There is More to Internet Invariants Than Meets the Eye
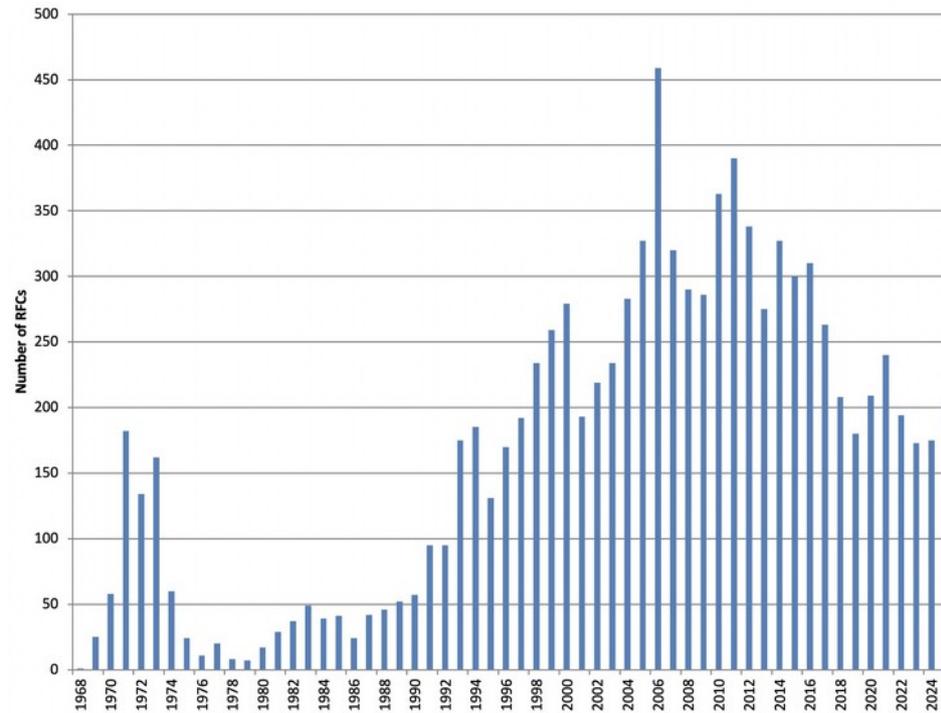
Chris Misa[1], Walter Willinger[2], Ramakrishnan Durairajan[1,3], Reza Rejaie[1]

1. University of Oregon   2. NIKSUN, Inc.   3. Link Oregon

**The Internet is
a moving target**

Reference: Difficulties in simulating the Internet, by S. Floyd and V. Paxson, Proc. IEEE/ACM ToN (2001).
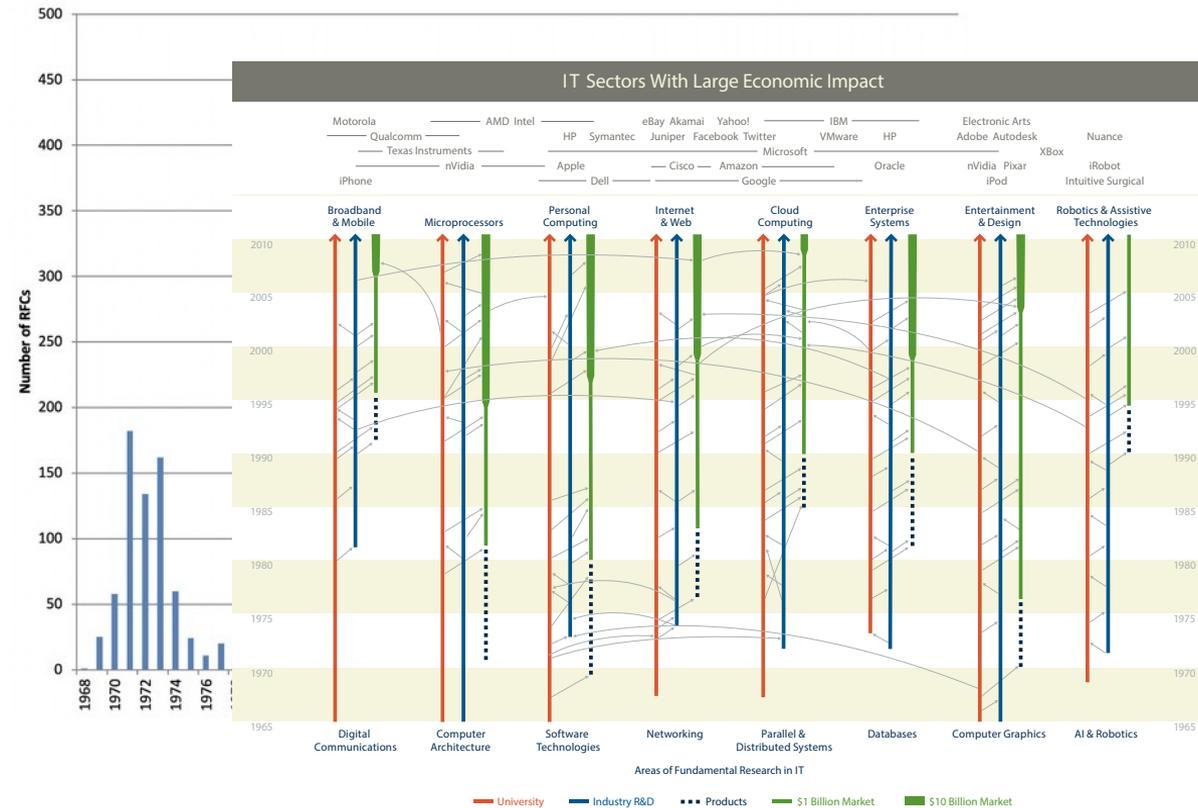
The Internet is a moving target

