Self-Driving Networks: Vision, Enablers, Challenges

Stefan Schmid

“We cannot direct the wind,
but we can adjust the sails.”

(Folklore)

It`s a Great Time to Be a Networking Researcher!

Rhone and Arve Rivers, Switzerland

Credits: George Varghese

Flexibilities

Along 3 Dimensions

Passau, Germany

Inn, Donau, Ilz

Flexibilities

Along 3 Dimensions

It‘s High Time

Increasing Traffic, Stringent Requirements

Datacenters (“hyper-scale”)

+network

Interconnecting networks:
a **critical infrastructure**
of our digital society.

Source: Facebook

Requirements vs Reality

Today, dependability requirements stand in contrast with reality:

Countries disconnected

Data Centre ▸ Networks

Google routing blunder sent Japan's Internet dark on Friday

Another big BGP blunder

By Richard Chirgwin 27 Aug 2017 at 22:35 40 SHARE ▼

Last Friday, someone in Google fat-thumbed a border gateway protocol (BGP) advertisement and sent Japanese Internet traffic into a black hole.

The trouble began when The Chocolate Factory "leaked" a big route table to Verizon, the result of which was traffic from Japanese giants like NTT and KDDI was sent to Google on the expectation it would be treated as transit.

Passengers stranded

British Airways' latest Total Inability To Support Upwardness of Planes* caused by Amadeus system outage

Stuck on the ground awaiting a load sheet? Here's why

By Gareth Corfield 19 Jul 2018 at 11:16 109 SHARE ▼

Even 911 affected

Officials: Human error to blame in Minn. 911 outage

According to a press release, CenturyLink told department of public safety that human error by an employee of a third party vendor was to blame for the outage

Aug 16, 2018

Duluth News Tribune

SAINT PAUL, Minn. — The Minnesota Department of Public Safety Emergency Communication Networks division was told by its 911 provider that an Aug. 1 outage was caused by human error.

Even tech-savvy companies struggle:

Credits:

Laurent Vanbever, Nate Foster

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Even tech-savvy companies struggle:

Mainly: human errors!

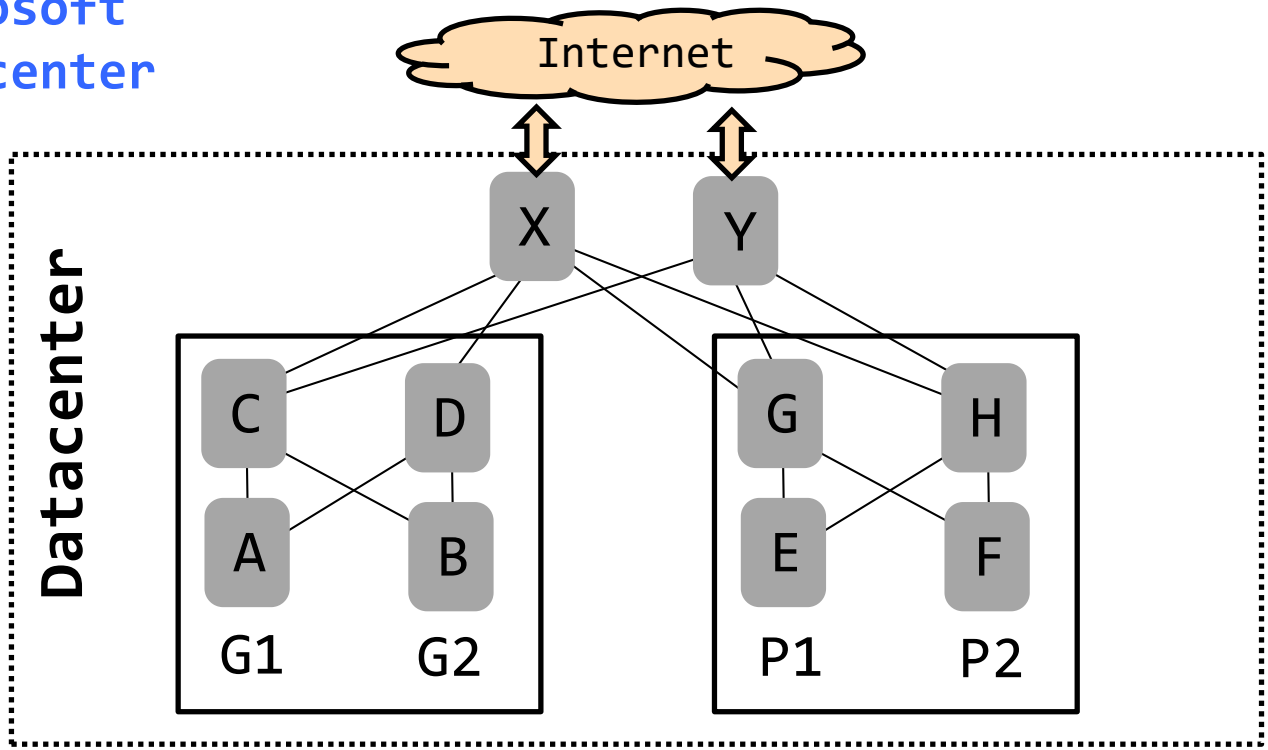
Credits:

Laurent Vanbever, Nate Foster

Reason: Complexity

Especially Under Failures (Policy Compliance)

Example: BGP in **Microsoft datacenter**



Credits: Ratul Mahajan

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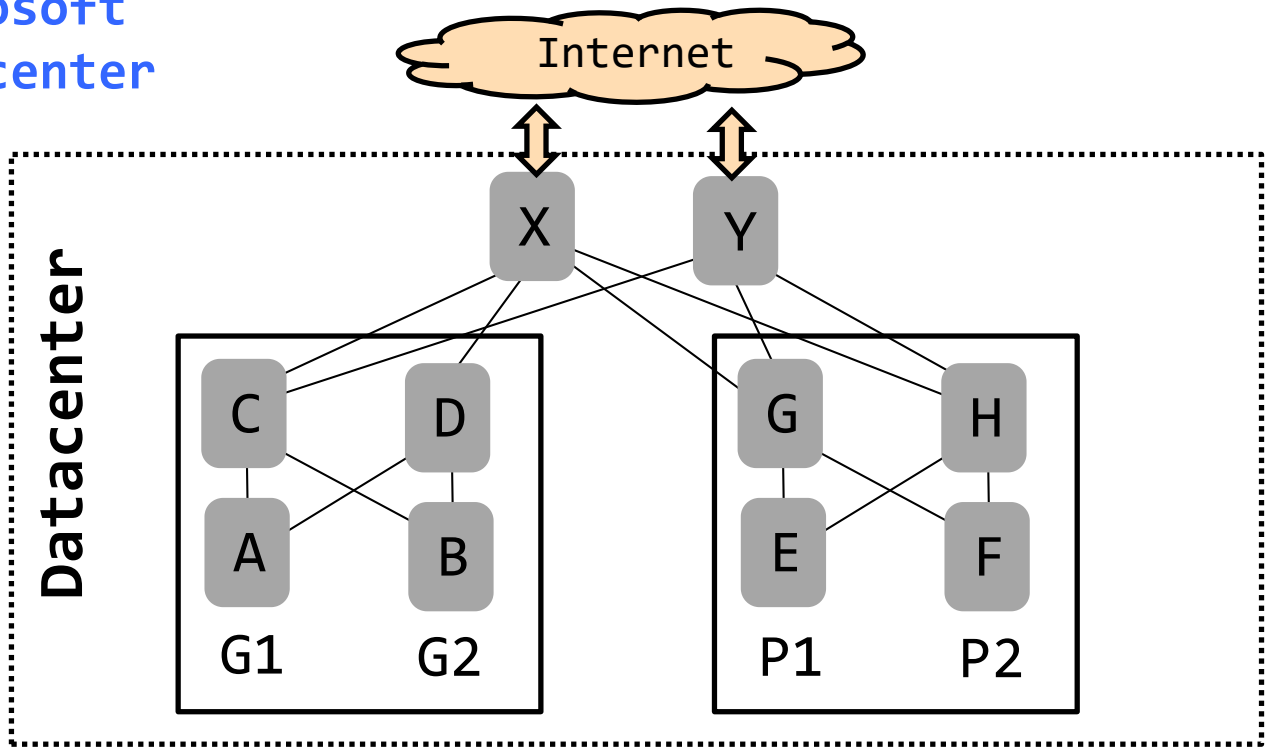

Cluster with globally reachable services

Cluster with internally accessible services

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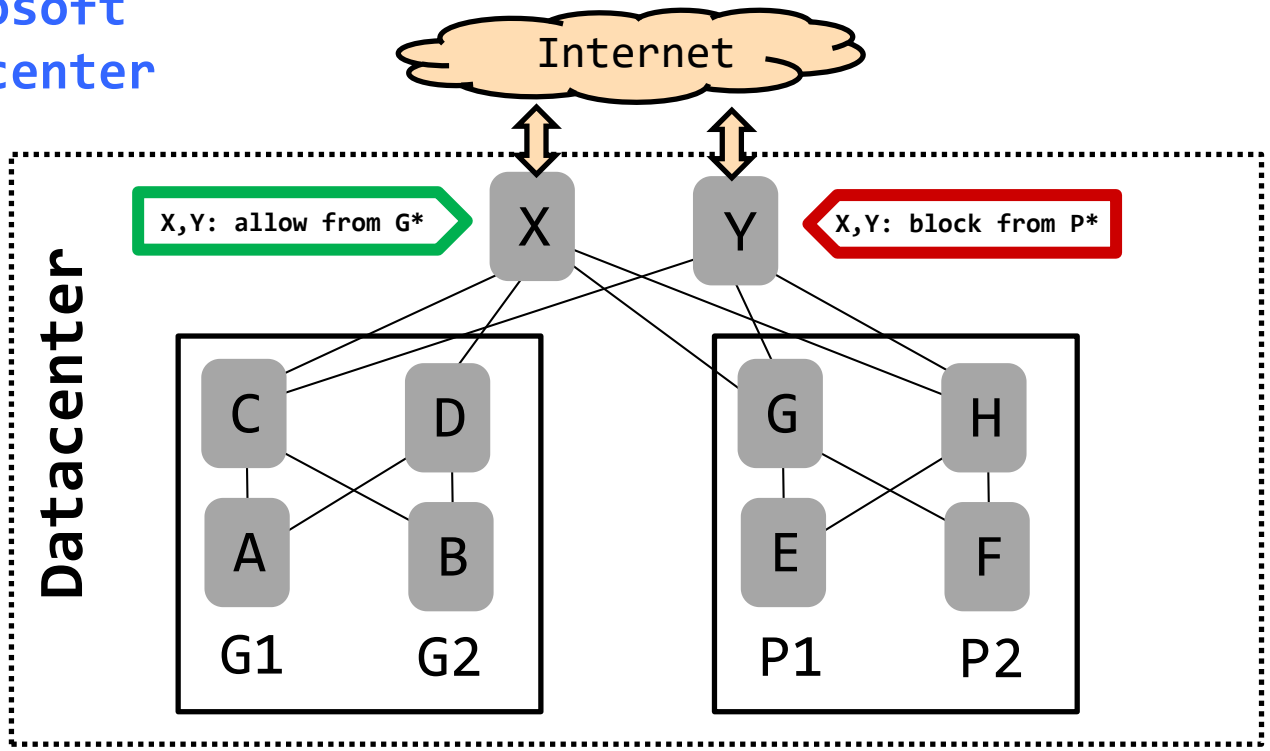

