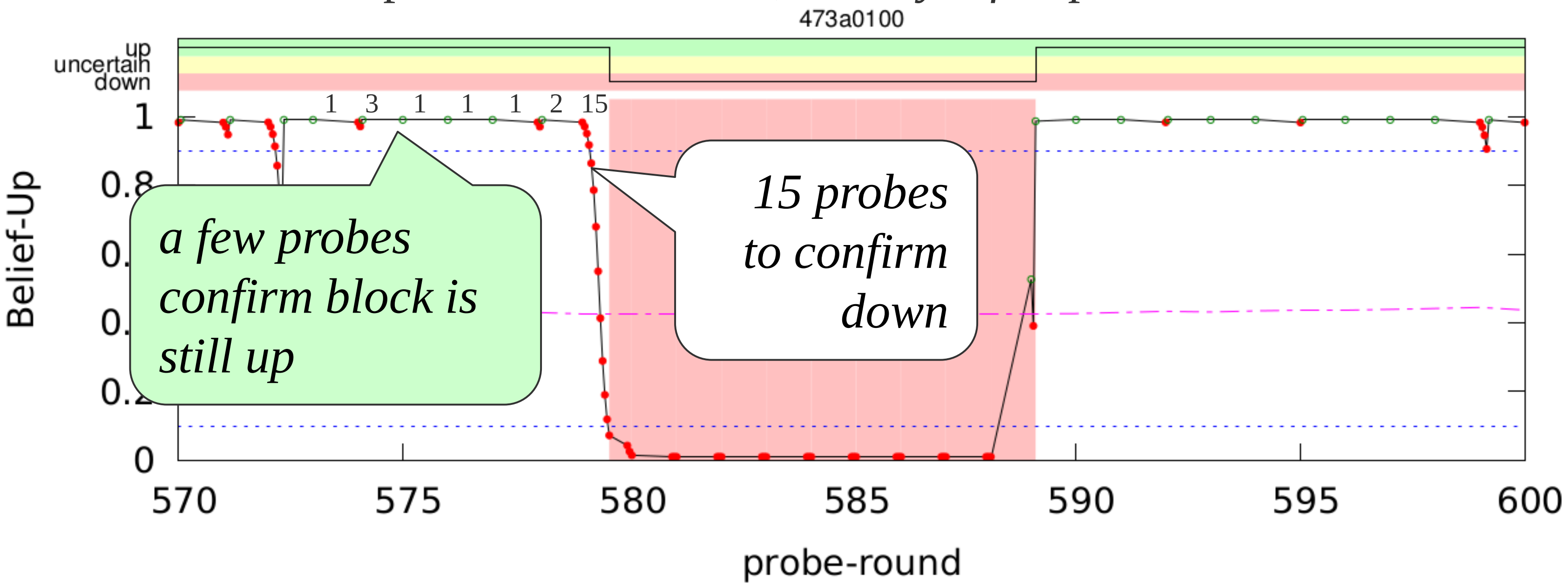
a few probes confirm block is still up

15 probes to confirm down

Principled: Bayesian Inference Interprets Probes

model: every responding |E(b)|=111, active A(E(b))=0.515

this block is sparse but consistent, so *only a few probes needed*



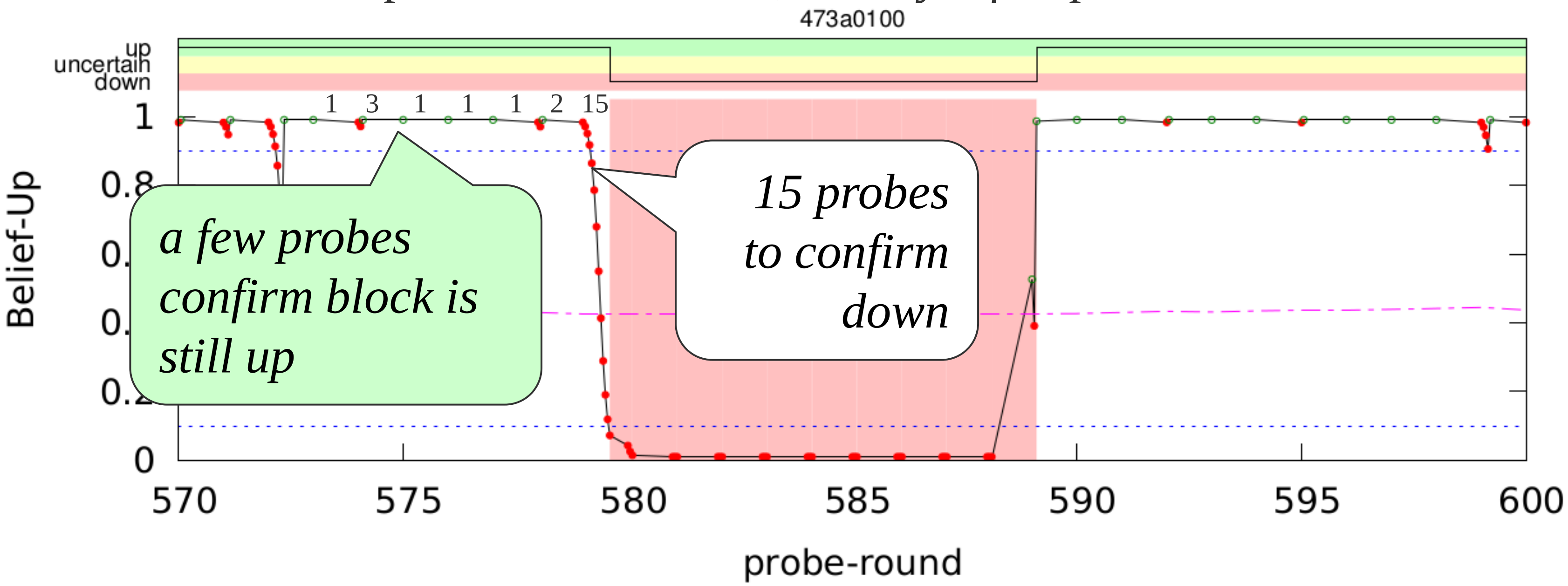
a few probes confirm block is still up

15 probes to confirm down

Principled: Bayesian Inference Interprets Probes

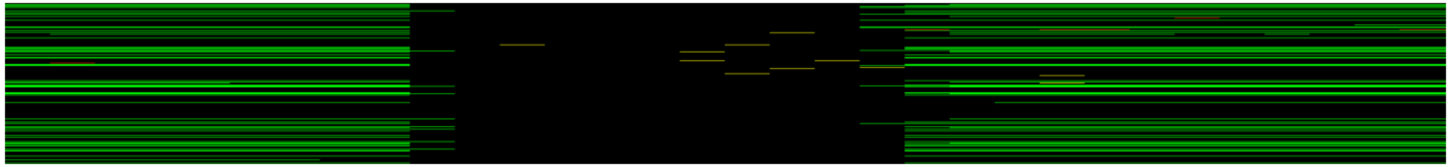
model: every responding |E(b)|=111, active A(E(b))=0.515

this block is sparse but consistent, so *only a few probes needed*



a few probes confirm block is still up

15 probes to confirm down

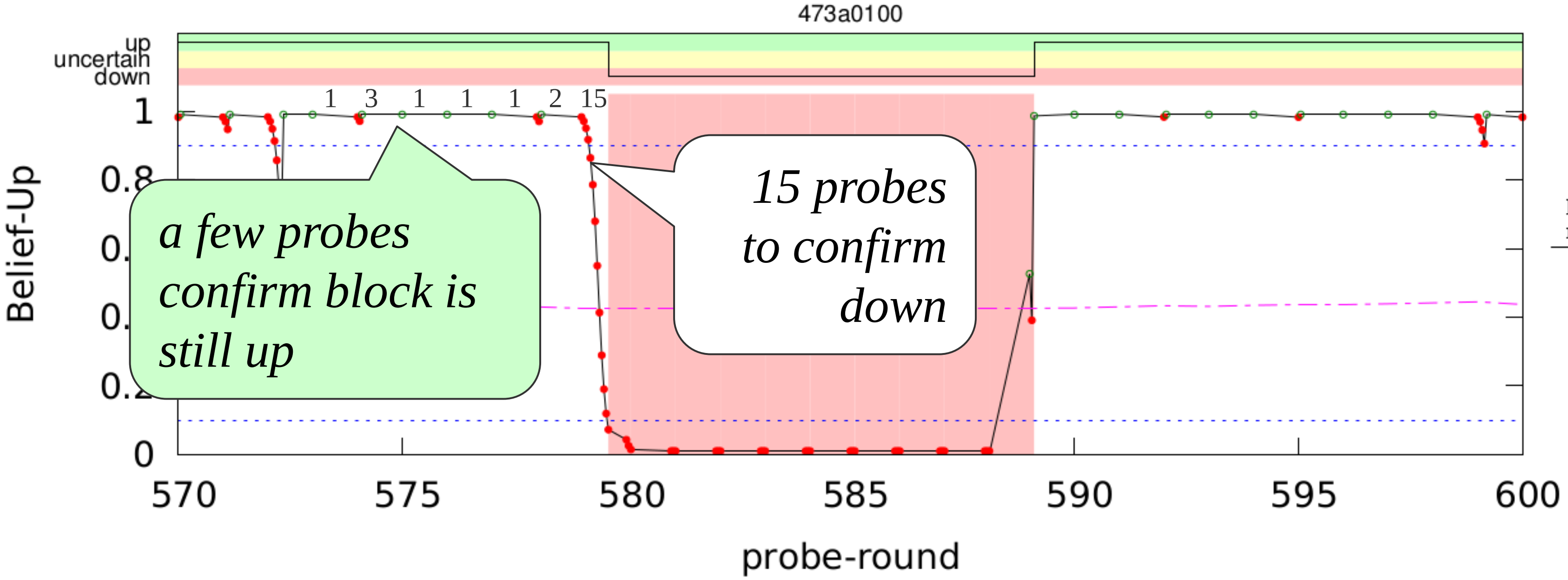


ground truth
(data for complete /24)

Principled: Bayesian Inference Interprets Probes

model: every responding |E(b)|=111, active A(E(b))=0.515

this block is sparse but consistent, so *only a few probes needed*



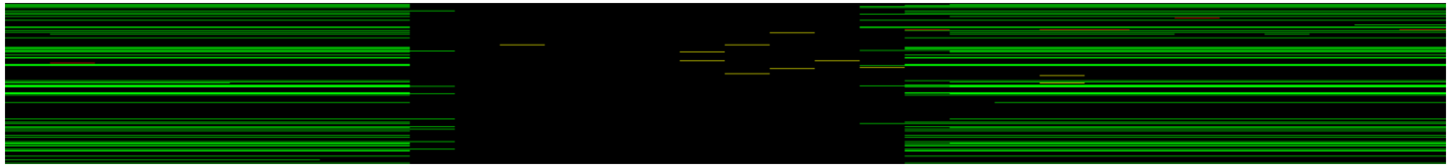
a few probes confirm block is still up

15 probes to confirm down

Modeling + Bayesian Inference says how many probes

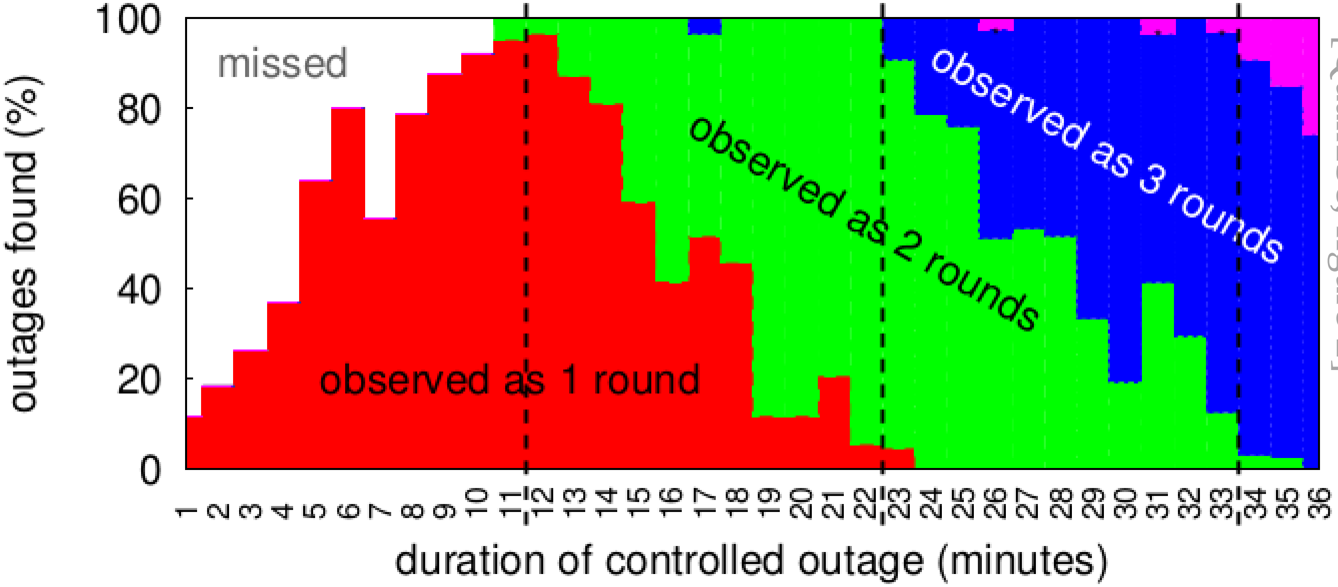
probe result	prior U^*	$P(probe \mid U^*)$	reason
n	U	$1 - A(E(b))$	inactive addr.
p	U	$A(E(b))$	active addr.
n	$\bar{U}$	$1 - (1 - \ell)/\lvert b \rvert$	non-response to block
p	$\bar{U}$	$(1 - \ell)/\lvert b \rvert$	lone router?

$$B'(\bar{U}) = \frac{P(p|\bar{U})B(\bar{U})}{P(p|\bar{U})B(\bar{U}) + P(p|U)B(U)}$$



ground truth
(data for complete /24)

Precise: Detect All Outages?

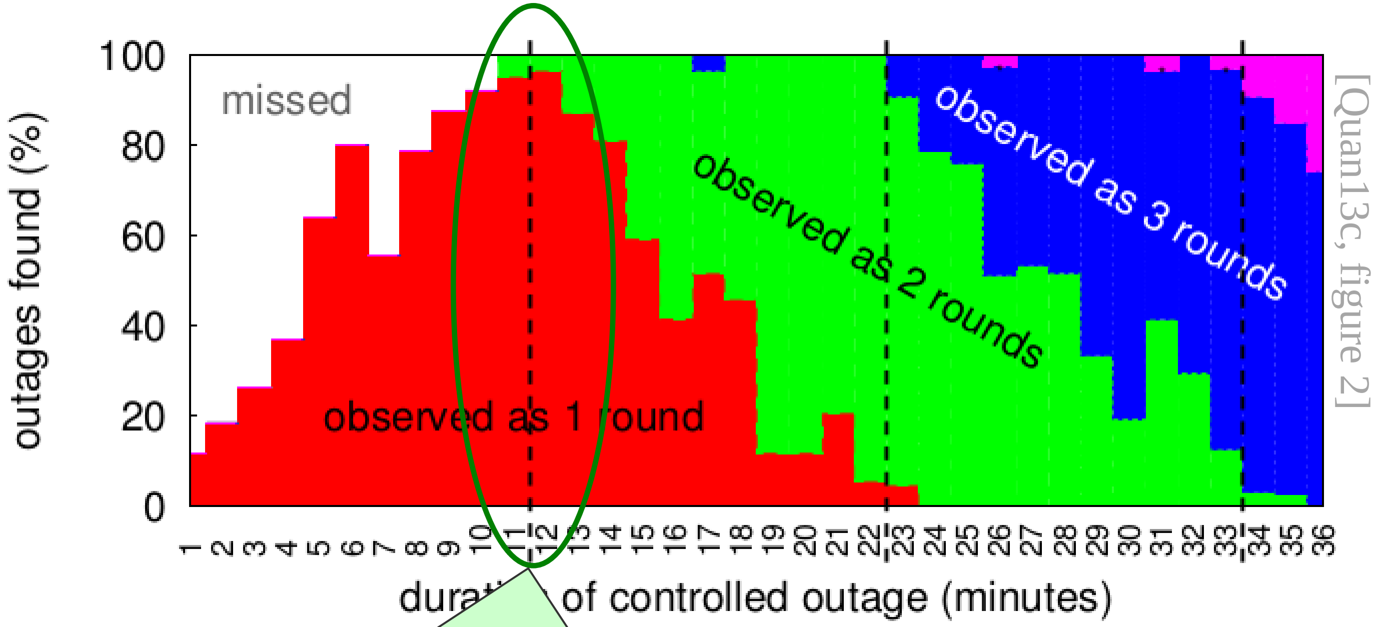


[Quan13c, figure 2]

Experiment:

Controlled outages (random duration, 1 to 36 minutes) in test block, measured from 3 different sites (2 in US, 1 in Japan).

Precise: Detect All Outages?

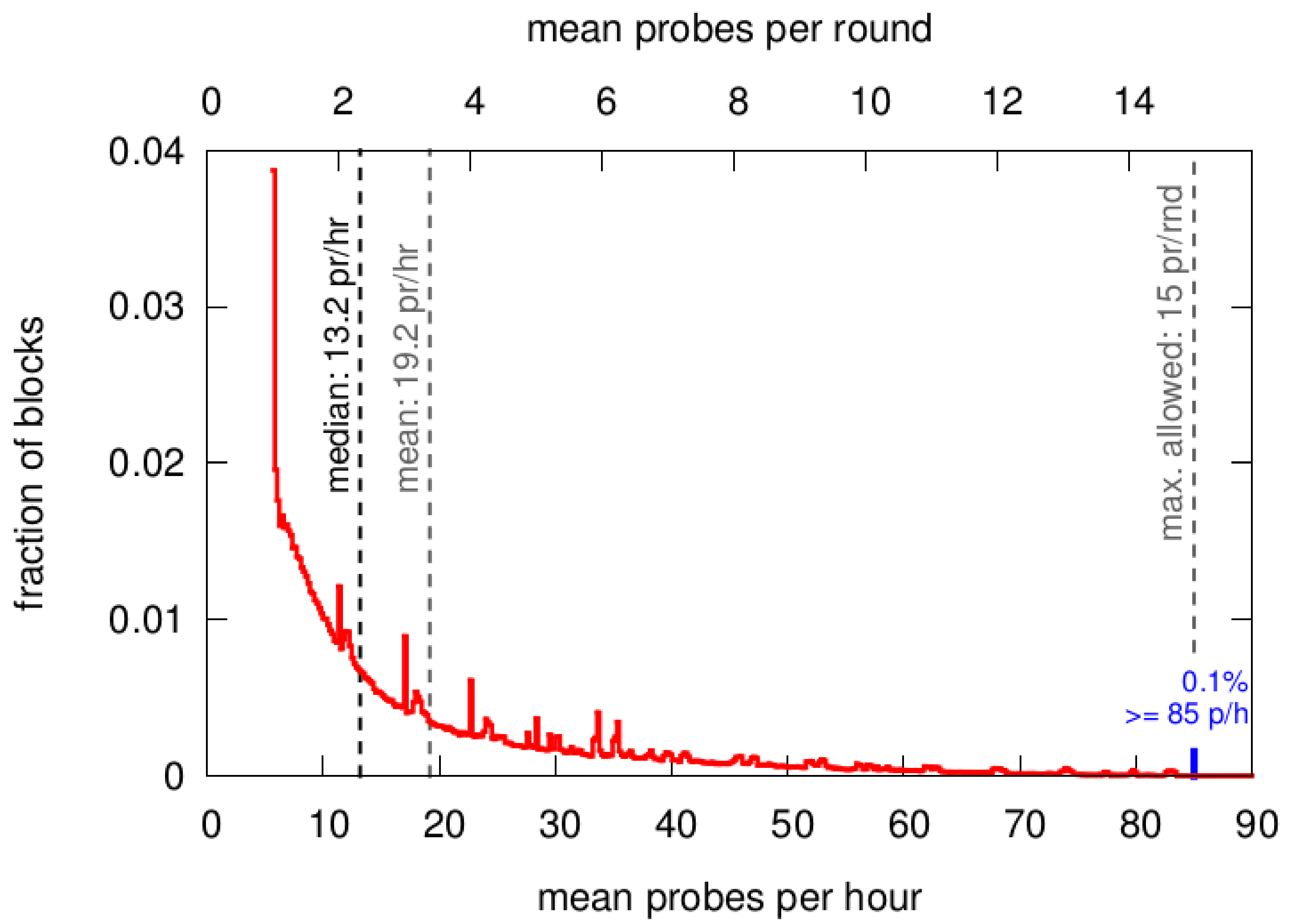


We detect **all** outages longer than 11 minutes (the probing interval)

Experiment:

Controlled outages (random duration, 1 to 36 minutes) in test block, measured from 3 different sites (2 in US, 1 in Japan).