Source: https://www.rfc-editor.org/rfcs-per-year/

Continuous technological development (e.g., ~200 RFCs / year) ...
- New protocols / applications / services
- Updates to existing protocols / applications / services
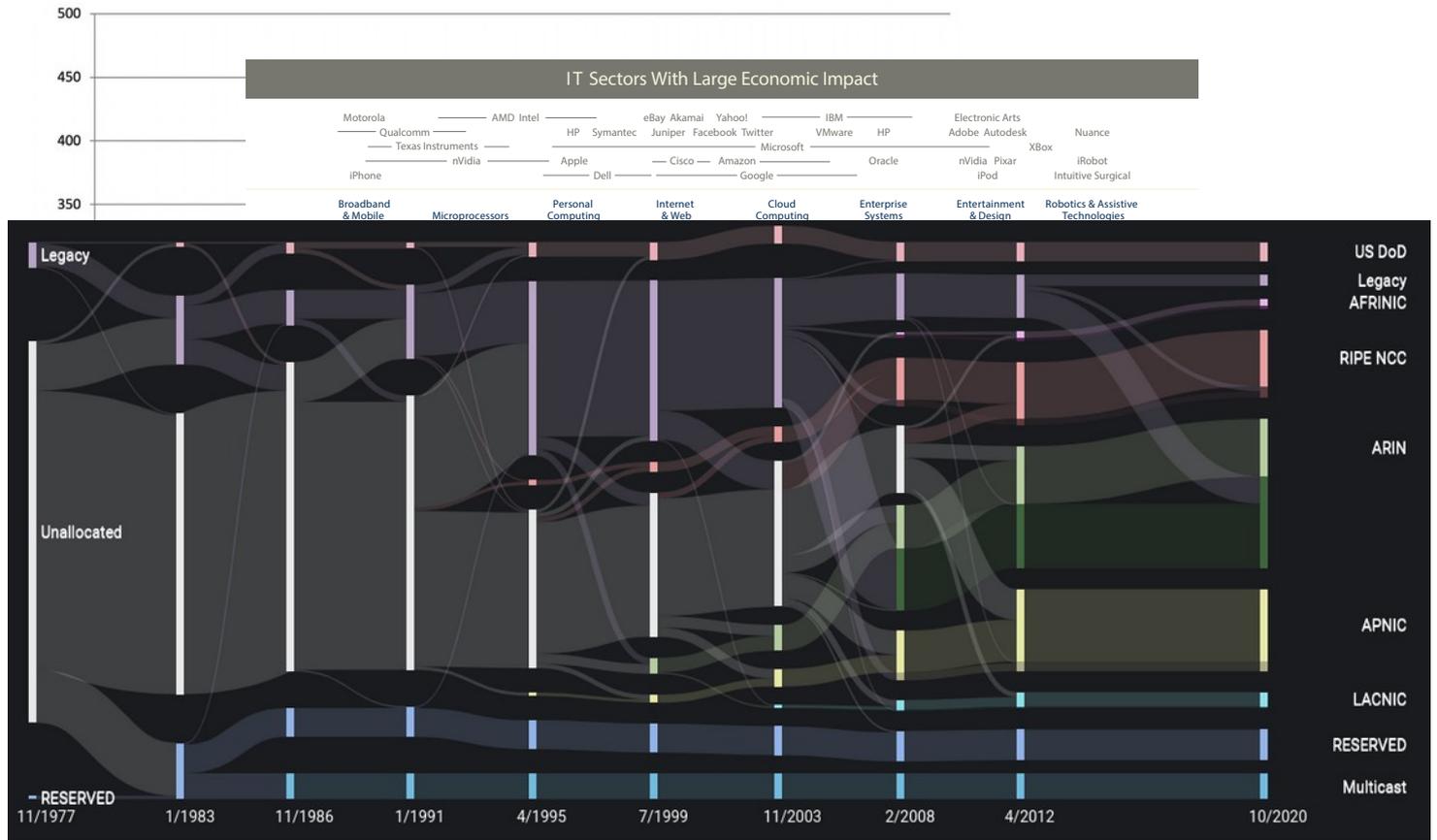
The Internet is a moving target

Source: https://doi.org/10.17226/23393 (page 5)

