Demand-Aware and Self-Adjusting Networks

Stefan Schmid (University of Vienna)

Our research vision:
Self-* networks!

Self-observing, self-adjusting, self-repairing, "self-driving", …

Enabler of Our Vision: Flexibilities

Passau, Germany

Inn, Donau, Ilz

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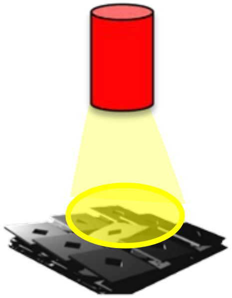
Inn, Donau, Ilz

Enabler of Our Vision: Flexibilities

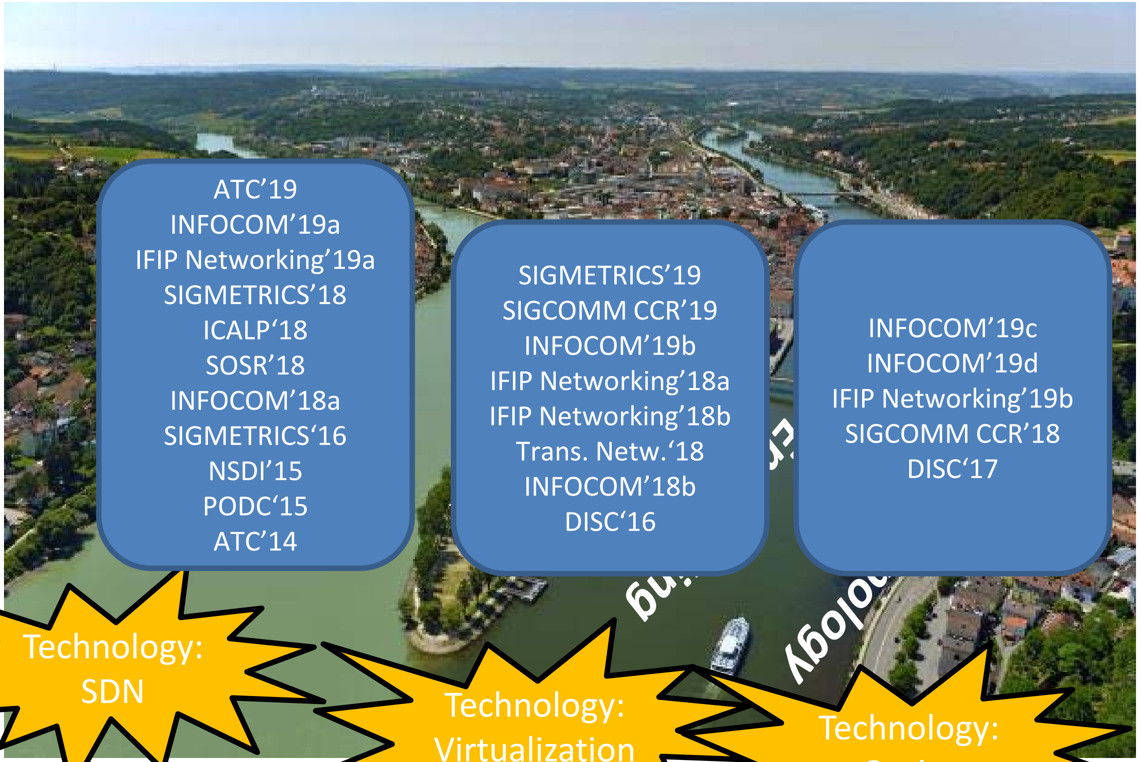
Enabler of Our Vision: Flexibilities

sa… …rmany

…nn, Donau, Ilz



Enabler of Our Vision: Flexibilities



ATC'19
INFOCOM'19a
IFIP Networking'19a
SIGMETRICS'18
ICALP'18
SOSR'18
INFOCOM'18a
SIGMETRICS'16
NSDI'15
PODC'15
ATC'14

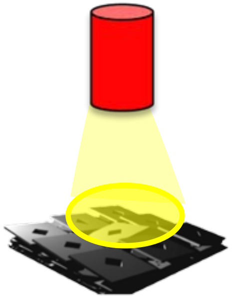
SIGMETRICS'19
SIGCOMM CCR'19
INFOCOM'19b
IFIP Networking'18a
IFIP Networking'18b
Trans. Netw.'18
INFOCOM'18b
DISC'16

INFOCOM'19c
INFOCOM'19d
IFIP Networking'19b
SIGCOMM CCR'18
DISC'17

Technology: SDN

Technology: Virtualization

Technology: Optics



Rewinding the clock of the Internet…

Shortest path routing only

Indirect control: via weights only

Proprietary, blackbox implementations

Difficult and slow innovation

Kudos to: Pedro Casas

Roadmap

- Opportunities of self-* networks
  - Example 1: Demand-aware, self-adjusting networks
  - Example 2: Self-repairing networks
- Challenges of desinging self-* networks

Roadmap

- Opportunities of self-* networks
  - **Example 1: Demand-aware, self-adjusting networks**
  - Example 2: Self-repairing networks
- Challenges of desinging self-* networks

Why Demand-Aware…?

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1. Easier to collect **data** (SDN, telemetry)

2. **Flexibilities**: possible to adapt

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2. **Flexibilities**: possible to adapt

3. Demand has **structure**!

Why Demand-Aware…?

Alternative: demand-oblivious networks

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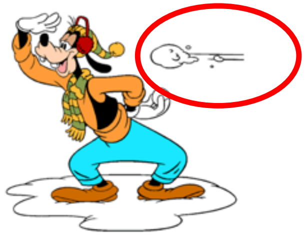
Alternative: demand-oblivious networks



„Demand has structure“

“less than 1% of the rack pairs account for 80% of the total traffic”

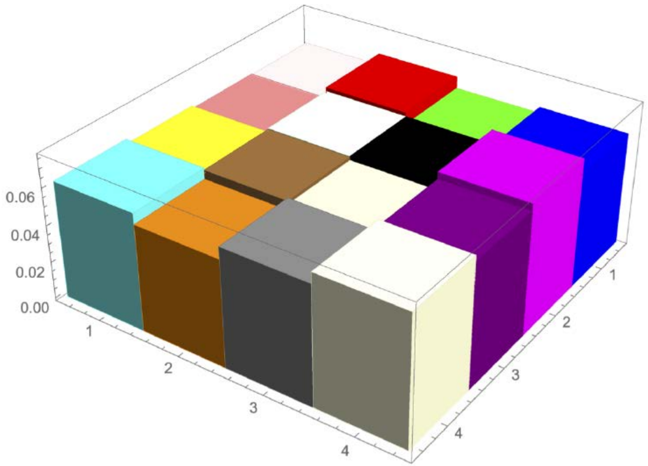
“only a few ToR switches are hot and most of their traffic goes to a few other ToRs”

“over 90% bytes in elephant flows”

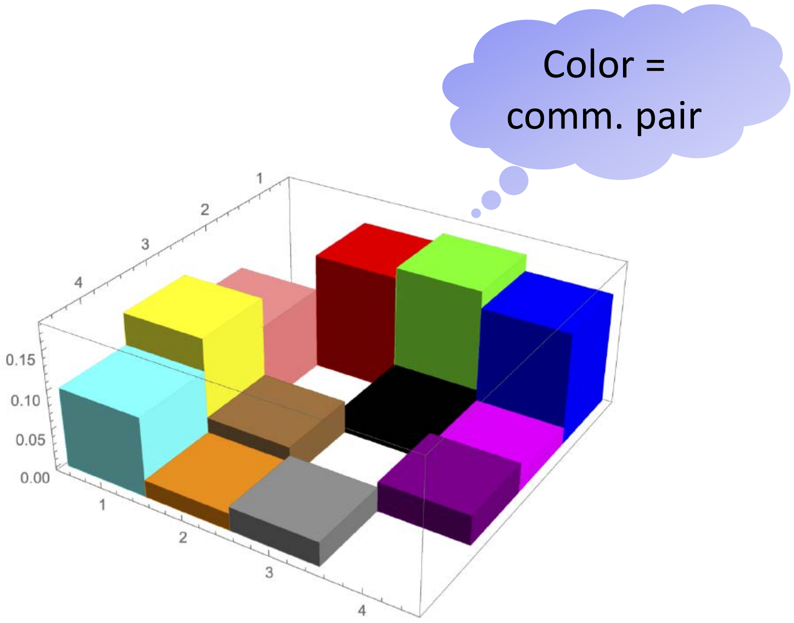
ProjecToR @ SIGCOMM 2016
Understanding Data Center Traffic Characteristics @ WREN 2009

Intuitive but: how to measure and quantify structure? We lack metrics!

Dimension 1: Non-Temporal Structure



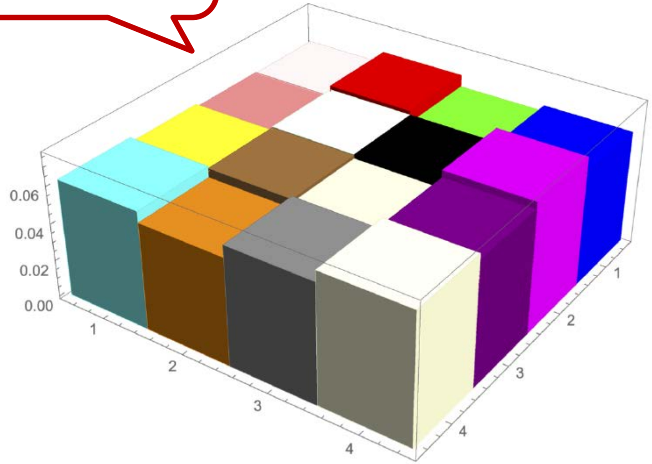
VS



Traffic matrix of two different **distributed ML** applications (GPU-to-GPU):

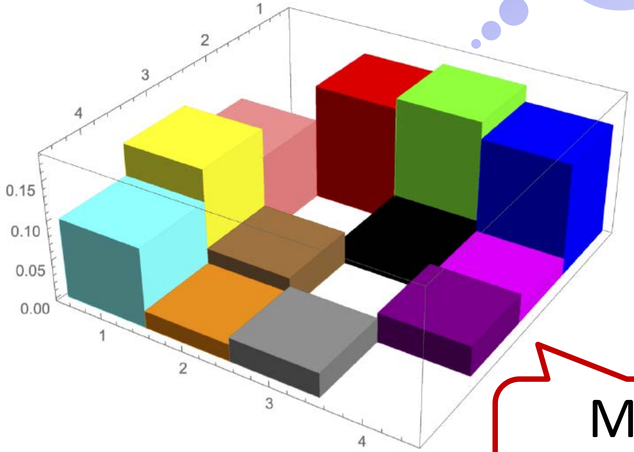
Dimension 1: Non-Temporal Structure

More random



VS

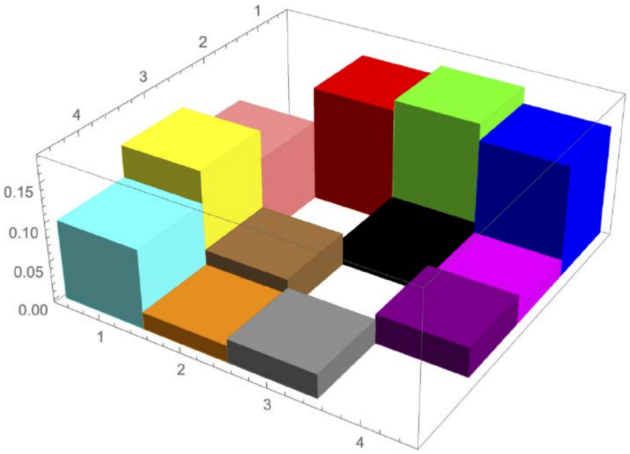
Color = comm. pair

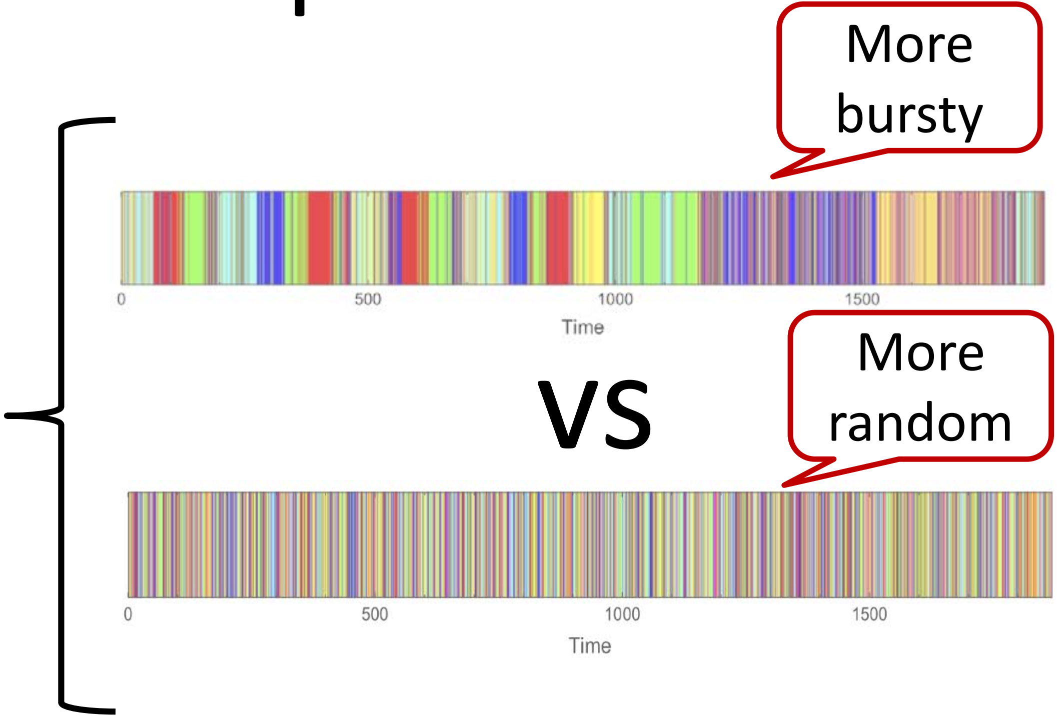


More structure

Traffic matrix of two different **distributed ML** applications (GPU-to-GPU):