Parsimonious: Few Probes

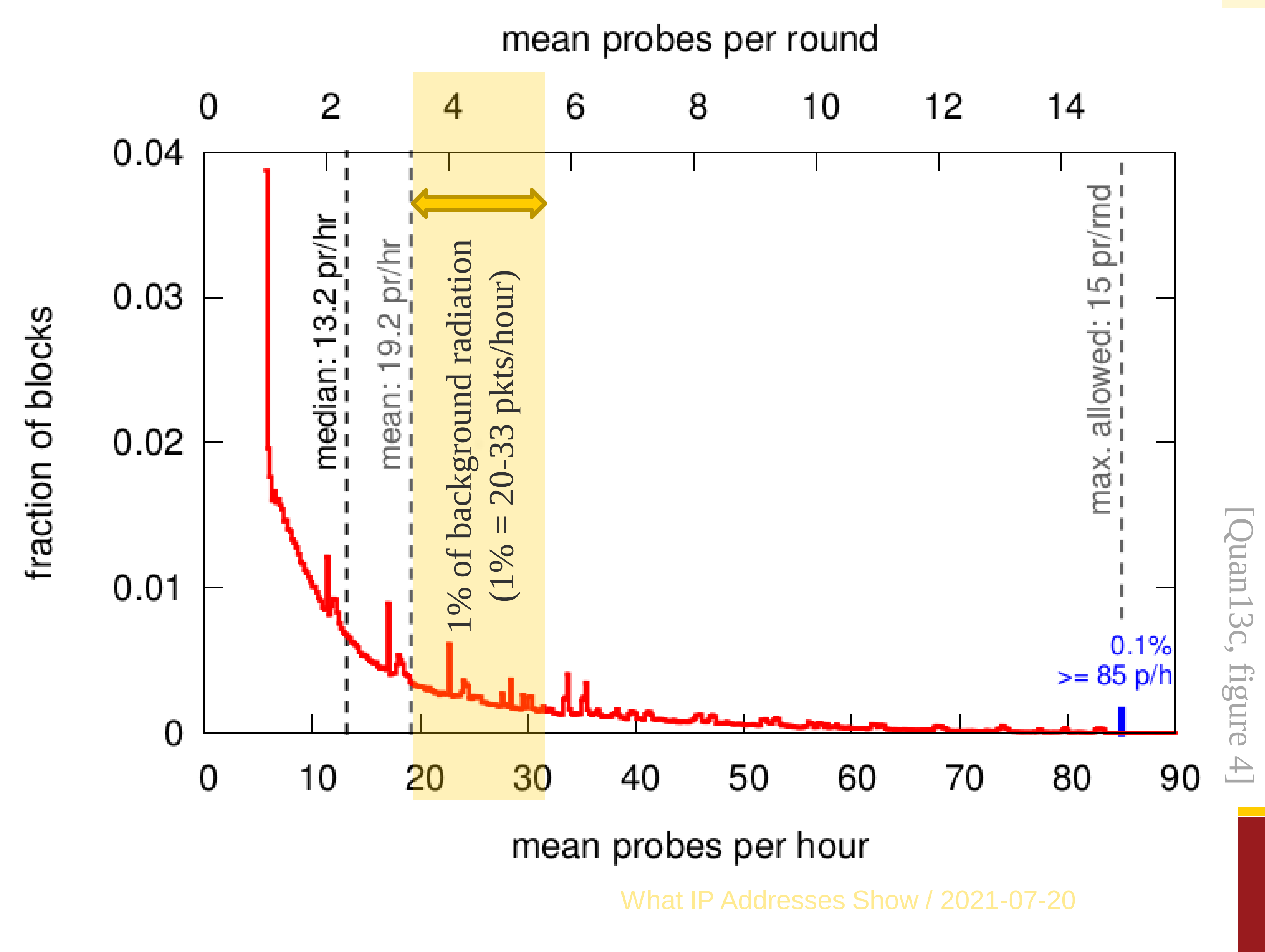


[Quan13c, figure 4]

Expirment:

Trinocular: post-facto analysis of 48 hours operation; background ration: from [Wustrow et al, ACM IMC 2010] ; today it is much higher

Parsimonious: Few Probes

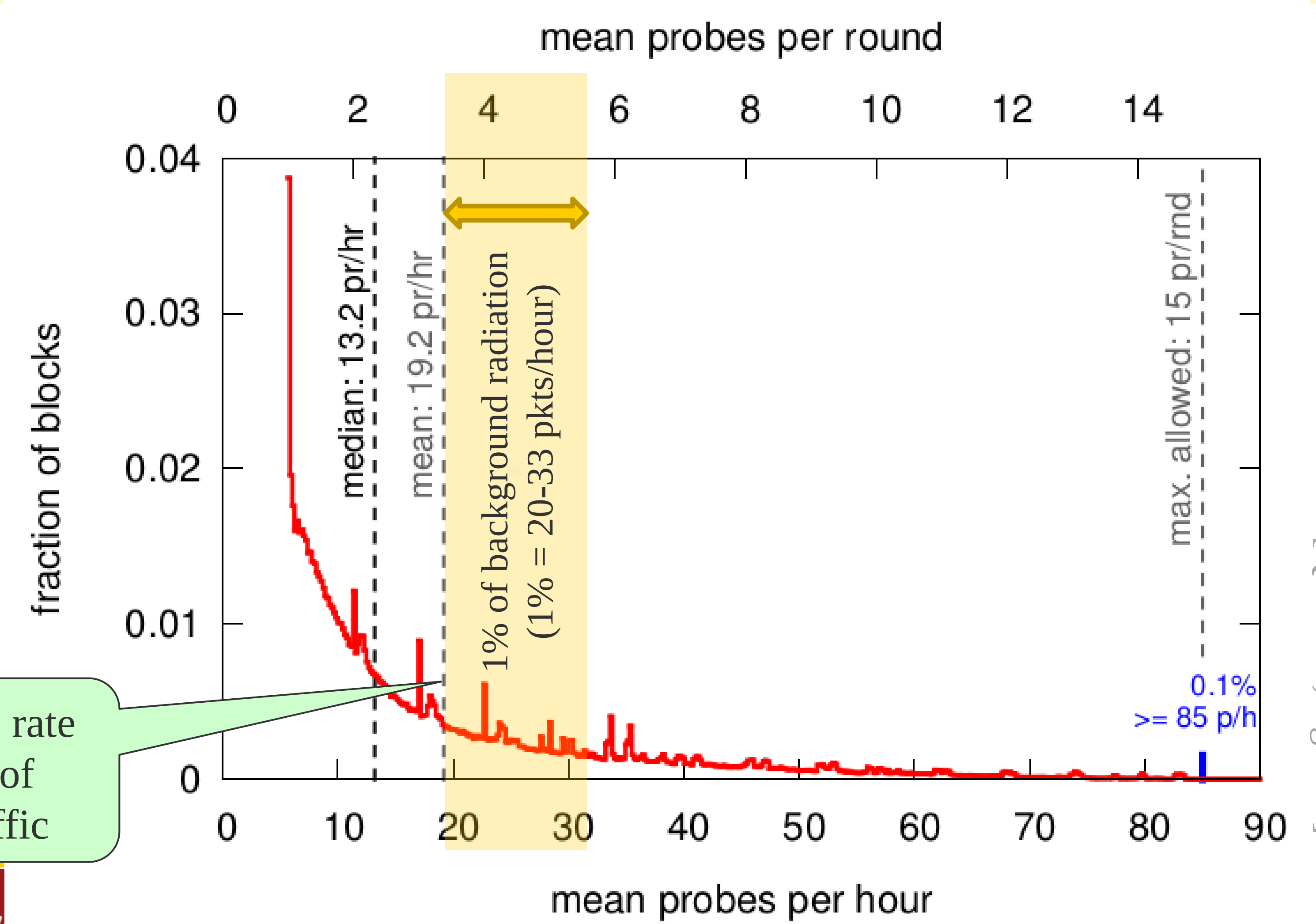


[Quan13c, figure 4]

Expirment:

Trinocular: post-facto analysis of 48 hours operation; background ration: from [Wustrow et al, ACM IMC 2010] ; today it is much higher

Parsimonious: Few Probes



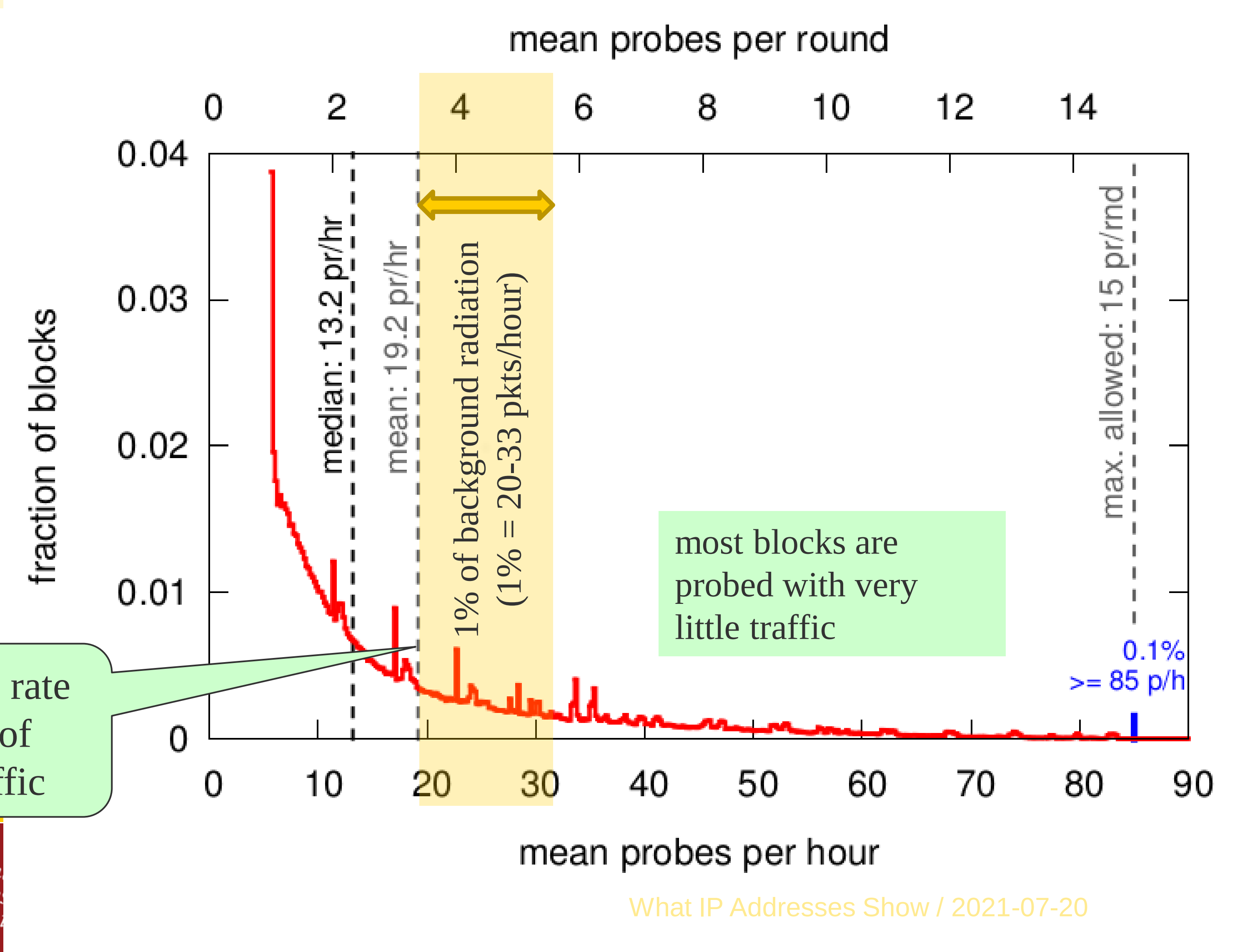
our mean probe rate is less than 1% of background traffic

[Quan13c, figure 4]

Expirment:

Trinocular: post-facto analysis of 48 hours operation; background ration: from [Wustrow et al, ACM IMC 2010] ; today it is much higher

Parsimonious: Few Probes



most blocks are probed with very little traffic

our mean probe rate is less than 1% of background traffic

[Quan13c, figure 4]

Expirment:

Trinocular: post-facto analysis of 48 hours operation;
background ration: from [Wustrow et al, ACM IMC 2010] ; today it is much higher

Improving Outages in the Toughest Blocks

probing politely means we *stop early*

details: Baltra and Heidemann. Improving Coverage of Internet Outage Detection in Sparse Blocks. PAM 2020. <https://www.isi.edu/%7ejohnh/PAPERS/Baltra20a.html>.

Improving Outages in the Toughest Blocks

probing politely means we *stop early*

details: Baltra and Heidemann. Improving Coverage of Internet Outage Detection in Sparse Blocks. PAM 2020. <https://www.isi.edu/%7ejohnh/PAPERS/Baltra20a.html>.

Improving Outages in the Toughest Blocks

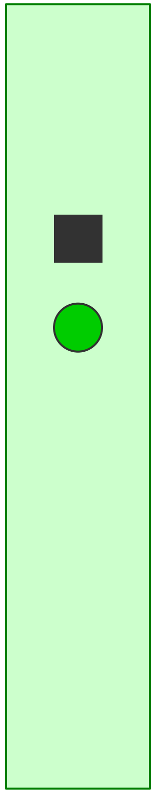
probing politely means we *stop early*

■

🟢

details: Baltra and Heidemann. Improving Coverage of Internet Outage Detection in Sparse Blocks. PAM 2020. <https://www.isi.edu/%7ejohnh/PAPERS/Baltra20a.html>.

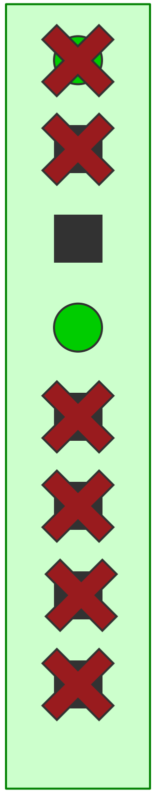
Improving Outages in the Toughest Blocks



probing politely means we *stop early*

details: Baltra and Heidemann. Improving Coverage of Internet Outage Detection in Sparse Blocks. PAM 2020. <https://www.isi.edu/%7ejohnh/PAPERS/Baltra20a.html>.

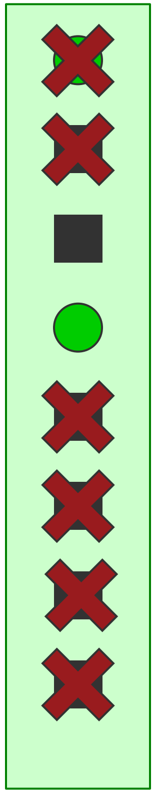
Improving Outages in the Toughest Blocks



probing politely means we *stop early*

details: Baltra and Heidemann. Improving Coverage of Internet Outage Detection in Sparse Blocks. PAM 2020. <https://www.isi.edu/%7ejohnh/PAPERS/Baltra20a.html>.

Improving Outages in the Toughest Blocks

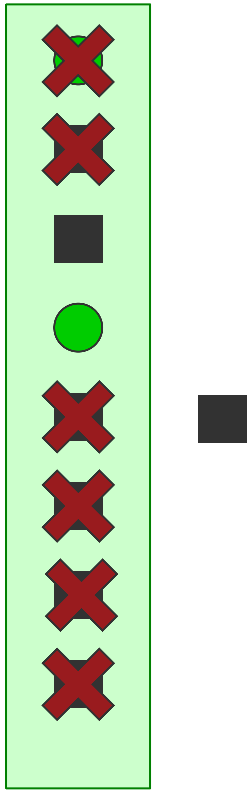


probing politely means we *stop early*

but in *sparse blocks* (=few active addrs, like 2 of 8)
    but can stop *too early:* a *false outage*

details: Baltra and Heidemann. Improving Coverage of Internet Outage Detection in Sparse Blocks. PAM 2020. <https://www.isi.edu/%7ejohnh/PAPERS/Baltra20a.html>.

Improving Outages in the Toughest Blocks

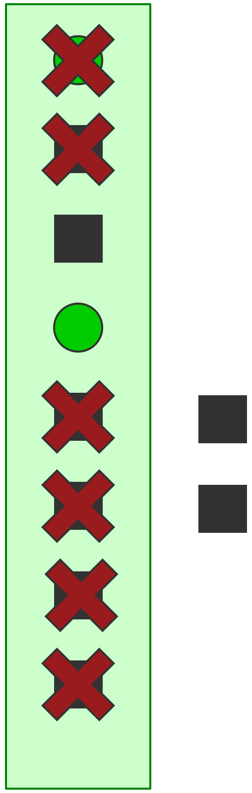


probing politely means we *stop early*

but in *sparse blocks* (=few active addrs, like 2 of 8)
    but can stop *too early:* a *false outage*

details: Baltra and Heidemann. Improving Coverage of Internet Outage Detection in Sparse Blocks. PAM 2020. <https://www.isi.edu/%7ejohnh/PAPERS/Baltra20a.html>.

Improving Outages in the Toughest Blocks



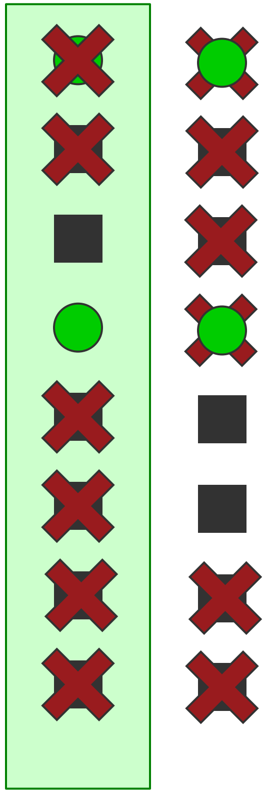
probing politely means we *stop early*

but in *sparse blocks* (=few active addrs, like 2 of 8)

but can stop *too early:* a *false outage*

details: Baltra and Heidemann. Improving Coverage of Internet Outage Detection in Sparse Blocks. PAM 2020. <https://www.isi.edu/%7ejohnh/PAPERS/Baltra20a.html>.

Improving Outages in the Toughest Blocks

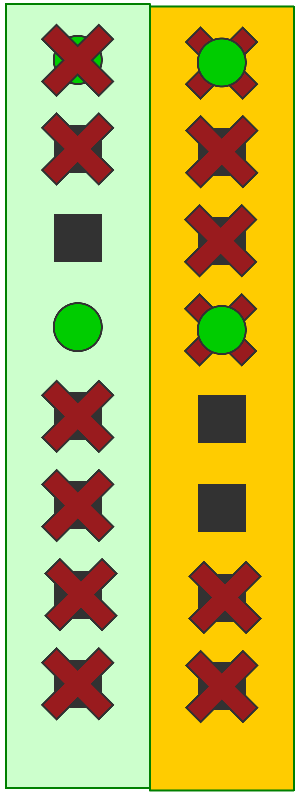


probing politely means we *stop early*

but in *sparse blocks* (=few active addrs, like 2 of 8)
but can stop *too early:* a *false outage*

details: Baltra and Heidemann. Improving Coverage of Internet Outage Detection in Sparse Blocks. PAM 2020. <https://www.isi.edu/%7ejohnh/PAPERS/Baltra20a.html>.

Improving Outages in the Toughest Blocks



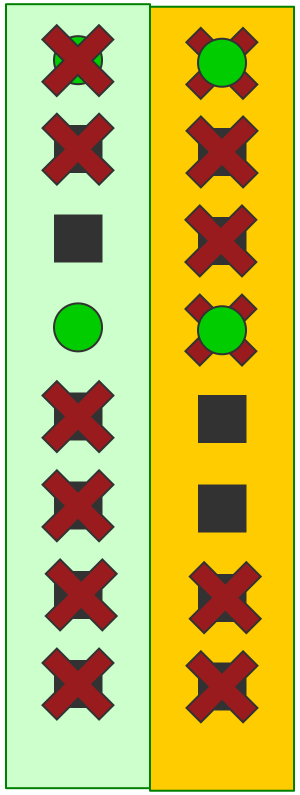
probing politely means we *stop early*

but in *sparse blocks* (=few active addrs, like 2 of 8)

but can stop *too early:* a *false outage*

details: Baltra and Heidemann. Improving Coverage of Internet Outage Detection in Sparse Blocks. PAM 2020. <https://www.isi.edu/%7ejohnh/PAPERS/Baltra20a.html>.

Improving Outages in the Toughest Blocks



probing politely means we *stop early*

but in *sparse blocks* (=few active addrs, like 2 of 8)

but can stop *too early:* a *false outage*

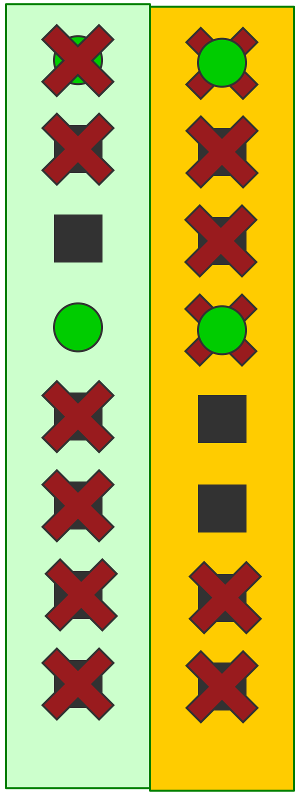
solution: Full Block Scanning

detect sparse blocks

for them (only), check *all* addrs (over several rounds)

details: Baltra and Heidemann. Improving Coverage of Internet Outage Detection in Sparse Blocks. PAM 2020. <https://www.isi.edu/%7ejohnh/PAPERS/Baltra20a.html>.

Improving Outages in the Toughest Blocks



probing politely means we *stop early*

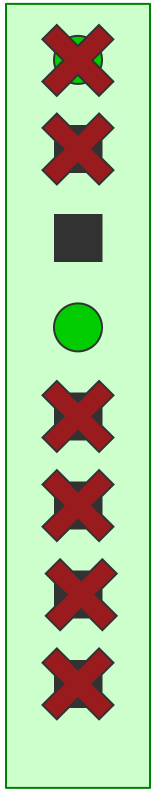
but in *sparse blocks* (=few active addrs, like 2 of 8)

but can stop *too early:* a *false outage*

solution: Full Block Scanning

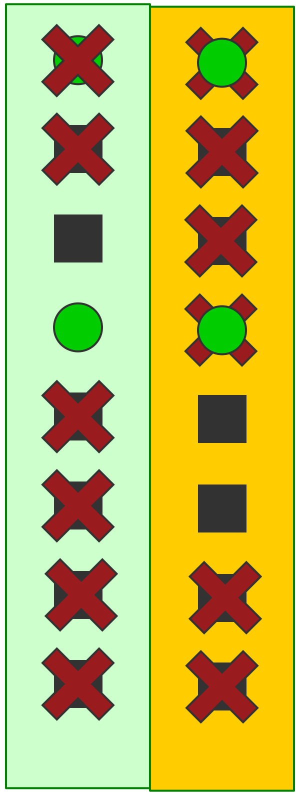
detect sparse blocks

for them (only), check *all* addrs (over several rounds)



details: Baltra and Heidemann. Improving Coverage of Internet Outage Detection in Sparse Blocks. PAM 2020. <https://www.isi.edu/%7ejohnh/PAPERS/Baltra20a.html>.

Improving Outages in the Toughest Blocks



probing politely means we *stop early*

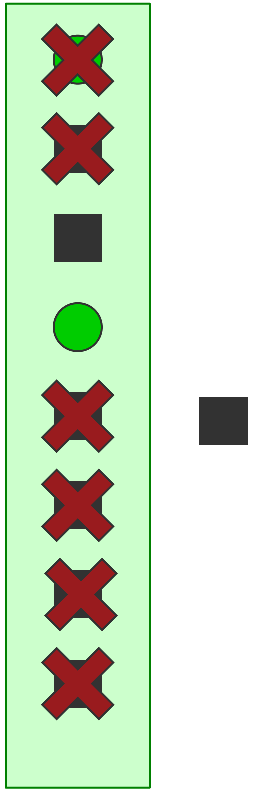
but in *sparse blocks* (=few active addrs, like 2 of 8)

but can stop *too early:* a *false outage*

solution: Full Block Scanning

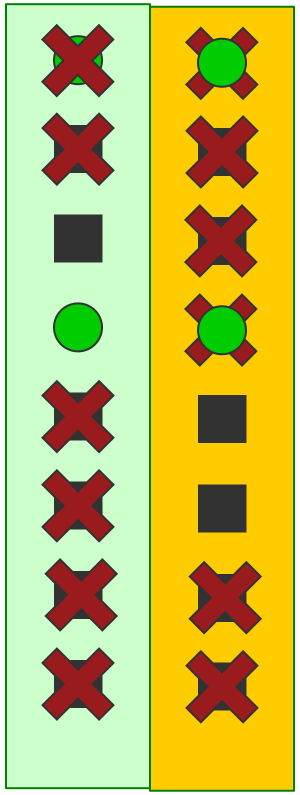
detect sparse blocks

for them (only), check *all* addrs (over several rounds)



details: Baltra and Heidemann. Improving Coverage of Internet Outage Detection in Sparse Blocks. PAM 2020. <https://www.isi.edu/%7ejohnh/PAPERS/Baltra20a.html>.

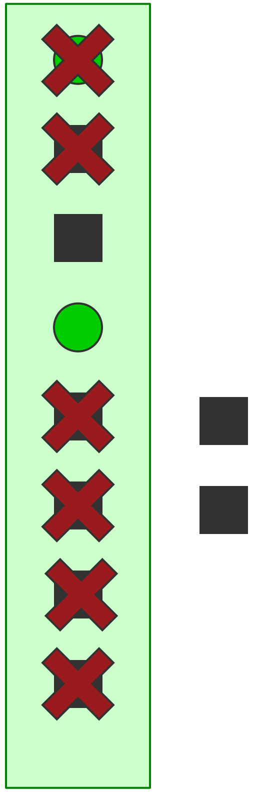
Improving Outages in the Toughest Blocks



probing politely means we *stop early*

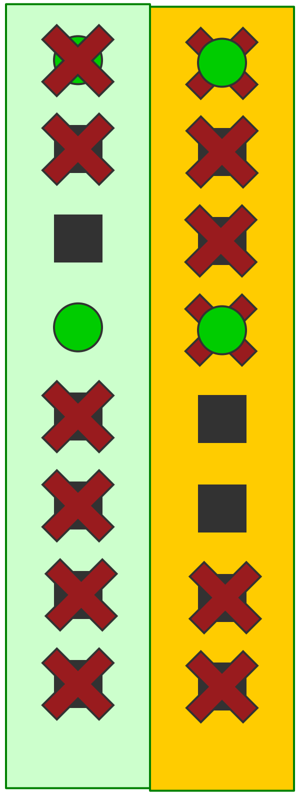
but in *sparse blocks* (=few active addrs, like 2 of 8)
but can stop *too early:* a *false outage*

solution: Full Block Scanning
detect sparse blocks
for them (only), check *all* addrs (over several rounds)



details: Baltra and Heidemann. Improving Coverage of Internet Outage Detection in Sparse Blocks. PAM 2020. <https://www.isi.edu/%7ejohnh/PAPERS/Baltra20a.html>.