Enables multiple new >$10 billion industries ...
- Cloud Computing
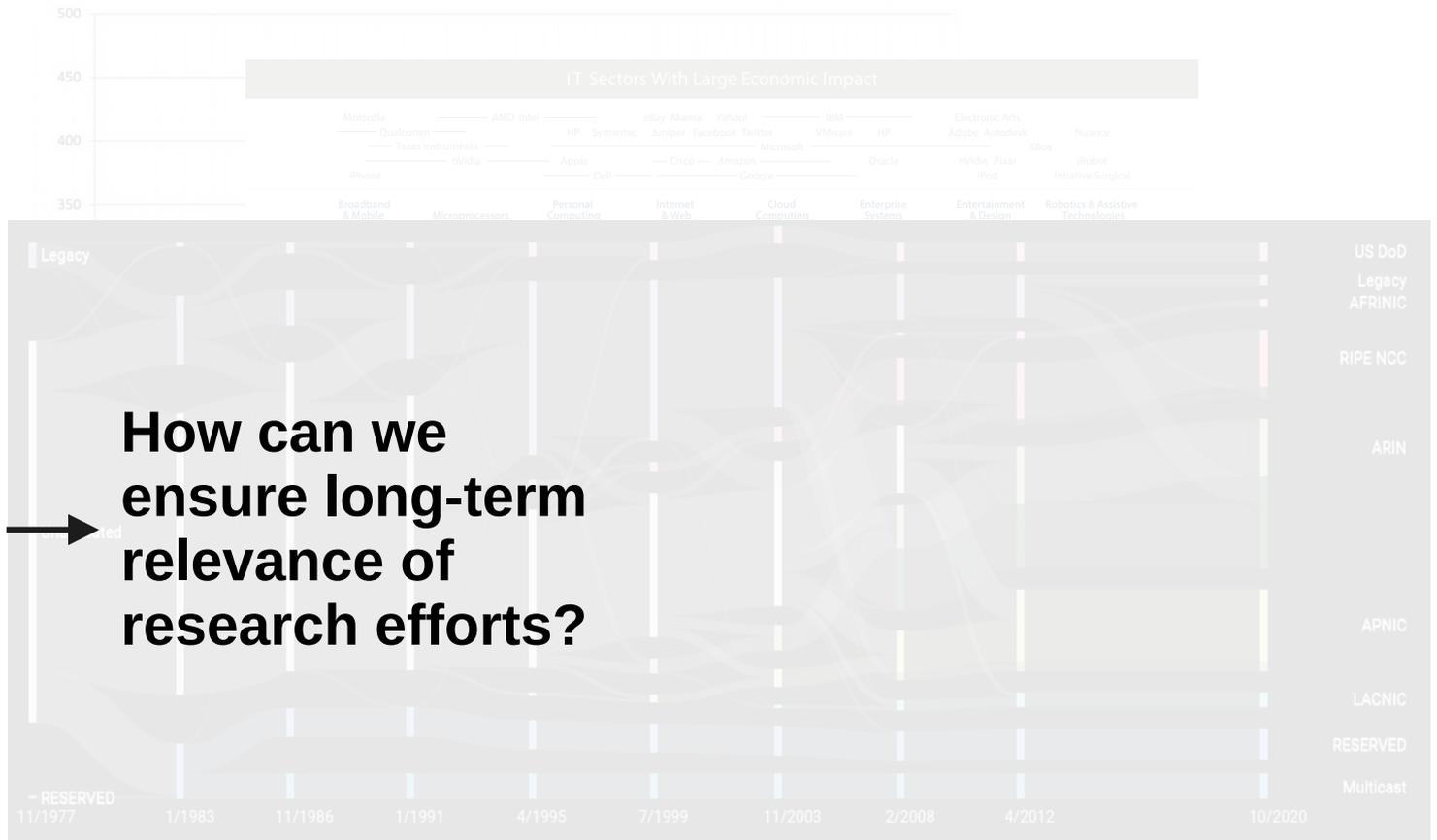- Broadband & Mobile

The Internet is a moving target

Source: https://www.caida.org/catalog/media/visualizations/ipv4-history/

Continuous negotiation of finite resources …
- Addresses, AS numbers, etc.

The Internet is a moving target → **How can we ensure long-term relevance of research efforts?**

Source: https://www.caida.org/catalog/media/visualizations/ipv4-history/

Reference: Difficulties in simulating the Internet, by S. Floyd and V. Paxson, Proc. IEEE/ACM ToN (2001).
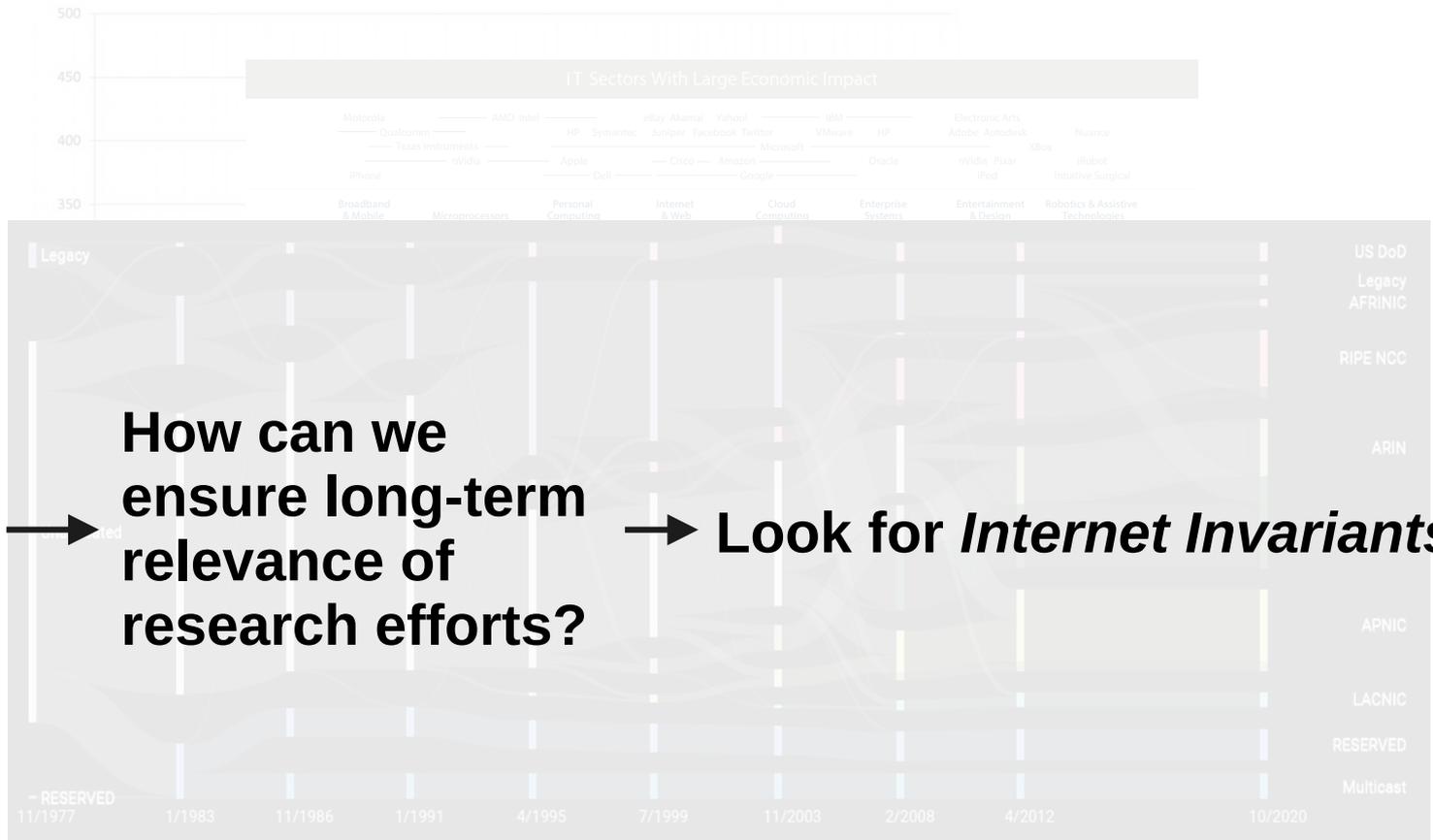
The Internet is a moving target → **How can we ensure long-term relevance of research efforts?** → **Look for *Internet Invariants!***