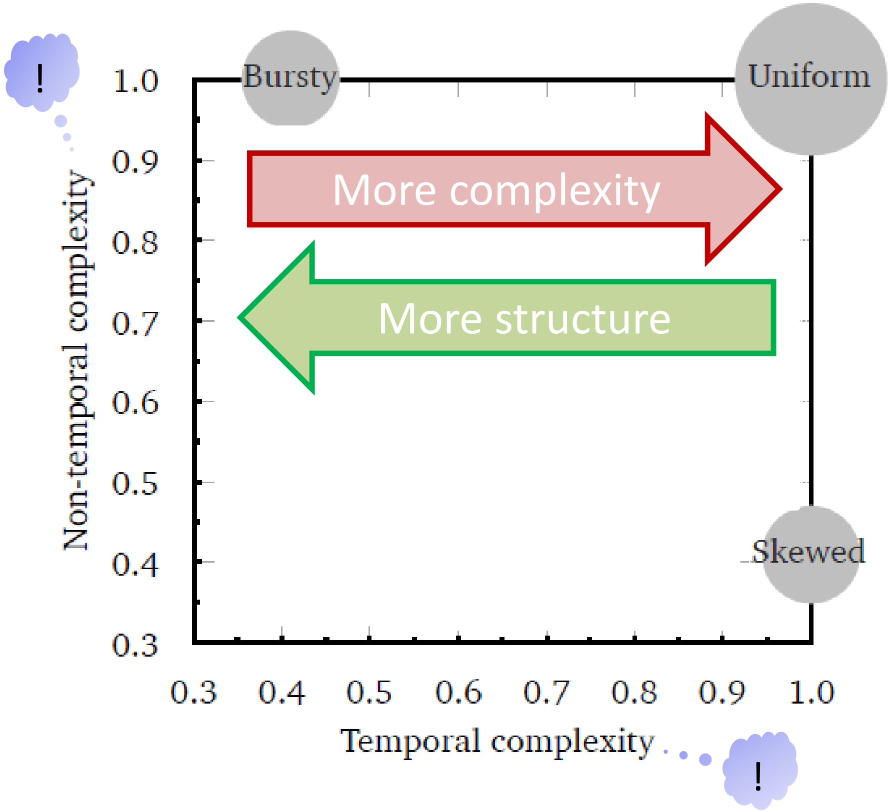
Dimension 2: Temporal Structure





Two different ways to generate *same traffic matrix* (same non-temporal structure)

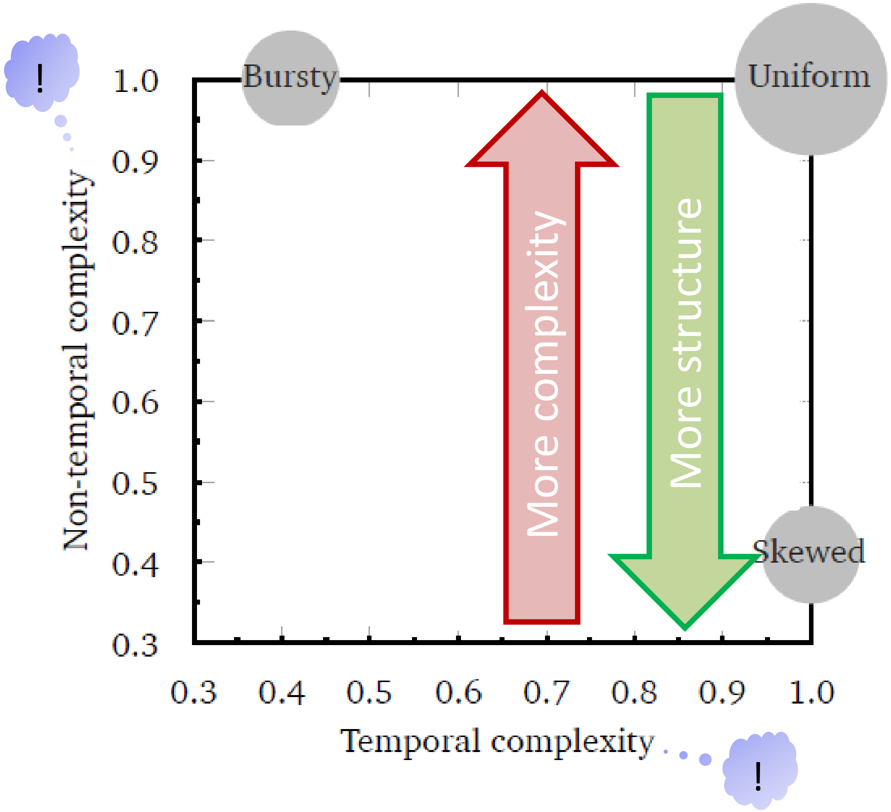
An Entropy Approach: The Complexity Map



Complexity Map: Entropy („complexity“) of traffic traces.

Measuring the Complexity of Packet Traces.
Avin, Ghobadi, Griner, Schmid. ArXiv 2019.

An Entropy Approach: The Complexity Map



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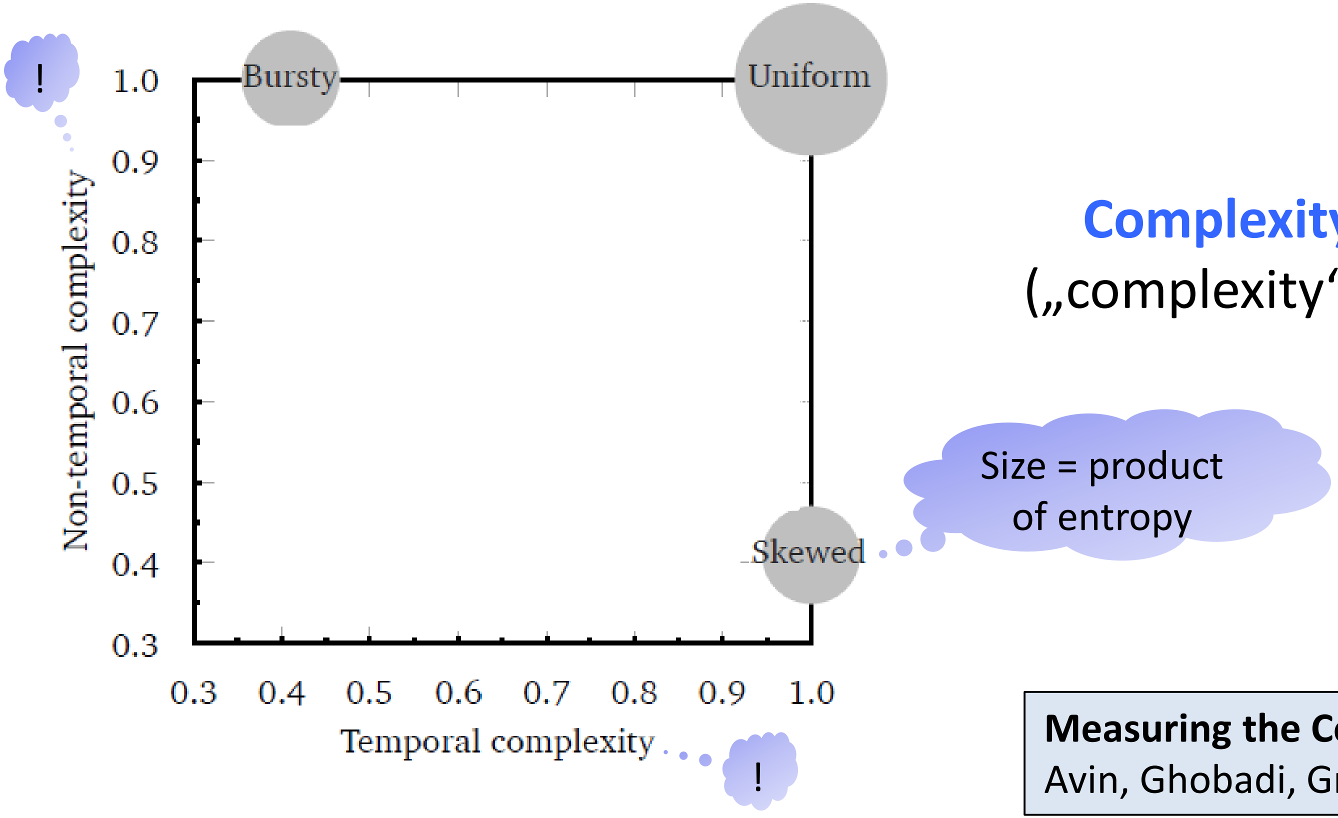

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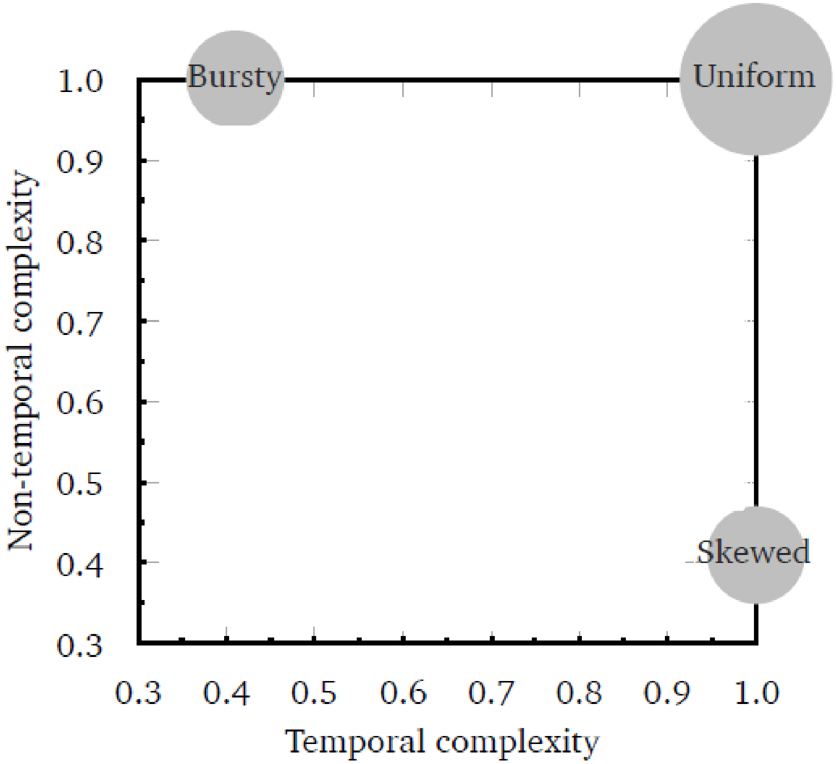
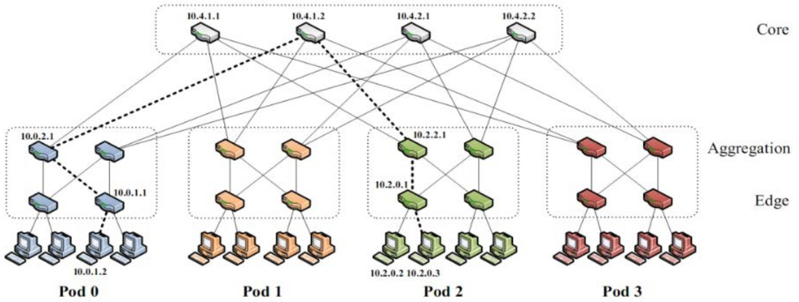


Uniform: Today's datacenters

- Traditional networks are optimized ***for the "worst-case"*** (**all-to-all** communication traffic)
- Example, fat-tree topologies: provide **full bisection bandwidth**



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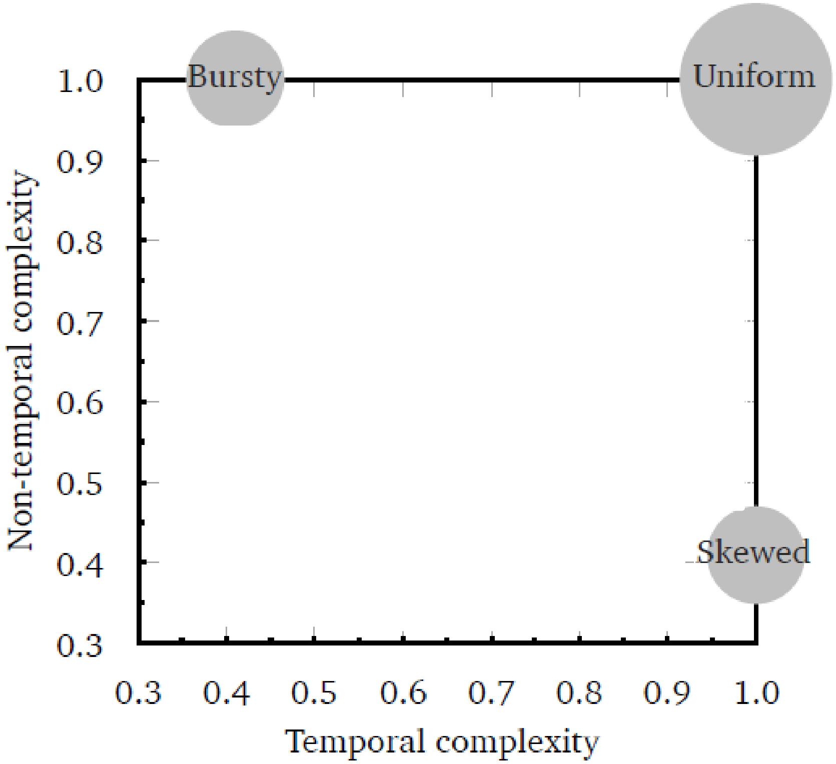
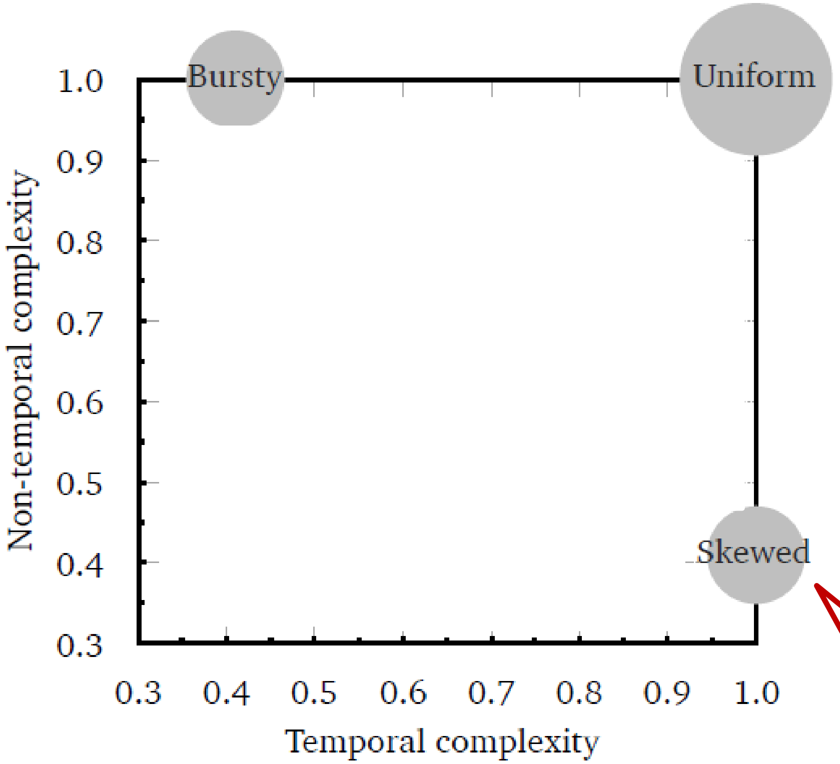


Good in the worst case ***but***: cannot leverage different **temporal** and **non-temporal** structures of traffic traces!