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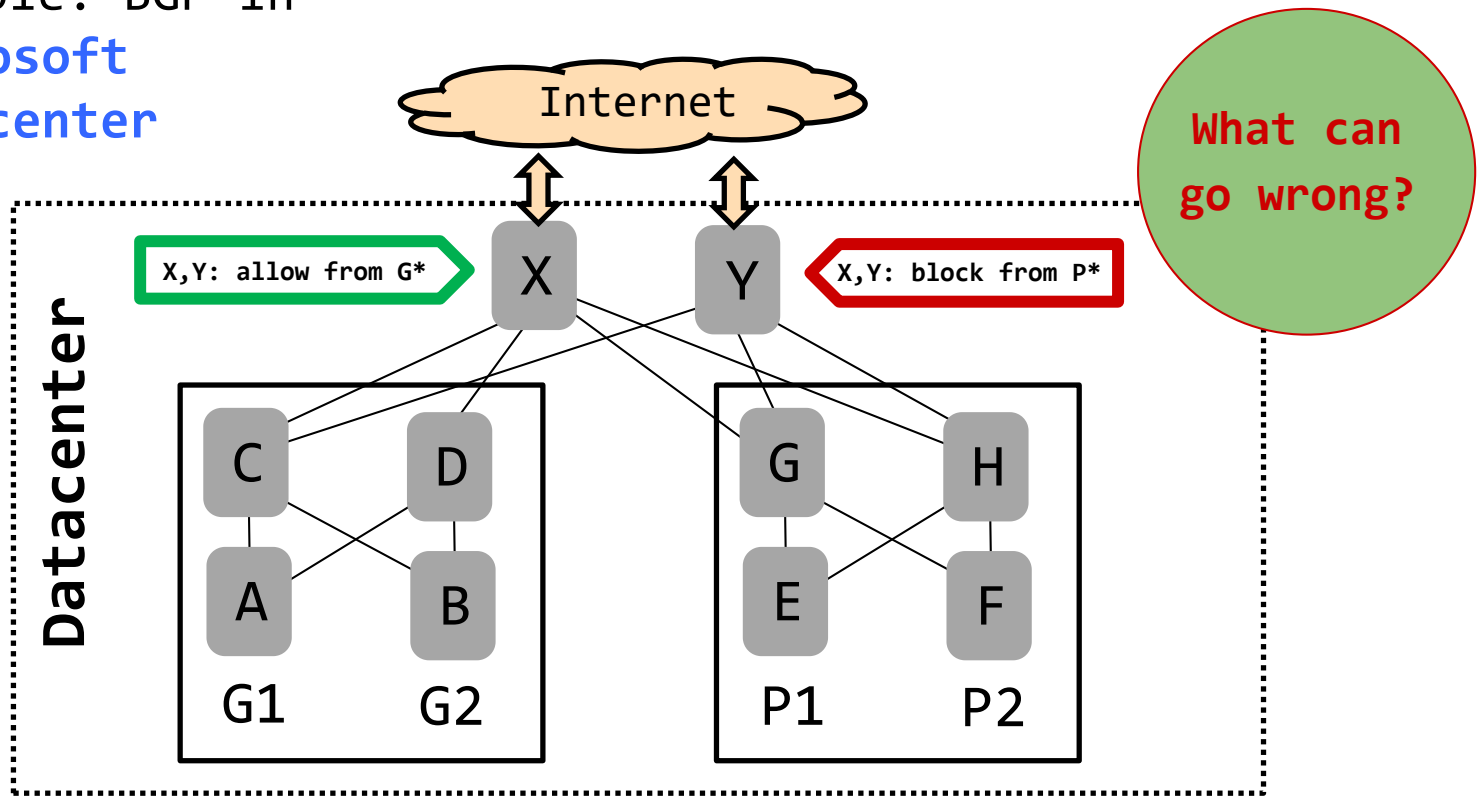

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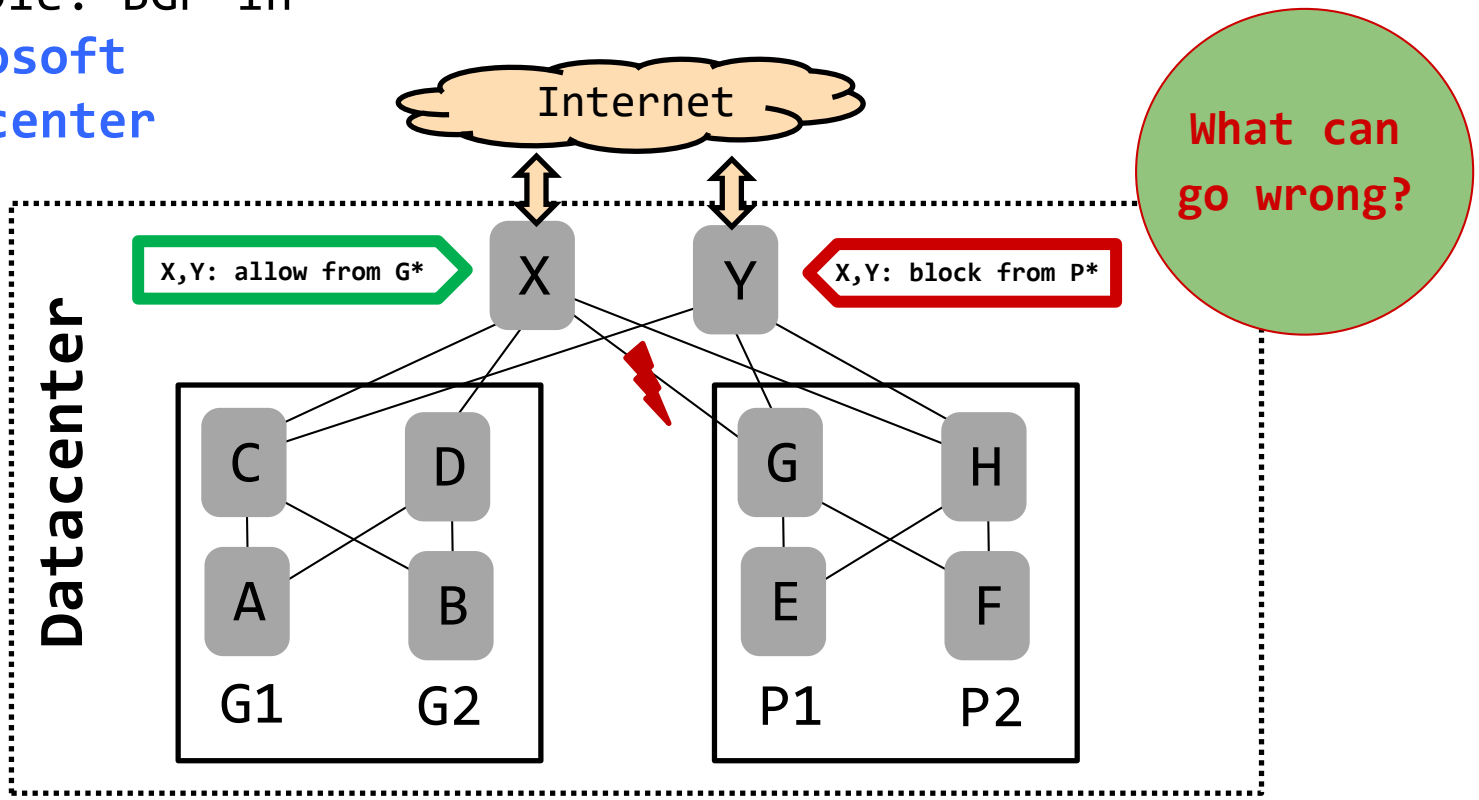

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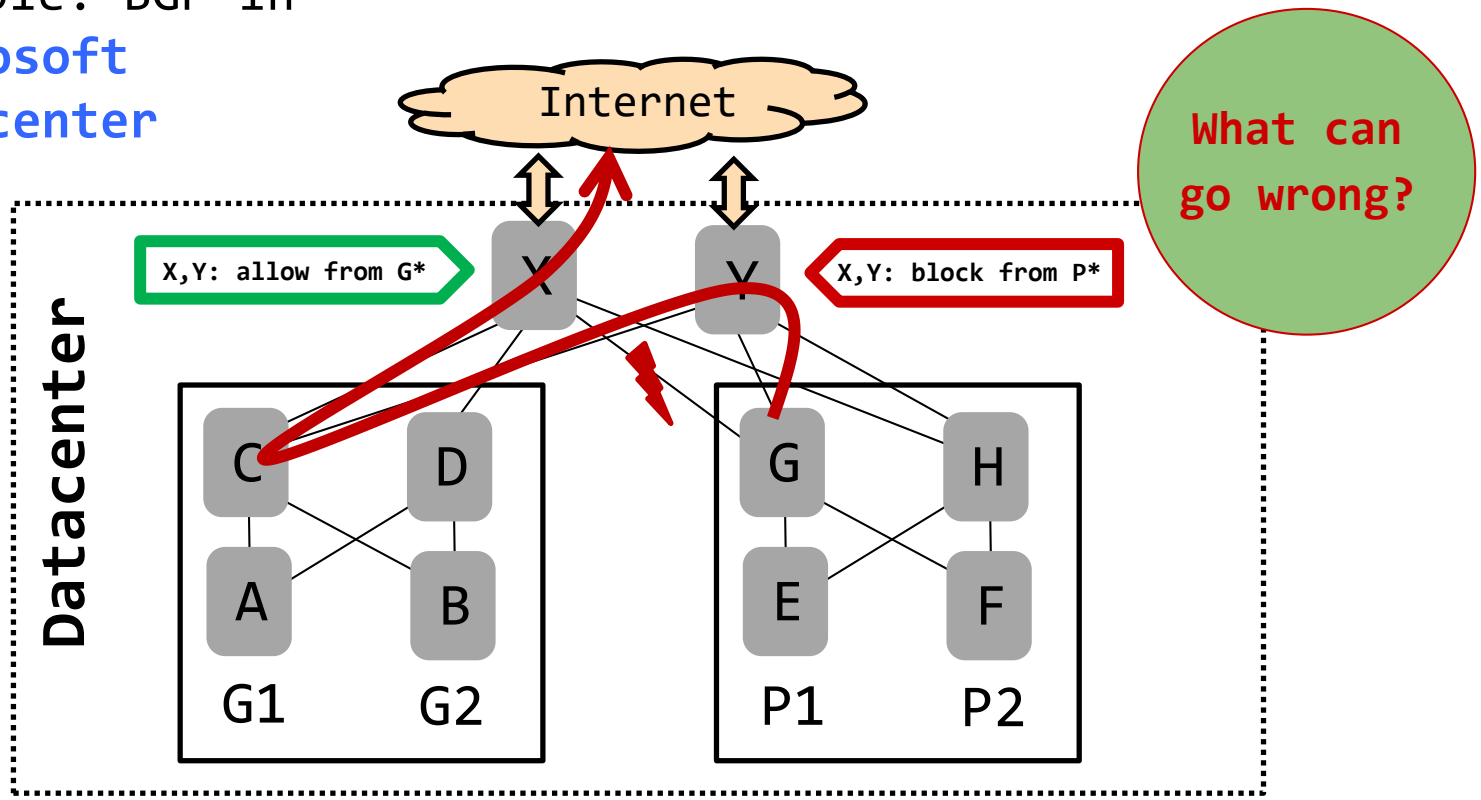
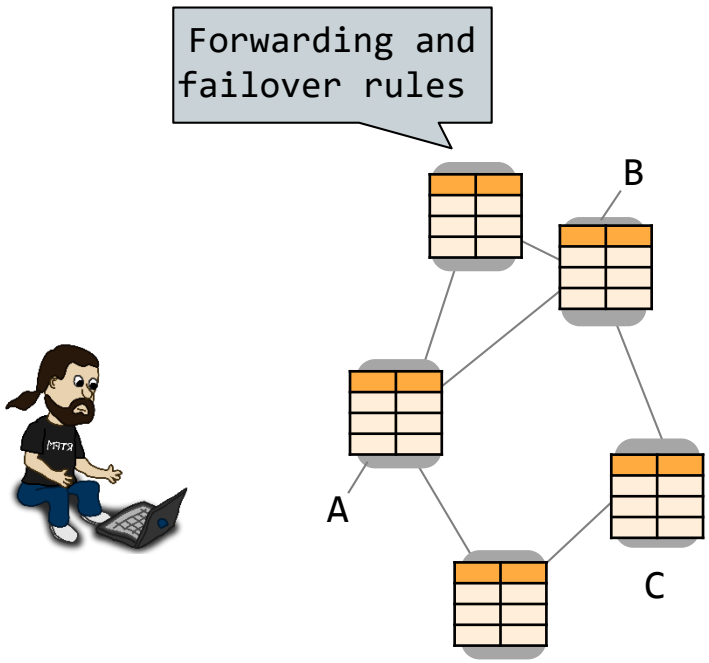


If link (G,X) fails and traffic from G is rerouted via Y and C to X:
X announces (does not block) G and H as it comes from C. (Note: BGP.)

Admin’s Responsibilities



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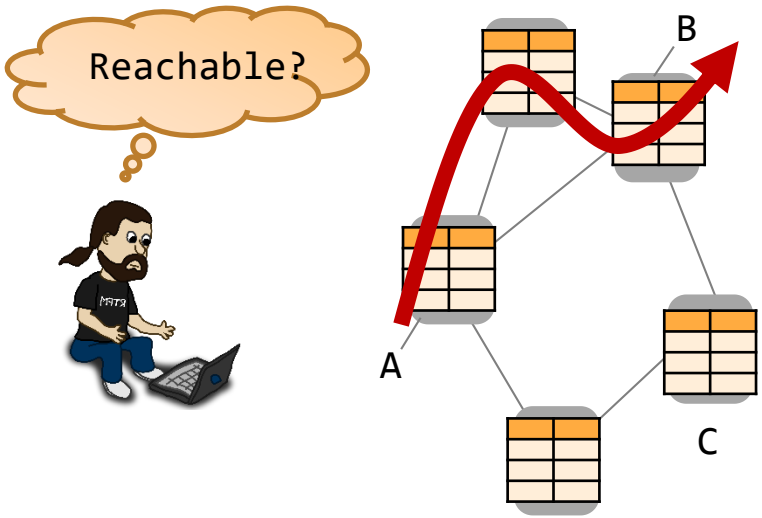
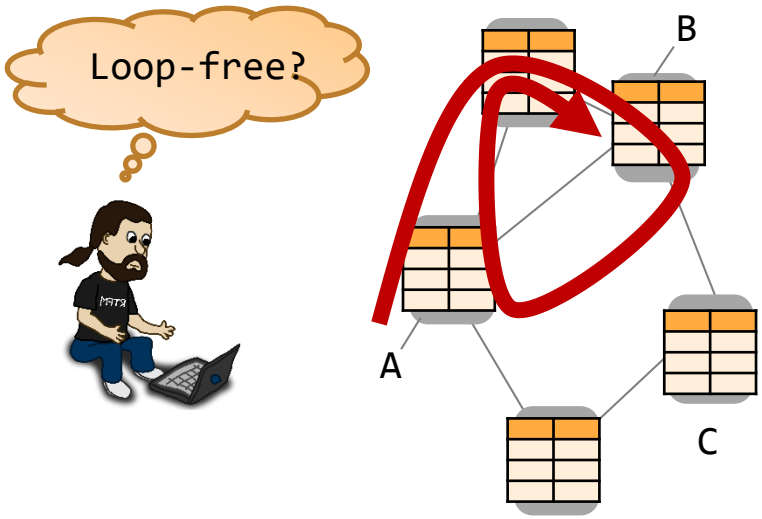


⇢ Reachability: Can traffic from ingress port A reach B?