Improving Outages in the Toughest Blocks



probing politely means we *stop early*

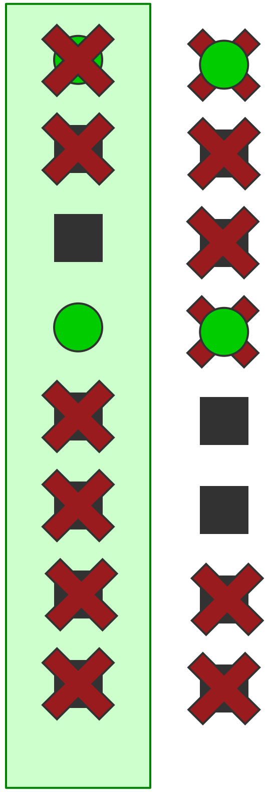
but in *sparse blocks* (=few active addrs, like 2 of 8)

but can stop *too early:* a *false outage*

solution: Full Block Scanning

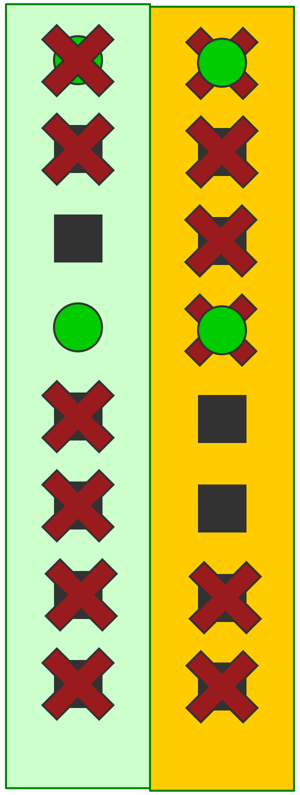
detect sparse blocks

for them (only), check *all* addrs (over several rounds)



details: Baltra and Heidemann. Improving Coverage of Internet Outage Detection in Sparse Blocks. PAM 2020. <https://www.isi.edu/%7ejohnh/PAPERS/Baltra20a.html>.

Improving Outages in the Toughest Blocks



probing politely means we *stop early*

but in *sparse blocks* (=few active addrs, like 2 of 8)

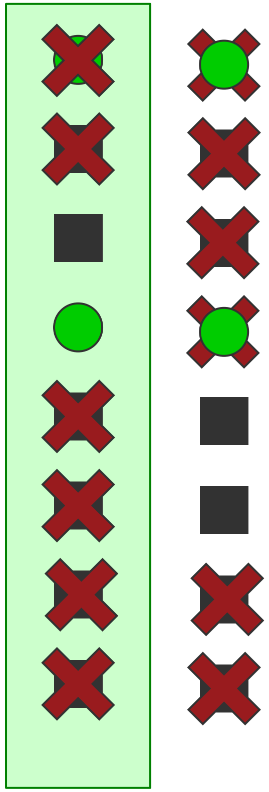
but can stop *too early:* a *false outage*

solution: Full Block Scanning

detect sparse blocks

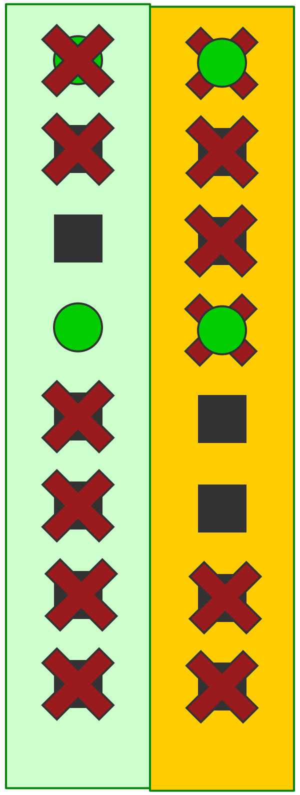
for them (only), check *all* addrs (over several rounds)

when sparse,
wait on bad news



details: Baltra and Heidemann. Improving Coverage of Internet Outage Detection in Sparse Blocks. PAM 2020. <https://www.isi.edu/%7ejohnh/PAPERS/Baltra20a.html>.

Improving Outages in the Toughest Blocks



probing politely means we *stop early*

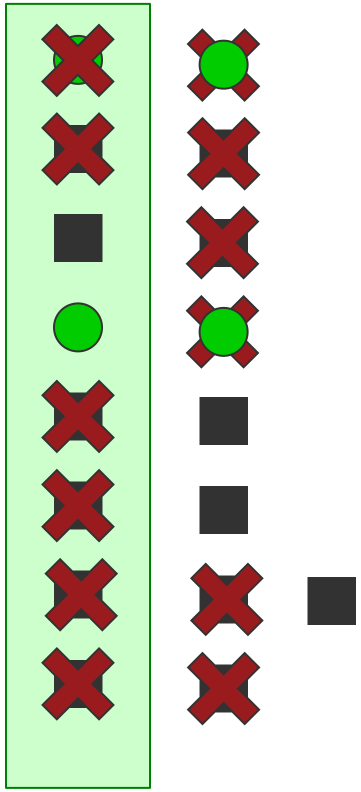
but in *sparse blocks* (=few active addrs, like 2 of 8)

but can stop *too early:* a *false outage*

solution: Full Block Scanning

detect sparse blocks

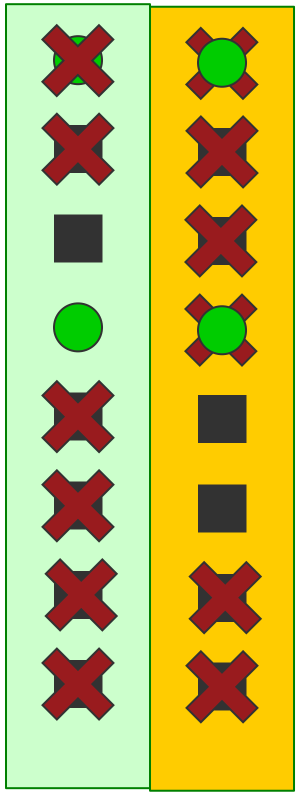
for them (only), check *all* addrs (over several rounds)



when sparse,
wait on bad news

details: Baltra and Heidemann. Improving Coverage of Internet Outage Detection in Sparse Blocks. PAM 2020. <https://www.isi.edu/%7ejohnh/PAPERS/Baltra20a.html>.

Improving Outages in the Toughest Blocks



probing politely means we *stop early*

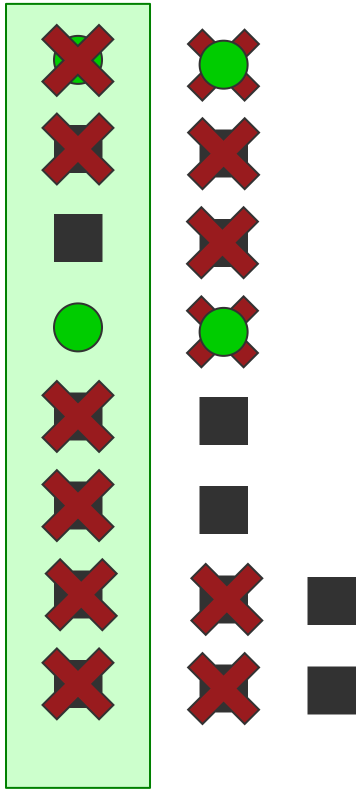
but in *sparse blocks* (=few active addrs, like 2 of 8)

but can stop *too early:* a *false outage*

solution: Full Block Scanning

detect sparse blocks

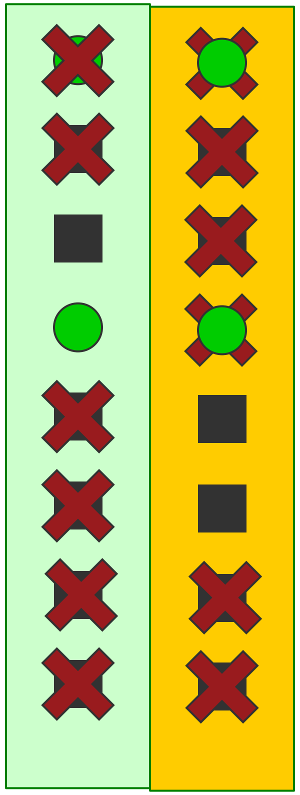
for them (only), check *all* addrs (over several rounds)



when sparse,
wait on bad news

details: Baltra and Heidemann. Improving Coverage of Internet Outage Detection in Sparse Blocks. PAM 2020. <https://www.isi.edu/%7ejohnh/PAPERS/Baltra20a.html>.

Improving Outages in the Toughest Blocks



probing politely means we *stop early*

but in *sparse blocks* (=few active addrs, like 2 of 8)

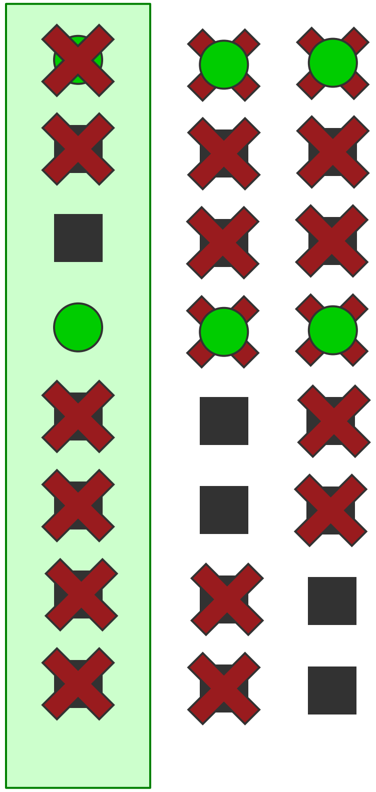
but can stop *too early:* a *false outage*

solution: Full Block Scanning

detect sparse blocks

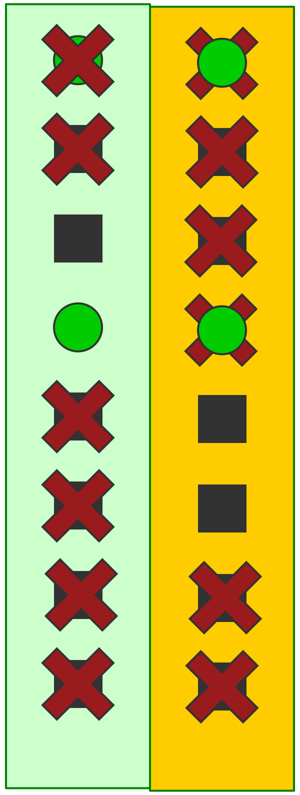
for them (only), check *all* addrs (over several rounds)

when sparse,
wait on bad news



details: Baltra and Heidemann. Improving Coverage of Internet Outage Detection in Sparse Blocks. PAM 2020. <https://www.isi.edu/%7ejohnh/PAPERS/Baltra20a.html>.

Improving Outages in the Toughest Blocks

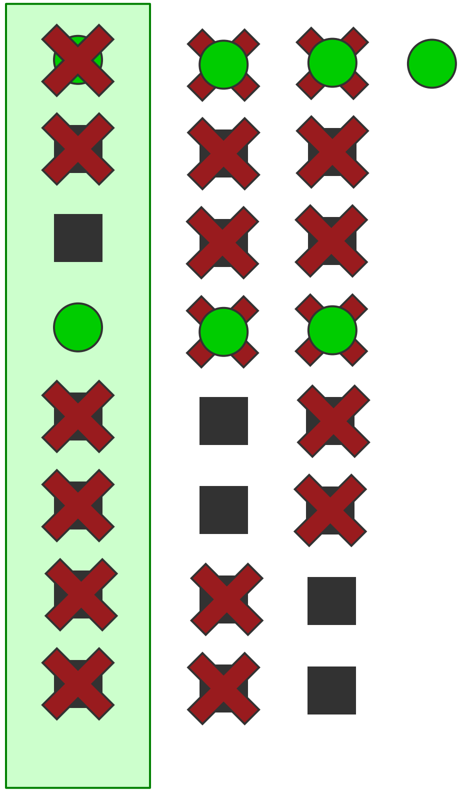


probing politely means we *stop early*

but in *sparse blocks* (=few active addrs, like 2 of 8)
but can stop *too early:* a *false outage*

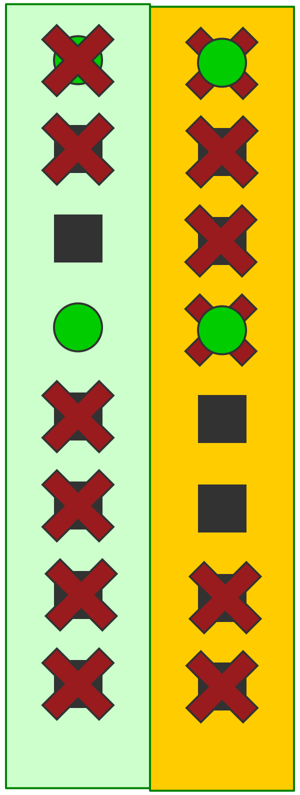
solution: Full Block Scanning
detect sparse blocks
for them (only), check *all* addrs (over several rounds)

when sparse,
wait on bad news



details: Baltra and Heidemann. Improving Coverage of Internet Outage Detection in Sparse Blocks. PAM 2020. <https://www.isi.edu/%7ejohnh/PAPERS/Baltra20a.html>.

Improving Outages in the Toughest Blocks

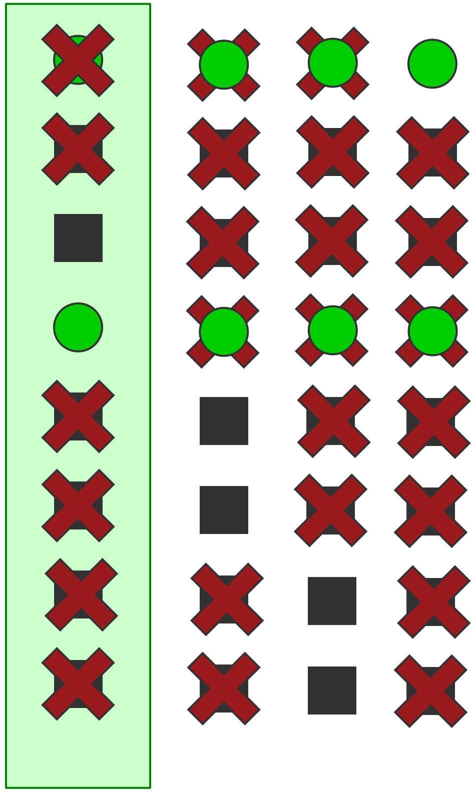


probing politely means we *stop early*

but in *sparse blocks* (=few active addrs, like 2 of 8)
but can stop *too early:* a *false outage*

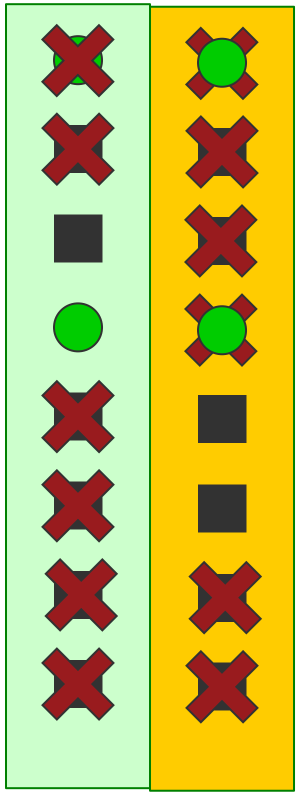
solution: Full Block Scanning
detect sparse blocks
for them (only), check *all* addrs (over several rounds)

when sparse,
wait on bad news



details: Baltra and Heidemann. Improving Coverage of Internet Outage Detection in Sparse Blocks. PAM 2020. <https://www.isi.edu/%7ejohnh/PAPERS/Baltra20a.html>.

Improving Outages in the Toughest Blocks



probing politely means we *stop early*

but in *sparse blocks* (=few active addrs, like 2 of 8)

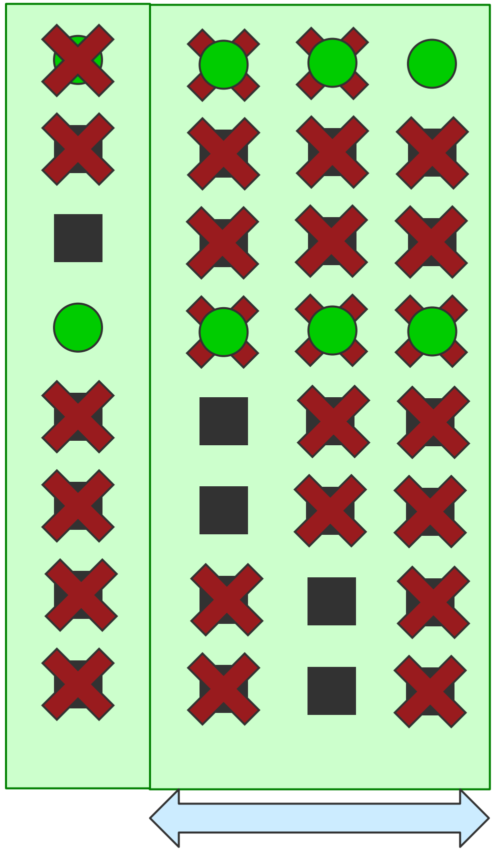
but can stop *too early:* a *false outage*

solution: Full Block Scanning

detect sparse blocks

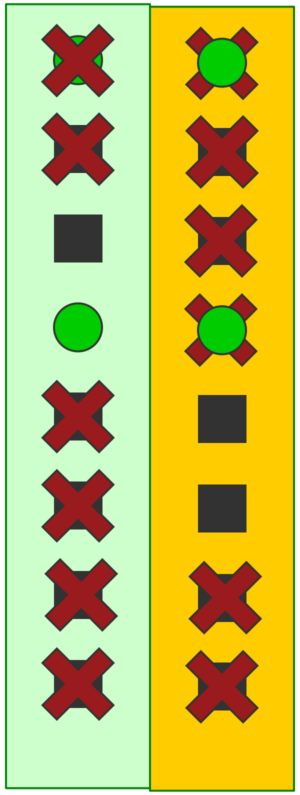
for them (only), check *all* addrs (over several rounds)

when sparse,
wait on bad news



details: Baltra and Heidemann. Improving Coverage of Internet Outage Detection in Sparse Blocks. PAM 2020. <https://www.isi.edu/%7ejohnh/PAPERS/Baltra20a.html>.

Improving Outages in the Toughest Blocks



probing politely means we *stop early*

but in *sparse blocks* (=few active addrs, like 2 of 8)

but can stop *too early:* a *false outage*

solution: Full Block Scanning

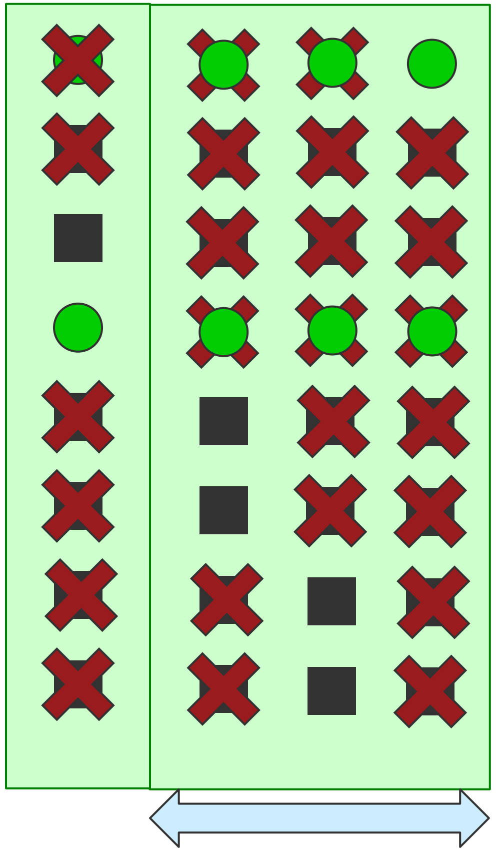
detect sparse blocks

for them (only), check *all* addrs (over several rounds)

improves correctness and retains ✖politeness✖

but lower temporal precision (for sparse blks only)

when sparse,
wait on bad news



details: Baltra and Heidemann. Improving Coverage of Internet Outage Detection in Sparse Blocks. PAM 2020. <https://www.isi.edu/%7ejohnh/PAPERS/Baltra20a.html>.