An Entropy Approach: The Complexity Map

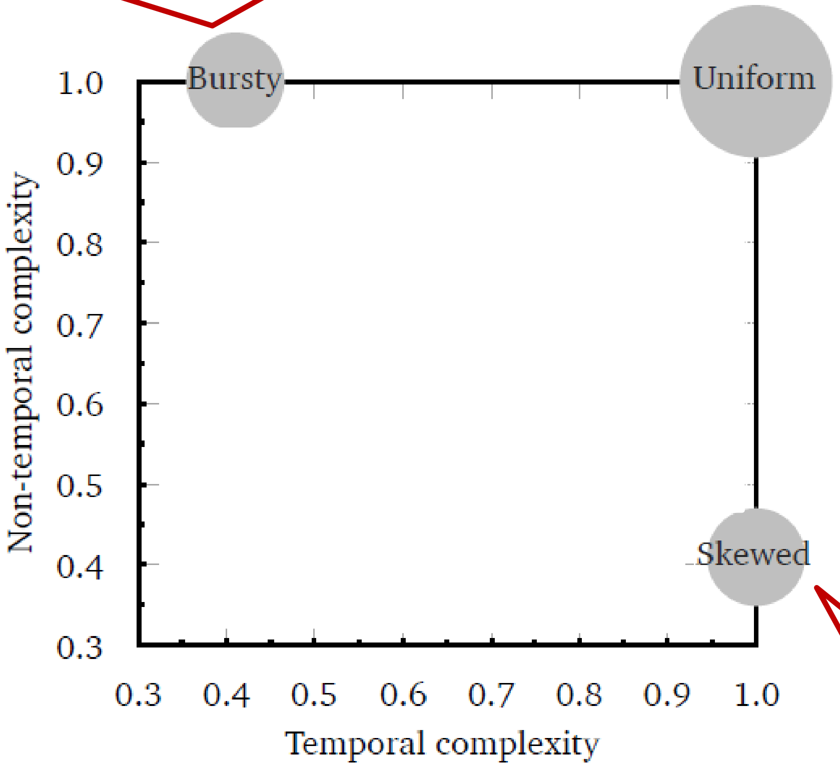


Good in the worst case ***but***: cannot leverage different **temporal** and **non-temporal** structures of traffic traces!

Non-temporal structure could be exploited already with ***static demand-aware networks***!

...ch: The Complexity Map

To exploit **temporal** structure, need ***adaptive demand-aware ("self-adjusting") networks***.



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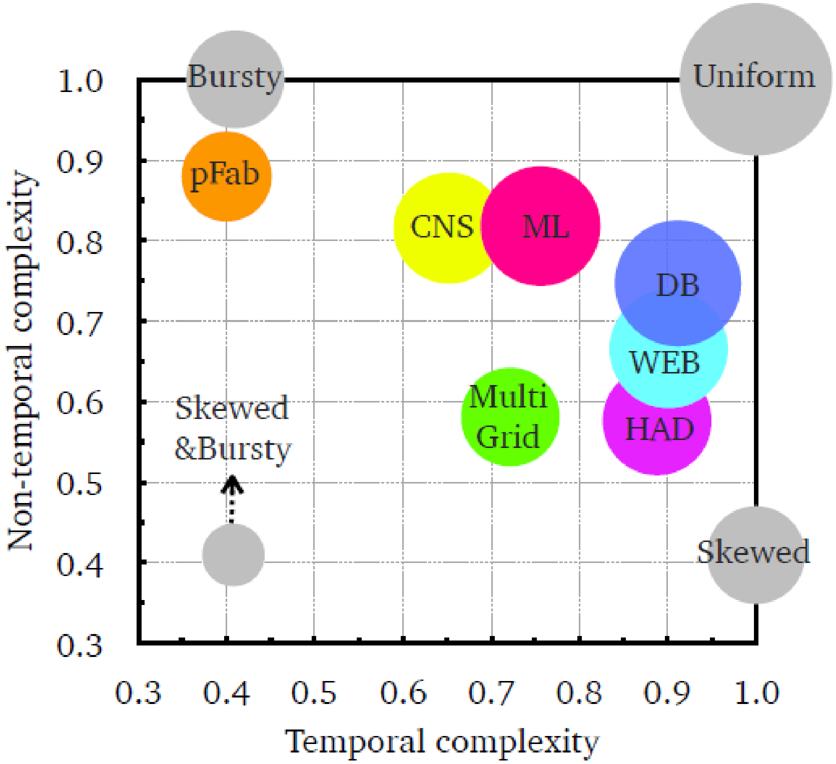
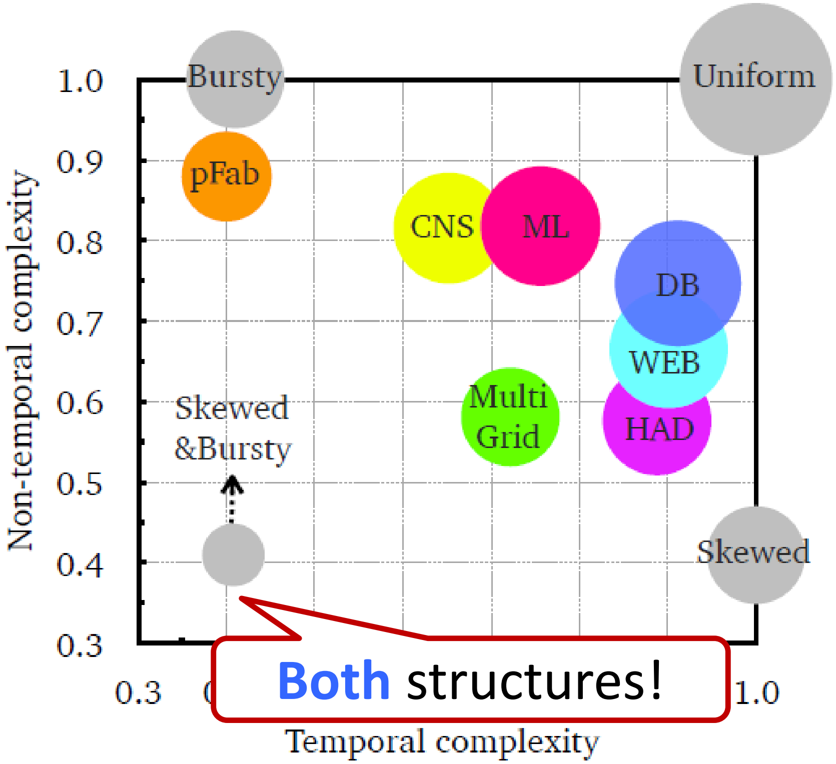


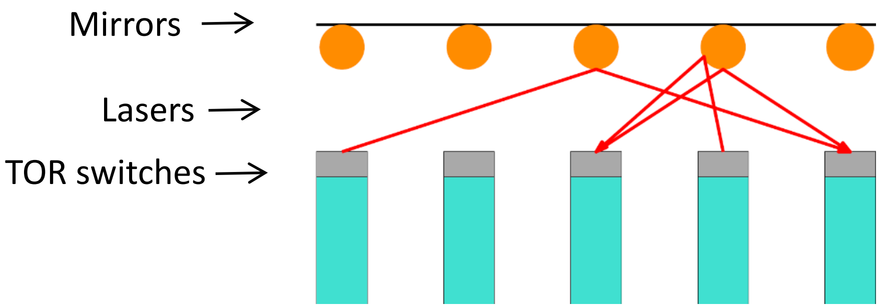
Observation: different applications feature quite significant (and different!) **temporal** and **non-temporal** structures.

- **Facebook** clusters: DB, WEB, HAD
- **HPC** workloads: CNS, Multigrid
- Distributed **Machine Learning** (ML)
- Synthetic traces like **pFabric**

An Entropy Approach: The Complexity Map



Goal: Design **self-adjusting networks** which leverage ***both*** dimensions of structure!



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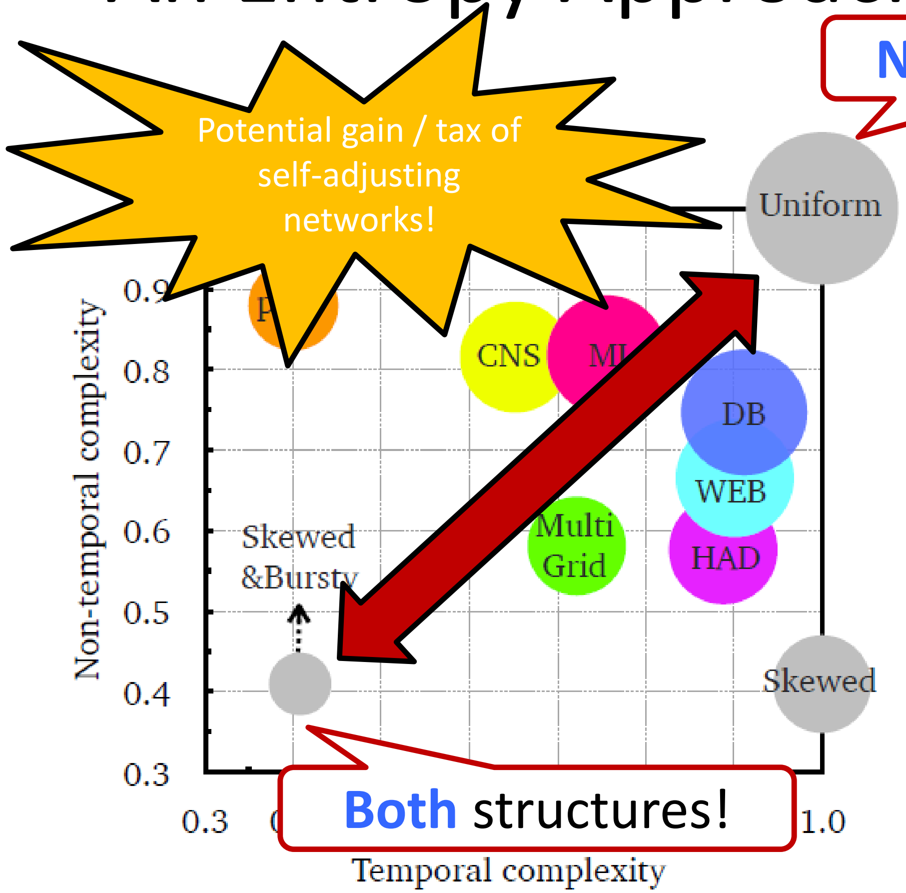
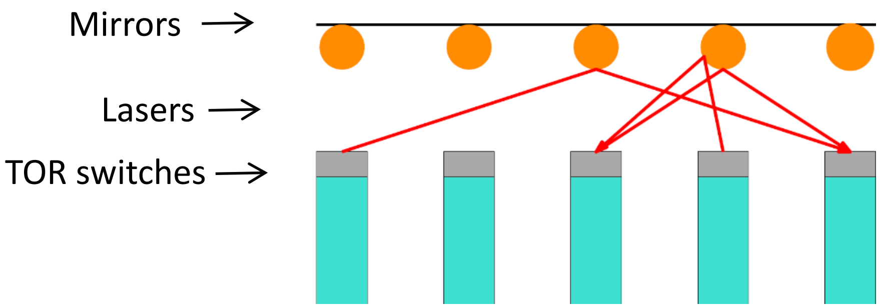


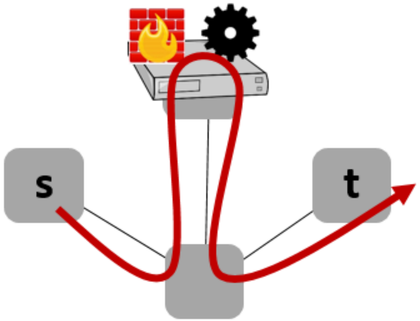
No structure!

Goal: Design **self-adjusting networks** which leverage ***both*** dimensions of structure!

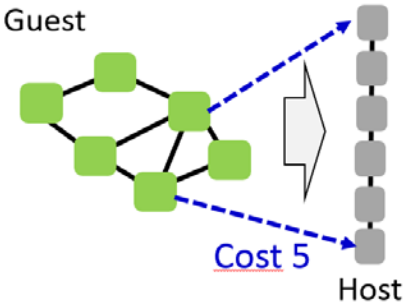


Algorithms to Exploit Structure

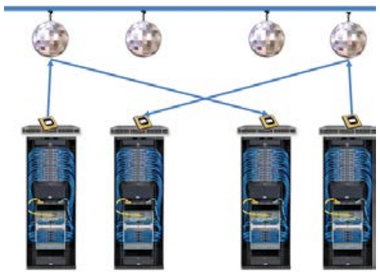
We are mainly interested in **online algorithms** (with *provable guarantees*: competitive ratio)



Online **admission control** and **routing** (***joint optimization***: placement and routing)

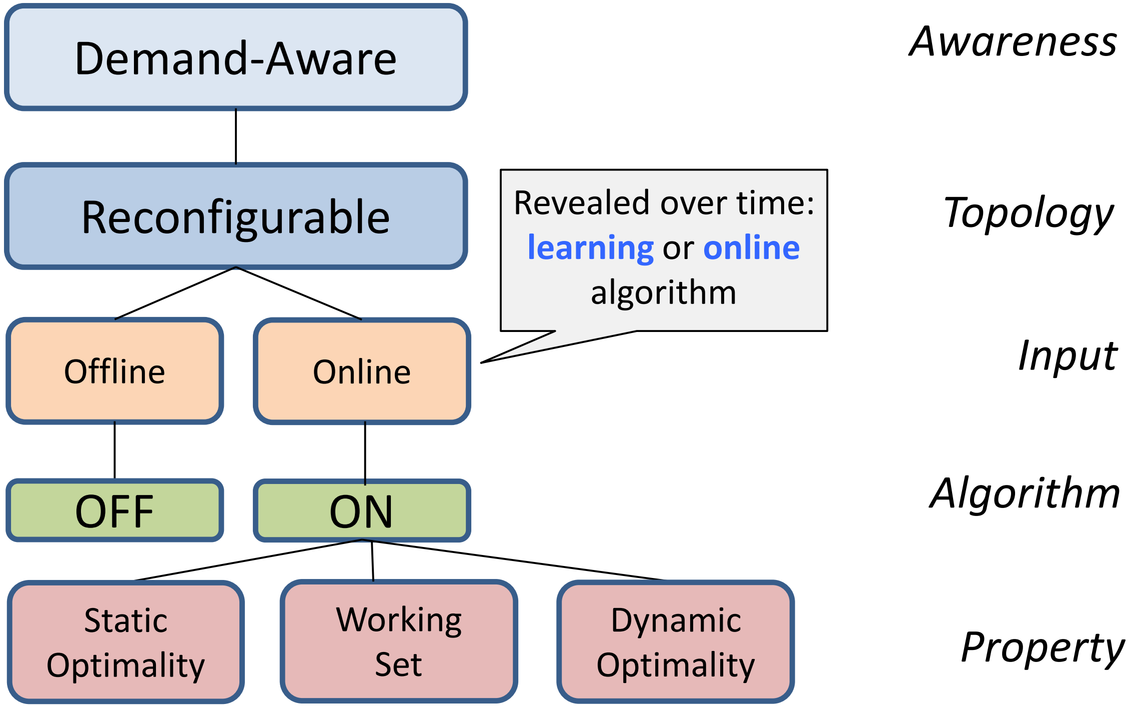


Virtual network embedding (slicing) and demand-aware reconfiguration/***migration***