Source: https://www.caida.org/catalog/media/visualizations/ipv4-history/

Reference: Difficulties in simulating the Internet, by S. Floyd and V. Paxson, Proc. IEEE/ACM ToN (2001).

Empirical Evidence ← *Internet Invariant*

A distinct statistical phenomenon is observed across wide range of scenarios.

Empirical Evidence ←———— *Internet Invariant* ————→ **Stated/unstated Design Principles**

A distinct statistical phenomenon is observed across wide range of scenarios.

Is this phenomenon caused by some underlying stated/unstated design principle?

Empirical Evidence ←——— *Internet Invariant* ———→ *Stated/unstated Design Principles*
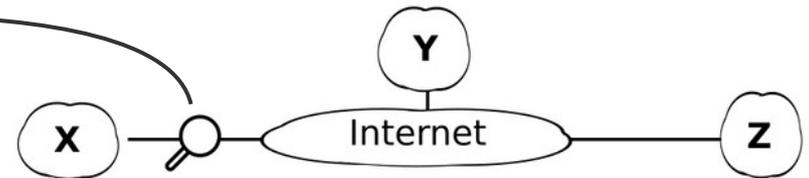
A distinct statistical phenomenon is observed across wide range of scenarios.

Is this phenomenon caused by some underlying stated/unstated design principle?

Internet Traffic Invariants
- **Temporal** (observed traffic dynamics)
- **Spatial** (observed address structure)

Empirical Evidence ←— *Internet Invariant* —→ **Stated/unstated Design Principles**

Temporal
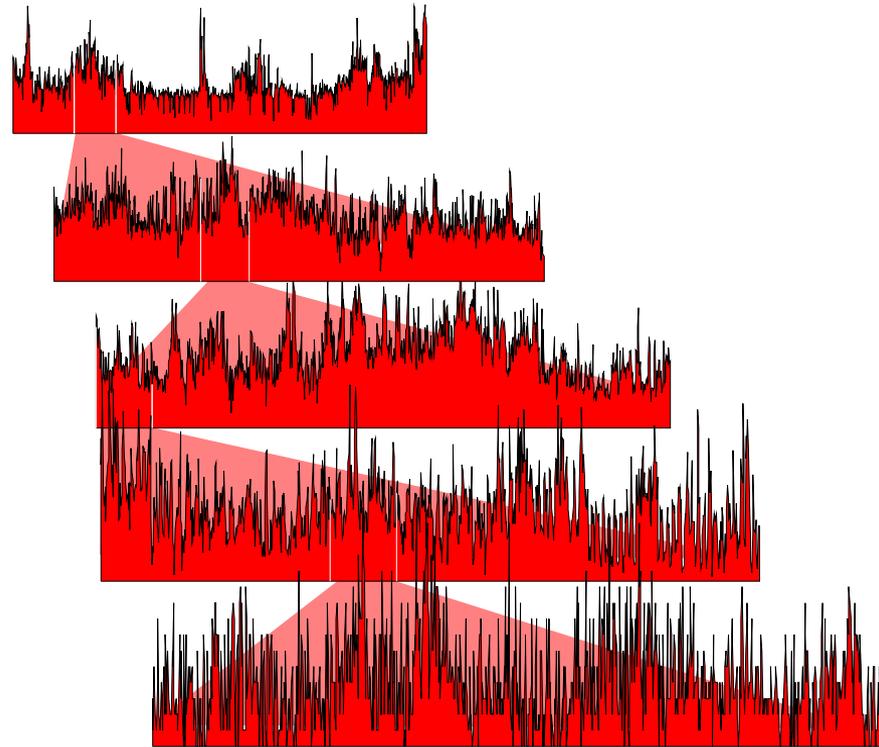
Empirical Evidence ←—— *Internet Invariant* ——→ **Stated/unstated Design Principles**