Impact of Outage Detection

- quantified impact of hurricanes
  - previously: Harvey (2017)
  - next: Irma (2017)
- outages in operational networks
- near-real time reporting

Hurricane Irma: Watching Recovery

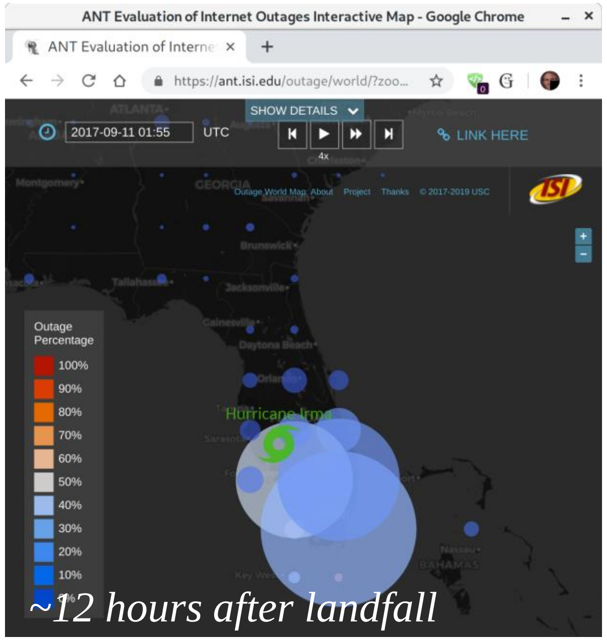
before, during and after disasters: Irma, Sept. 2017 in Florida…

good recovery underway 24 hours after landfall

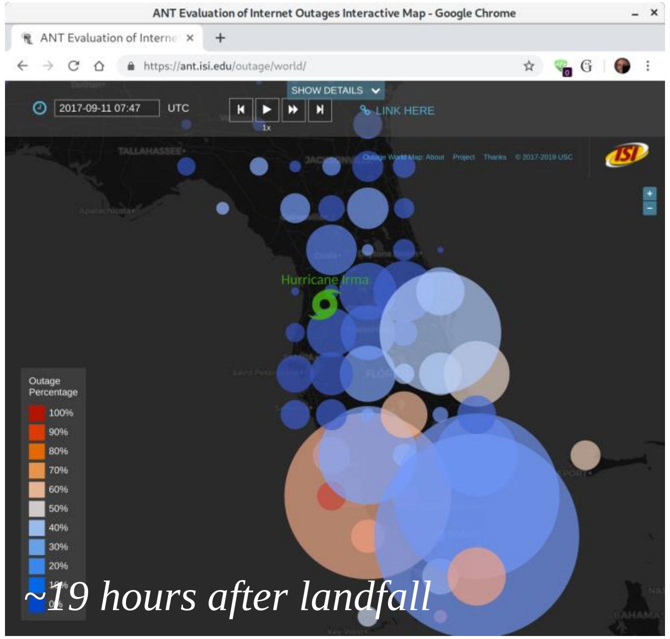
Irma landfall: 2017-09-10t13:10Z at Cudjoe Key, Florida

(play)

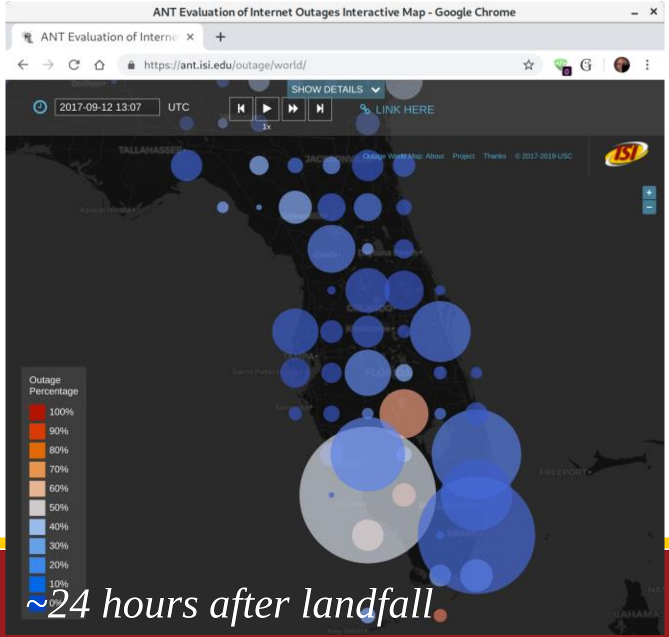
https://ant.isi.edu/url/irma2017/


ANT Evaluation of Internet Outages Interactive Map - Google Chrome
https://ant.isi.edu/outage/world/?zoo...
SHOW DETAILS
2017-09-11 01:55
UTC
LINK HERE
Hurricane Irma
Outage Percentage
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%

~12 hours after landfall


ANT Evaluation of Internet Outages Interactive Map - Google Chrome
https://ant.isi.edu/outage/world/
SHOW DETAILS
2017-09-11 07:47
UTC
LINK HERE
Hurricane Irma
Outage Percentage
100%
90%
80%
70%
60%
50%
40%
30%
20%

~19 hours after landfall


ANT Evaluation of Internet Outages Interactive Map - Google Chrome
https://ant.isi.edu/outage/world/
SHOW DETAILS
2017-09-12 13:07
UTC
LINK HERE
Outage Percentage
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%

~24 hours after landfall

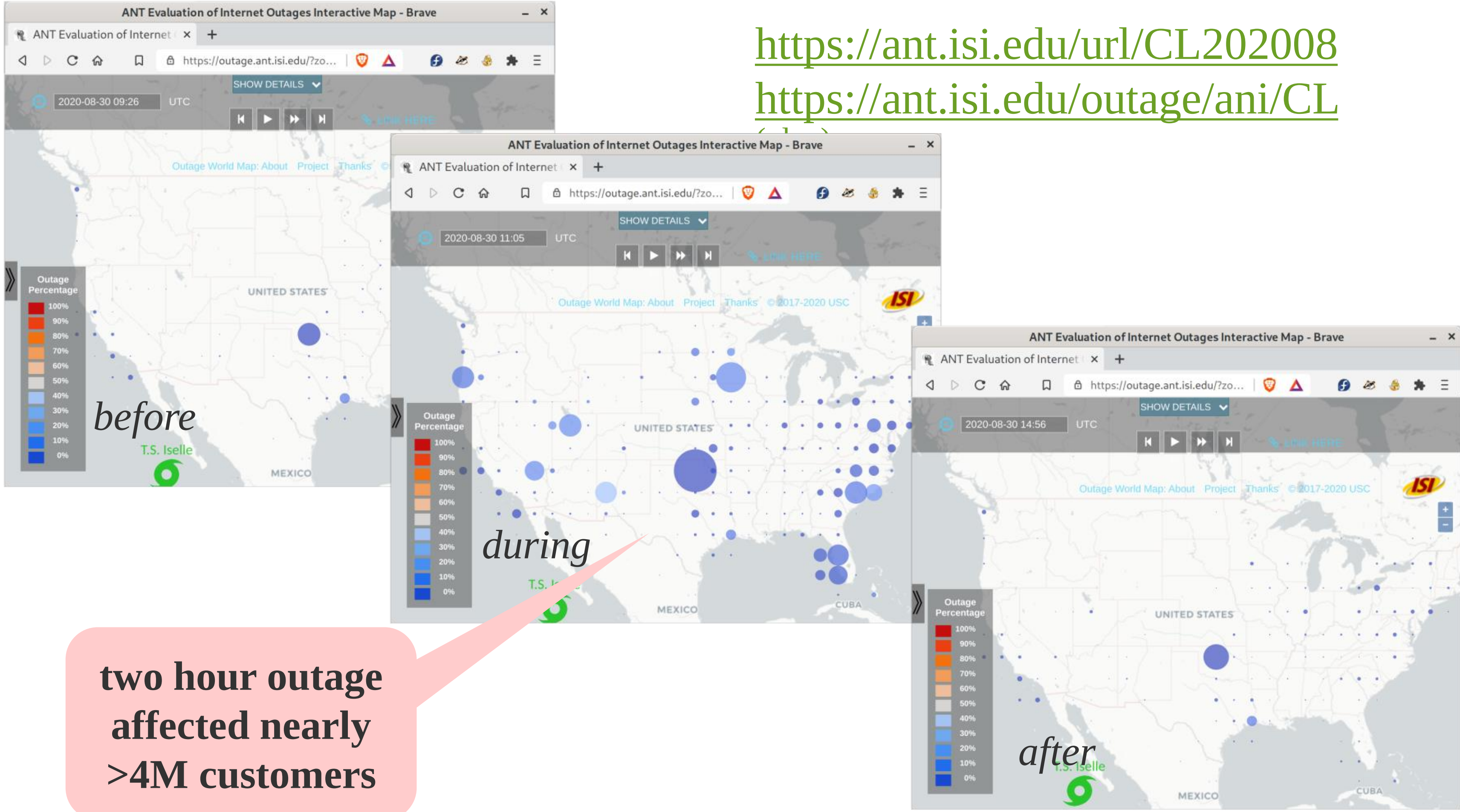
Outages in Operational Networks: CenturyLink, August 2020

we also see problems due to network ops

https://ant.isi.edu/url/CL202008

https://ant.isi.edu/outage/ani/CL

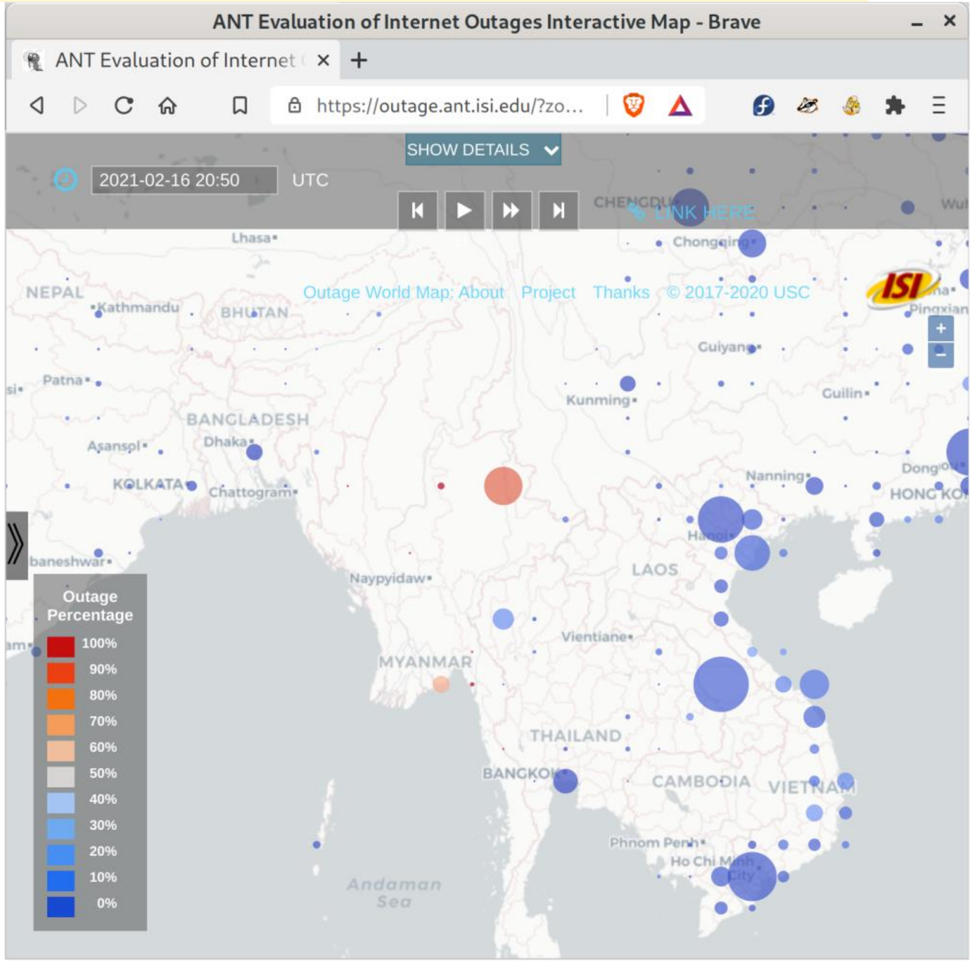
- this dataset:
  - 5M blocks
  - all of 2020q3
- events:
  - CenturyLink outage on 2020-08-30 starting 9:55Z
  - >4 million customers



two hour outage affected nearly >4M customers

Near-Real Time Reporting (Now!)

- https://outage.ant.isi.edu/
- outages 24x7, within ~2h of observation
- visualized in your browser
  - circle size: *number* of blocks out
  - color: *percent* of blocks out
  - pan in geography and time
- goals:
  - support first responders
  - support the general public
  - global coverage



Myanmar,
Internet shutdown
2021-02-16,
2 weeks after
a military coup
https://ant.isi.edu/url/mm210206

Understanding Internet Reliability

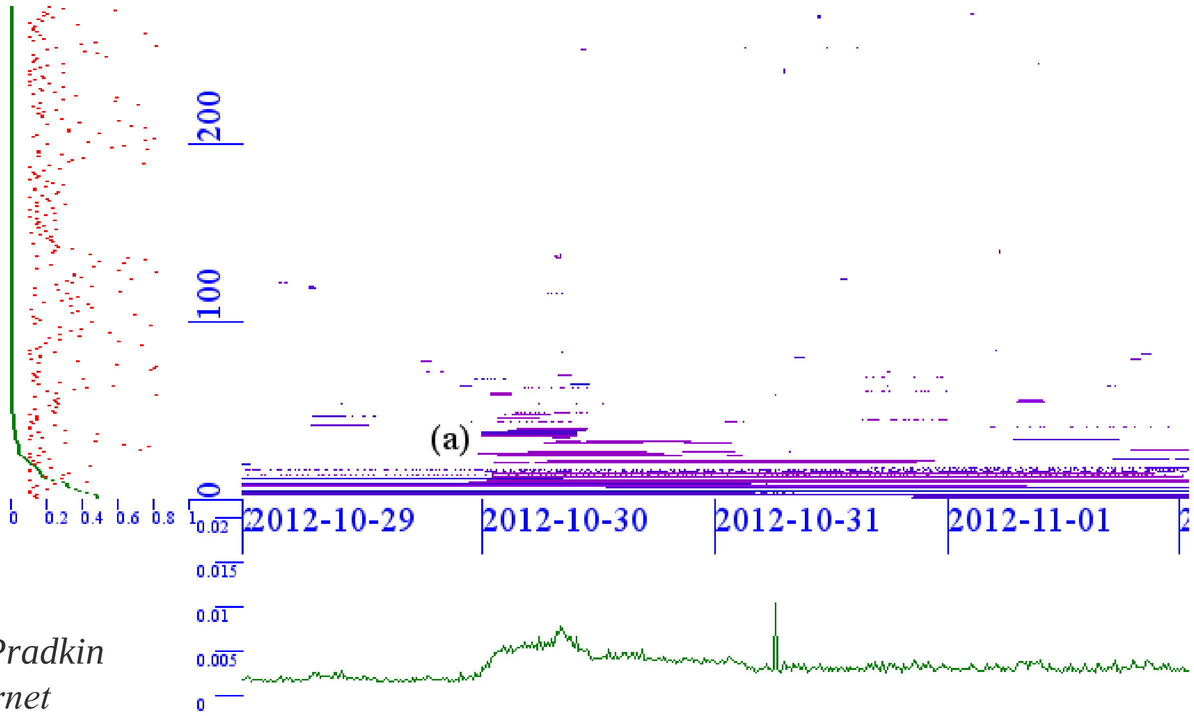
- opportunities observing Internet reliability
- from scanning to outages
- **from outages to clusters: hidden dependencies**
- finding work-from-home

Analyzing Long-Term Data

- outage data, 24x7, since Nov. 2013
- more than 45TB (!)
- about 20k observations x 5M blocks: 100G datapoints (!!)

- how to make sense of it?
  - interactive visualization
  - automated clustering

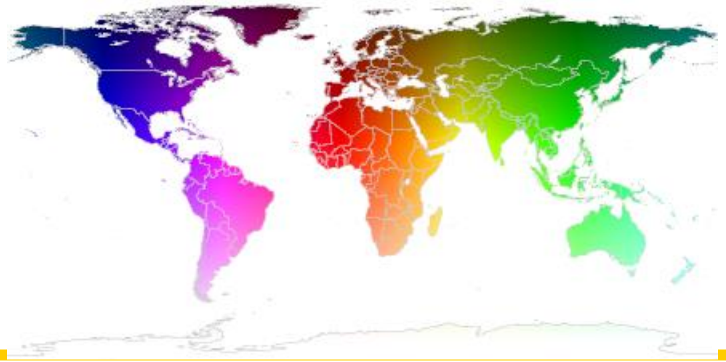
Non-Geographic Visualizations: the *Network* in Outages



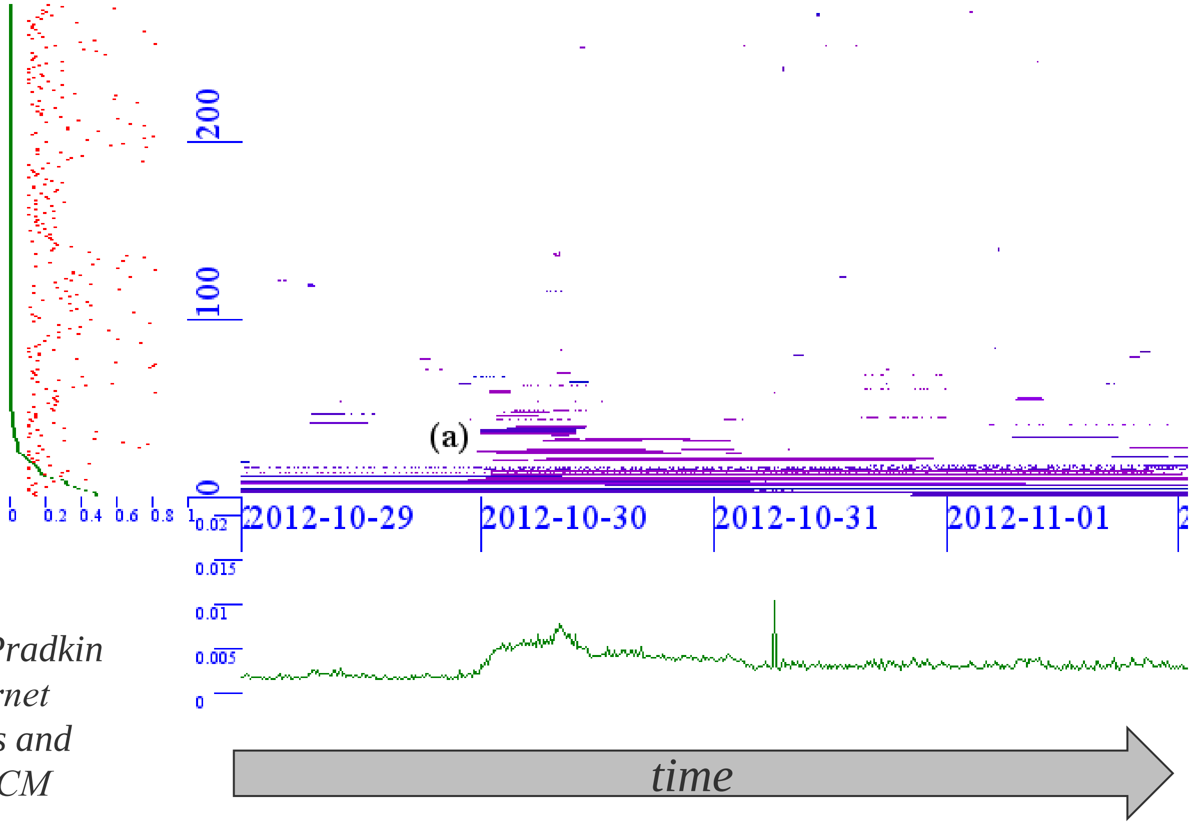
Quan, Heidemann, and Pradkin "Visualizing Sparse Internet Events: Network Outages and Route Changes", First ACM Workshop on Internet Visualization, Nov. 2012

goal: reveal patterns

find dependencies among networks

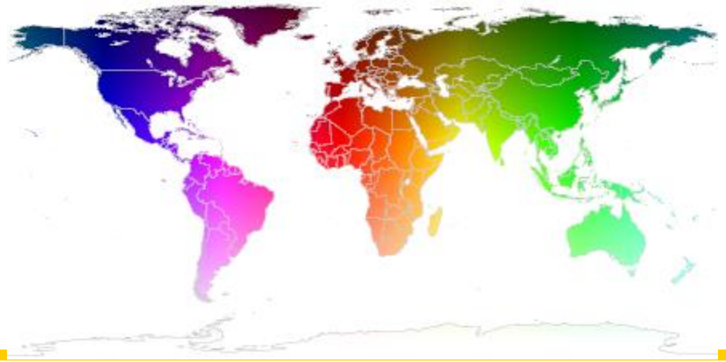


Non-Geographic Visualizations: the *Network* in Outages



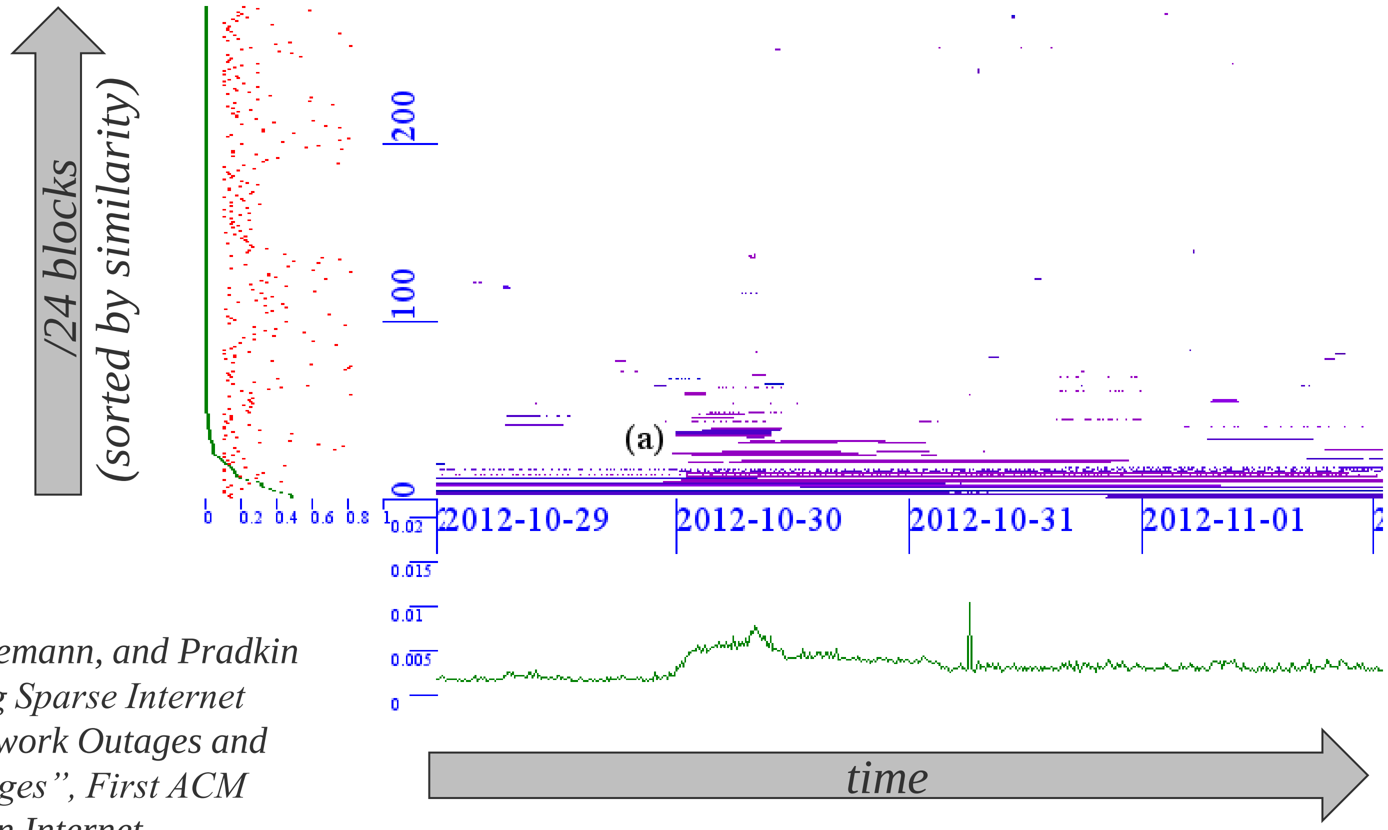
goal: reveal patterns

find dependencies among networks



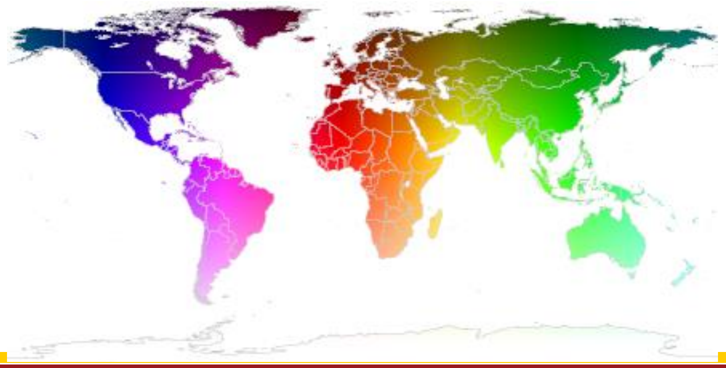
Quan, Heidemann, and Pradkin "Visualizing Sparse Internet Events: Network Outages and Route Changes", First ACM Workshop on Internet Visualization, Nov. 2012