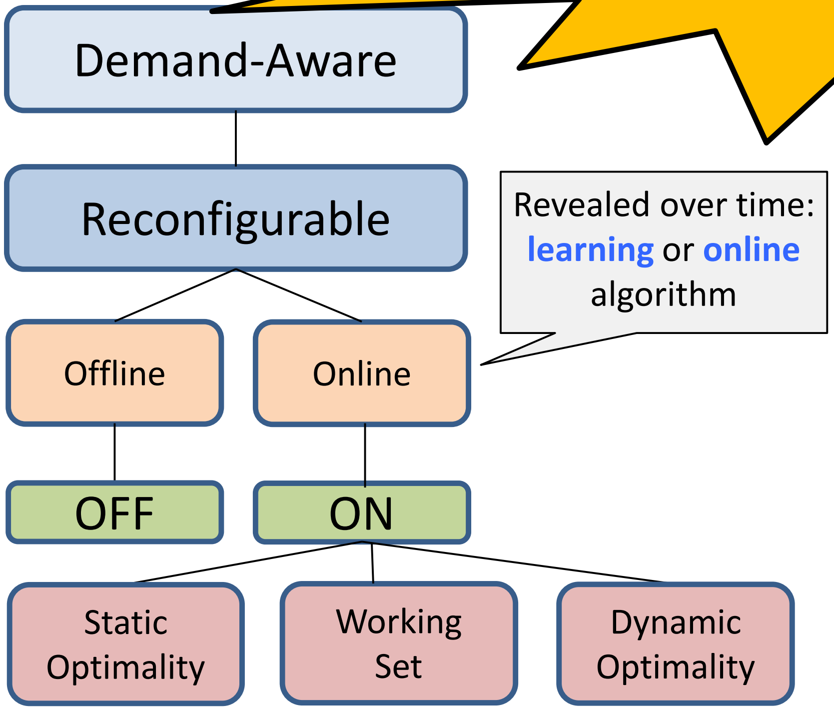
Topology design: **Graph spanners**

A Taxonomy: Reconfigurable Networks



A Taxonomy: Reconfigurable Networks

Structure does not imply predictable!



Aw

Topology

Input

Algorithm

Property

Roadmap

- Opportunities of self-* networks
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  - **Example 2: Self-repairing networks**
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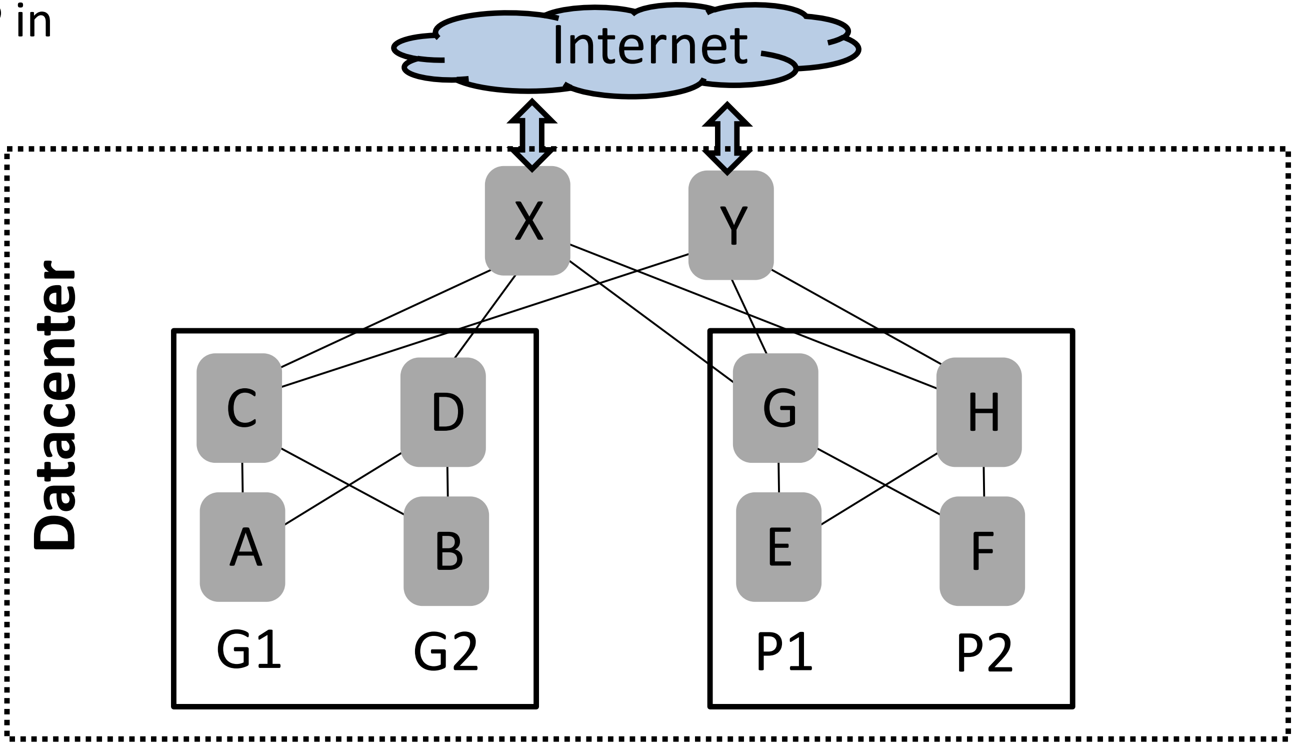
Reasoning About Failures is Hard for Humans

Example: BGP in datacenter (!)



Credits: Beckett et al. (SIGCOMM 2016): Bridging Network-wide Objectives and Device-level Configurations.

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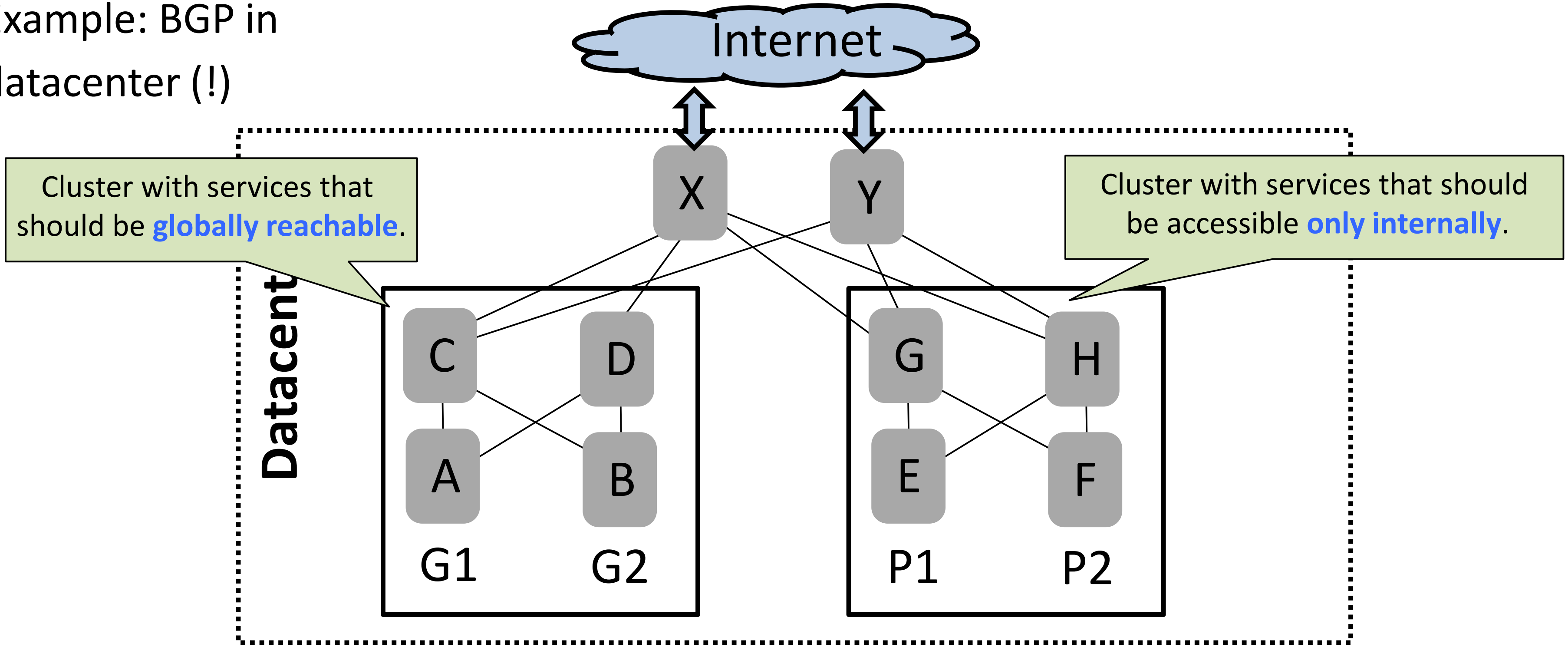

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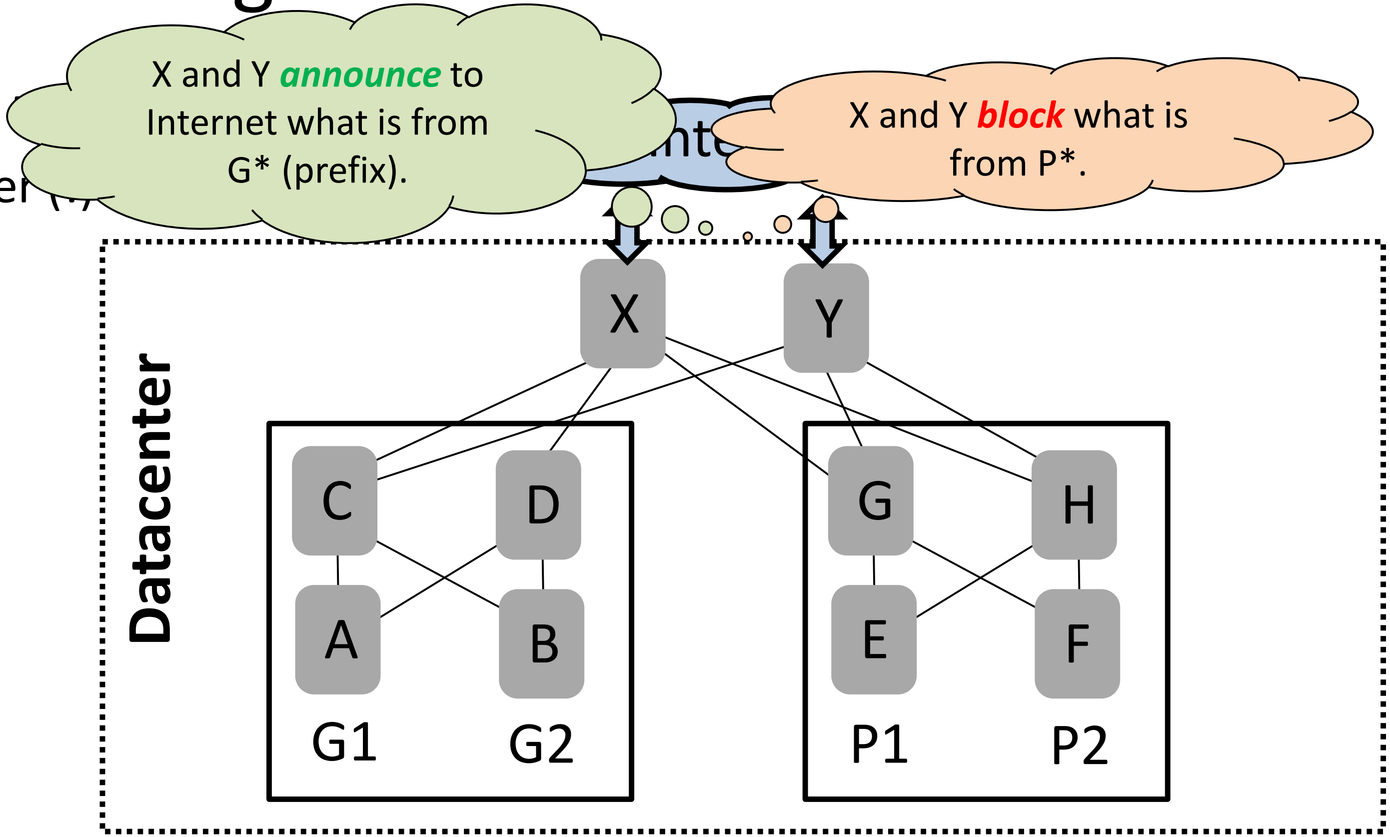
datacenter