Temporal

Self-similar scaling

Reference: On the self-similar nature of Ethernet traffic, by W.E. Leland, M.S. Taqqu, W. Willinger, and D.V. Wilson, Proc. ACM SIGCOMM (1993).
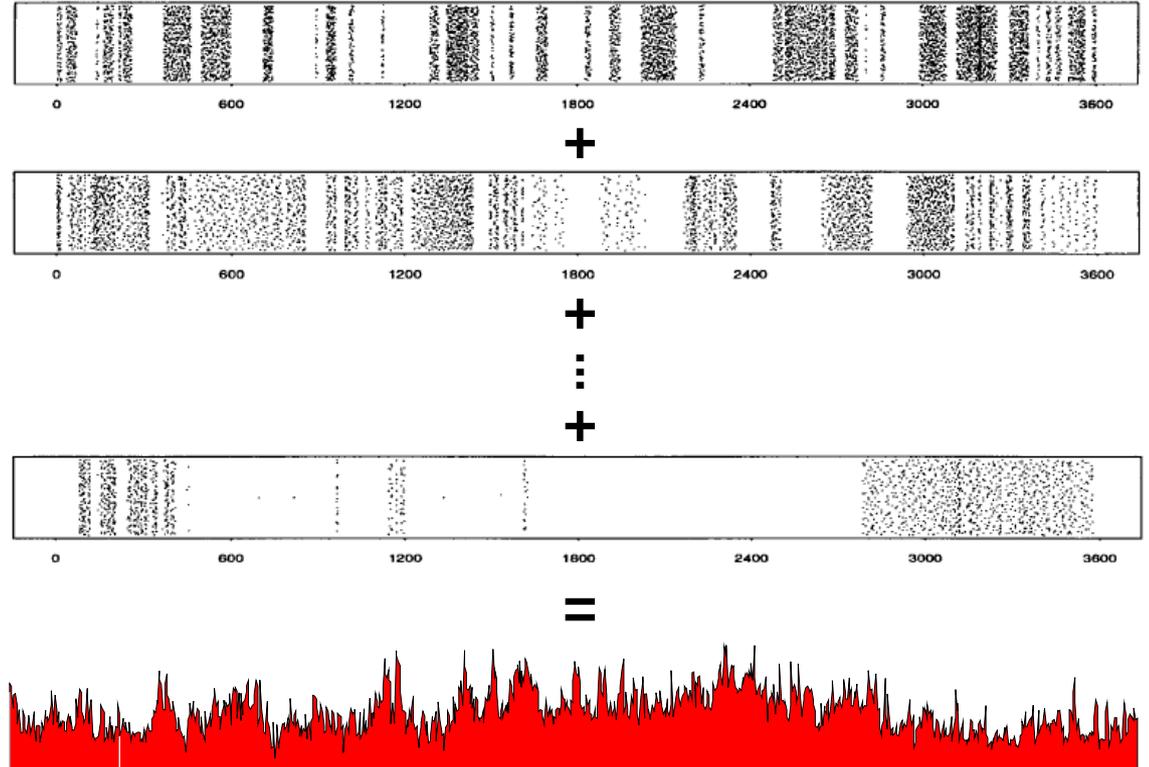
Temporal

Self-similar scaling

ON/OFF burst processes; **Heavy-tailed flow sizes.**

Reference: Self-similarity through high-variability: Statistical analysis of Ethernet LAN traffic at the source level, by W. Willinger, M.S. Taqqu, R. Sherman, and D.V. Wilson, Proc. ACM SIGCOMM (1995).

+

...

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Empirical Evidence	Generating Model	Reverse Engineering	Stated/unstated Design Principles

Temporal

Self-similar scaling

ON/OFF burst processes; **Heavy-tailed flow sizes.**

Optimal web layout results in **heavy-tailed flow sizes.**

HOT model of web layout

Content

Entry point

1-D web layout

Reference: Heavy Tails, Generalized Coding, and Optimal Web Layout, by X. Zhu, J. Yu, and J. Doyle, Proc. IEEE INFOCOM (2001).

	Empirical Evidence	**Generating Model**	**Reverse Engineering**	**Stated/unstated Design Principles**
Temporal	Self-similar scaling	ON/OFF burst processes; **Heavy-tailed flow sizes.**	Optimal web layout results in **heavy-tailed flow sizes.**	Organizing information for human consumption.

HOT model of web layout

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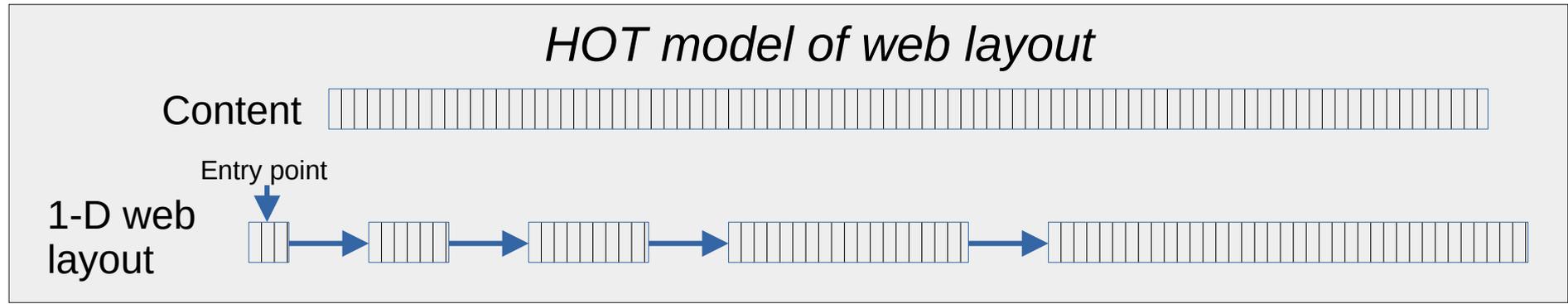|	Empirical Evidence	Generating Model	Reverse Engineering	Stated/unstated Design Principles
Temporal	Self-similar scaling	ON/OFF burst processes; **Heavy-tailed flow sizes.**	Optimal web layout results in **heavy-tailed flow sizes.**	Organizing information for human consumption.
Spatial				