Non-Geographic Visualizations: the *Network* in Outages



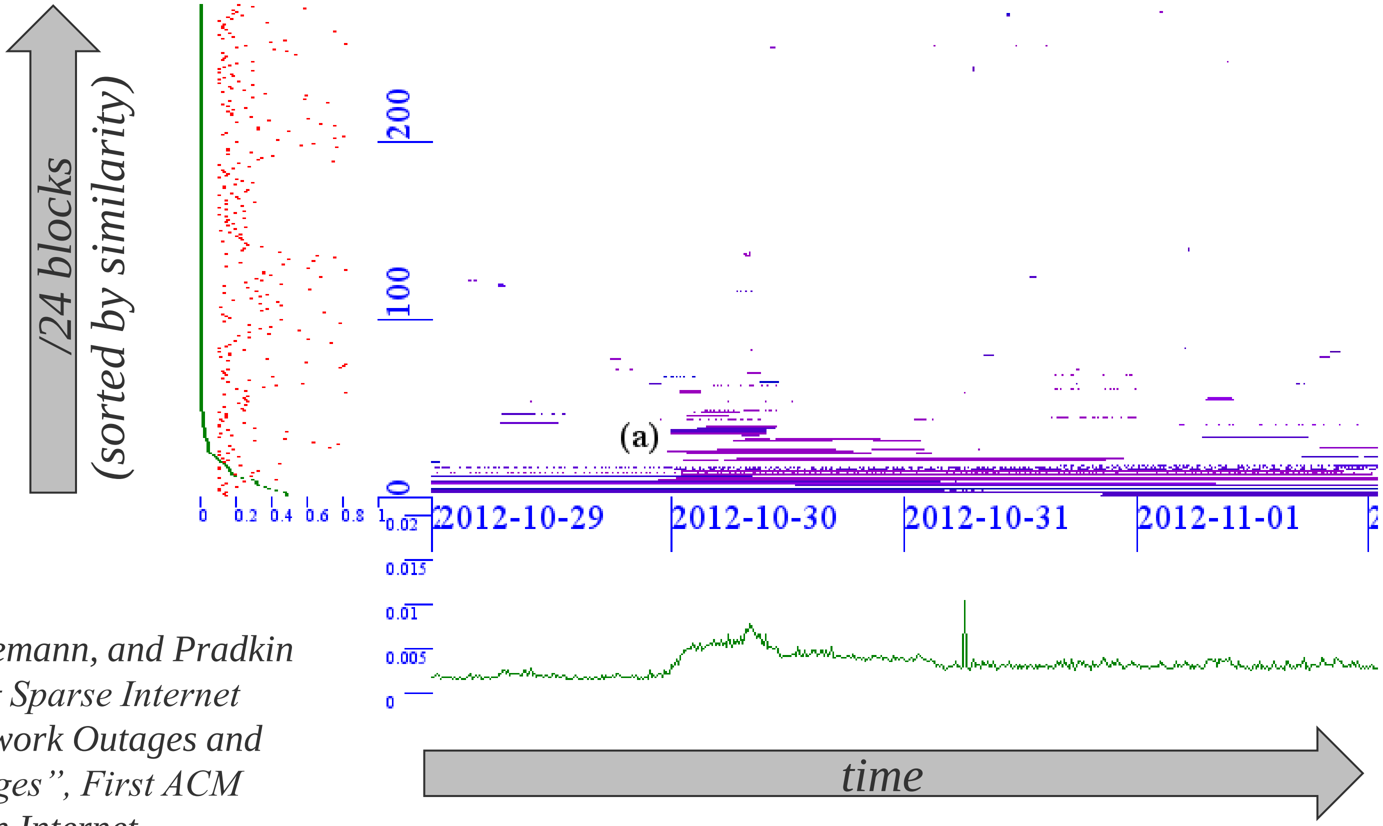
goal: reveal patterns

find dependencies among networks



Quan, Heidemann, and Pradkin “Visualizing Sparse Internet Events: Network Outages and Route Changes”, First ACM Workshop on Internet Visualization, Nov. 2012

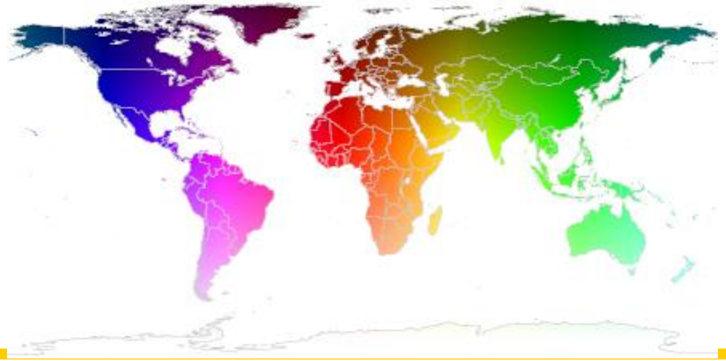
Non-Geographic Visualizations: the *Network* in Outages



goal: reveal patterns

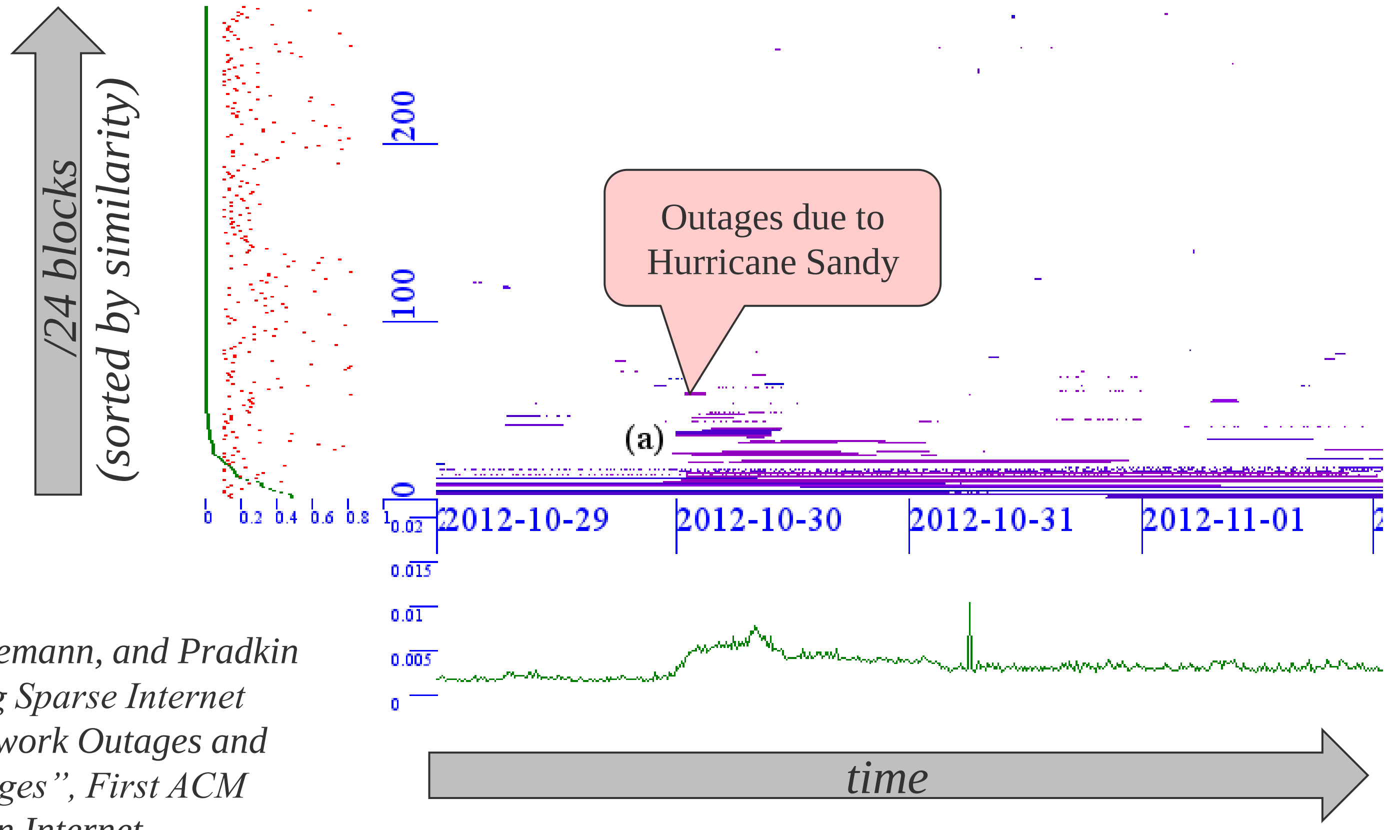
find dependencies among networks

(colored areas are outages, color shows location)



Quan, Heidemann, and Pradkin "Visualizing Sparse Internet Events: Network Outages and Route Changes", First ACM Workshop on Internet Visualization, Nov. 2012

Non-Geographic Visualizations: the *Network* in Outages



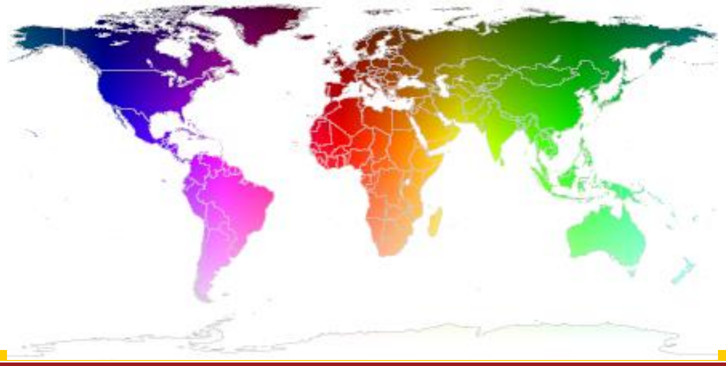
Outages due to Hurricane Sandy

Quan, Heidemann, and Pradkin "Visualizing Sparse Internet Events: Network Outages and Route Changes", First ACM Workshop on Internet Visualization, Nov. 2012

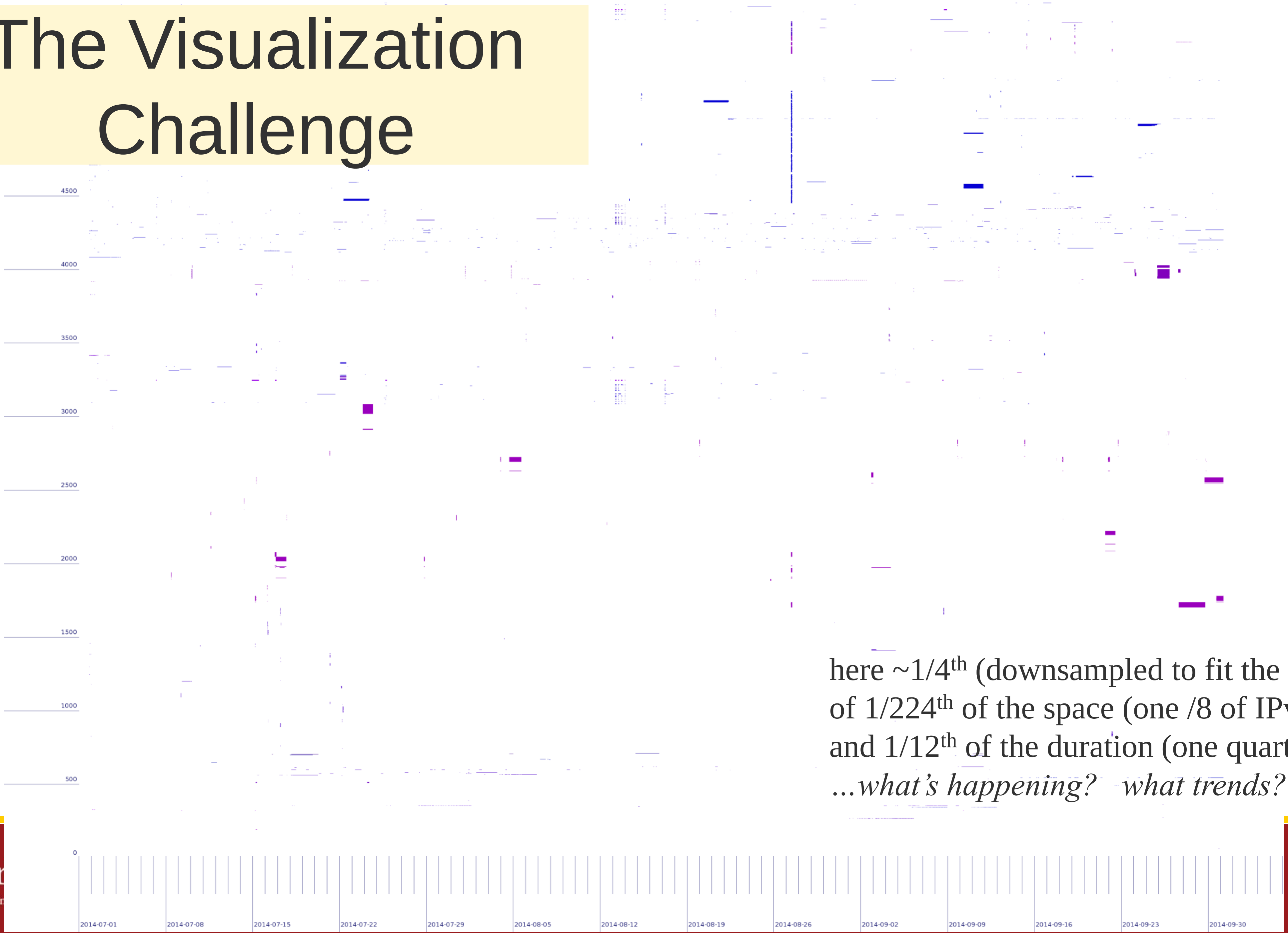
goal: reveal patterns

find dependencies among networks

(colored areas are outages, color shows location)

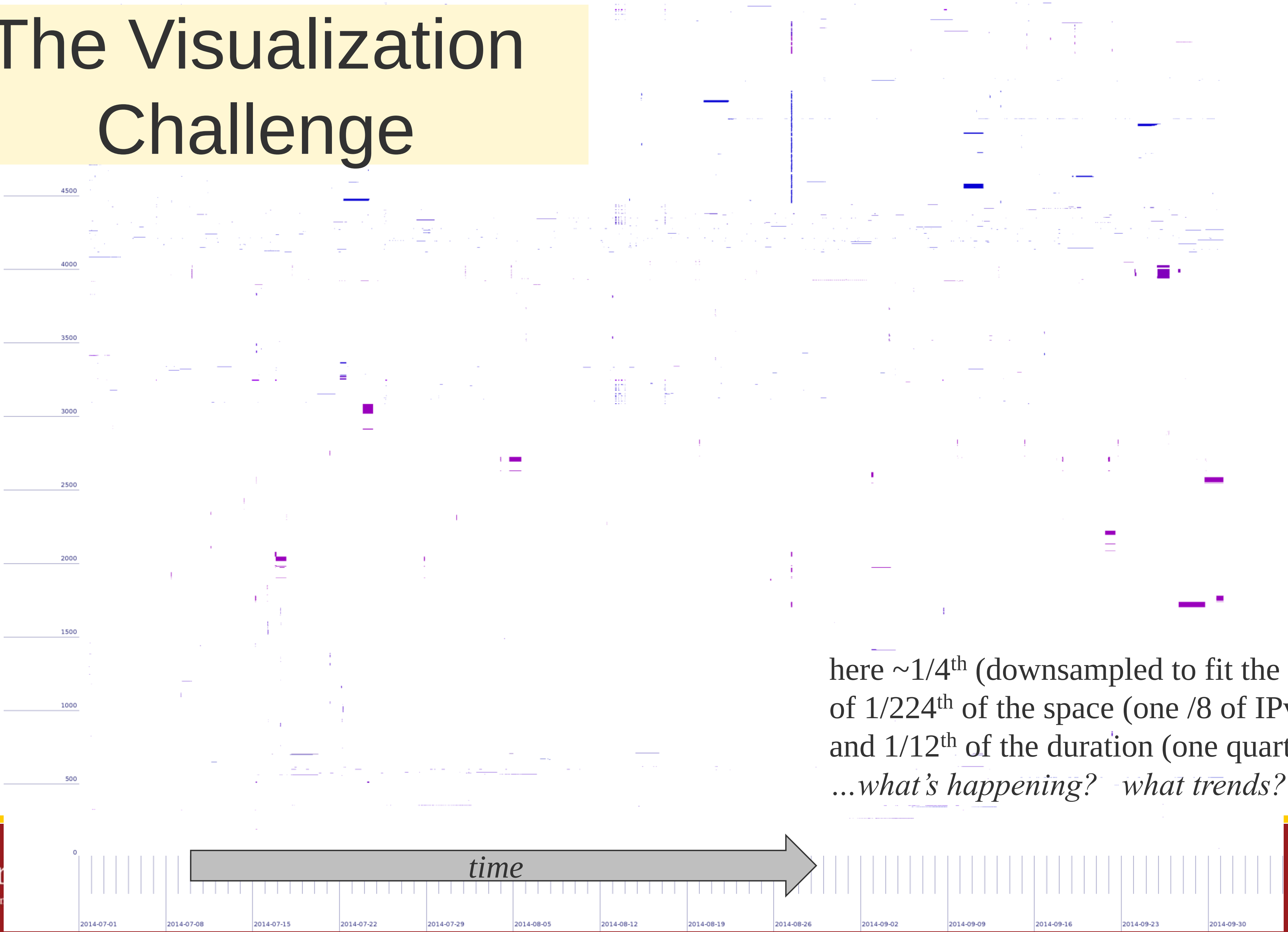


The Visualization Challenge



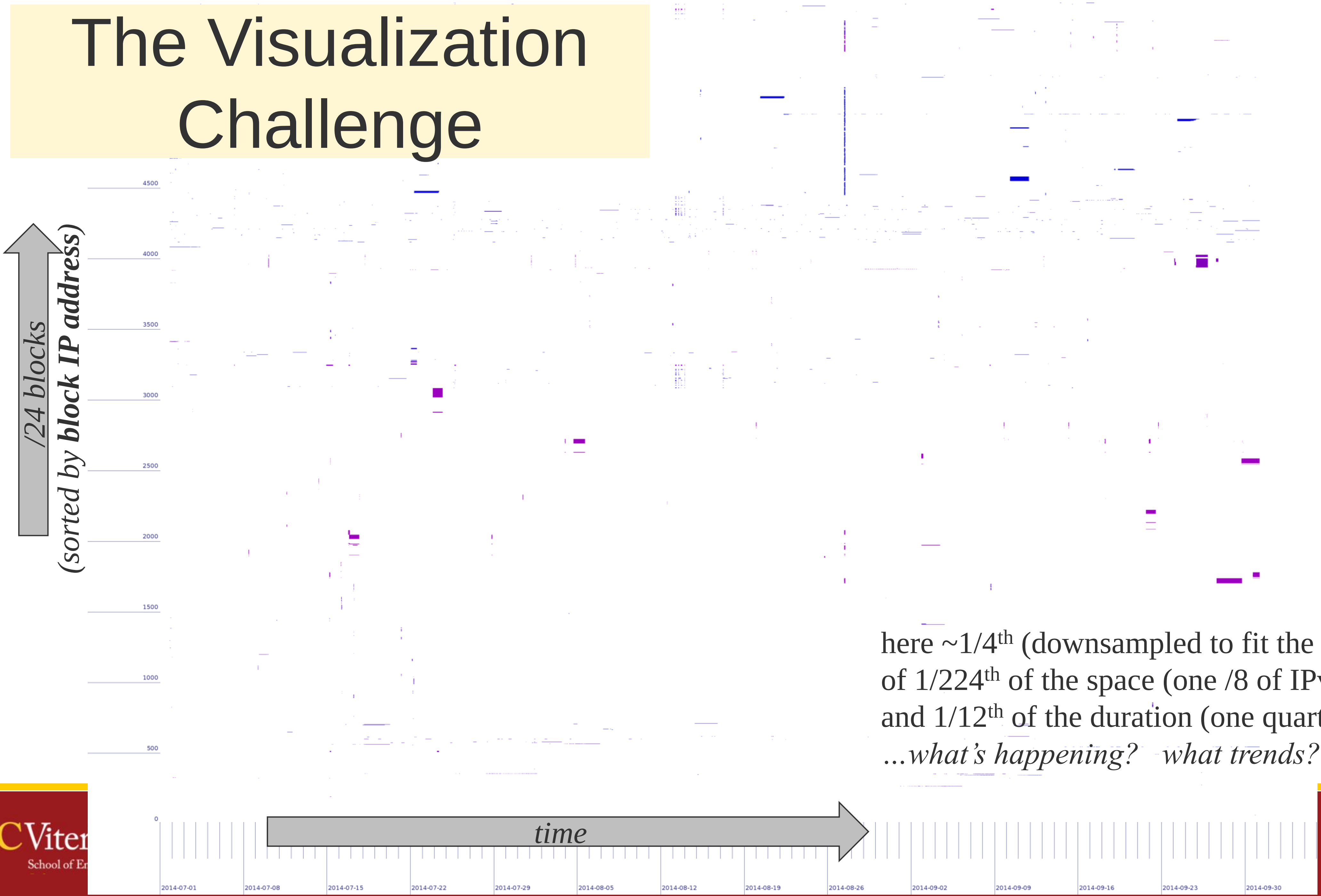
here ~1/4th (downsampled to fit the screen)
of 1/224th of the space (one /8 of IPv4)
and 1/12th of the duration (one quarter of ~3 years)
…what's happening?   what trends?   what's new?

The Visualization Challenge



here ~1/4th (downsampled to fit the screen)
of 1/224th of the space (one /8 of IPv4)
and 1/12th of the duration (one quarter of ~3 years)
…what's happening? what trends? what's new?