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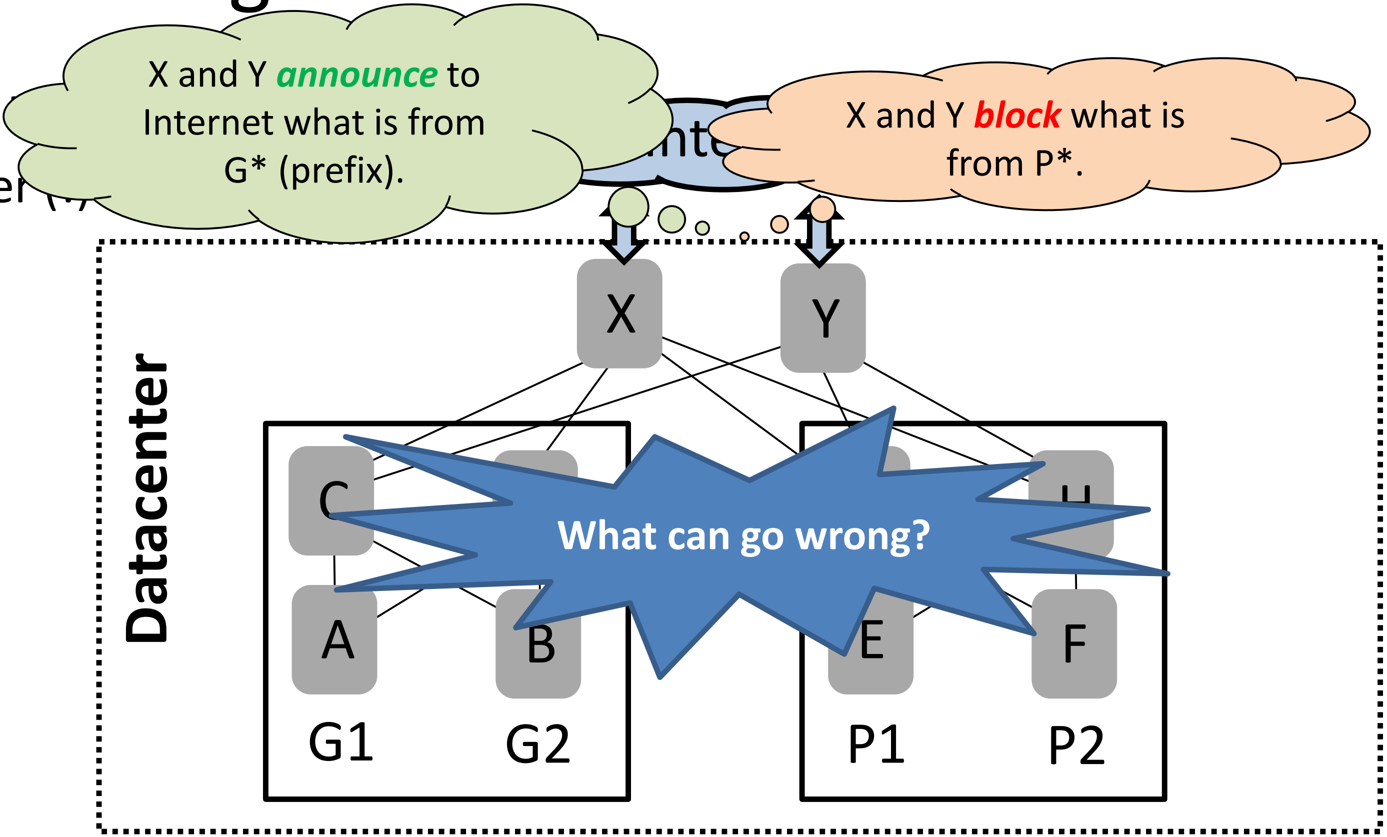

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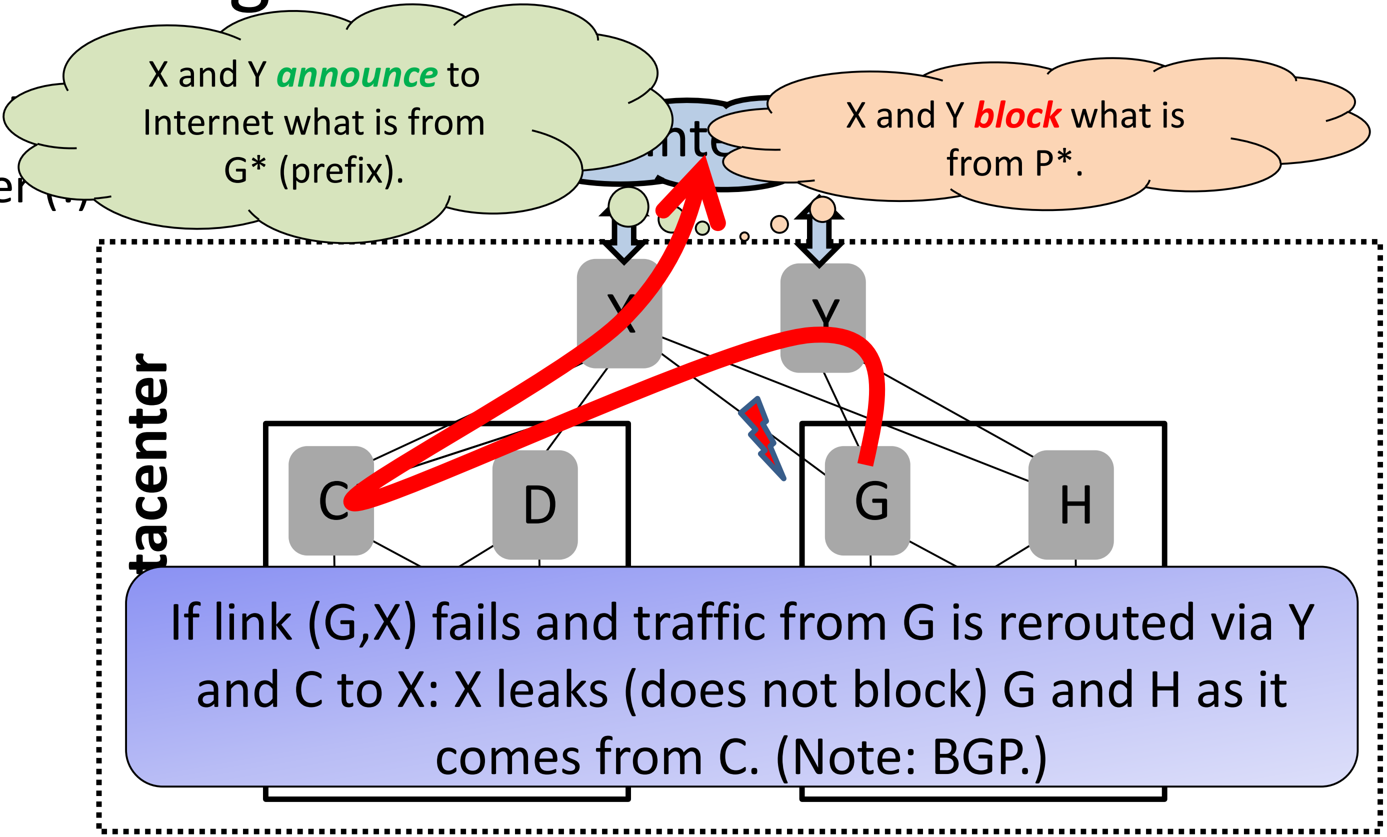
Reasoning About Failures is Hard for Humans

Example: [partly hidden]

datacenter [partly hidden]



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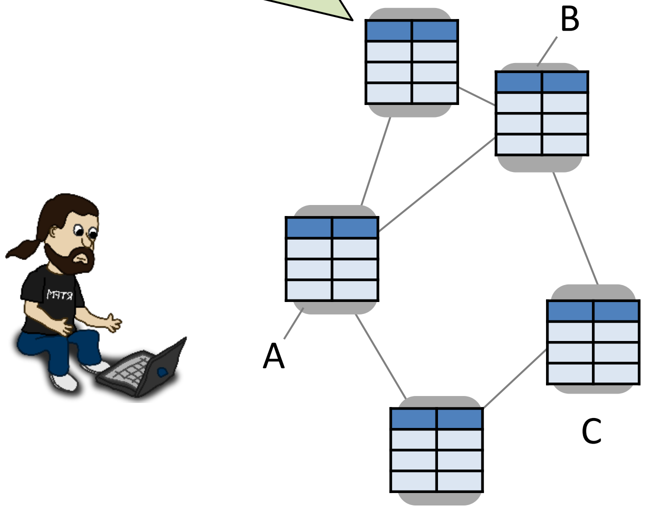
Responsibilities of a Sysadmin

Routers and switches store list of forwarding rules, and conditional failover rules.



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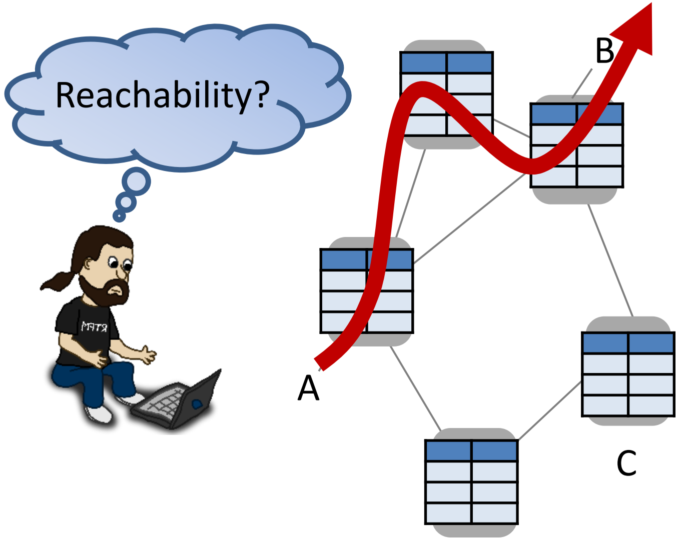
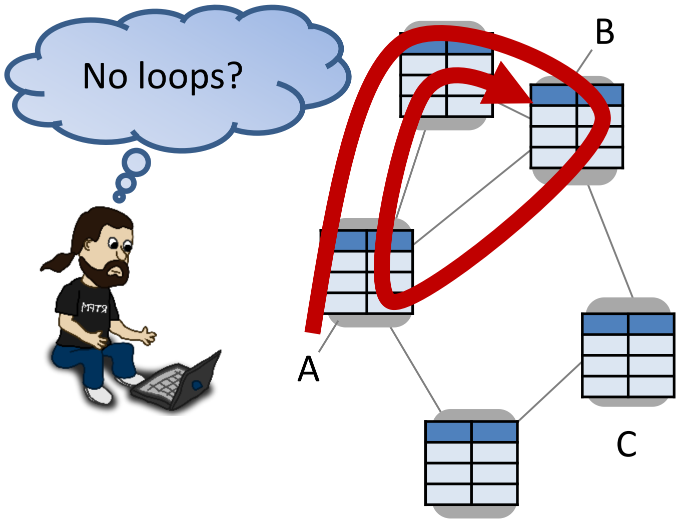


Sysadmin responsible for:

- **Reachability:** Can traffic from ingress port A reach egress port B?

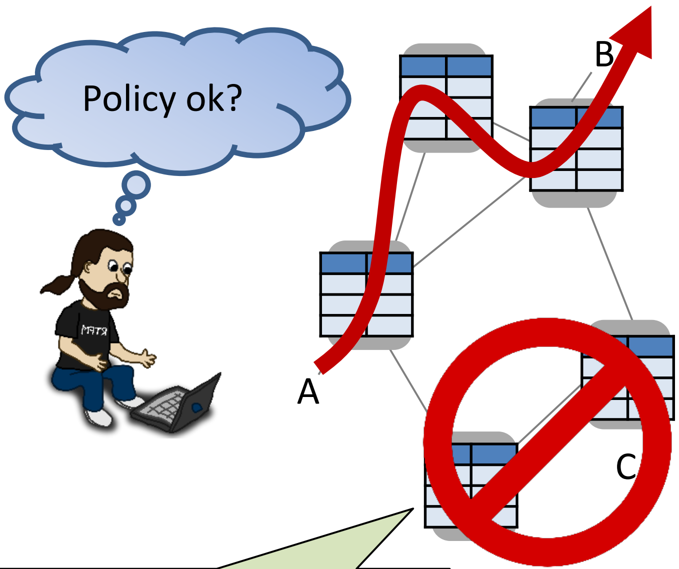
Responsibilities of a Sysadmin



Sysadmin responsible for:

- **Reachability:** Can traffic from ingress port A reach egress port B?
- **Loop-freedom:** Are the routes implied by the forwarding rules loop-free?

Responsibilities of a Sysadmin



E.g. ***NORDUnet***: no traffic via Iceland (expensive!). Or no traffic through ***route reflectors***.

Sysadmin responsible for:

- **Reachability:** Can traffic from ingress port A reach egress port B?
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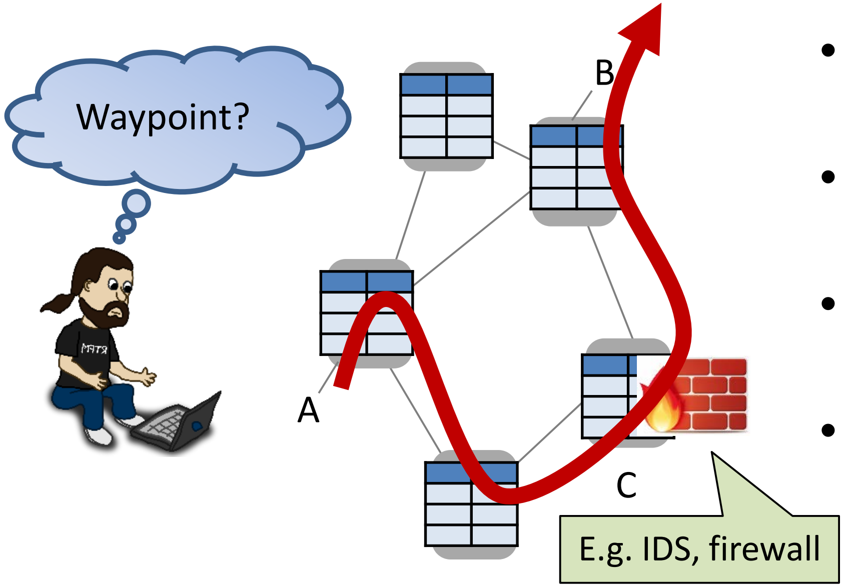

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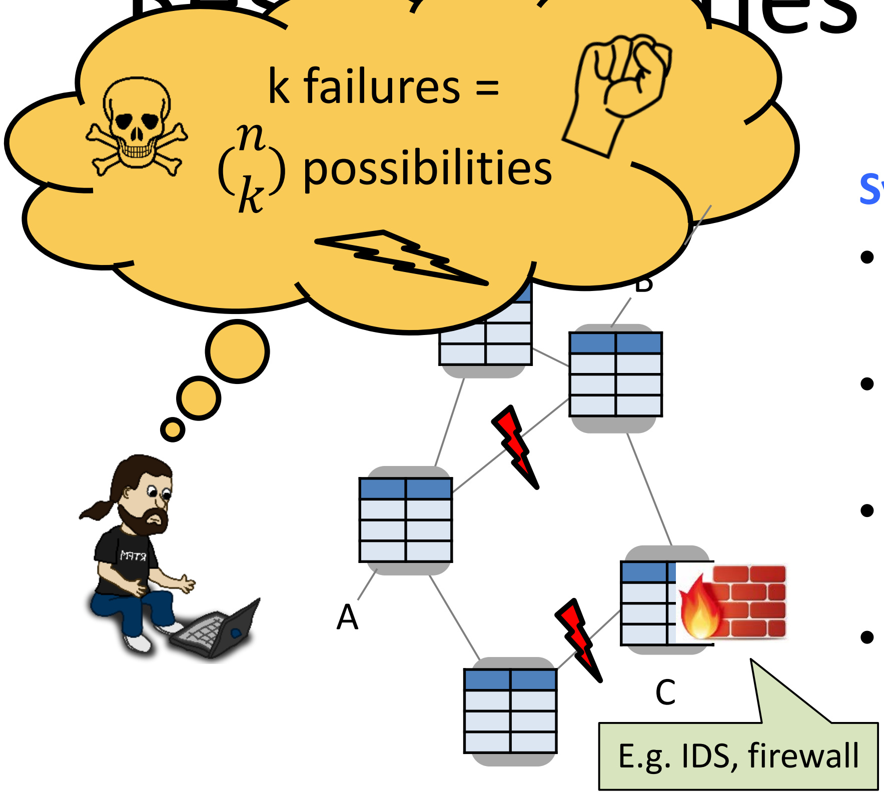

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… and everything even under multiple failures?!