Admin's Responsibilities



⇢ Reachability: Can traffic from ingress port A reach B?

⇢ Loop-freedom: Do forwarding rules imply loop-free routes?

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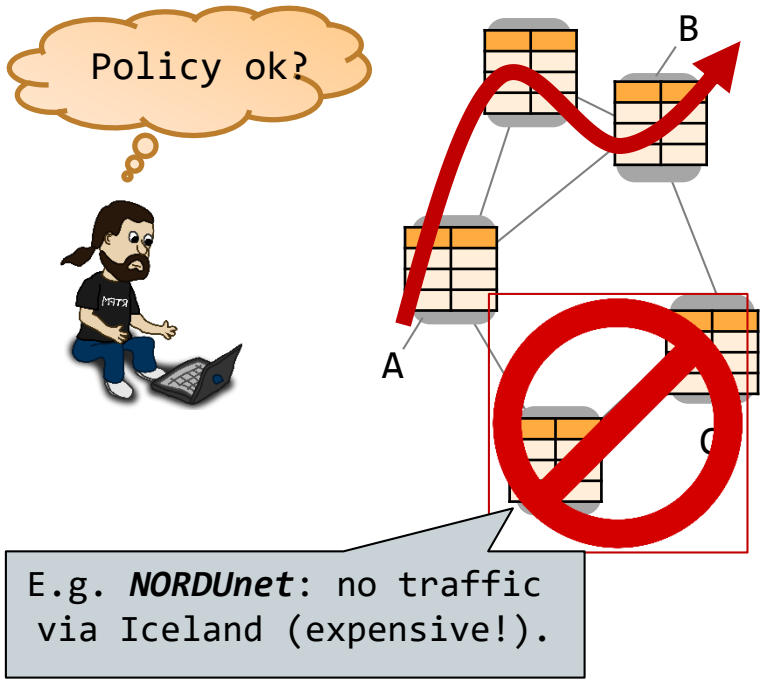

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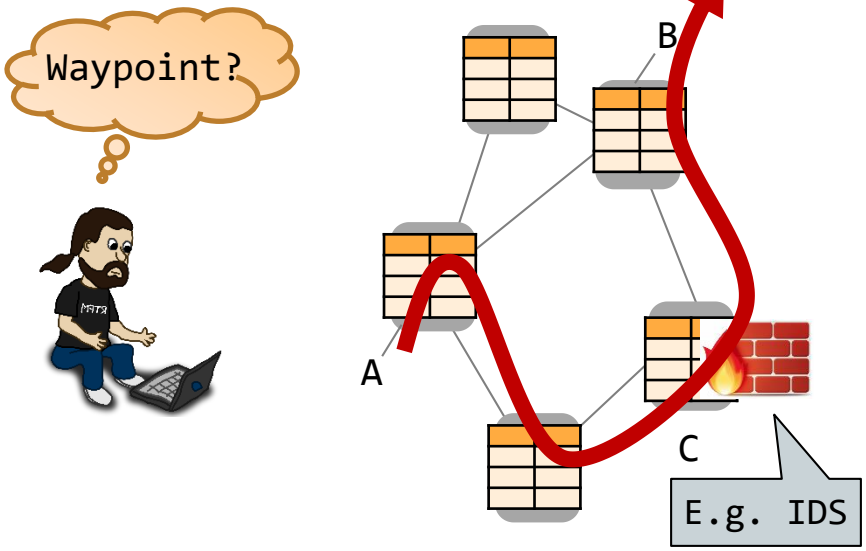

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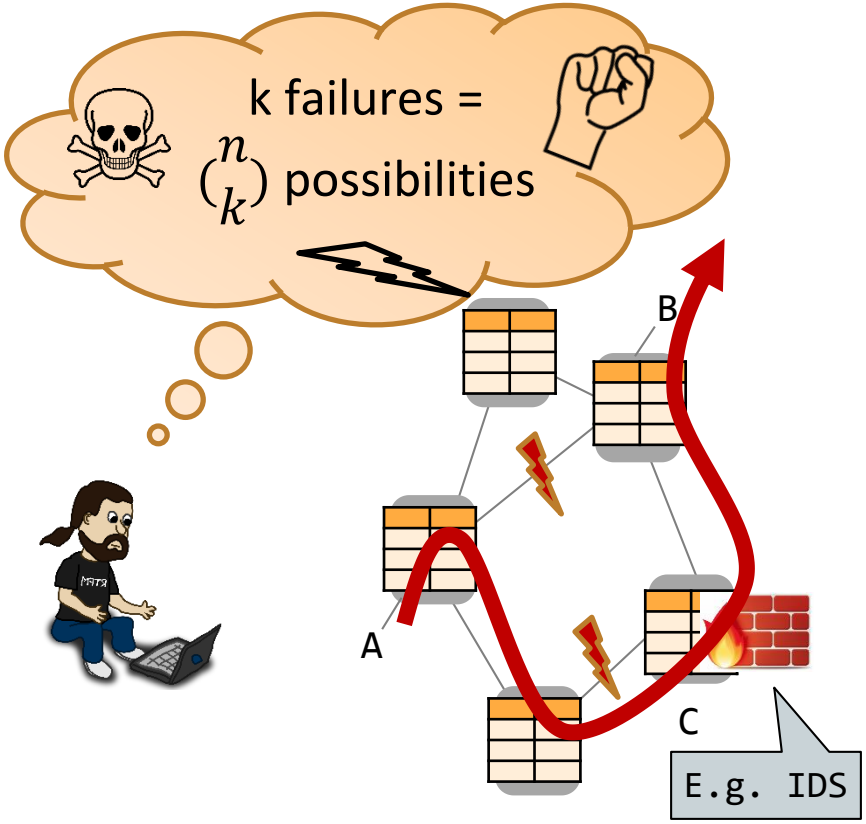

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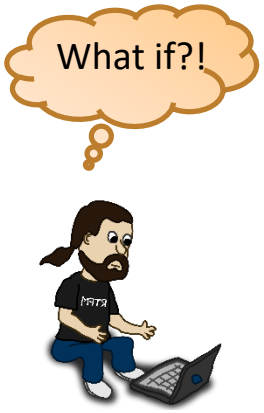
… and everything even under multiple failures?!

A Modern Approach:

Automated Whatif Analysis



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)	$swap(11)$
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τ_{v_3}	(v_2, v_3)	11	(v_3, v_4)	$swap(12)$
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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)	$swap(31)$
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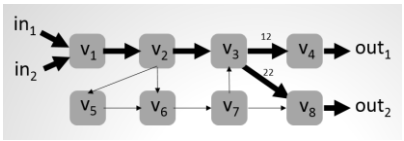

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Router **configurations**
(Cisco, Juniper, etc.)

Compilation

Interpretation

$$pX \Rightarrow qXX$$
$$pX \Rightarrow qYX$$
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$$rX \Rightarrow pX$$

Formal language
which supports
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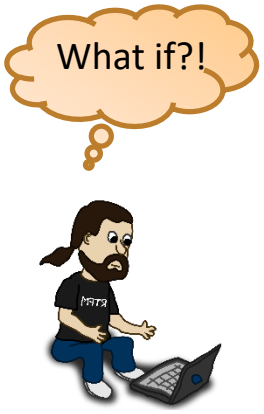

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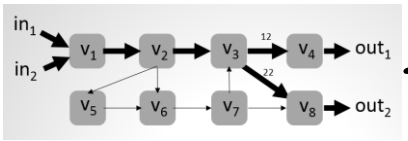

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On request or regularly.

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Formal language which supports ***automated analysis***

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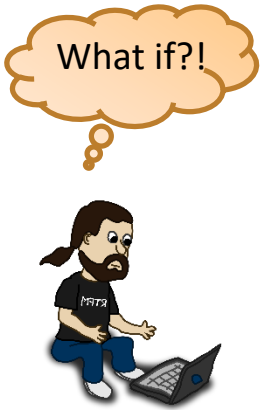

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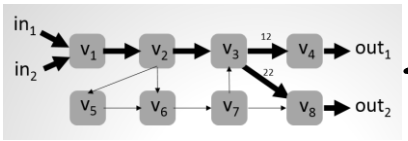

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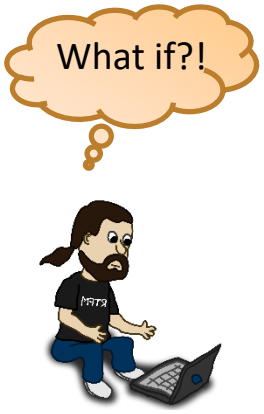

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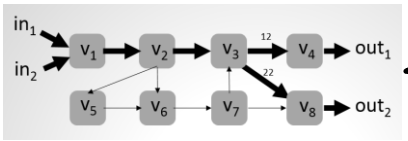

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Router **configura**
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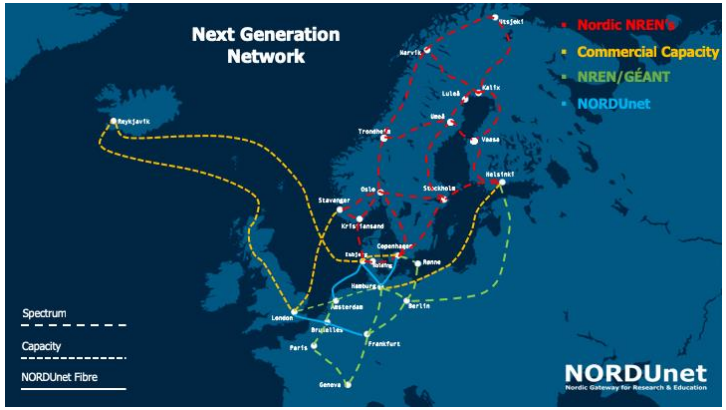
Challenge:

Hard Even for Computers?

⇢ NORDUnet: provider for Nordic countries

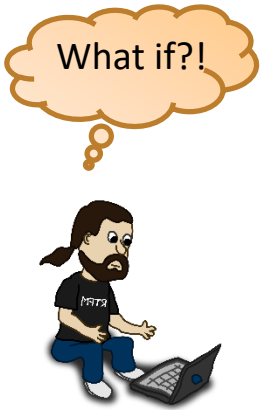
⇢ 24 MPLS routers, running Juniper OS

⇢ More than 30,000 labels!

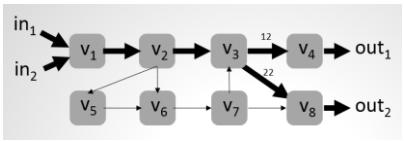


Case Study:

Whatif Analysis of MPLS



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)	$push(40)$

Router **configurations**
(Cisco, Juniper, etc.)

Compilation

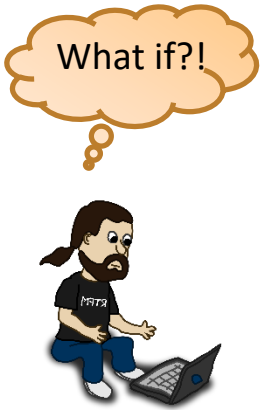
Interpretation

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

MPLS is a ***stack-based pushdown system:*** can solve with **finite automata-theory**

Case Study:

Whatif Analysis of MPLS



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τ_{v_1}	in_1	$\perp$	(v_1, v_2)	$push(10)$
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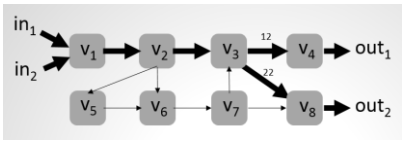
τ_{v_8}	(v_3, v_8)	22	out_2	pop
	(v_7, v_8)	22	out_2	pop



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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)	$push(40)$
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Router **configurations**
(Cisco, Juniper, etc.)

Compilation

Interpretation

FAST!

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

MPLS is a ***stack-based pushdown system:*** can solve with **finite automata-theory**

Counting for congestion? Yes: weighted automata.