The Visualization Challenge



here ~1/4th (downsampled to fit the screen)
of 1/224th of the space (one /8 of IPv4)
and 1/12th of the duration (one quarter of ~3 years)
…*what's happening? what trends? what's new?*

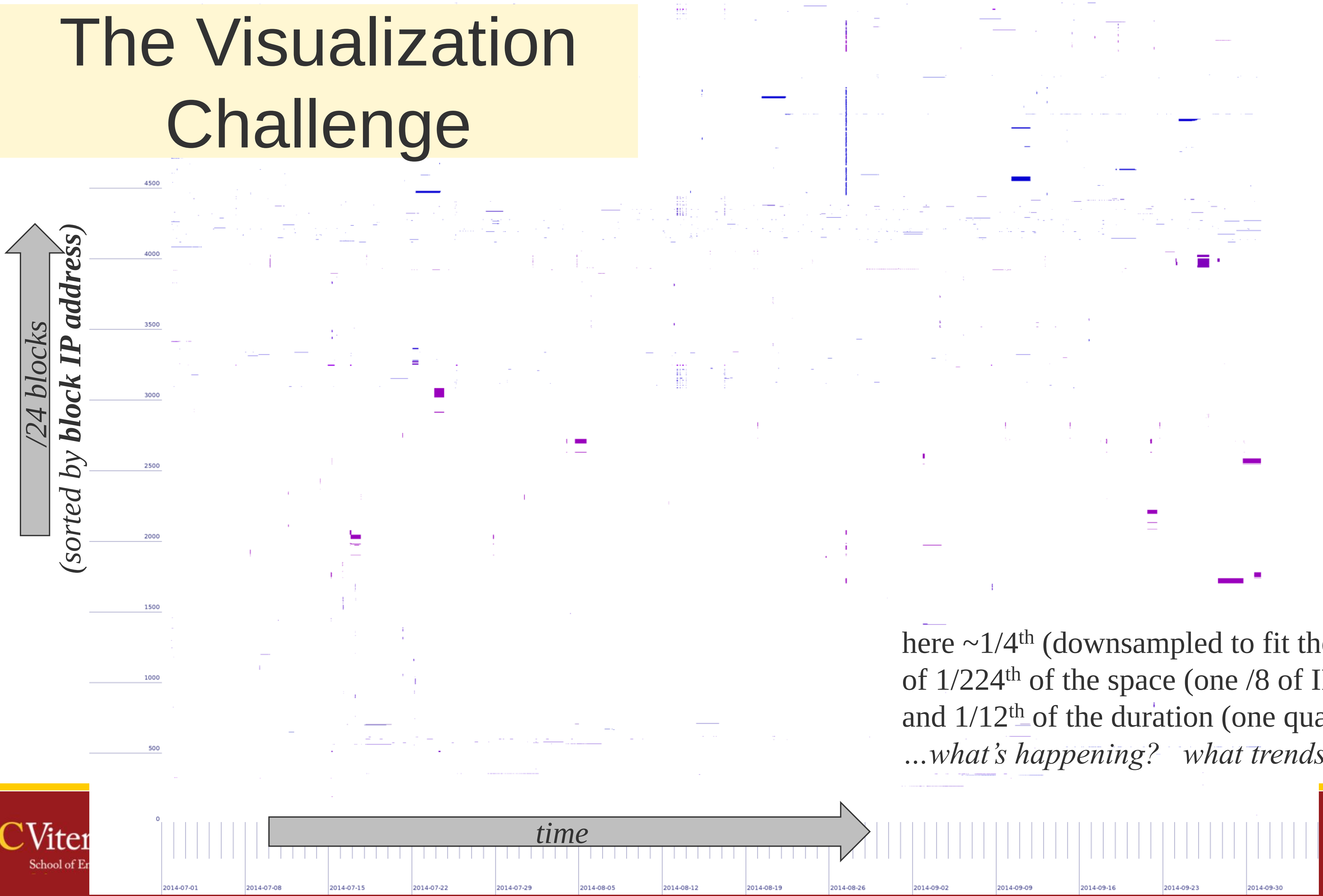
Efficient Visualization and Clustering

- **visualization with linear ordering algorithm**
  - runtime: O($n \log n \log m$)
  - for n blocks and m duration timesteps
- approach:
  - map clustering to sorting: O($n \log n$) in time
  - sort on *multi-timescale bitmap:* O($\log m$) in space

- **event clustering**
  - runtime O(n^2)
  - parallelizes with Map/Reduce
- approach
  - find blocks that transition at the same time

Details in "Back Out: End-to-end Inference of Common Points-of-Failure in the Internet (extended)". ISI-TR-724, Feb., 2018. www.isi.edu/~johnh/PAPERS/Heidemann18b.pdf

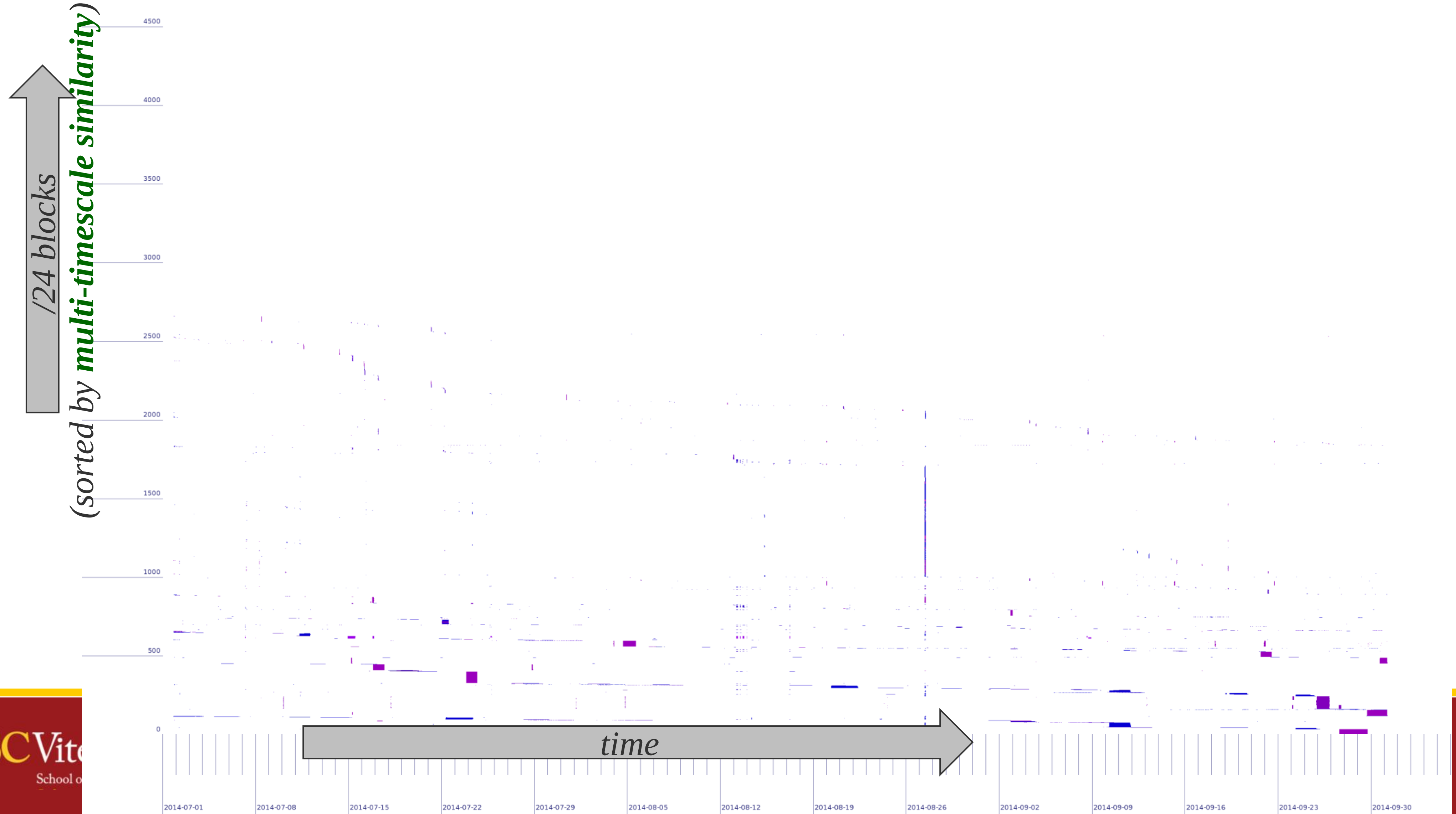
The Visualization Challenge



here ~1/4th (downsampled to fit the screen)
of 1/224th of the space (one /8 of IPv4)
and 1/12th of the duration (one quarter of ~3 years)
…what's happening? what trends? what's new?

One Visualization Result

here ~1/4th (downsampled to fit the screen)
of 1/224th of the space (one /8 of IPv4)
and 1/12th of the duration (one quarter of ~3 years)

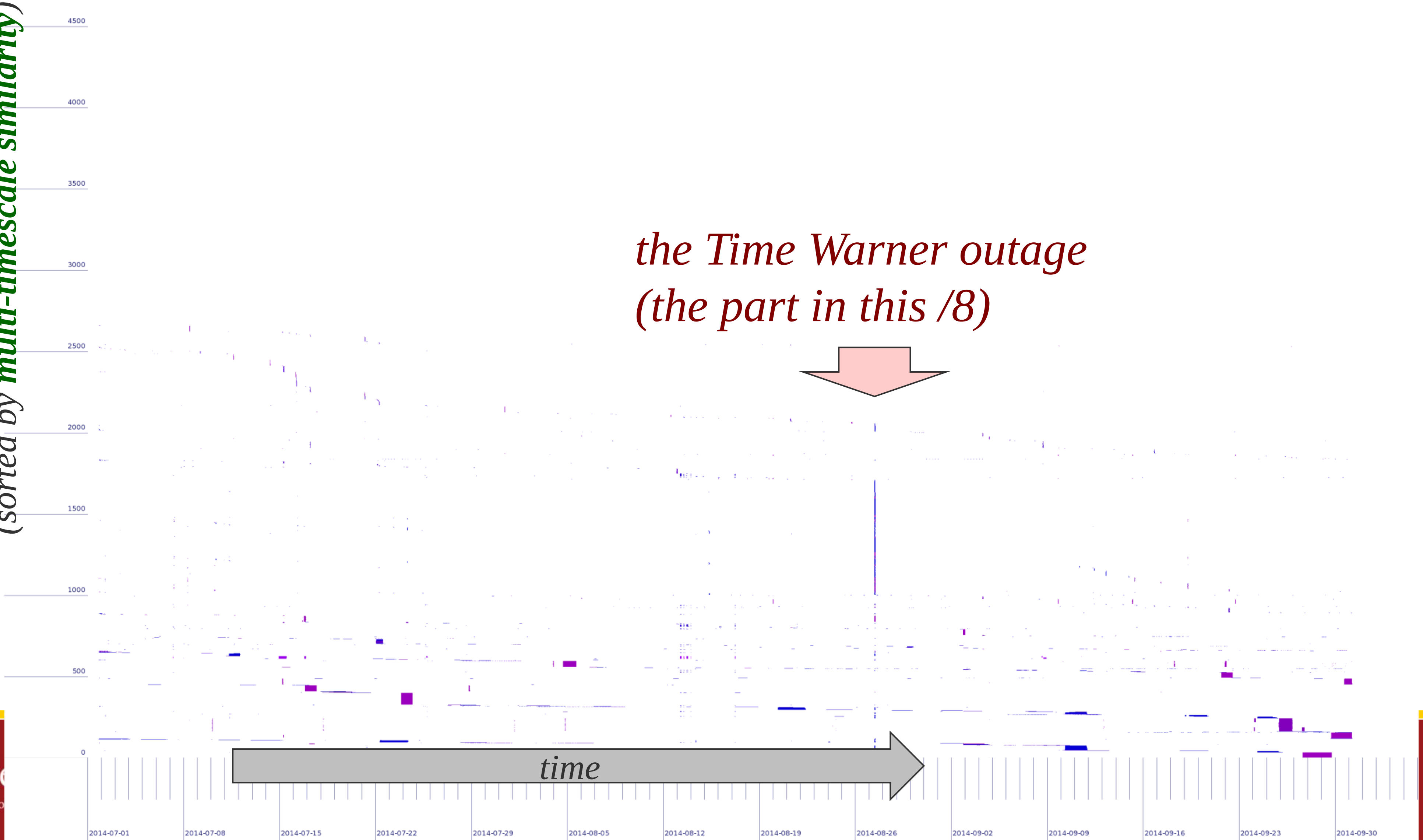


One Visualization Result

here ~1/4th (downsampled to fit the screen)
of 1/224th of the space (one /8 of IPv4)
and 1/12th of the duration (one quarter of ~3 years)

/24 blocks

(sorted by **multi-timescale similarity**)

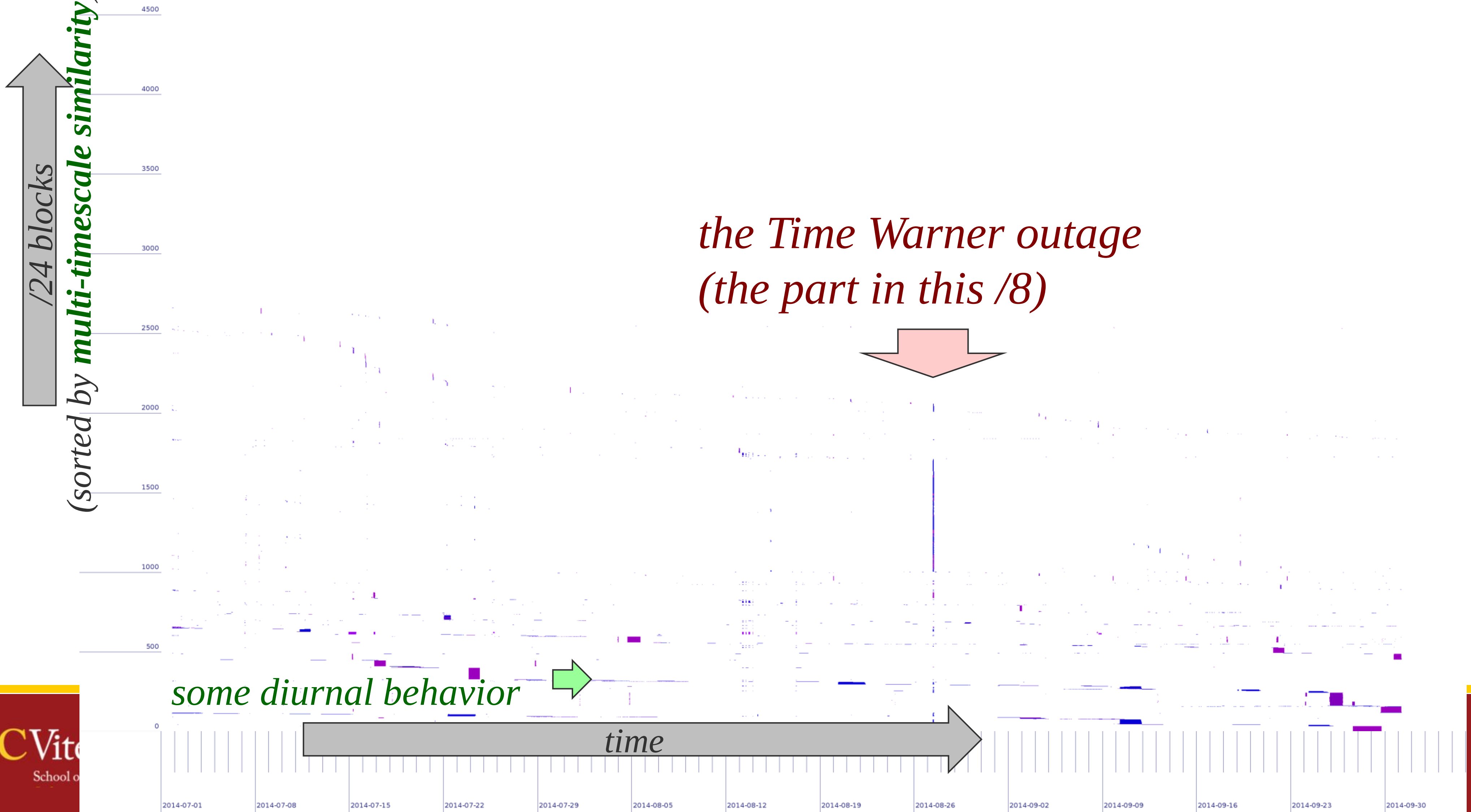


the Time Warner outage
(the part in this /8)

time

One Visualization Result

here ~1/4th (downsampled to fit the screen)
of 1/224th of the space (one /8 of IPv4)
and 1/12th of the duration (one quarter of ~3 years)



/24 blocks

(sorted by **multi-timescale similarity**)

the Time Warner outage
(the part in this /8)

some diurnal behavior

time

Clustering to Discovery Dependencies

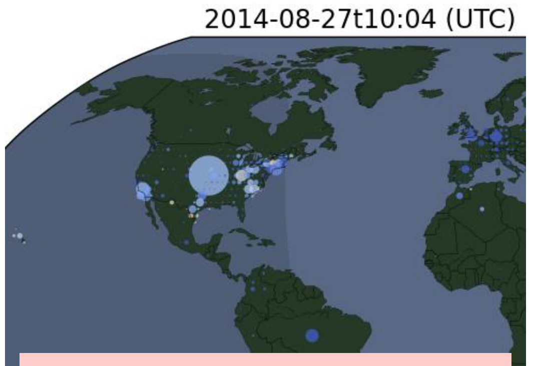
- visualization is nice, but humans can’t look at everything

- new clustering algorithms can *discovery dependencies*
  - insight: failure at the same time,
    multiple times => dependency
  - cluster on similarity of fail/recovery events

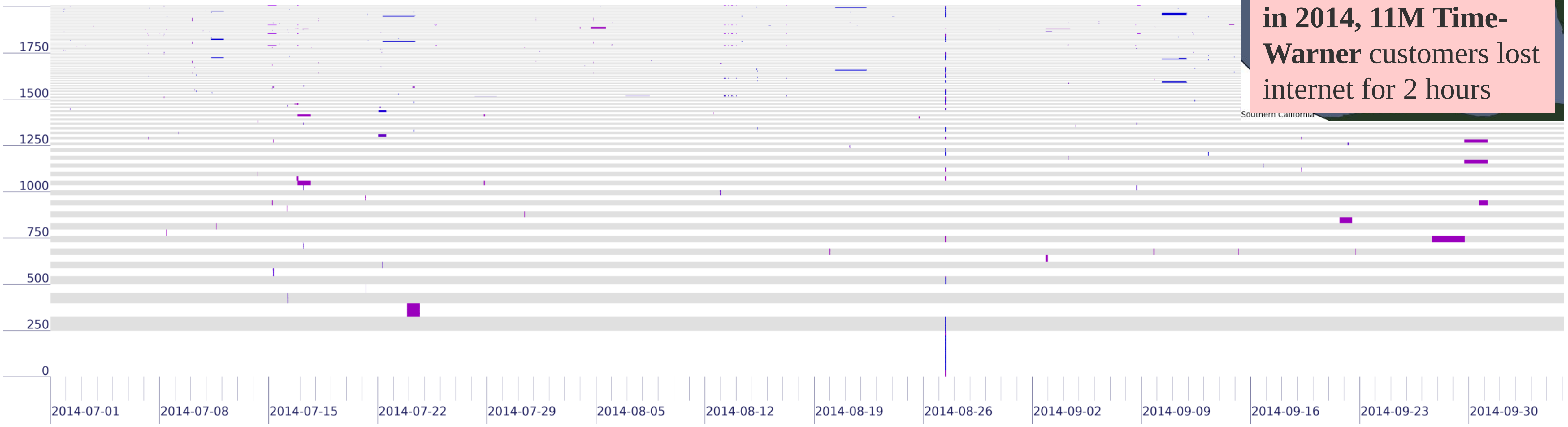
(Details: John Heidemann, Yuri Pradkin, and Aqib Nisar. Back Out: End-to-end Inference of Common Points-of-Failure in the Internet (extended). ISI-TR-724, February, 2018. https://www.isi.edu/%7ejohnh/PAPERS/Heidemann18b.html *.)*

Outages Reveal Network Topology

to find patterns, group 2014q3 outages into clusters by similarity (fail and recovery)

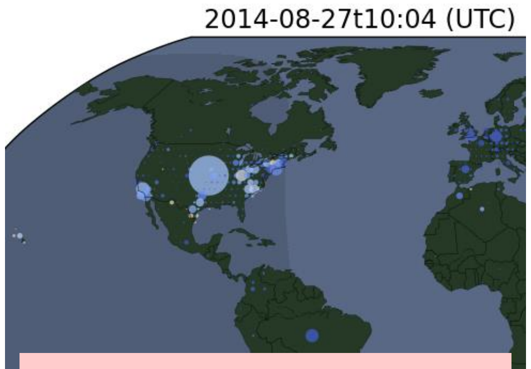


in 2014, 11M Time-Warner customers lost internet for 2 hours

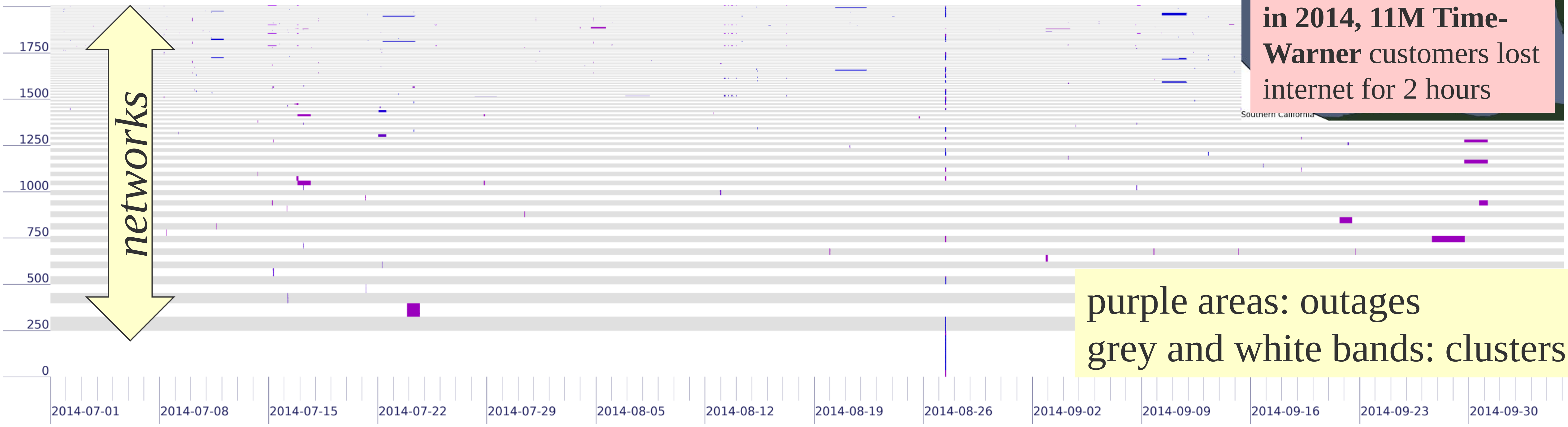


Outages Reveal Network Topology

to find patterns, group 2014q3 outages into clusters by similarity (fail and recovery)



in 2014, 11M Time-Warner customers lost internet for 2 hours



networks

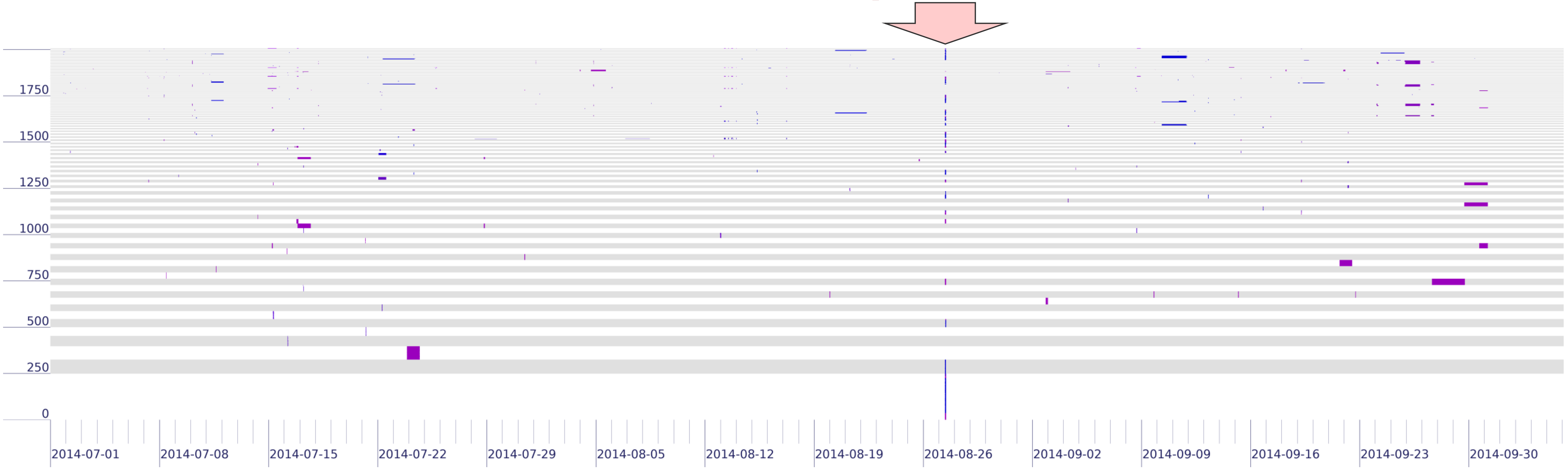
purple areas: outages

grey and white bands: clusters

time (3 months)