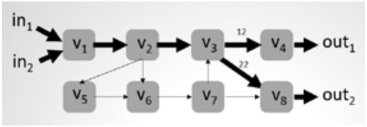
Can we automate such tests
or even self-repair?

Can we automate such tests or even self-repair?

Yes! Automated **What-if Analysis Tool** for MPLS and SR in ***polynomial time***.

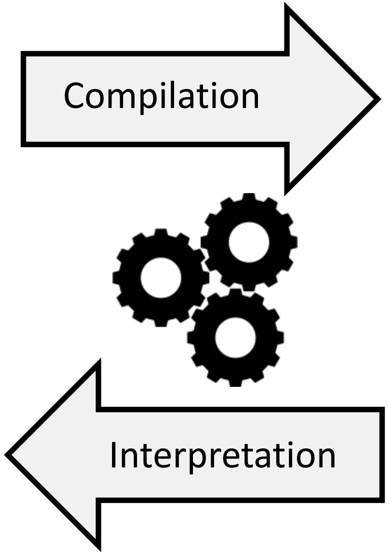
Leveraging Automata-Theoretic Approach

FT	In-I	In-Label	Out-I	op
τ_{v_1}	in_1	$\perp$	(v_1, v_2)	$push(10)$
	in_2	$\perp$	(v_1, v_2)	$push(20)$
τ_{v_2}	(v_1, v_2)	10	(v_2, v_3)	$swap(11)$
	(v_1, v_2)	20	(v_2, v_3)	$swap(21)$
τ_{v_3}	(v_2, v_3)	11	(v_3, v_4)	$swap(12)$
	(v_2, v_3)	21	(v_3, v_8)	$swap(22)$
	(v_7, v_3)	11	(v_3, v_4)	$swap(12)$
	(v_7, v_3)	21	(v_3, v_8)	$swap(22)$
τ_{v_4}	(v_3, v_4)	12	out_1	pop
τ_{v_5}	(v_2, v_5)	40	(v_5, v_6)	pop
τ_{v_6}	(v_2, v_6)	30	(v_6, v_7)	$swap(31)$
	(v_5, v_6)	30	(v_6, v_7)	$swap(31)$
	(v_5, v_6)	61	(v_6, v_7)	$swap(62)$
	(v_5, v_6)	71	(v_6, v_7)	$swap(72)$
τ_{v_7}	(v_6, v_7)	31	(v_7, v_3)	pop
	(v_6, v_7)	62	(v_7, v_3)	$swap(11)$
	(v_6, v_7)	72	(v_7, v_8)	$swap(22)$
τ_{v_8}	(v_3, v_8)	22	out_2	pop
	(v_7, v_8)	22	out_2	pop



local FFT	Out-I	In-Label	Out-I	op
τ_{v_2}	(v_2, v_3)	11	(v_2, v_6)	$push(30)$
	(v_2, v_3)	21	(v_2, v_6)	$push(30)$
	(v_2, v_6)	30	(v_2, v_5)	$push(40)$
global FFT	**Out-I**	**In-Label**	**Out-I**	**op**
τ'_{v_2}	(v_2, v_3)	11	(v_2, v_6)	$swap(61)$
	(v_2, v_3)	21	(v_2, v_6)	$swap(71)$
	(v_2, v_6)	61	(v_2, v_5)	$push(40)$
	(v_2, v_6)	71	(v_2, v_5)	$push(40)$

MPLS **configurations**, Segment Routing etc.



$$pX \Rightarrow qXX$$
$$pX \Rightarrow qYX$$
$$qY \Rightarrow rYY$$
$$rY \Rightarrow r$$
$$rX \Rightarrow pX$$

Pushdown Automaton (PDA) and **Prefix Rewriting Systems** Theory

Leveraging Autom… …oach

Use cases: Sysadmin ***issues queries*** to test certain properties, or do it on a ***regular basis*** automatically!

FT	In-I	In-Label	Out-I	op
τ_{v_1}	in_1	$\perp$	(v_1, v_2)	$push(10)$
	in_2	$\perp$	(v_1, v_2)	$push(20)$
τ_{v_2}	(v_1, v_2)	10	(v_2, v_3)	$swap(11)$
	(v_1, v_2)	20	(v_2, v_3)	$swap(21)$
τ_{v_3}	(v_2, v_3)	11	(v_3, v_4)	$swap(12)$
	(v_2, v_3)	21	(v_3, v_8)	$swap(22)$
	(v_7, v_3)	11	(v_3, v_4)	$swap(12)$
	(v_7, v_3)	21	(v_3, v_8)	$swap(22)$
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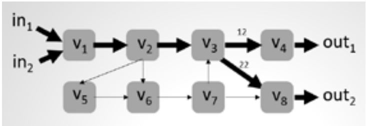
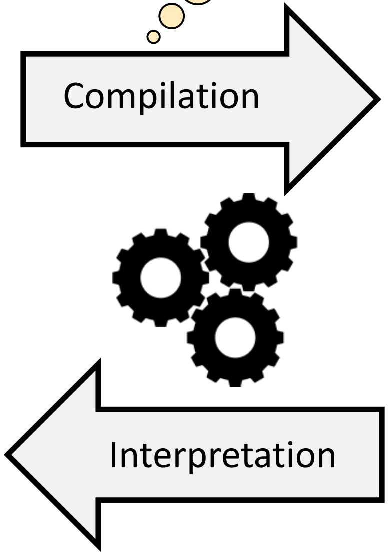
τ_{v_5}	(v_2, v_5)	40	(v_5, v_6)	pop
τ_{v_6}	(v_2, v_6)	30	(v_6, v_7)	$swap(31)$
	(v_5, v_6)	30	(v_6, v_7)	$swap(31)$
	(v_5, v_6)	61	(v_6, v_7)	$swap(62)$
	(v_5, v_6)	71	(v_6, v_7)	$swap(72)$
τ_{v_7}	(v_6, v_7)	31	(v_7, v_3)	pop
	(v_6, v_7)	62	(v_7, v_3)	$swap(11)$
	(v_6, v_7)	72	(v_7, v_8)	$swap(22)$
τ_{v_8}	(v_3, v_8)	22	out_2	pop
	(v_7, v_8)	22	out_2	pop



local FFT	Out-I	In-Label	Out-I	op
τ_{v_2}	(v_2, v_3)	11	(v_2, v_6)	$push(30)$
	(v_2, v_3)	21	(v_2, v_6)	$push(30)$
	(v_2, v_6)	30	(v_2, v_5)	$push(40)$
global FFT	**Out-I**	**In-Label**	**Out-I**	**op**
τ'_{v_2}	(v_2, v_3)	11	(v_2, v_6)	$swap(61)$
	(v_2, v_3)	21	(v_2, v_6)	$swap(71)$
	(v_2, v_6)	61	(v_2, v_5)	$push(40)$
	(v_2, v_6)	71	(v_2, v_5)	$push(40)$

MPLS **configurations**, Segment Routing etc.



$$pX \Rightarrow qXX$$
$$pX \Rightarrow qYX$$
$$qY \Rightarrow rYY$$
$$rY \Rightarrow r$$
$$rX \Rightarrow pX$$

Pushdown Automaton (PDA) and **Prefix Rewriting Systems** Theory

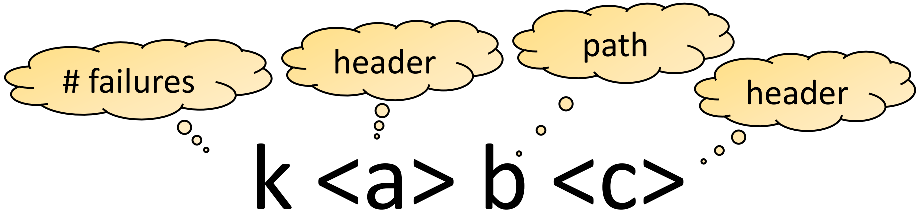
Tool and Query Language

<u>Part 1:</u> Parses query and constructs Push-Down System (PDS)

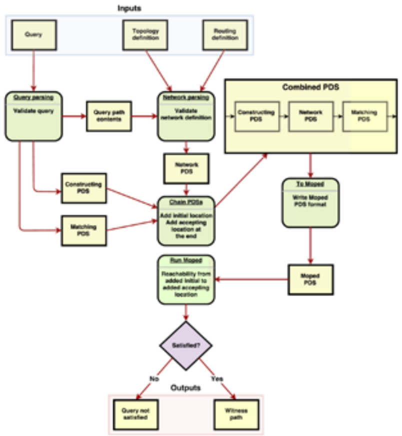
- In Python 3

<u>Part 2:</u> Reachability analysis of constructed PDS

- Using ***Moped*** tool



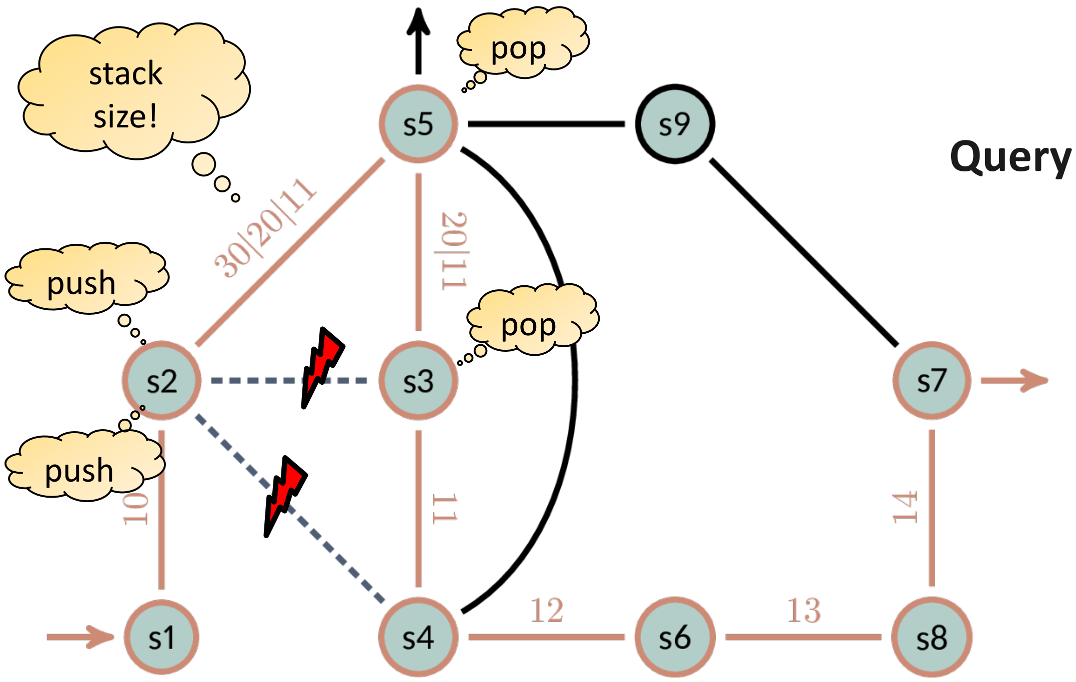
Regular query language



query processing flow

Example: Traversal Testing With 2 Failures

Traversal test with k=2: Can traffic starting with [] go through s5, under up to k=2 failures?



2 failures

Query: k=2 [] s1 >> s5 >> s7 []

YES!

(Gives witness!)

A Complex and Big Formal Language!
Why Polynomial Time?

- Arbitrary number k of failures: How can I avoid checking all $\binom{n}{k}$ many options?
- Even if we reduce to **push-down automaton**: simple operations such as emptiness testing or intersection on PDA is computationally non-trivial and sometimes even **undecidable**!

Time for Automata Theory (from Switzerland!)

- Classic result by **Büchi** 1964: the set of all reachable configurations of a pushdown automaton a is regular set
- Hence, we can operate only on Nondeterministic Finite Automata (NFAs) when reasoning about the pushdown automata
- The resulting **regular operations** are all polynomial time
  - Important result of **model checking**

Julius Richard Büchi

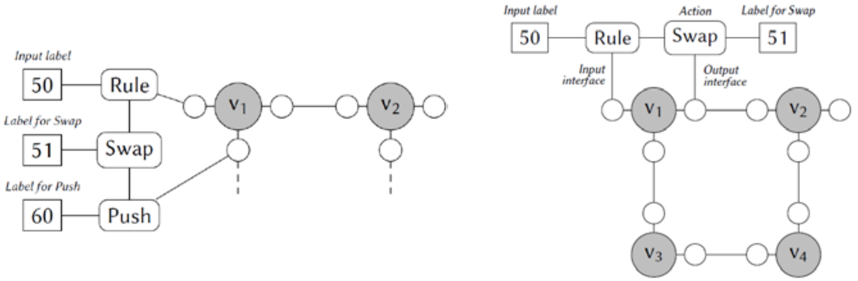
1924-1984

Swiss logician

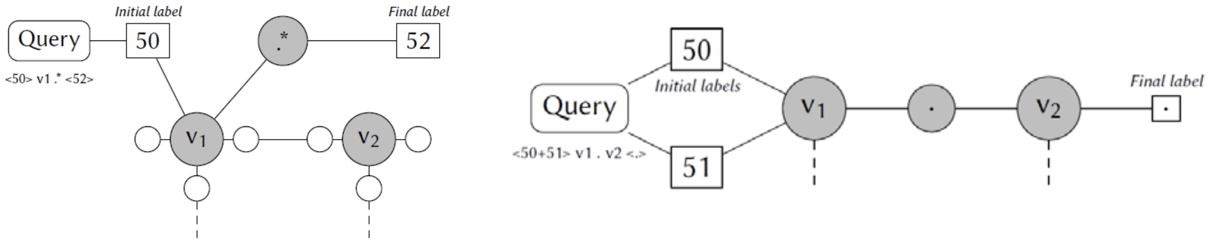
Speedup with Machine Learning

Speed Up Further and Synthesize: Deep Learning

- Yes sometimes **without losing guarantees**
- Extend **graph-based neural networks**
- **Predict** counter-examples and **fixes**



Network topologies and MPLS rules



Network topologies and query

Roadmap

- Opportunities of self-* networks
  - Example 1: Demand-aware, self-adjusting networks
  - Example 2: Self-repairing networks
- Challenges of desinging self-* networks

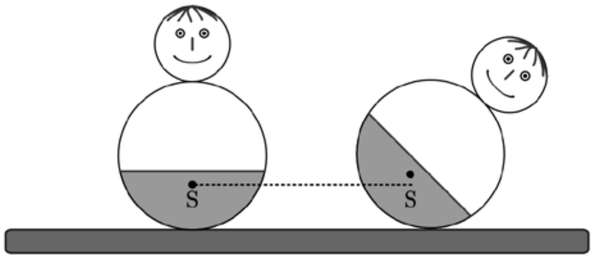
Challenge 1: Realizing Limits?