The AalWiNes Tool

Online demo: https://demo.aalwines.cs.aau.dk/
Source code: https://github.com/DEIS-Tools/AalWiNes

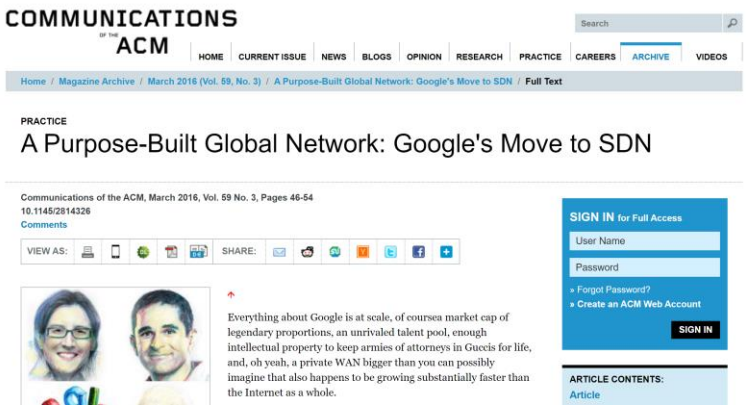
Another Benefit of Self-Driving Networks:

More Adaptive Operation

⇢ Automation and programmability: enables more **adaptable networks**

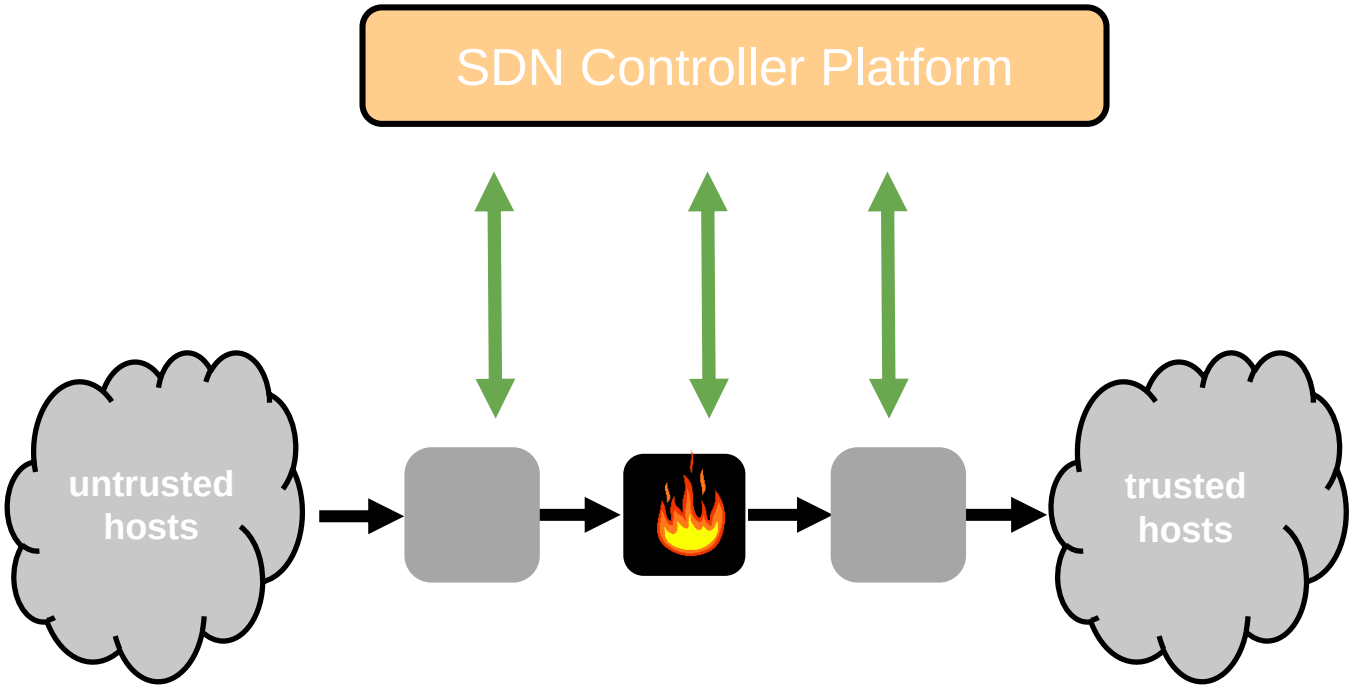
⇢ Attractive for:

- ⇢ Fine-grained traffic engineering (e.g., at Google)
- ⇢ Accounting for changes in the demand (spatio-temporal structure)
- ⇢ Security policy changes
- ⇢ Service relocation
- ⇢ Maintenance work
- ⇢ Link/node failures



Another Benefit of Self-Driving Networks:

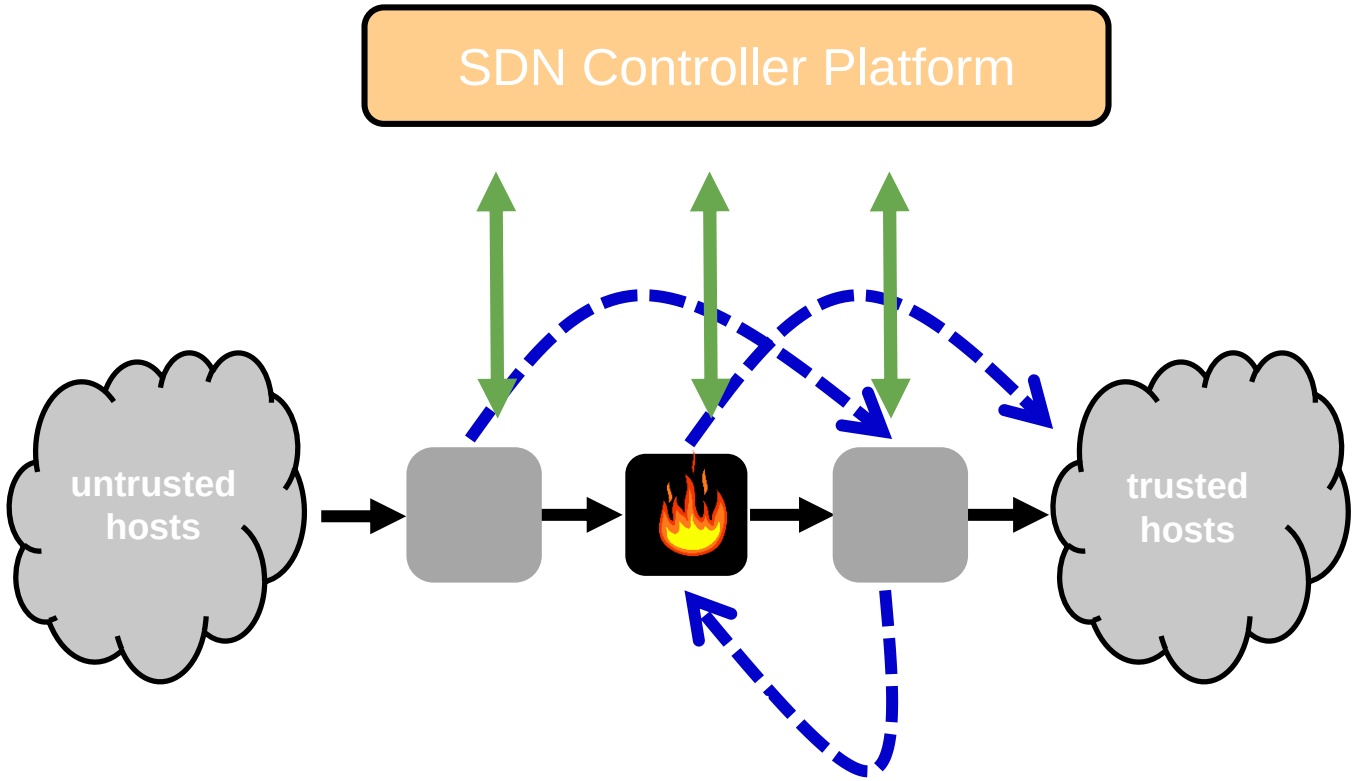
More Adaptive Operation



SDN outsources and consolidates control: direct definition of forwarding tables!

Another Benefit of Self-Driving Networks:

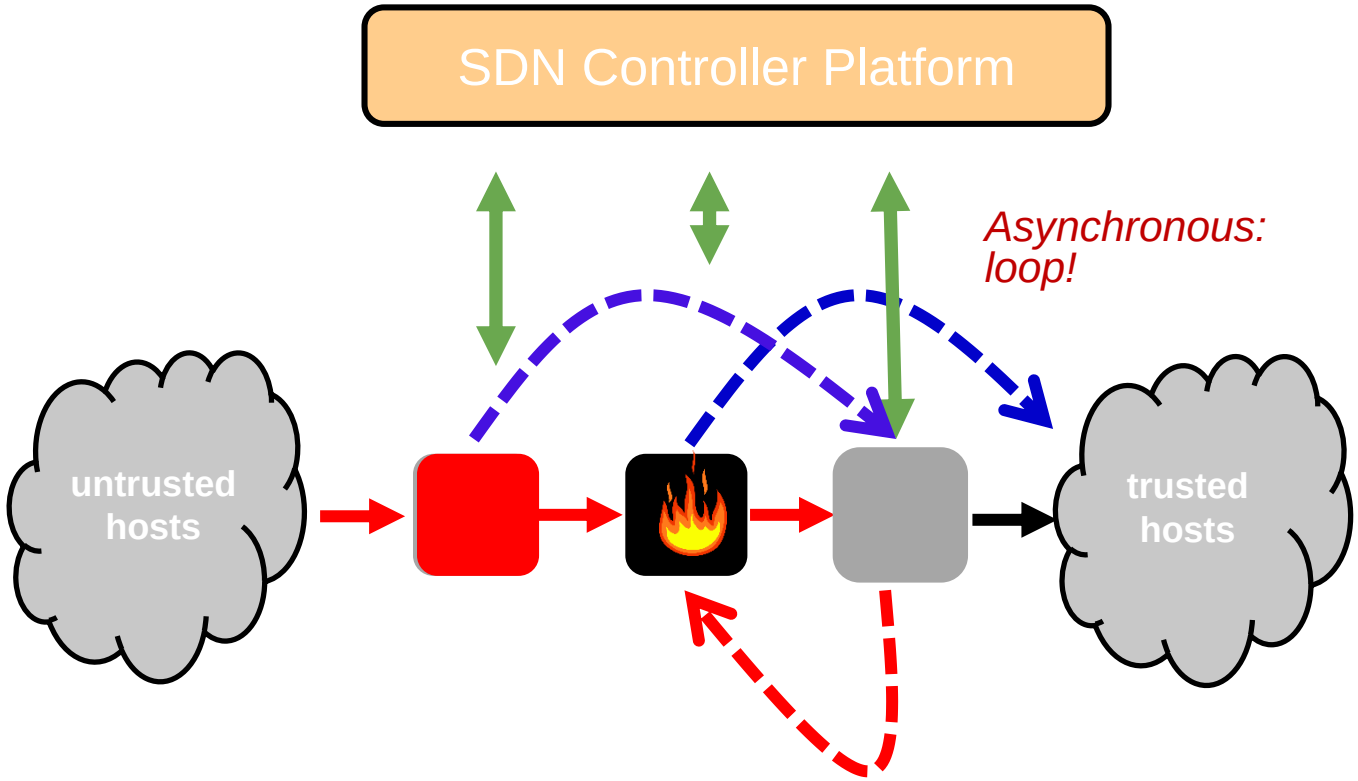
More Adaptive Operation



Can programmatically change route to blue route.

Another Benefit of Self-Driving Networks:

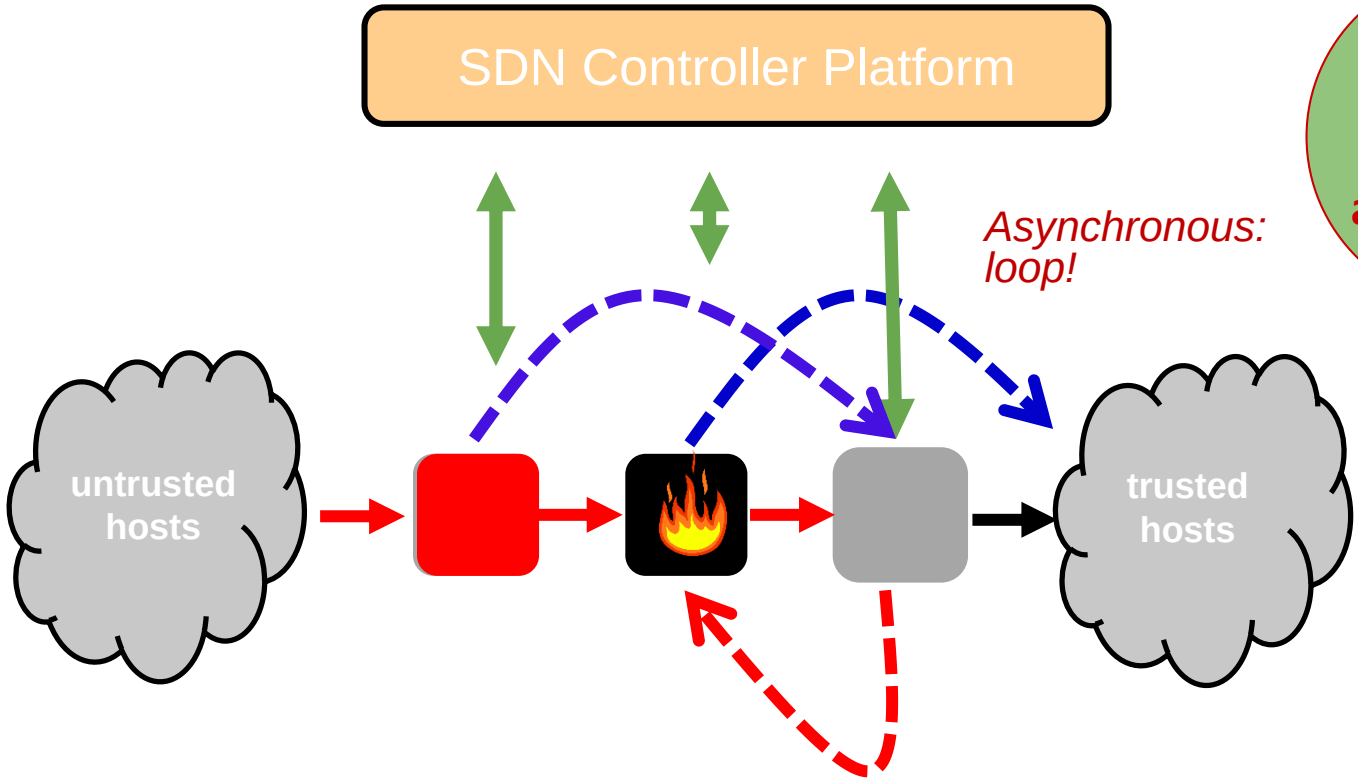
More Adaptive Operation



Updates are asynchronous: can be challenging to update the network configuration consistently!