Temporal

Self-similar scaling

% of addrs   1e-05   1e-04   1e-03   1e-02
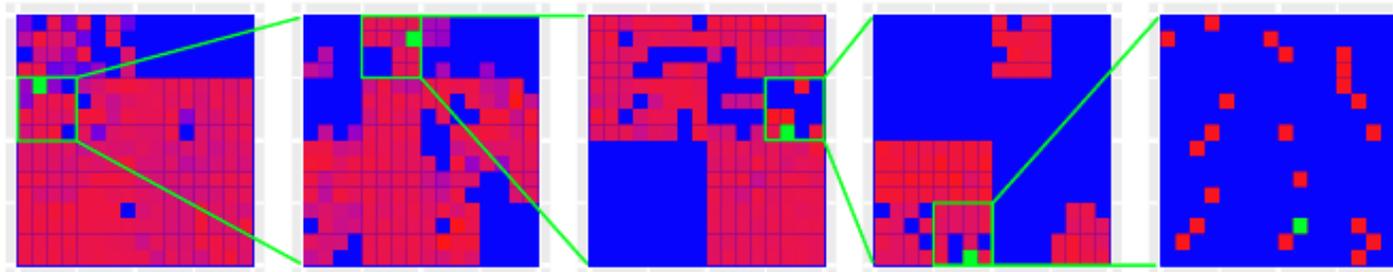
/8   /12   /16   /20   /24

Spatial

Multifractal scaling

Reference: Observed structure of addresses in IP traffic, by E. Kohler, J. Li, V. Paxson, and S. Shenker, Proc. SIGCOMM Workshop on Internet measurement (2002).
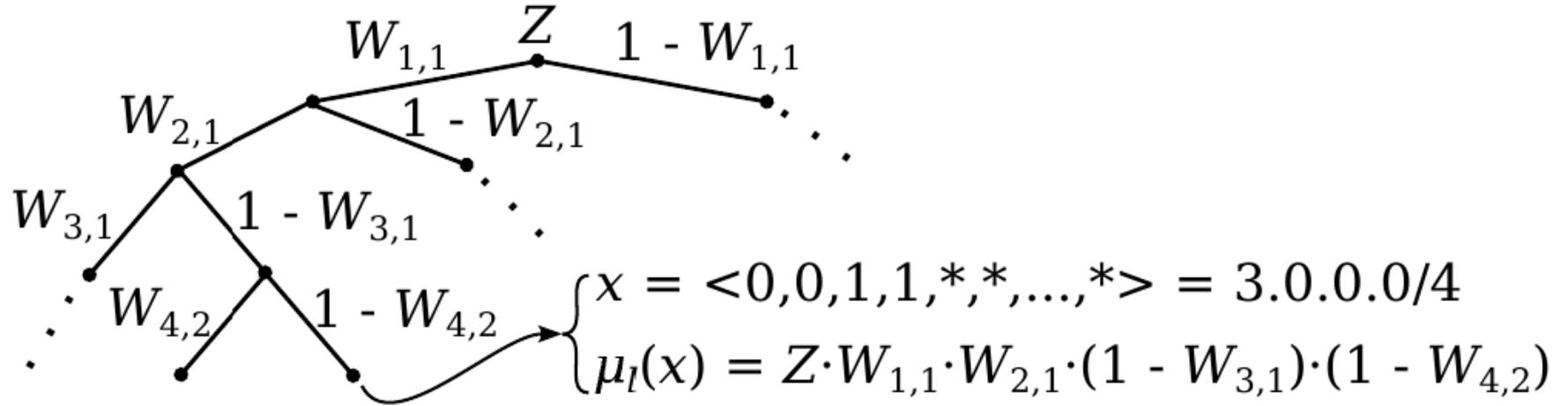
Temporal

$$W_{1,1} \quad Z \quad 1 - W_{1,1}$$
$$W_{2,1} \quad 1 - W_{2,1}$$
$$W_{3,1} \quad 1 - W_{3,1}$$
$$W_{4,2} \quad 1 - W_{4,2}$$

$$x = <0,0,1,1,*,*,...,*> = 3.0.0.0/4$$
$$\mu_l(x) = Z \cdot W_{1,1} \cdot W_{2,1} \cdot (1 - W_{3,1}) \cdot (1 - W_{4,2})$$

Spatial

Multifractal scaling

Conservative Cascade; ...

Reference: Toward a model for source addresses of Internet background radiation, by P. Barford, R. Nowak, R.Willett, and V. Yegneswaran, Proc. Passive and Active Measurement Conference (2006).

	Empirical Evidence	Generating Model	Reverse Engineering	Stated/unstated Design Principles
Temporal	Self-similar scaling	ON/OFF burst processes; **Heavy-tailed flow sizes.**	Optimal web layout results in **heavy-tailed flow sizes.**	Organizing information for human consumption.
Spatial	Multifractal scaling	Conservative Cascade; ...	Known Unknown ?	?

?