Clustering To Drill-Down on Network Structure

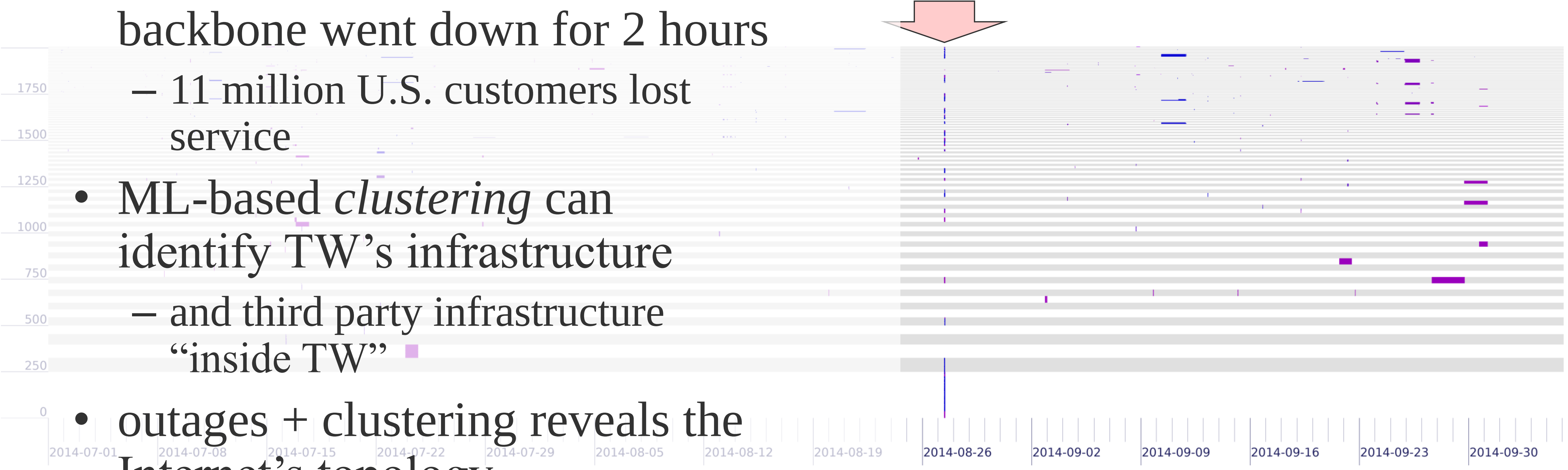
the Time Warner outage
(the part in this /8)



(Details: John Heidemann, Yuri Pradkin, and Aqib Nisar. Back Out: End-to-end Inference of Common Points-of-Failure in the Internet (extended). ISI-TR-724, February, 2018. [*https://www.isi.edu/%7ejohnh/PAPERS/Heidemann18b.html*](https://www.isi.edu/%7ejohnh/PAPERS/Heidemann18b.html) *.)*

Clustering To Drill-Down on Network Structure

- in 2017, Time Warner's backbone went down for 2 hours
  - – 11 million U.S. customers lost service
- ML-based *clustering* can identify TW's infrastructure
  - – and third party infrastructure "inside TW"
- outages + clustering reveals the Internet's topology

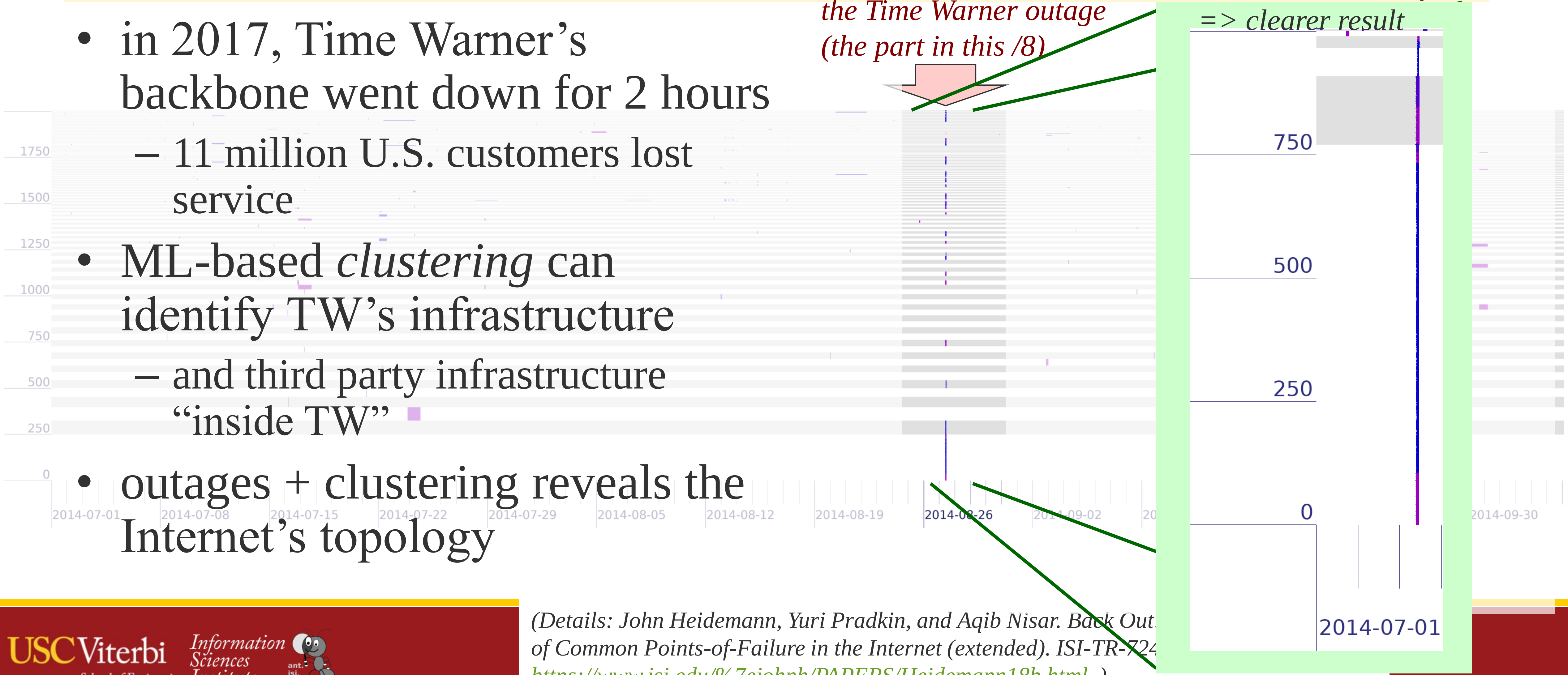


the Time Warner outage
(the part in this /8)

(Details: John Heidemann, Yuri Pradkin, and Aqib Nisar. Back Out: End-to-end Inference of Common Points-of-Failure in the Internet (extended). ISI-TR-724, February, 2018. [*https://www.isi.edu/%7ejohnh/PAPERS/Heidemann18b.html*](https://www.isi.edu/%7ejohnh/PAPERS/Heidemann18b.html) *.)*

Clustering To Drill-Down on Network Structure

- in 2017, Time Warner's backbone went down for 2 hours
  - – 11 million U.S. customers lost service
- ML-based *clustering* can identify TW's infrastructure
  - – and third party infrastructure "inside TW"
- outages + clustering reveals the Internet's topology



the Time Warner outage (the part in this /8)

recluster over 3 days => clearer result

(Details: John Heidemann, Yuri Pradkin, and Aqib Nisar. Back Out... of Common Points-of-Failure in the Internet (extended). ISI-TR-724 https://www.isi.edu/%7ejohnh/PAPERS/Heidemann18b.html .)

Understanding Internet Reliability

- opportunities observing Internet reliability
- from scanning to outages
- from outages to clusters: hidden dependencies
- **finding work-from-home**

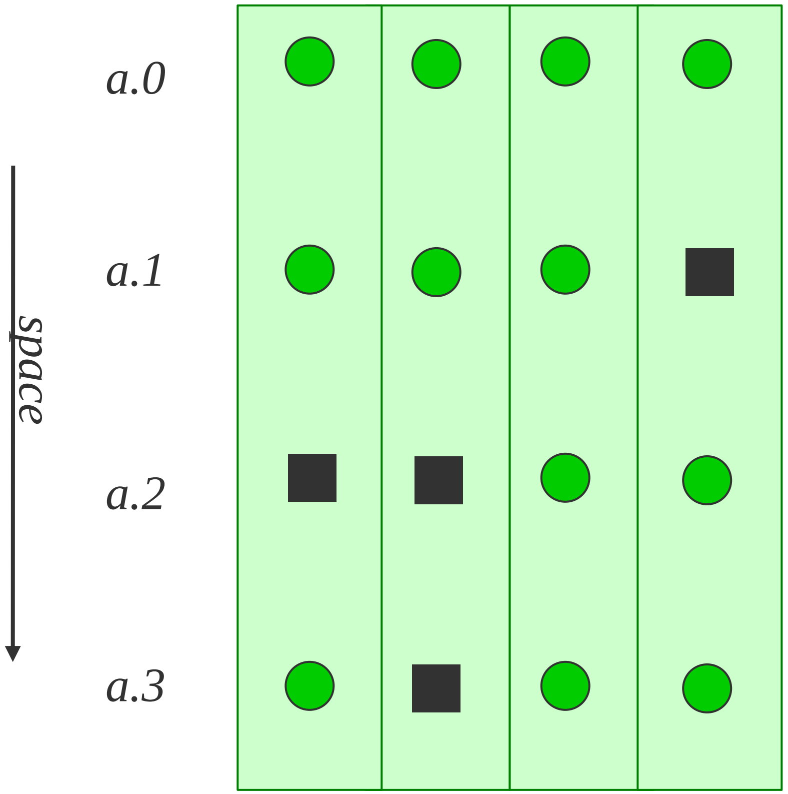
Q: Can We find Work-from-Home from Changes in IPv4 Address Usage?

Goal:

- do people *really* work-from home?
- can we confirm compliance?
- globally

Insight:

- when we probe all these addresses…
- we learn how the Internet "moves"
  - as computers are turned on and off
- so we learn how *people* move
  - as laptops come and go



(blocks really have 256 addresses, we show 4 here)

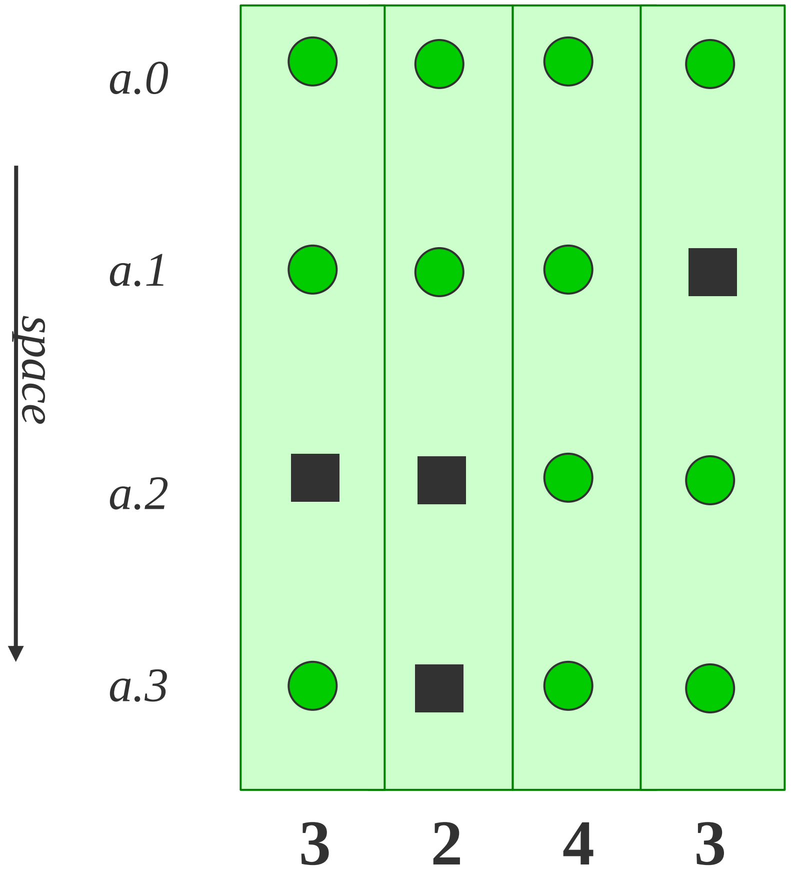
Q: Can We find Work-from-Home from Changes in IPv4 Address Usage?

Goal:

- do people *really* work-from home?
- can we confirm compliance?
- globally

Insight:

- when we probe all these addresses…
- we learn how the Internet “moves”
  - as computers are turned on and off
- so we learn how *people* move
  - as laptops come and go



a.0	●	●	●	●
a.1	●	●	●	■
a.2	■	■	●	●
a.3	●	■	●	●
	3	2	4	3

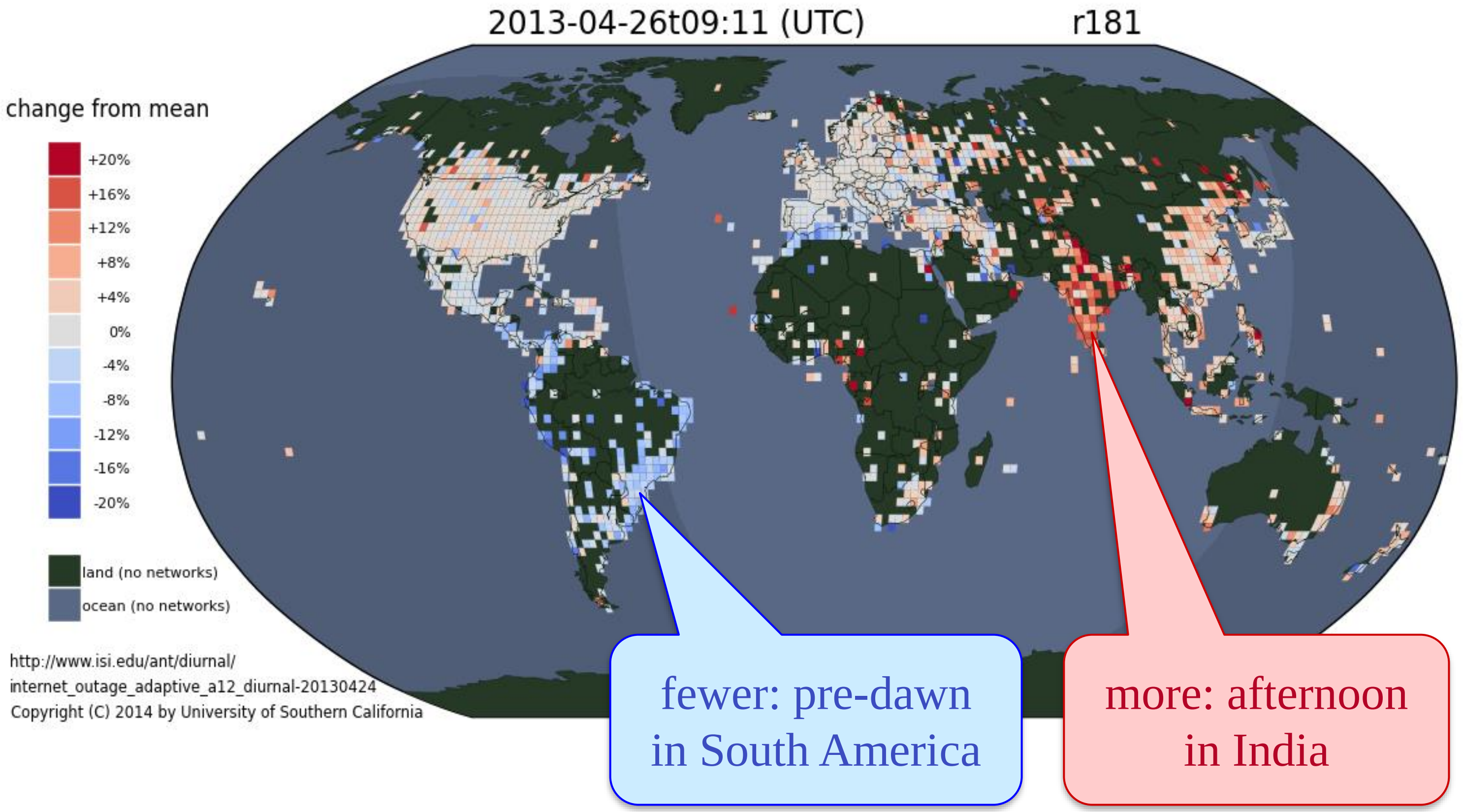
(blocks really have 256 addresses, we show 4 here)

Our Prior Work: The Internet Sleeps

we know we see diurnal trends across the Internet:

parts of the Internet sleep:
more activity during the day

red: more than typical
white: typical
blue: fewer



http://www.isi.edu/ant/diurnal/
internet_outage_adaptive_a12_diurnal-20130424
Copyright (C) 2014 by University of Southern California

fewer: pre-dawn in South America

more: afternoon in India

https://ant.isi.edu/diurnal/ani/

(play)

Details in "When the Internet Sleeps: Correlating Diurnal Newtorks with External Factors", by Quan, Heidemann, Pradkin in ACM IMC 2014. https://doi.org/10.1145/2663716.2663721

Finding Work-from-Home due to Covid

Insight:

- when we probe all these addresses…
- we learn how the Internet “moves”
  - as computers are turned on and off
- so we learn how *people* move
  - as laptops come and go

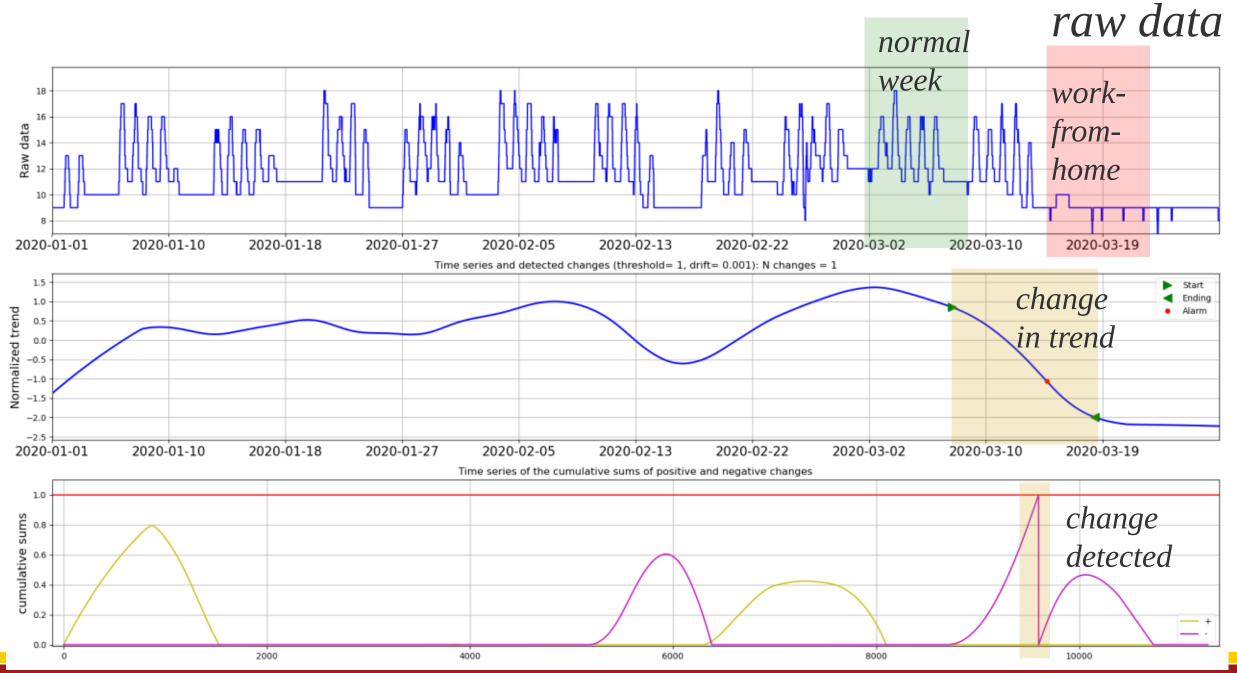
Method:

- reuse data from Trinocular scanning
- find **change-sensitive blocks**
  - blocks that show people moving every day
  - about 150k to 280k blocks, globally
  - (many blocks do not)
- look for **changes in usage**
  - (details on next slide)

Algorithm: Detect Changes in Daily Usage

1. extract active addresses
   - Trinocular cycles through all responsive addresses
   - track which respond over a day (cumulative)
2. identify change-sensitive blocks
   - blocks are diurnal
   - and change “enough” (5 addrs, 4 in 7 days)
3. de-trend: extract “seasonality”
4. change detect: CUSUM
5. confirm results