Another Benefit of Self-Driving Networks:

More Adaptive Operation

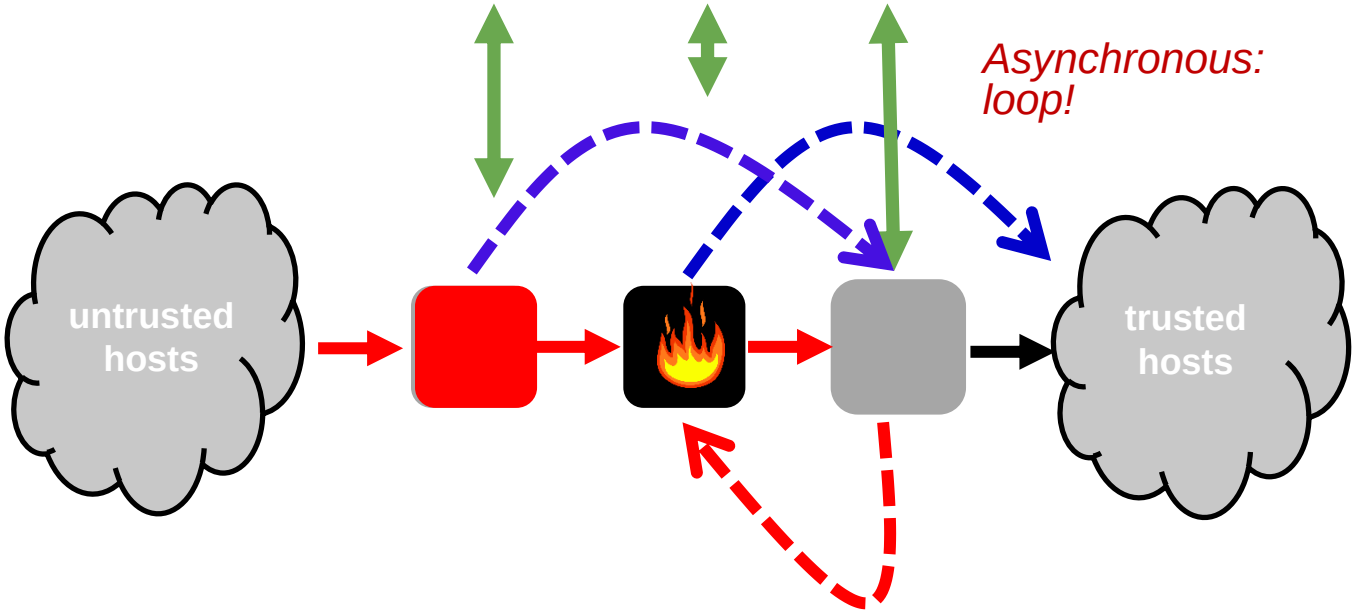


Survey: 100s of algorithms

Updates are asynchronous: can be challenging to update the network configuration consistently!

Again: Formal Approaches Enable More

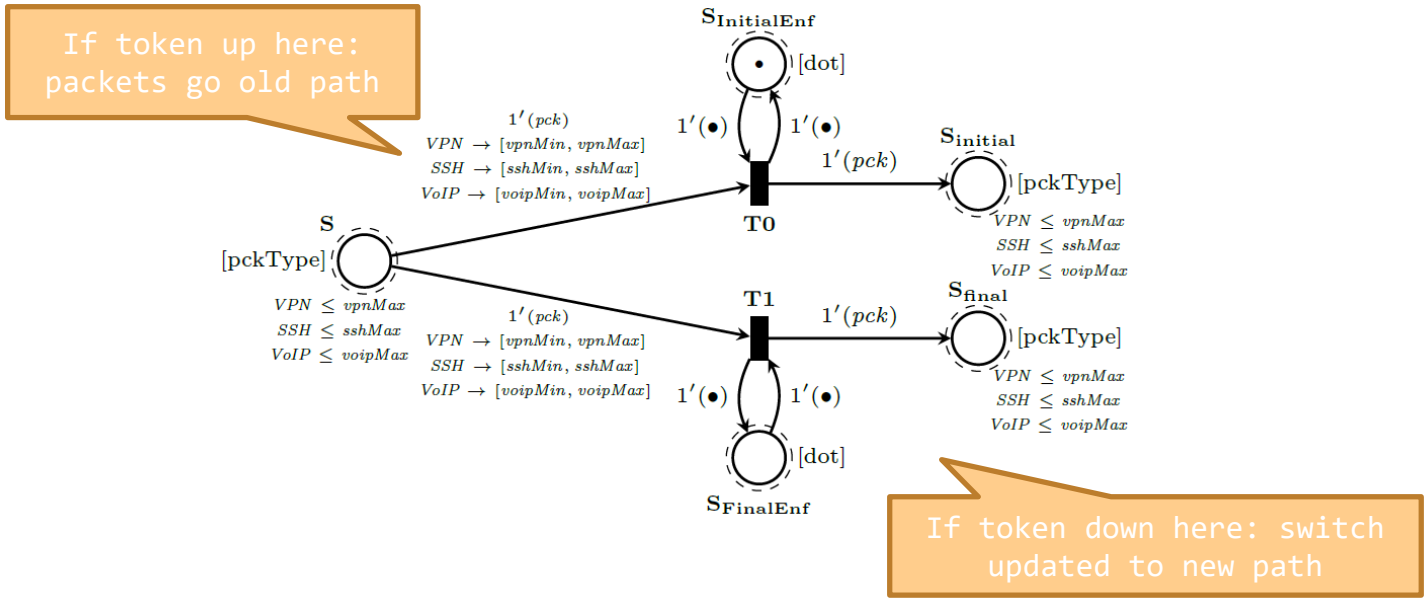
Automated Approaches



Emerging tools allow to verify and synthesize update schedules for a wide range of networks and objectives.

Example: The Latte Tool

- ⇢ SDN can be modelled as distributed system: **Petri net**
- ⇢ Latte allows to verify and synthesize update schedules
- ⇢ Example: Gadget to model switches:

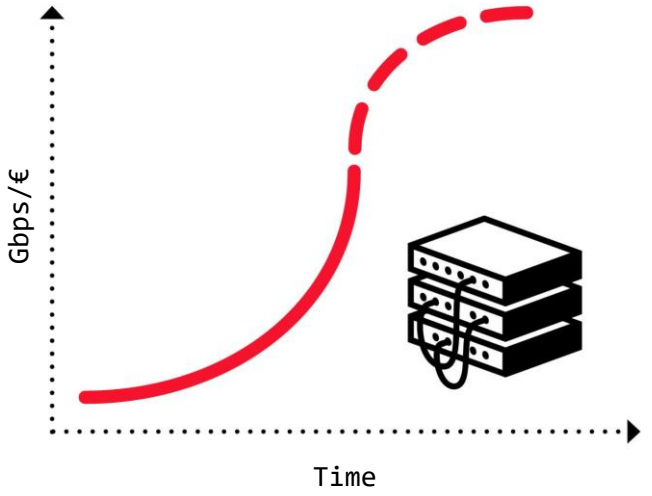


Adaptions also on Lower Layers: Emerging Topology Programming

Let’s go back to datacentre use case:

Moore’s Law of Datacenters

- ⇢ Recall: **explosive growth** of demand
- ⇢ Problem: network equipment reaching capacity limits
  - ⇀ Transistor density rates stalling
  - ⇀ “End of **Moore‘s Law** in networking”
- ⇢ Hence: more equipment, larger networks
- ⇢ Resource intensive and: **inefficient**



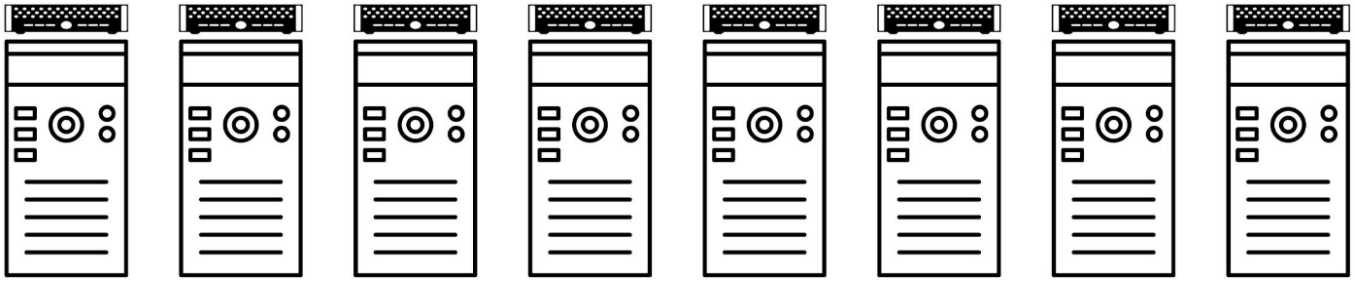
[1] Source: Microsoft, 2019

Annoying for companies,
opportunity for researchers

Root Cause

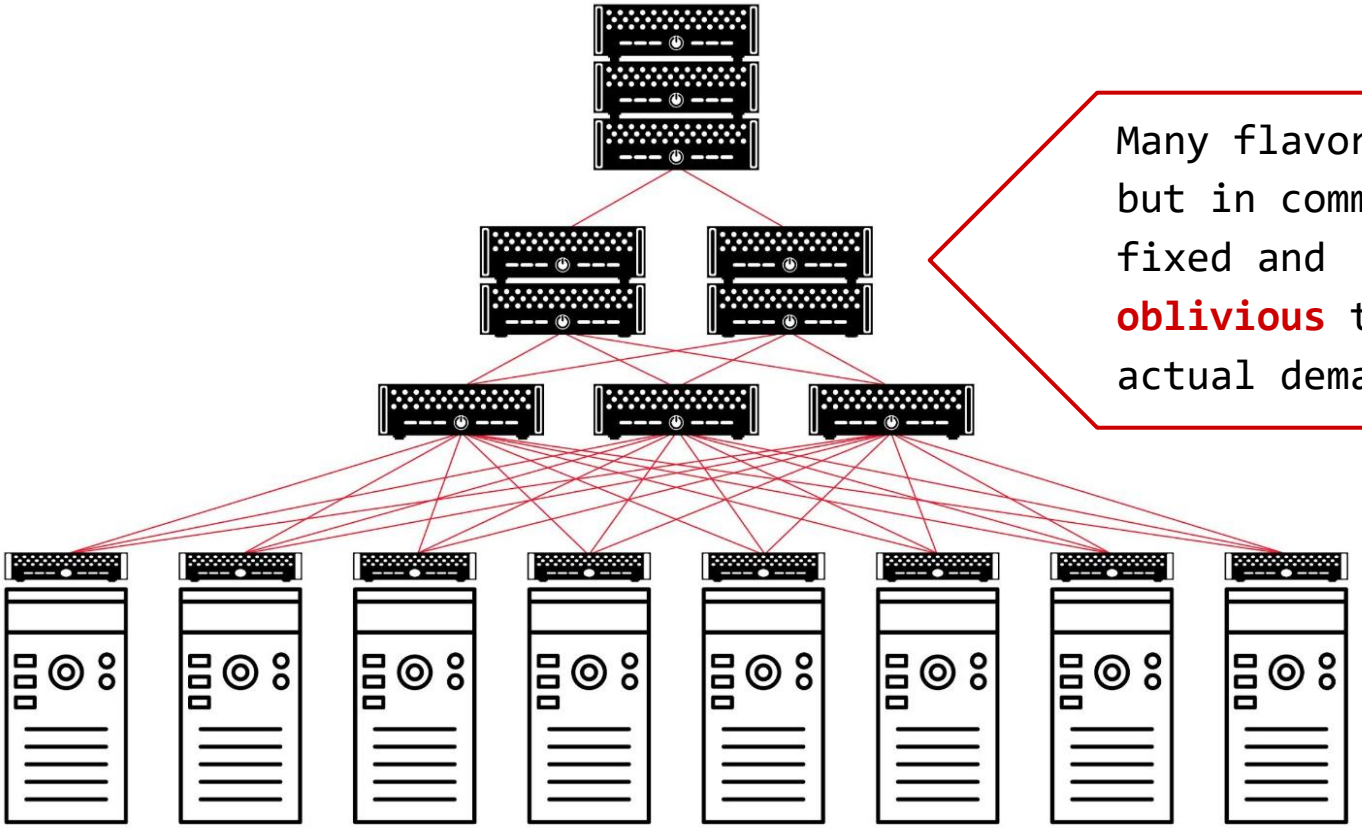
Fixed and Demand-Oblivious Topology

How to interconnect?