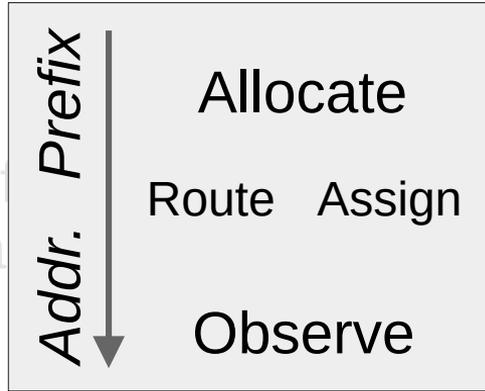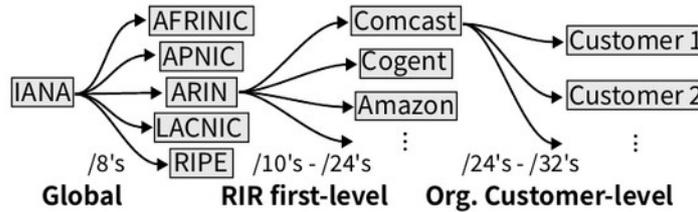|	Empirical Evidence	Generating Model	Reverse Engineering	Stated/unstated Design Principles
Temporal	Self scal...	Allocate / Route / Assign / Observe / Addr. Prefix ... burst ...; **...ailed ...es.**	Optimal web layout results in **heavy-tailed flow sizes.**	Organizing information for human consumption.
Spatial	Multifractal scaling	Conservative Cascade; ...		

Empirical Evidence **Generating Model** **Reverse Engineering** **Stated/unstated Design Principles**

Temporal

Addr. Prefix

Allocate

Route   Assign

Observe

Spatial

Multifractal scaling

Conservative Cascade;

...

Empirical Evidence | Generating Model | Reverse Engineering | Stated/unstated Design Principles

Temporal

Spatial
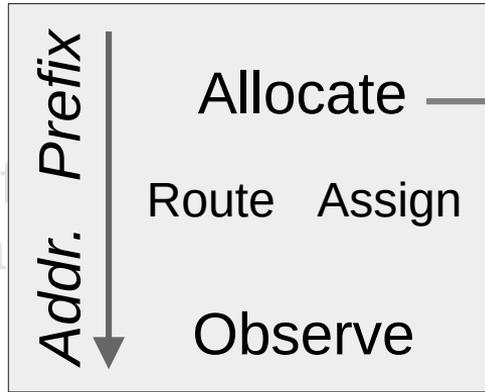
Addr. Prefix

Allocate

Route   Assign

Observe

Multifractal scaling

Conservative Cascade;
Heavy-tailed allocation sizes.

Empirical Evidence	Generating Model	Reverse Engineering	Stated/unstated Design Principles

Temporal

Clients request addrs from **Upstream**.

Upstream must satisfy each request.

HOT formulation

Don't know # addrs / client.

Minimize fragmentation.
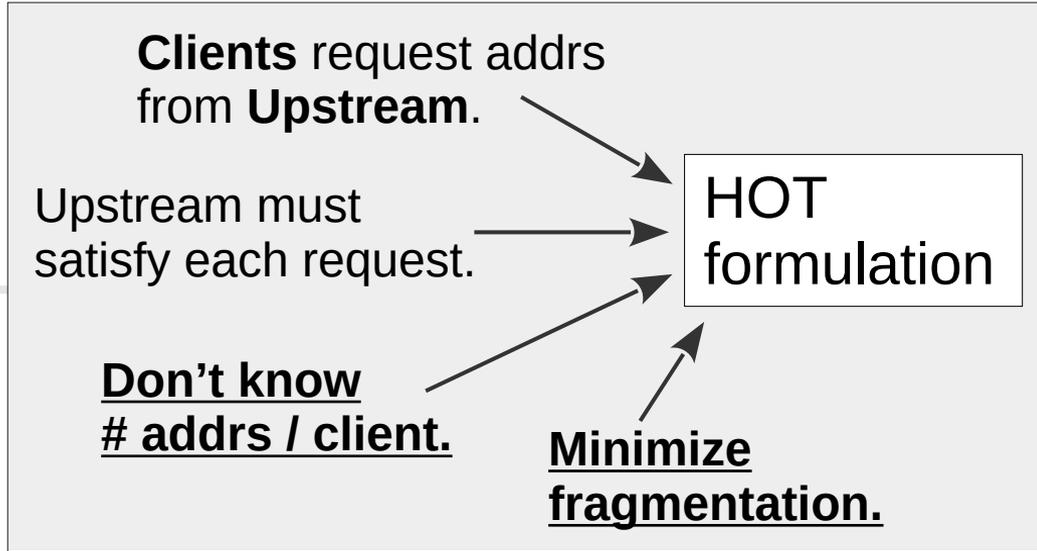
al web results **vy-tailed izes.**

Organizing information for human consumption.

Spatial
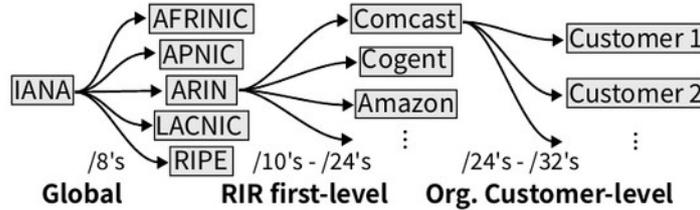
Multifractal scaling

Conservative Cascade; **Heavy-tailed allocation sizes.**

Empirical Evidence   *Generating Model*   *Reverse Engineering*   *Stated/unstated Design Principles*

Temporal

Clients request addrs from **Upstream**.

Upstream must satisfy each request.

Don't know # addrs / client.

Minimize fragmentation.

HOT formulation

(...regardless of # addrs / client!)

Spatial

Multifractal scaling

Conservative Cascade; **Heavy-tailed allocation sizes.**

Optimal allocation policy results in **heavy-tailed allocation sizes.**

Temporal

4.2.3.1. Efficient Utilization

ISPs are required to apply a <u>utilization efficiency</u> criterion in providing address space to their customers. ...