- Can a self-* network realize its **limits**?
- E.g., when quality of **input data** is not good enough?
- When to hand over to human? Or **fall back** to „safe/oblivious mode“?
- Can we learn from self-driving **cars**?

Challenge 2: Self-Stabilization

- Could be an attractive property of self-* network!

A **self-stabilizing** system guarantees that it *reconverges to a desirable configuration* or state, *from any initial state*.



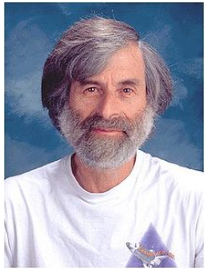
„Stehaufmännchen“

Self-Stabilization

Self-stabilizing algorithms pioneered by **Dijkstra** (1973): for example self-stabilizing mutual exclusion.

“I regard this as Dijkstra’s most brilliant work. Self-stabilization is a very important concept in fault tolerance.”

Leslie **Lamport** (PODC 1983)

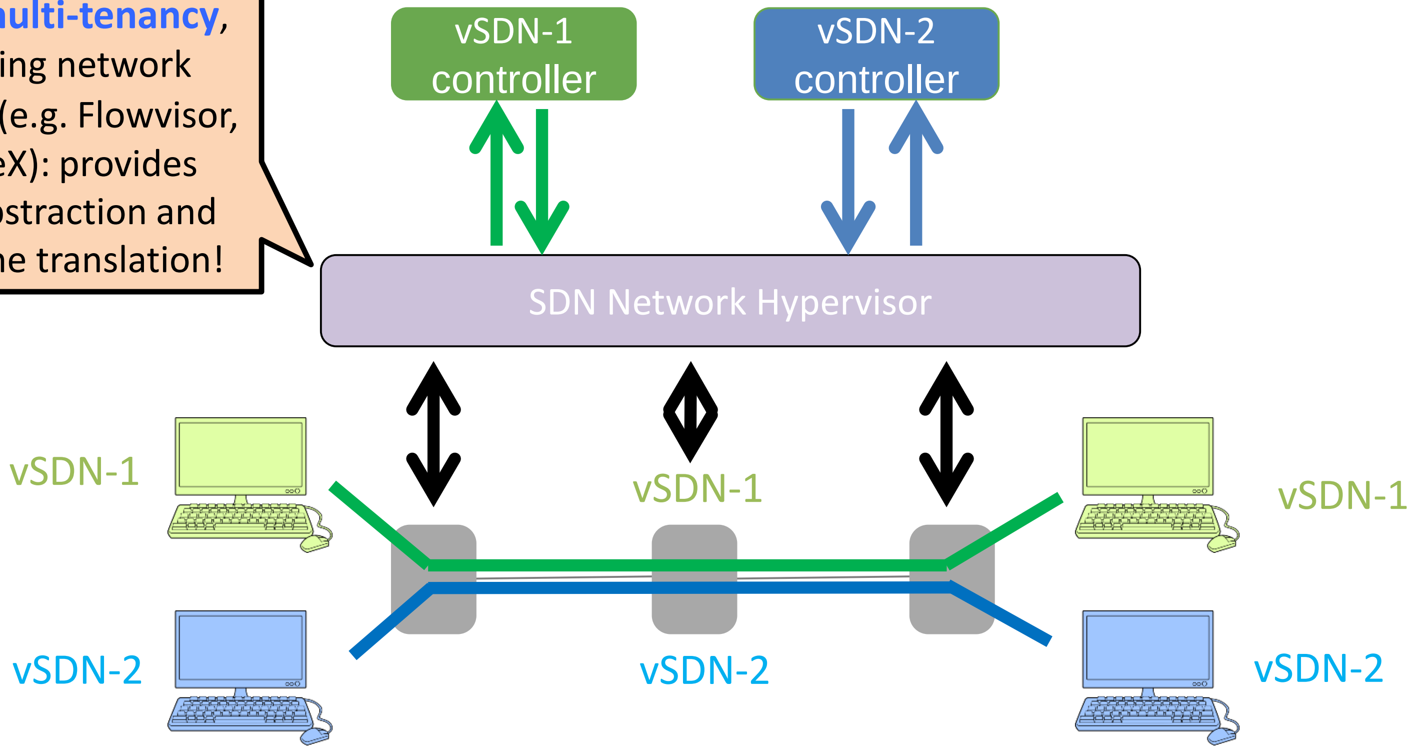


Some notable works by **Perlman** toward self-stabilizing Internet, e.g., self-stabilizing spanning trees.

Yet, many protocols in the Internet are *not* self-stabilizing. Much need for future work.

Challenge 3: Modelling

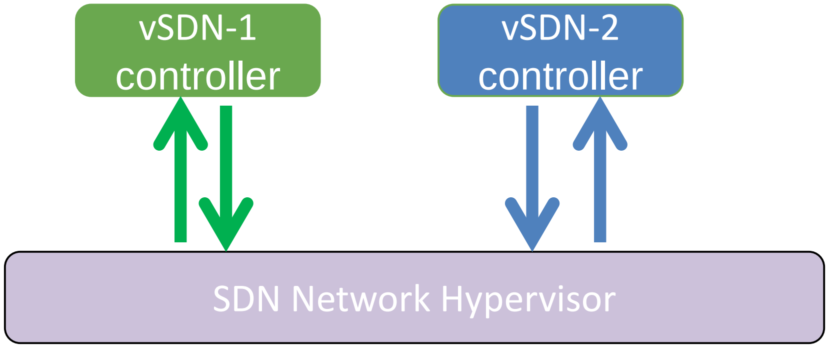
To enable **multi-tenancy**, take existing network **hypervisor** (e.g. Flowvisor, OpenVirteX): provides network abstraction and control plane translation!

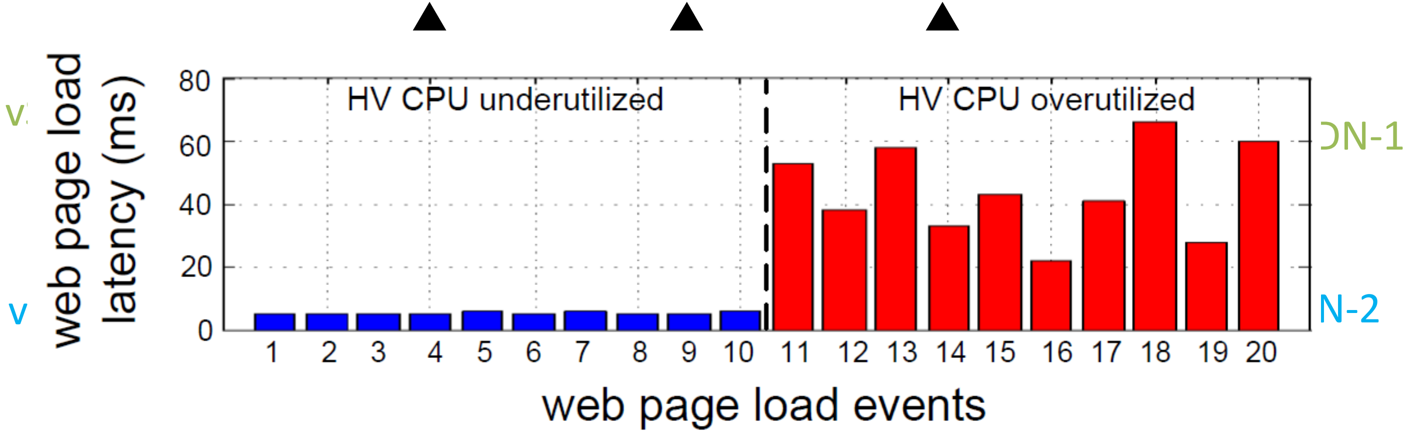


An Experiment: 2 vSDNs with bw guarantee!

Challenge 3: Modelling

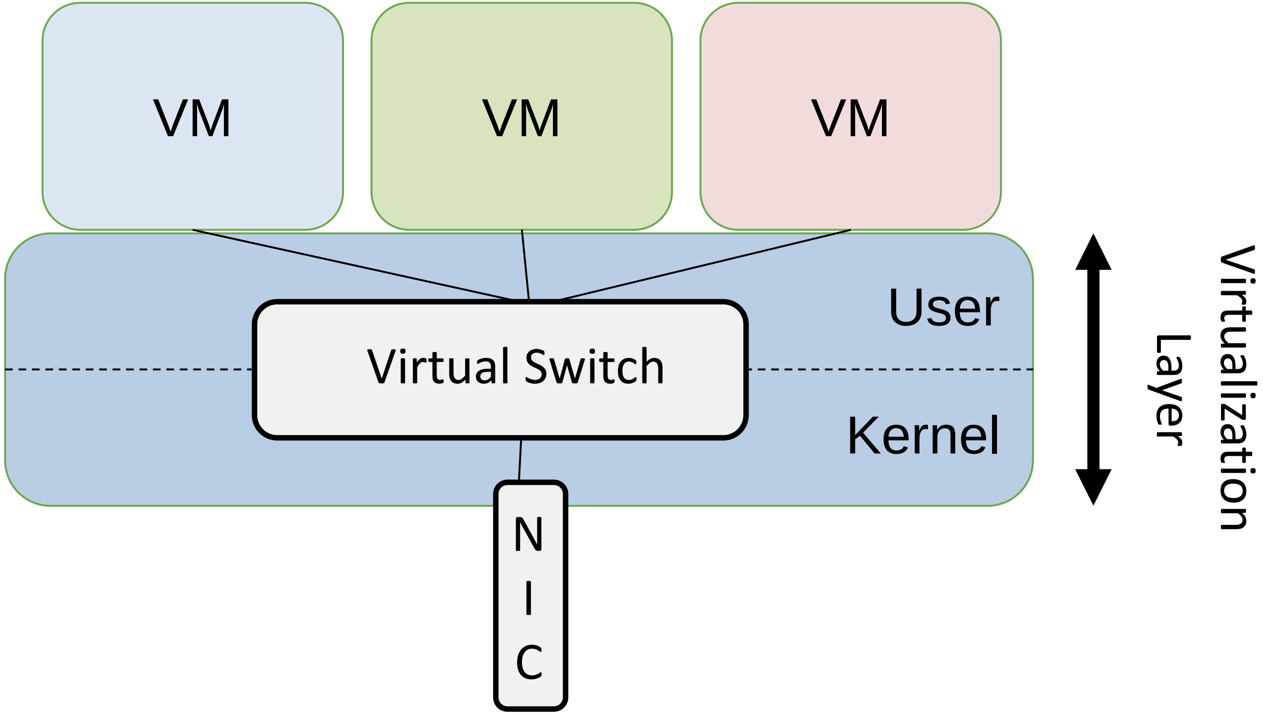
To enable **multi-tenancy**, take existing network **hypervisor** (e.g. Flowvisor, OpenVirteX): provides network abstraction and control plane translation!





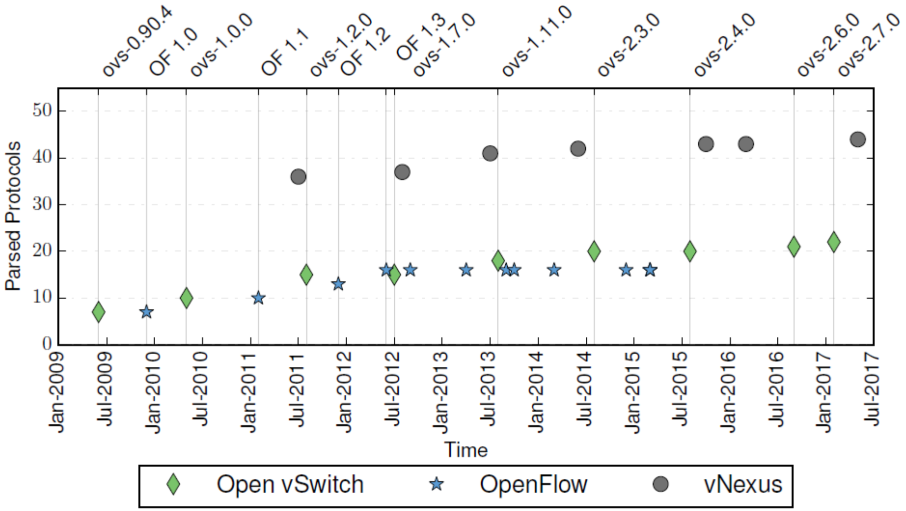
An Experiment: 2 vSDNs with bw guarantee!

Challenge 4: Security



Virtual switches reside in the **server's virtualization layer** (e.g., Xen's Dom0). Goal: provide connectivity and isolation.