Root Cause

Fixed and Demand-Oblivious Topology



Many flavors, but in common: fixed and **oblivious** to actual demand.

Root Cause

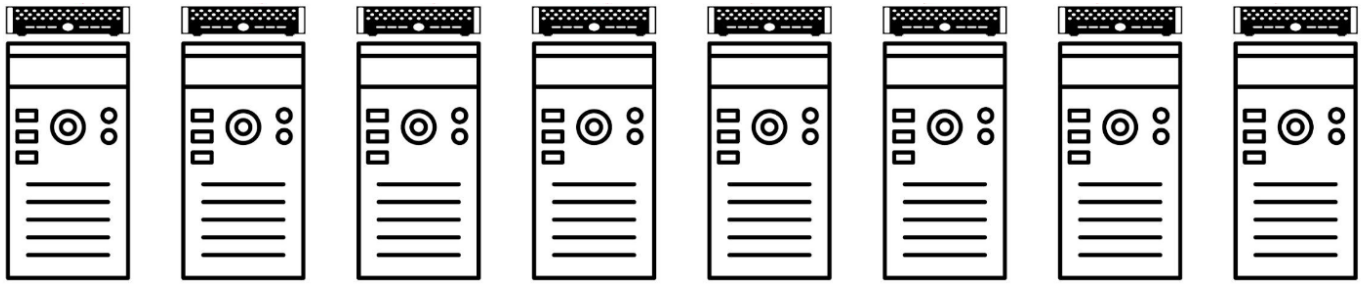
Fixed and Demand-Oblivious Topology

Highway which ignores actual traffic: frustrating!

Many flavors, but in common: fixed and **oblivious** to actual demand.

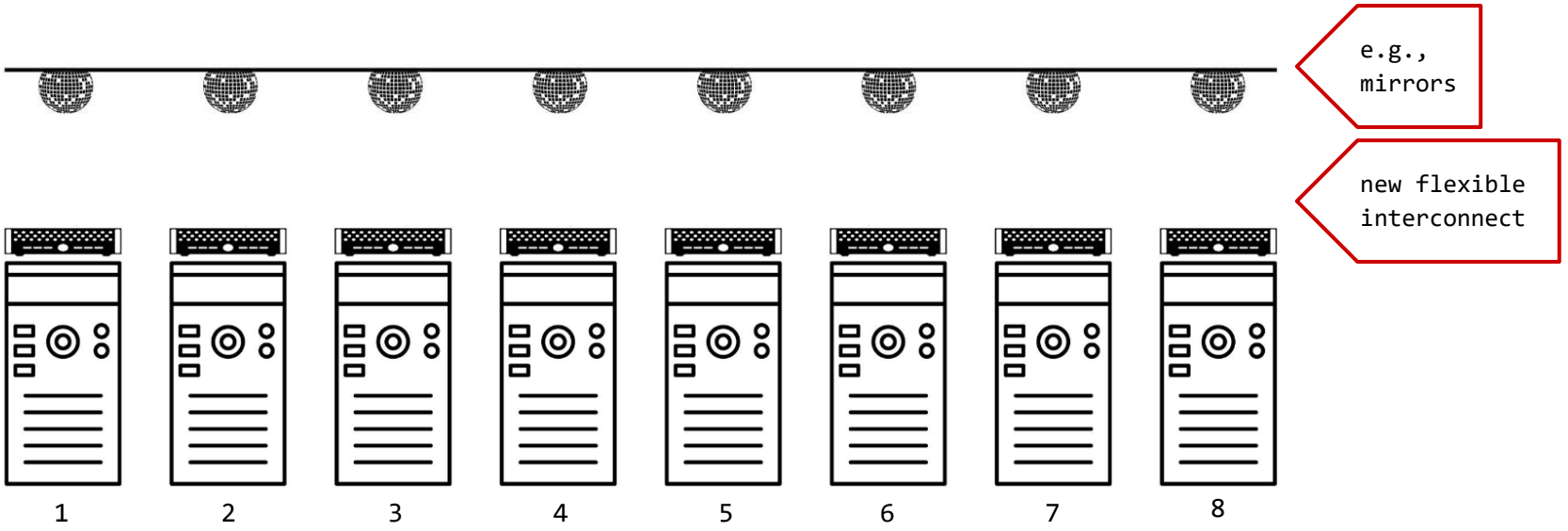
A Vision

Flexible and Demand-Aware Topologies



A Vision

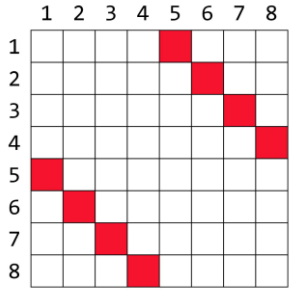
Flexible and Demand-Aware Topologies

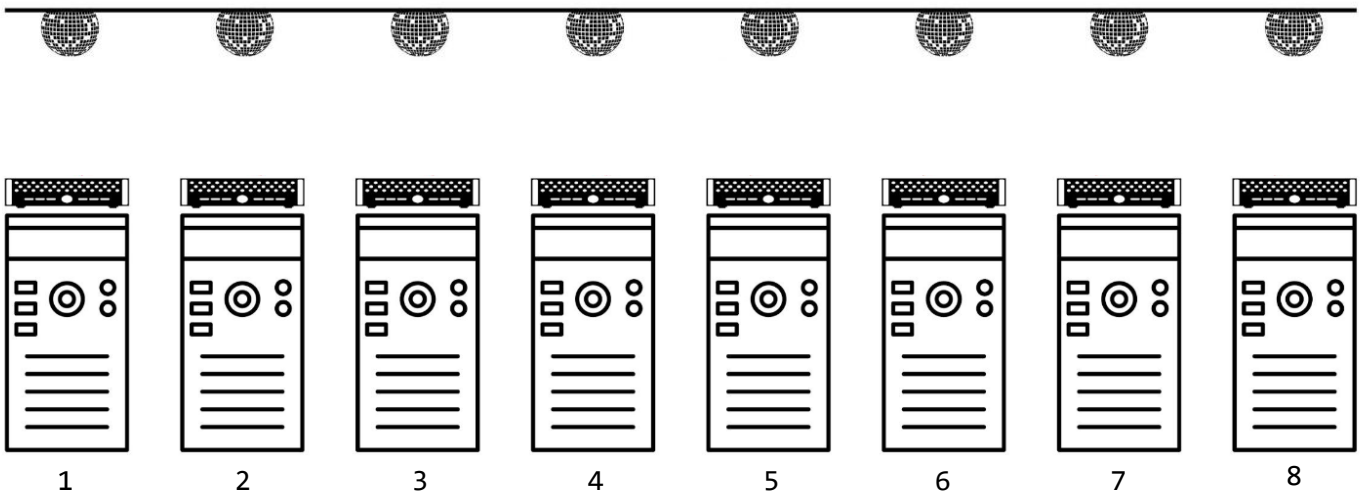


A Vision

Flexible and Demand-Aware Topologies

demand matrix:



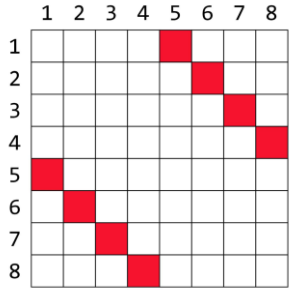


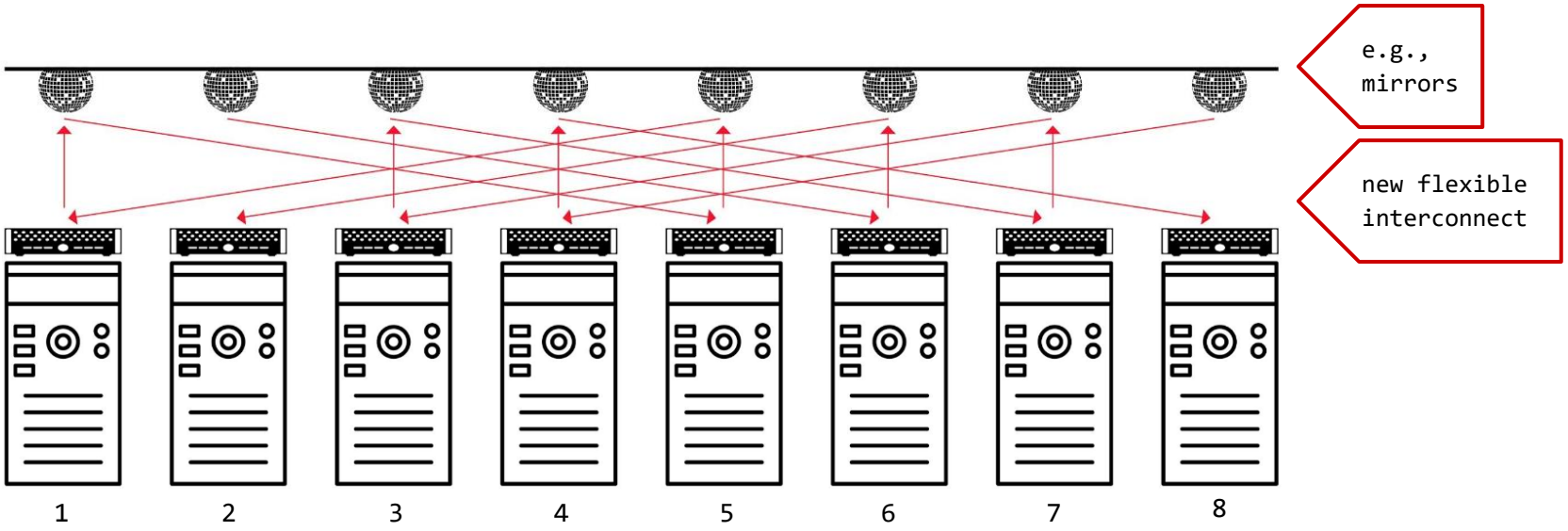
A Vision

Flexible and Demand-Aware Topologies

Matches demand

demand matrix:

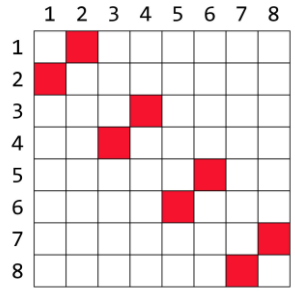


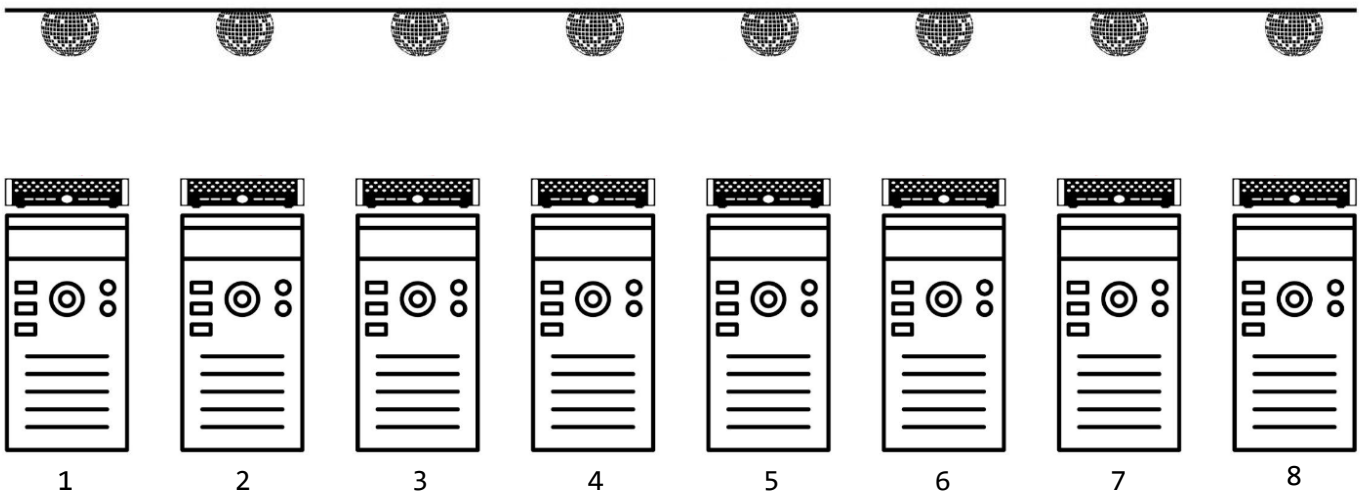


A Vision

Flexible and Demand-Aware Topologies

new demand:



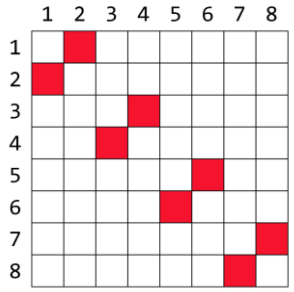


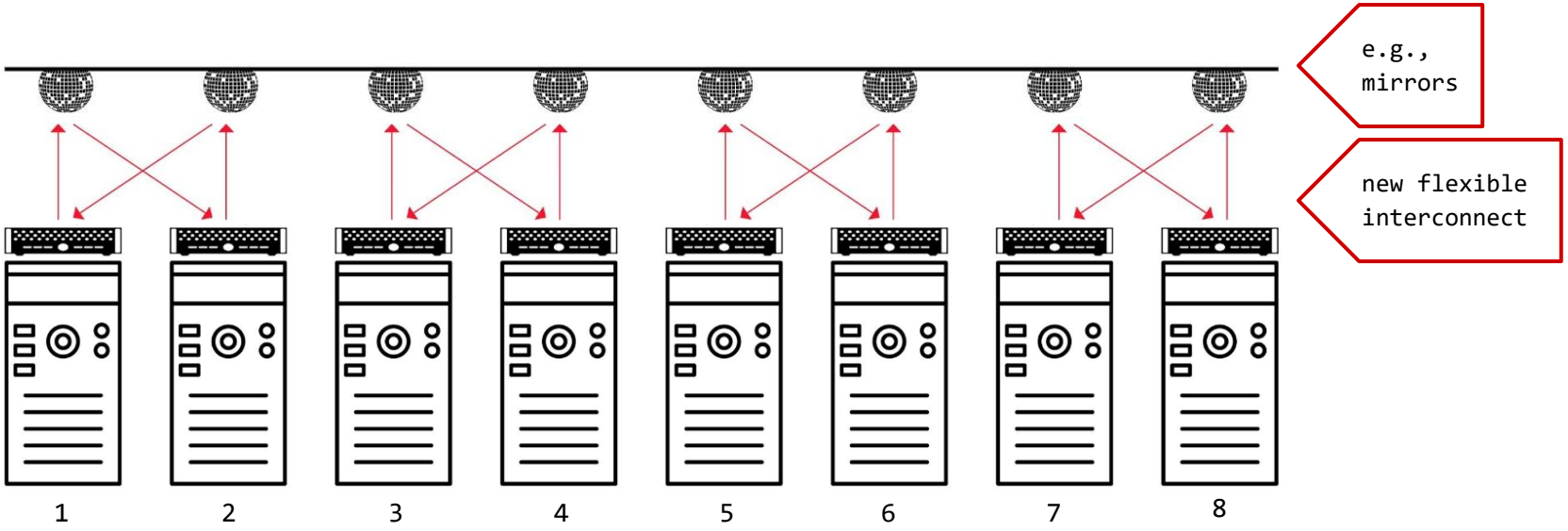
A Vision

Flexible and Demand-Aware Topologies

Matches demand

new demand:



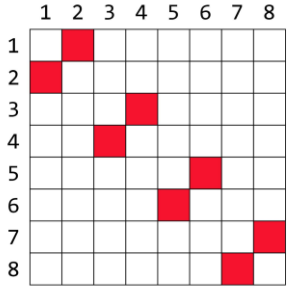


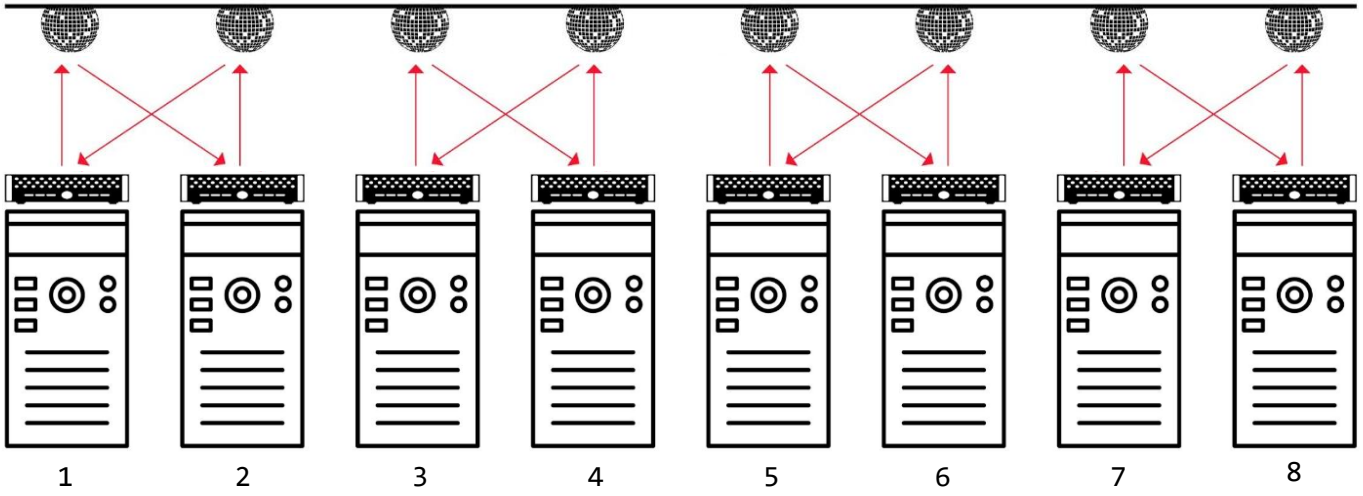
A Vision

Flexible and Demand-Aware Topologies

Self-Adjusting Networks

new demand:



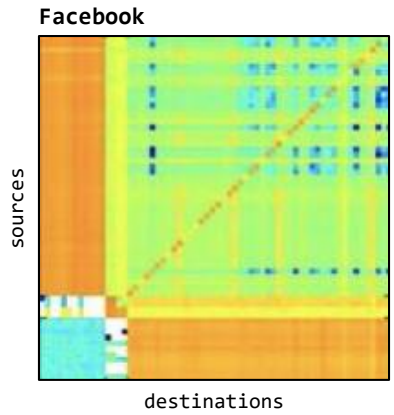


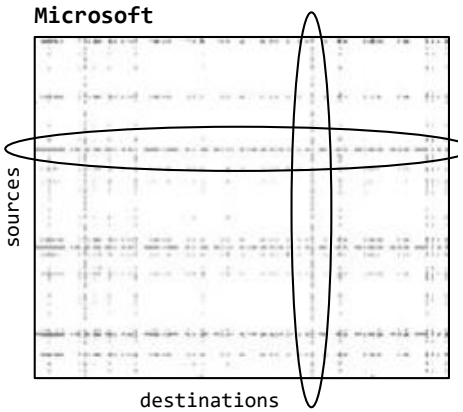
The Motivation

Much Structure in the Demand

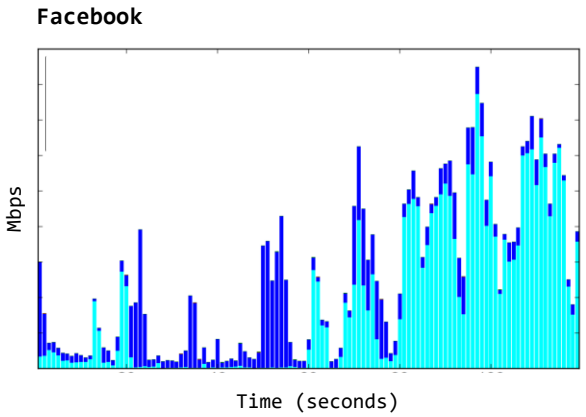
Empirical studies:

traffic matrices sparse and skewed



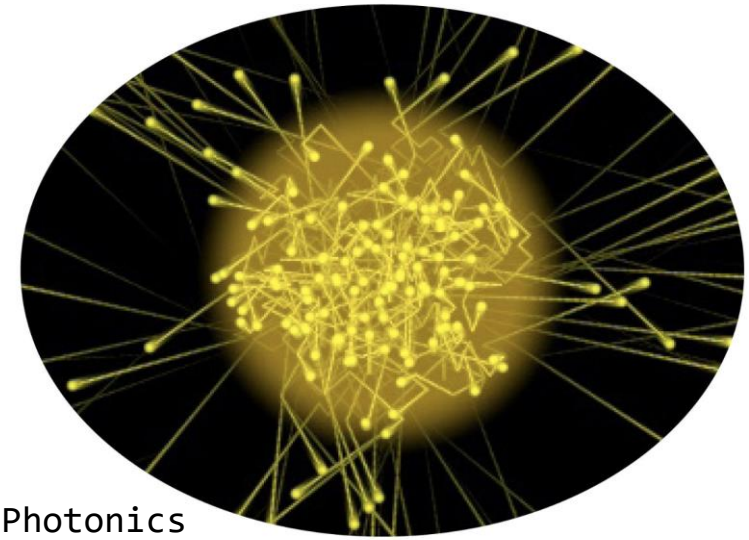


traffic bursty over time



Our hypothesis: can be exploited.

Sounds Crazy? Emerging Enabling Technology.



Photonics

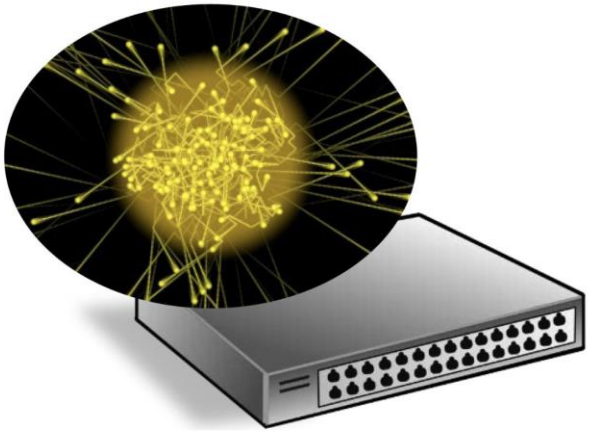
H2020:
“Photonics one of only five key enabling technologies for future prosperity.”

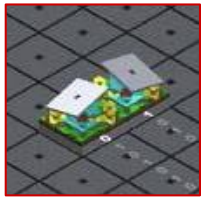
US National Research Council:
“Photons are the new Electrons.”

Enabler

Novel Reconfigurable Optical Switches

- **Spectrum** of prototypes
  - Different sizes, different reconfiguration times
  - From our last years' ACM **SIGCOMM** workshop OptSys