4.2.3.3. Contiguous Blocks

IP addresses are allocated to ISPs in contiguous blocks, which should remain intact. <u>Fragmentation of blocks is discouraged</u>. ...

Source: https://www.arin.net/participate/policy/nrpm/

Principles *are* actually stated (e.g., in RIR policy).

Spatial

Multifractal scaling

Conservative Cascade; **Heavy-tailed allocation sizes.**

Optimal allocation policy results in **heavy-tailed allocation sizes.**

Organizing allocations to maximize utilization and avoid fragmentation.

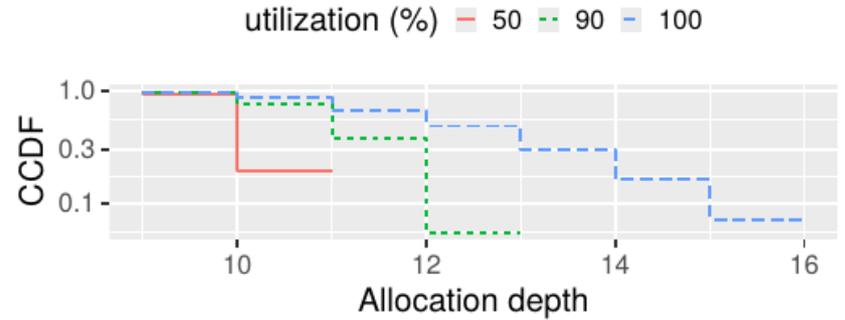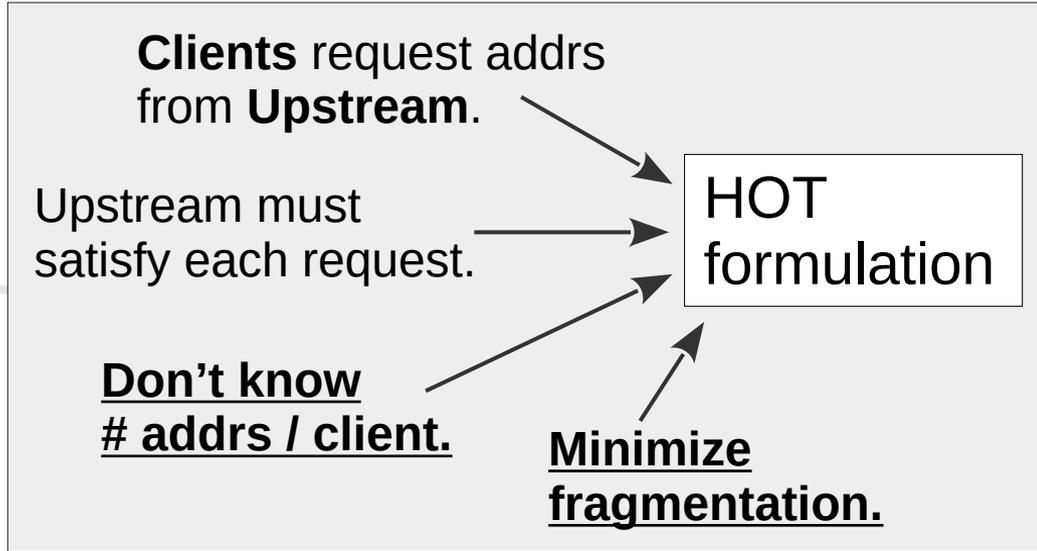| Empirical Evidence	Generating Model	Reverse Engineering	Stated/unstated Design Principles
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Spatial Multifractal scaling	Conservative Cascade; **Heavy-tailed allocation sizes.**	Optimal allocation policy results in **heavy-tailed allocation sizes.**	Organizing allocations to maximize utilization and avoid fragmentation.

… see our paper for details!

Empirical Evidence	Generating Model	Reverse Engineering	Stated/unstated Design Principles
Temporal			
Self-similar scaling	ON/OFF burst processes; **Heavy-tailed flow sizes.**	Optimal web layout results in **heavy-tailed flow sizes.**	Organizing information for human consumption.
Spatial			
Multifractal scaling	Conservative Cascade; **Heavy-tailed allocation sizes.**	Optimal allocation policy results in **heavy-tailed allocation sizes.**	Organizing allocations to maximize utilization and avoid fragmentation.

But future AI-based applications and services will certainly change everything! Or will they?

Empirical Evidence	Generating Model	Reverse Engineering	Stated/unstated Design Principles
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Spatial Multifractal scaling	Conservative Cascade; **Heavy-tailed allocation sizes.**	Optimal allocation policy results in **heavy-tailed allocation sizes.**	Organizing allocations to maximize utilization and avoid fragmentation.

Why is it important for applications to organize information for human consumption?

	Empirical Evidence	Generating Model	Reverse Engineering	Stated/unstated Design Principles
Temporal	Self-similar scaling	ON/OFF burst processes;	Optimal web layout results	Organizing information ...ption.
Spatial	Multifractal scaling	Conservative Cascade; **Heavy-tailed allocation sizes.**	Optimal allocation policy results in **heavy-tailed allocation sizes.**	Organizing allocations to maximize utilization and avoid fragmentation.

But future changes in how the Internet is owned and managed will certainly change everything! Or will they?

	Empirical Evidence	Generating Model	Reverse Engineering	Stated/unstated Design Principles
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Spatial	Multifractal scaling	Conservative Cascade; **Heavy-tailed allocation sizes.**	Optimal allocation policy results in **heavy-tailed allocation sizes.**	Organizing allocations to maximize utilization and avoid fragmentation.

Why is it important to optimize for scalability and stability of IP address allocations?

Thanks!

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Project page:

Chris Misa

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chrismisa.com