3 months of change-sensitive block raw data



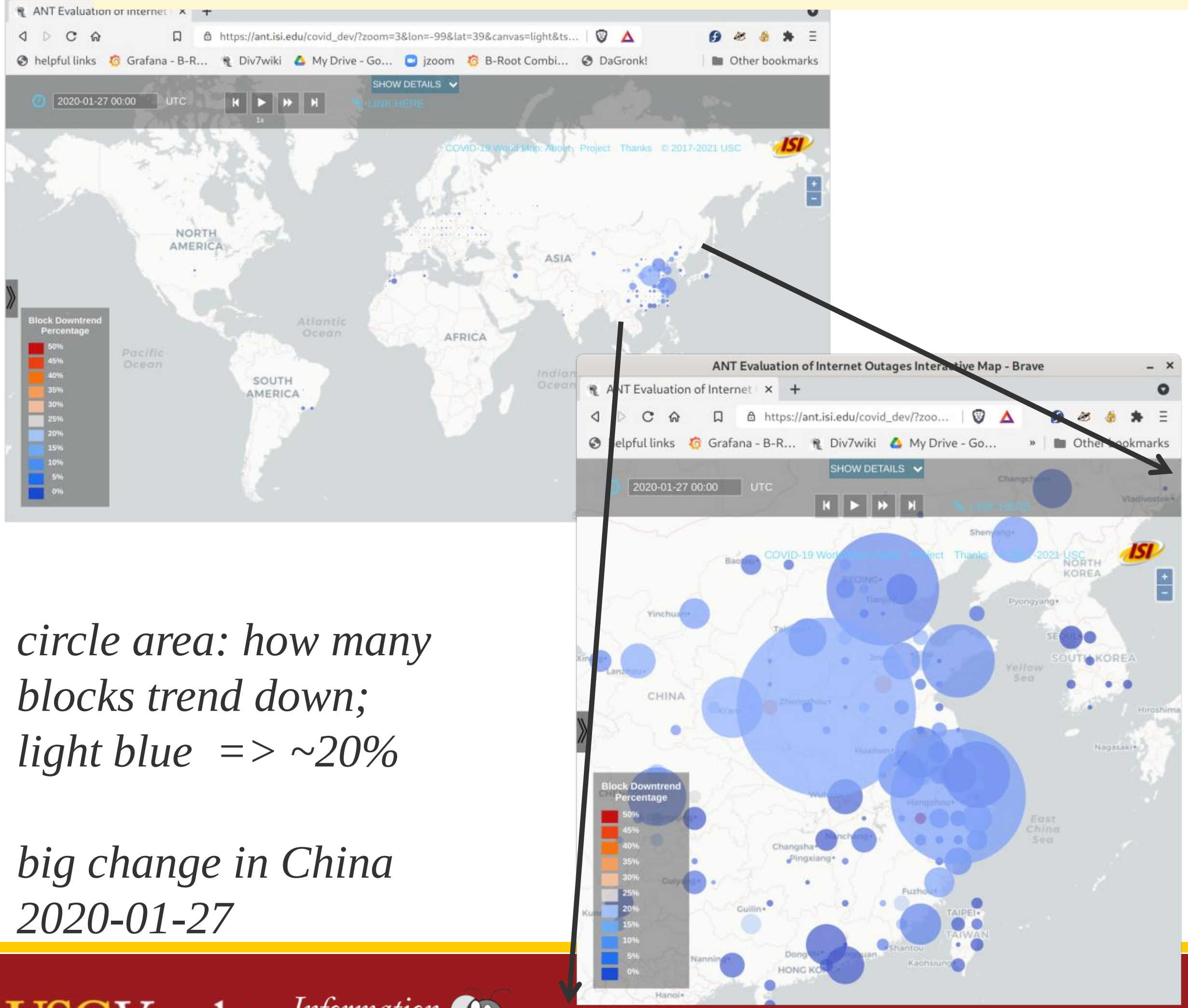
normal week

work-from-home

change in trend

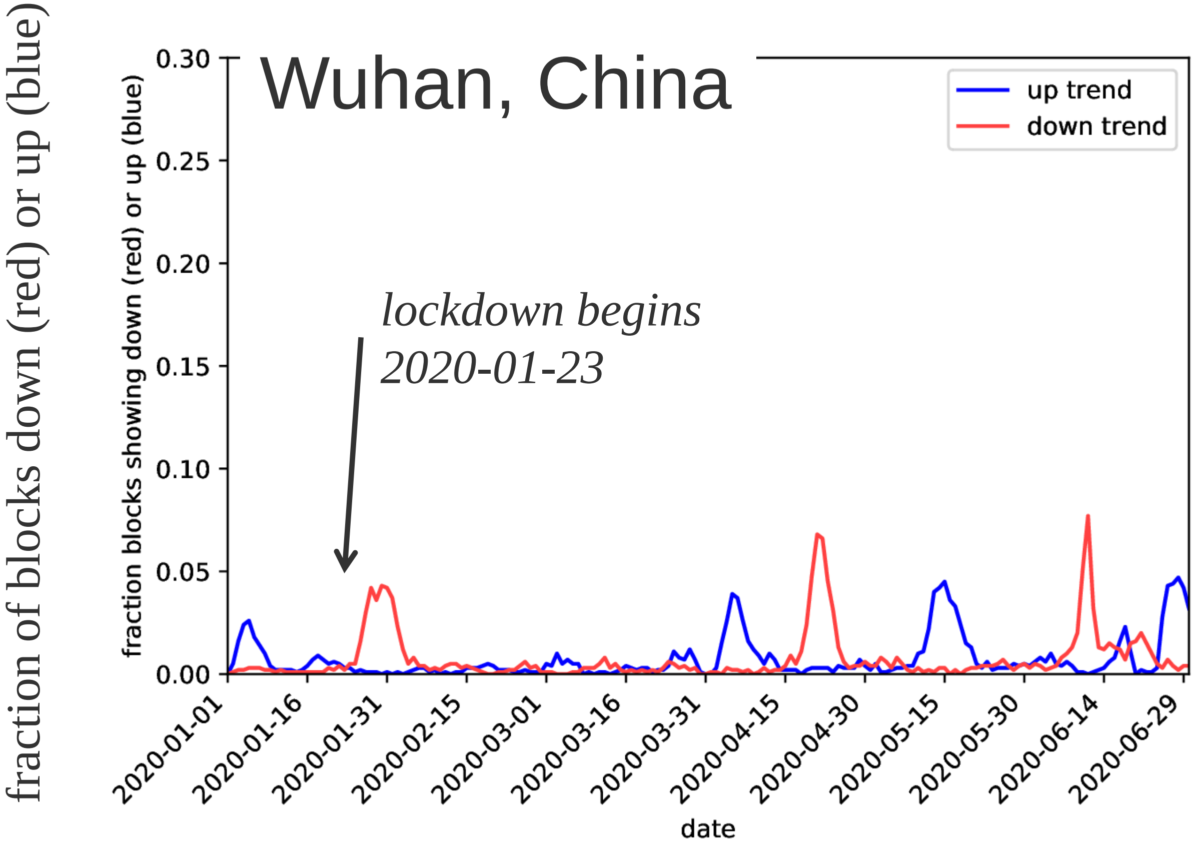
change detected

Results: World Map with Details (Wuhan)



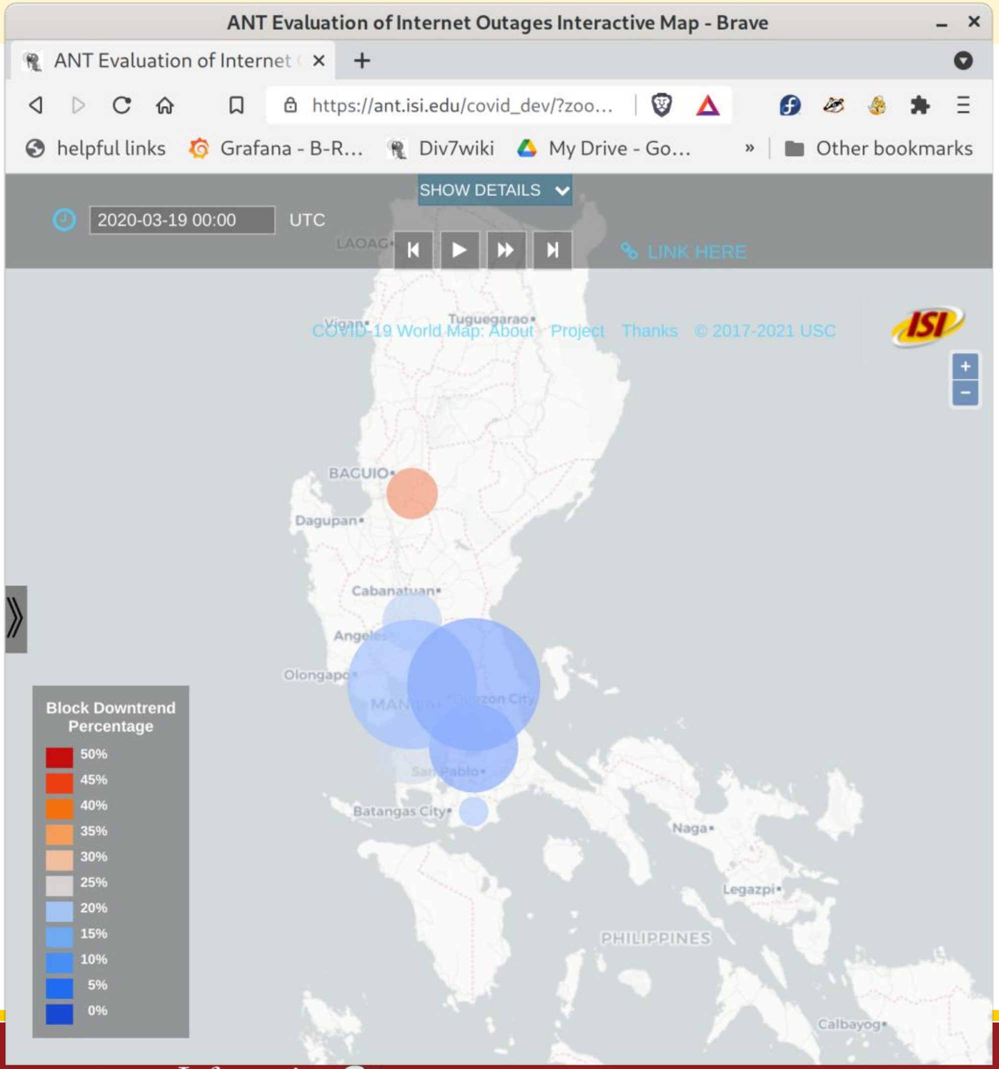
circle area: how many blocks trend down; light blue => ~20%

big change in China 2020-01-27



⇒ example Covid-19 related event we knew about

Results: World Map and Details (Manila)

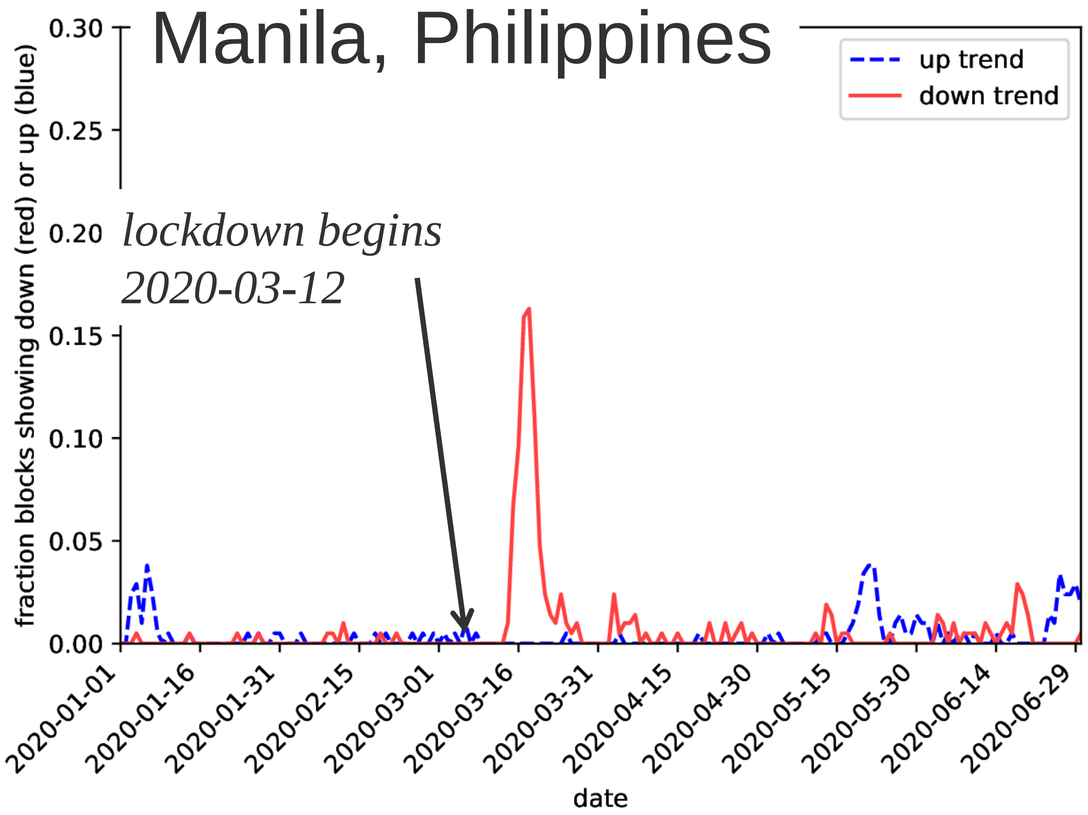


ANT Evaluation of Internet Outages Interactive Map - Brave

https://ant.isi.edu/covid_dev/?zoo…

2020-03-19 00:00 UTC

COVID-19 World Map: About Project Thanks © 2017-2021 USC

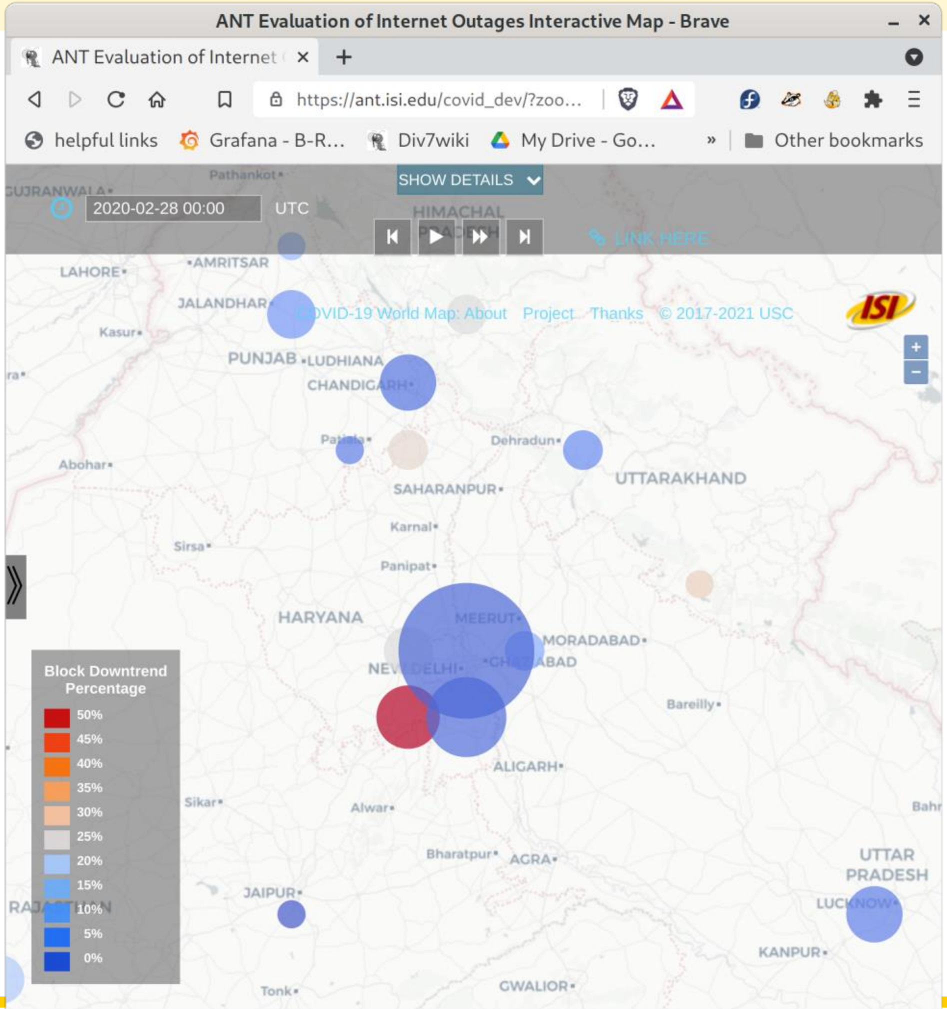


Manila, Philippines

lockdown begins
2020-03-12

⇒ example Covid-19 related event we **discovered**

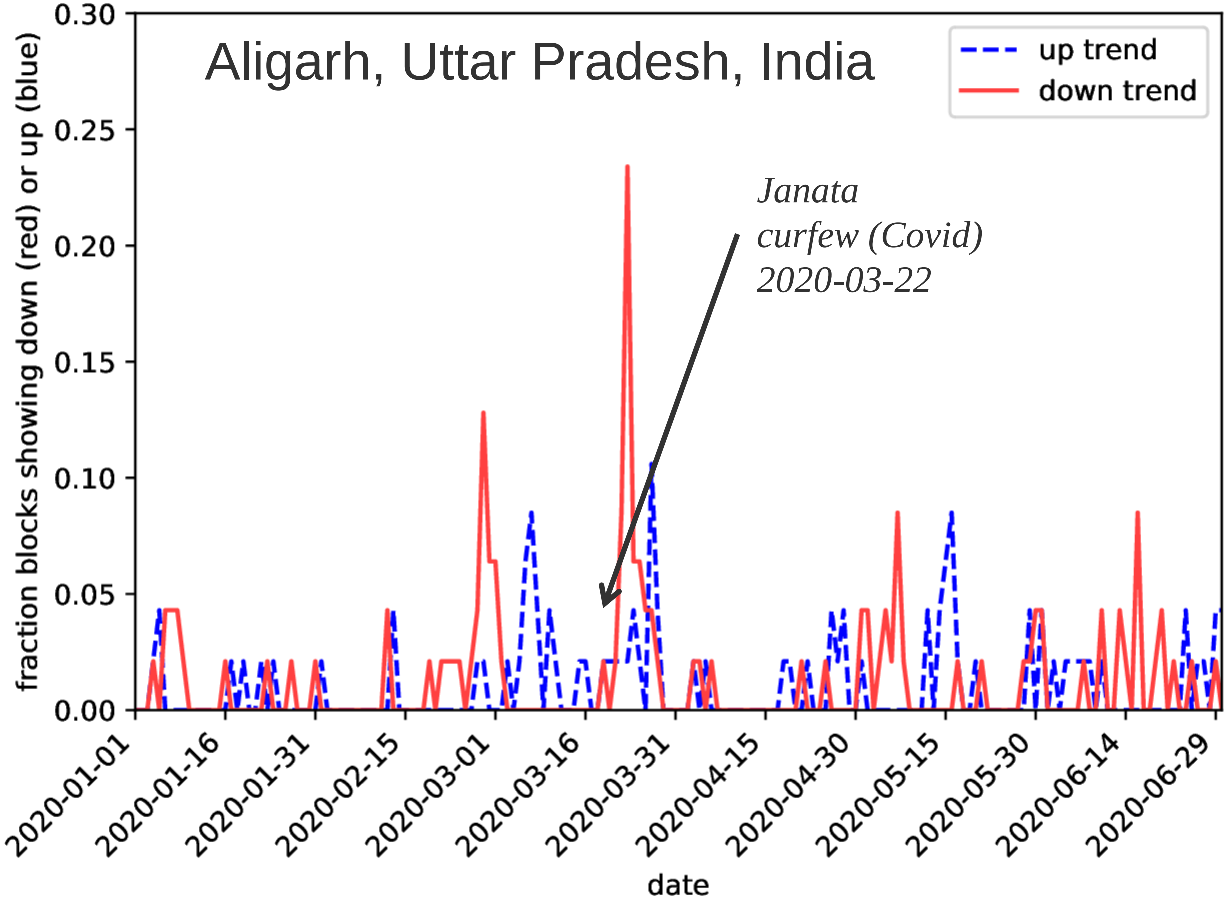
Results: Covid and Non-Covid Events (India)



ANT Evaluation of Internet Outages Interactive Map - Brave

https://ant.isi.edu/covid_dev/?zoo…

2020-02-28 00:00 UTC



⇒ example Covid-19 related event and **non-Covid event, both discovered**

Work-from-Home Status

- algorithm and initial results are promising
- work-in-progress: web-based visualization

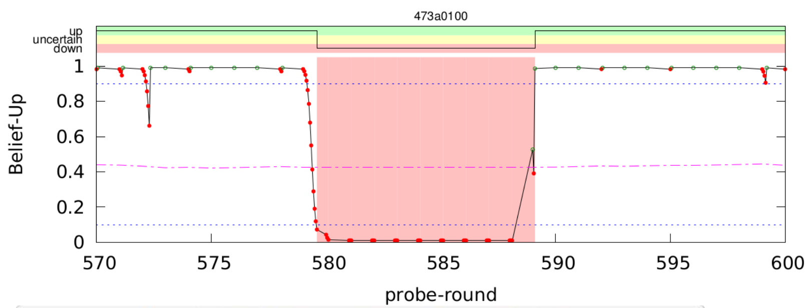
- early technical report
  - “Measuring the Internet During Covid-19 to Evaluate Work-from-Home” by Song and Heidemann
  - https://ant.isi.edu/minceq/arxiv2021.pdf or arxiv:2102.07433v2
  - more complete paper currently under review

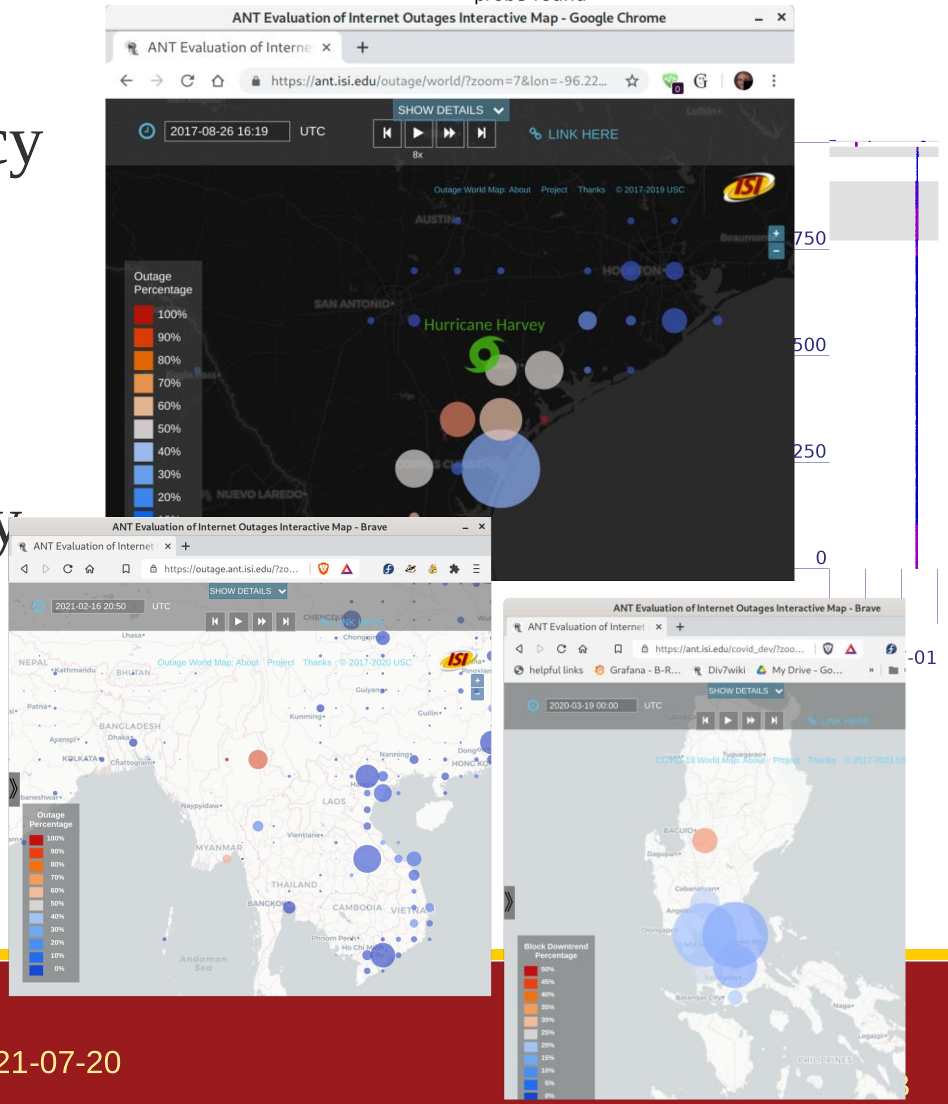
Directions from Here

- extending the algorithms
  - what *else* can the data teach us? outages, sleep, work-from-home, …
- from IPv4 to IPv6
  - 2^{128} is *much* bigger than 2^{32}, requiring new approaches
- helping others use the data
  - joint evaluation with the FCC
  - can export data via near-real-time API
  - what other applications can use outages?

Conclusions

- we *can* measure Internet outages
  - precisely: for millions of nets; ~11-minute accuracy
  - in near-real time
- outages have many applications:
  - short-term: helping first responders, ISPs, citizens
  - long-term: understanding and improving reliability
- looking for partners and data consumers
- more info? papers and data https://ant.isi.edu/
  - maps: https://outage.ant.isi.edu/




ANT Evaluation of Internet Outages Interactive Map - Google Chrome

https://ant.isi.edu/outage/world/?zoom=7&lon=-96.22...

2017-08-26 16:19 UTC

SHOW DETAILS

LINK HERE

Hurricane Harvey

ANT Evaluation of Internet Outages Interactive Map - Brave

https://outage.ant.isi.edu/?zo...

2021-02-16 20:50 UTC

ANT Evaluation of Internet Outages Interactive Map - Brave

https://ant.isi.edu/covid_dev/?zoo...

2020-03-19 00:00 UTC

"Any opinions, findings, conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the Networking and Information Technology Research and Development Program."

The Networking and Information Technology Research and Development
(NITRD) Program

Mailing Address: NCO/NITRD, 2415 Eisenhower Avenue, Alexandria, VA 22314

Physical Address: 490 L'Enfant Plaza SW, Suite 8001, Washington, DC 20024, USA Tel: 202-459-9674,
Fax: 202-459-9673, Email: nco@nitrd.gov, Website: https://www.nitrd.gov