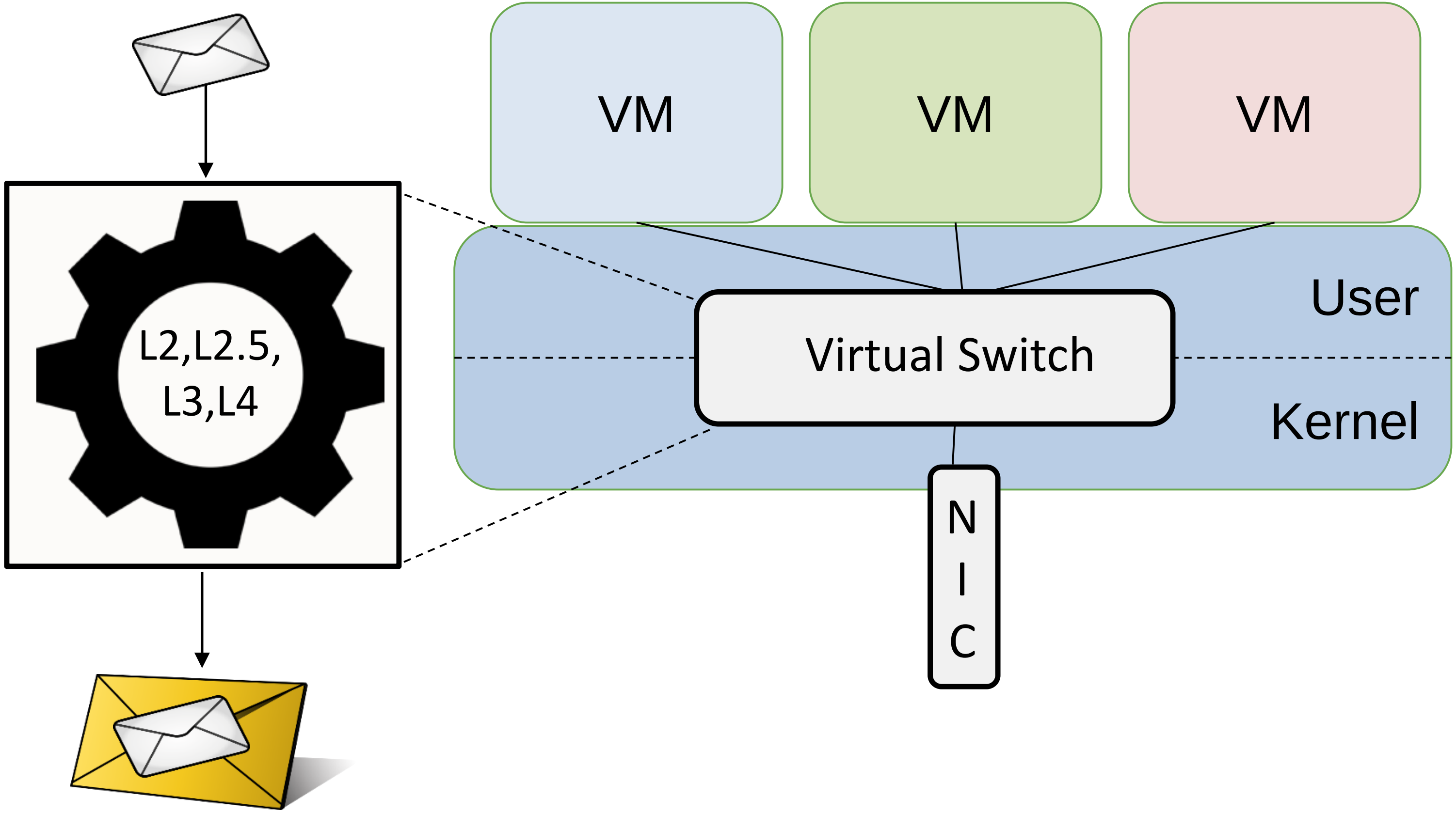
Challenge 4: Security



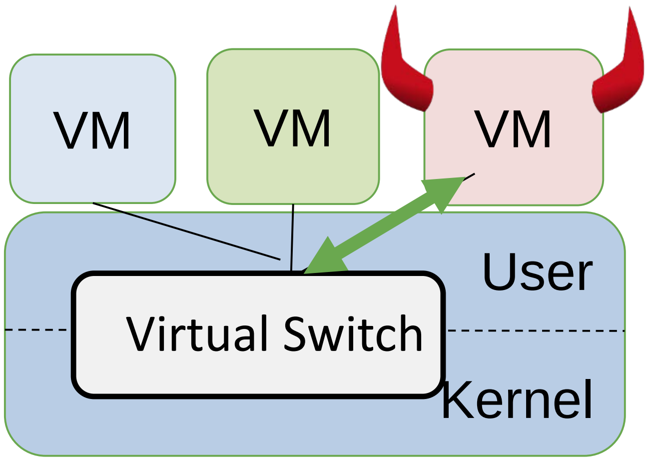
Number of parsed high-level protocols constantly increases…

Challenge 4: Security

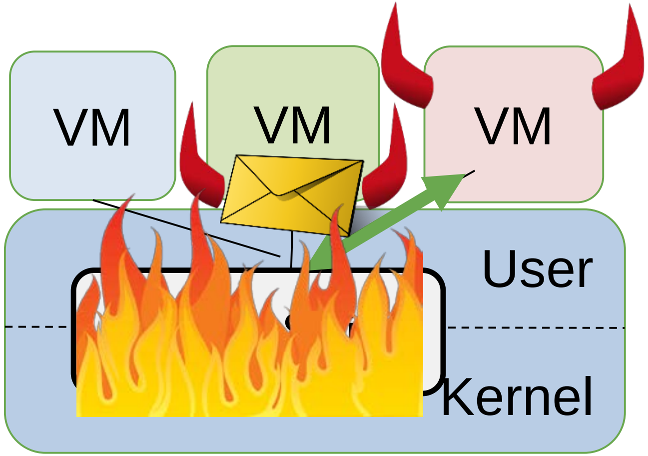
Ethernet
LLC
VLAN
MPLS
IPv4
ICMPv4
TCP
UDP
ARP
SCTP
IPv6
ICMPv6
IPv6 ND
GRE
LISP
VXLAN
PBB
IPv6 EXT HDR
TUNNEL-ID
IPv6 ND
IPv6 EXT HDR
IPv6HOPOPTS
IPv6ROUTING
IPv6Fragment
IPv6DESTOPT
IPv6ESP
IPv6 AH
RARP
IGMP



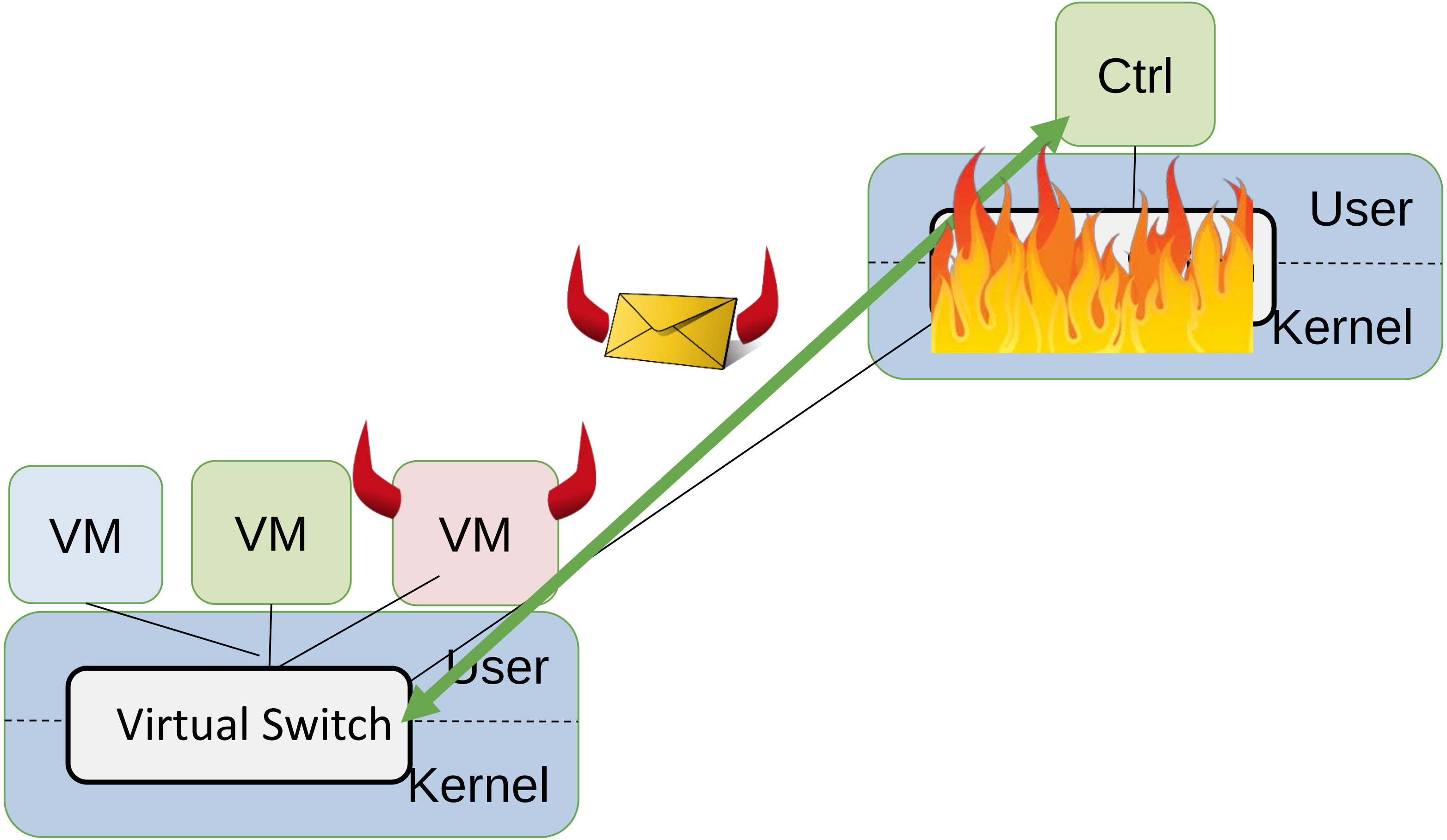
Challenge 4: Security



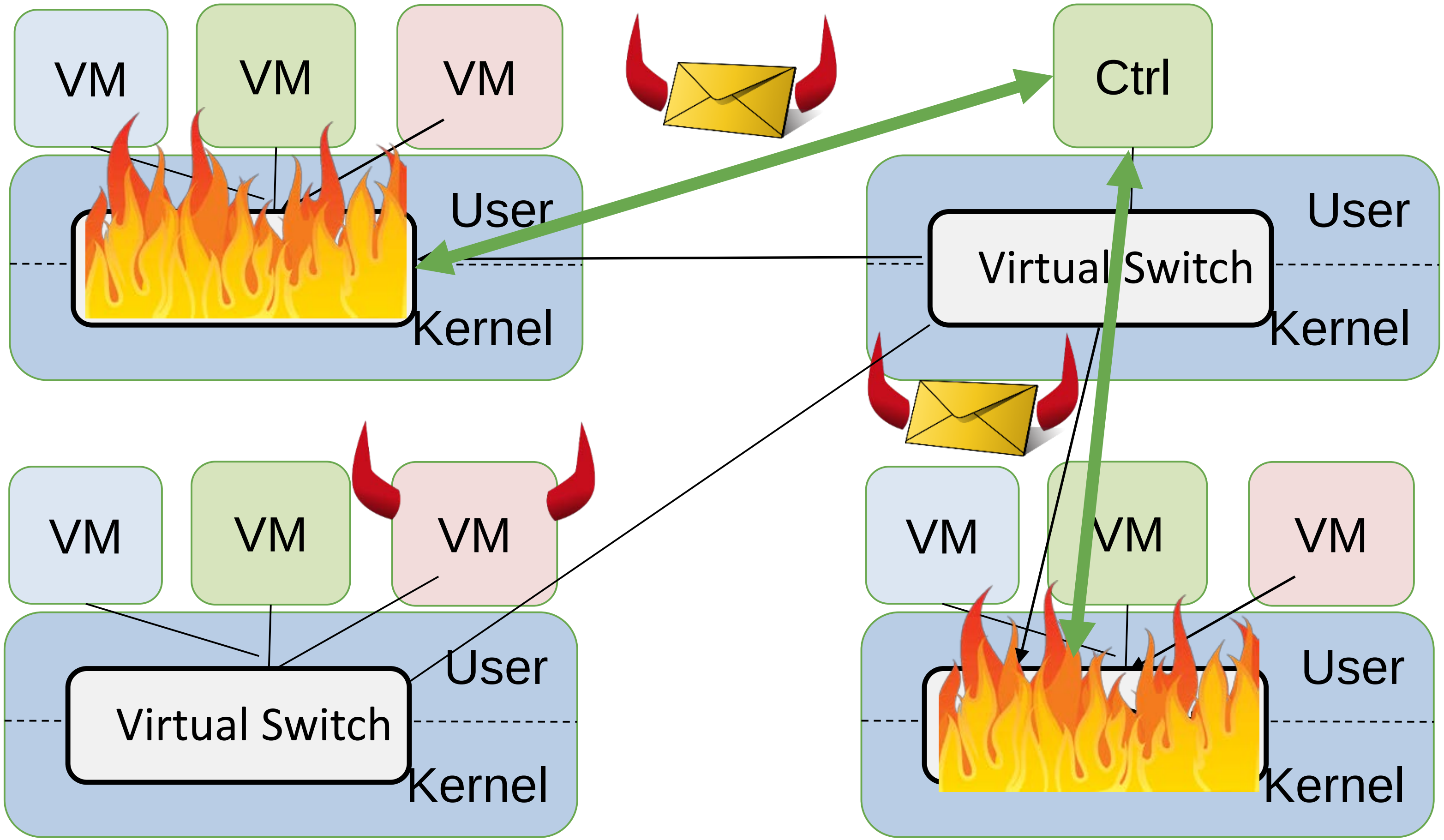
Challenge 4: Security



Challenge 4: Security



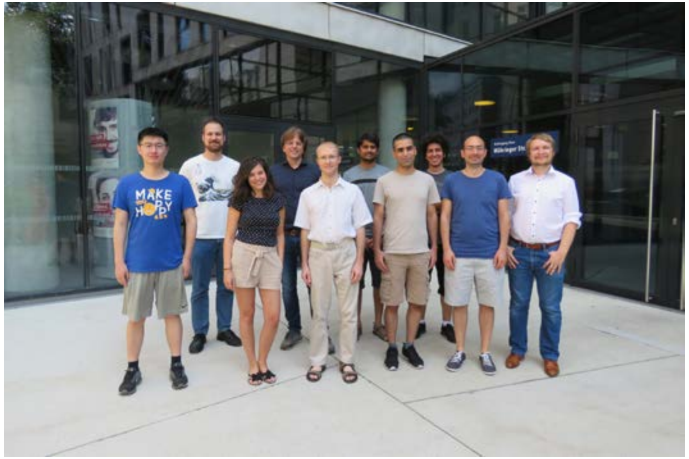
Challenge 4: Security



Conclusions

- Self-* networks: great opportunities (data and flexibilities), great challenges (algorithm design: metrics, formal methods, machine learning)

- We are hiring and looking for interns



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Thanks. Questions?

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Further Reading

Flexibilities and Complexity

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Andreas Blenk, Arsany Basta, Wolfgang Kellerer, and Stefan Schmid.
IFIP Networking, Warsaw, Poland, May 2019.
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ACM/IEEE Symposium on Architectures for Networking and Communications Systems (**ANCS**), Ithaca, New York, USA, July 2018.

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Klaus-Tycho Foerster and Stefan Schmid.
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Chen Avin, Kaushik Mondal, and Stefan Schmid.
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Stefan Schmid, Chen Avin, Christian Scheideler, Michael Borokhovich, Bernhard Haeupler, and Zvi Lotker.
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Klaus-Tycho Foerster, Monia Ghobadi, and Stefan Schmid.
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Self-Repairing Networks

P-Rex: Fast Verification of MPLS Networks with Multiple Link Failures
Jesper Stenbjerg Jensen, Troels Beck Krogh, Jonas Sand Madsen, Stefan Schmid, Jiri Srba, and Marc Tom Thorgersen.
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MTS: Bringing Multi-Tenancy to Virtual Switches
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Kashyap Thimmaraju, Bhargava Shastry, Tobias Fiebig, Felicitas Hetzelt, Jean-Pierre Seifert, Anja Feldmann, and Stefan Schmid.
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Modeling Challenges

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Andreas Blenk, Arsany Basta, Wolfgang Kellerer, and Stefan Schmid.
IFIP Networking, Warsaw, Poland, May 2019.

Self-Stabilization

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