Prototype 1

Prototype 2

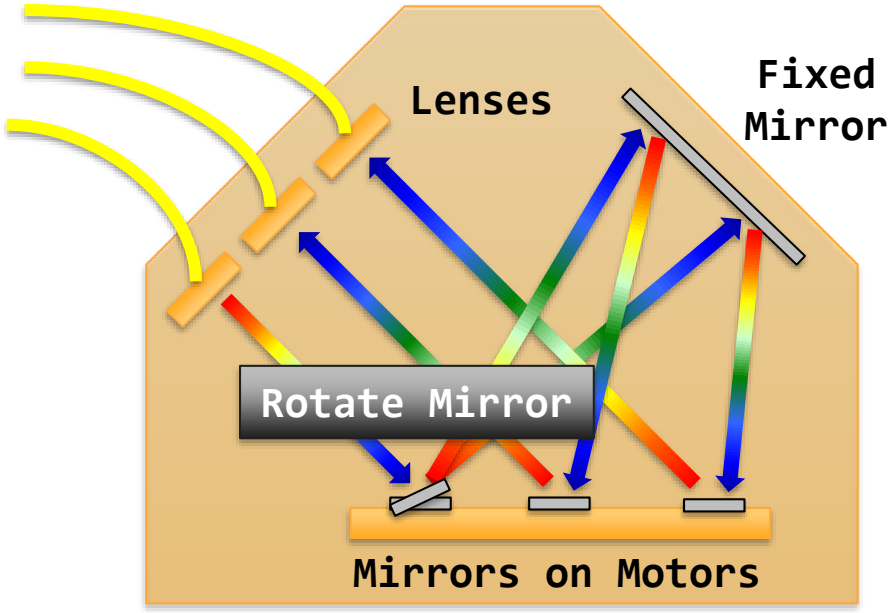
Prototype 3

Example

Optical Circuit Switch

⇢ Optical Circuit Switch rapid adaption of physical layer

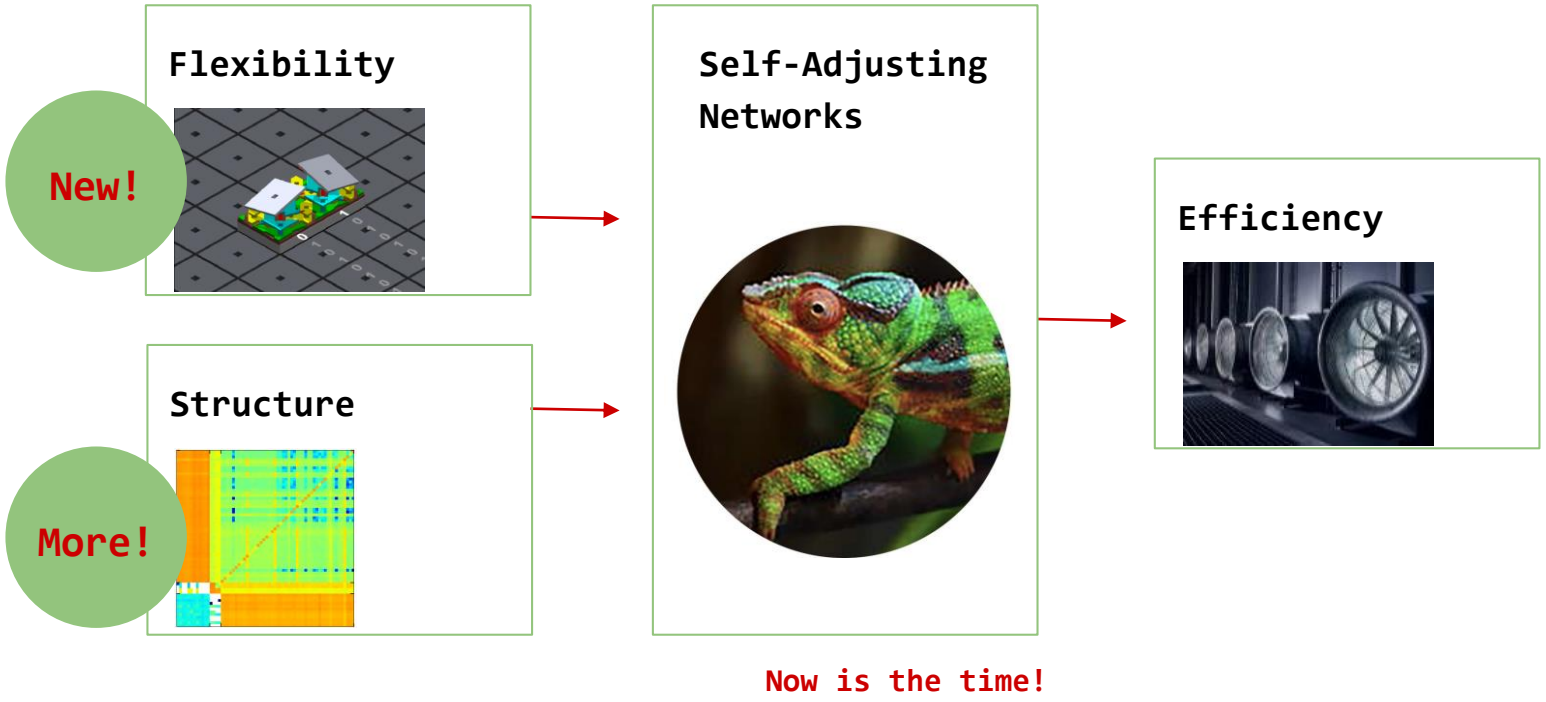
→ Based on rotating mirrors



Optical Circuit Switch

By Nathan Farrington, SIGCOMM 2010

The Big Picture



Unique Position

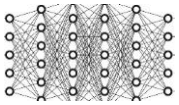
Demand-Aware, Self-Adjusting Systems

Everywhere, but mainly in software

Algorithmic trading

NETFLIX

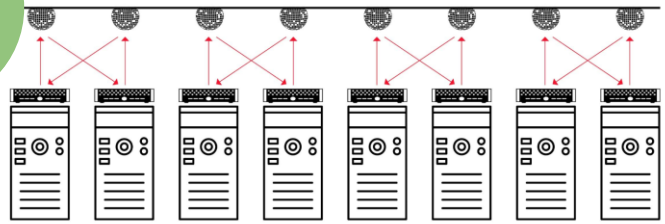
Recommender systems



Neural networks

VS

Our focus: in hardware

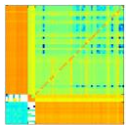


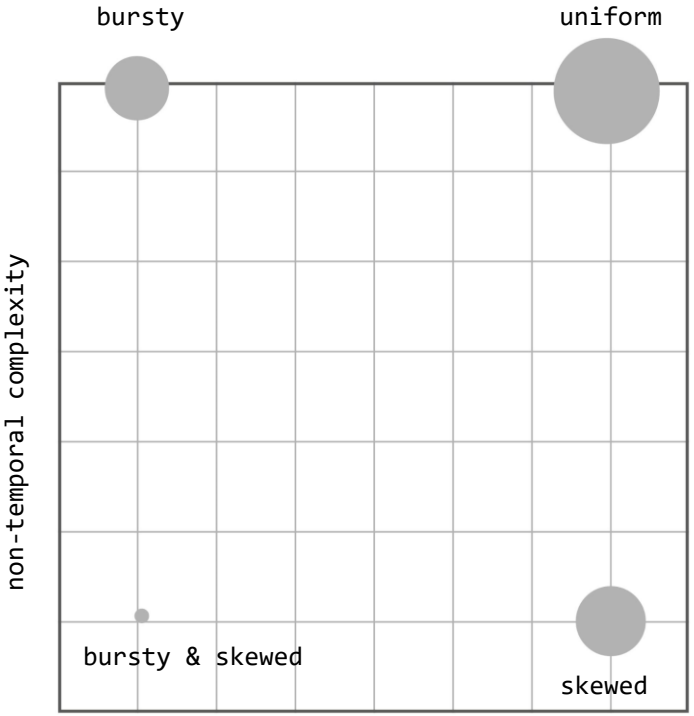
Question 1:

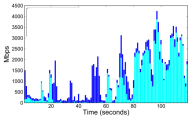
How to Quantify such “Structure” in the Demand?

An Information-Theoretic Approach

Complexity Map



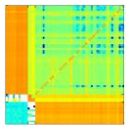


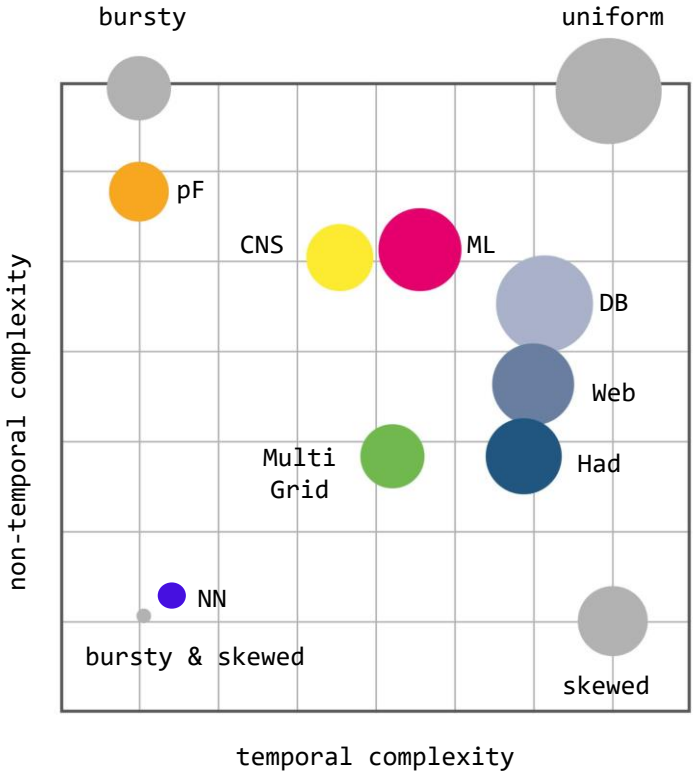


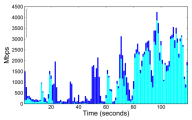
Our **approach**: iterative **randomization and compression** of trace to identify dimensions of structure.

An Information-Theoretic Approach

Complexity Map





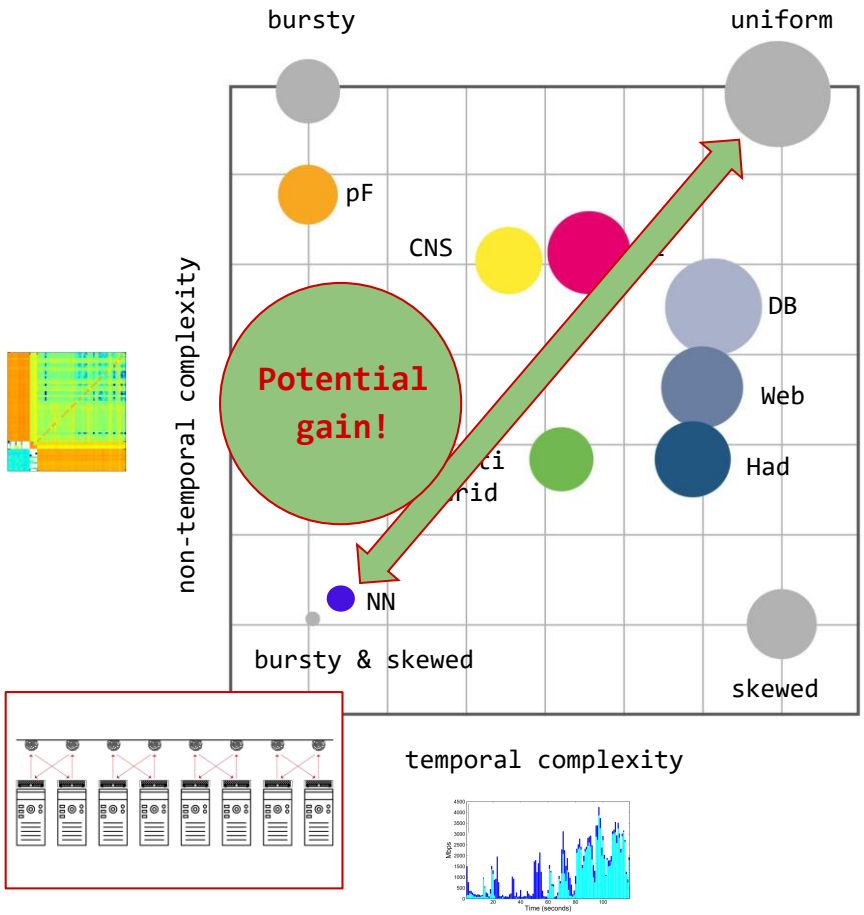


Our **approach**: iterative **randomization and compression** of trace to identify dimensions of structure.

Different structures!

An Information-Theoretic Approach

Complexity Map



Our **approach**: iterative **randomization and compression** of trace to identify dimensions of structure.

Question 2:

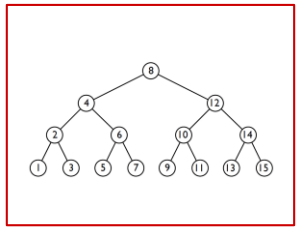
Given This Structure, What Can Be Achieved? Metrics and Algorithms?

A first insight: entropy of the demand.

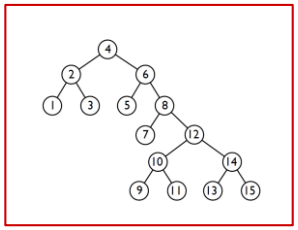
Our Approach:

Connection to Datastructures

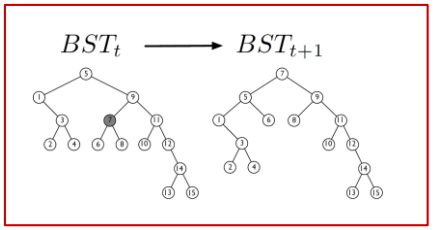
Traditional BST



Demand-aware BST



Self-adjusting BST

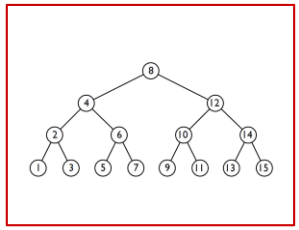


More structure: improved **access cost**

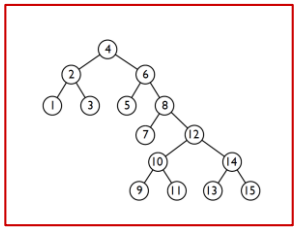
Our Approach:

Connection to Datastructures & Coding

Traditional BST
(Worst-case coding)



Demand-aware BST
(Huffman coding)



Self-adjusting BST
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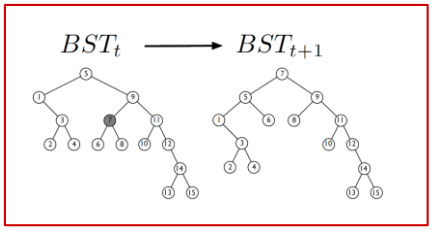

More structure: improved **access cost** / shorter **codes**

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Connection to Datastructures & Coding

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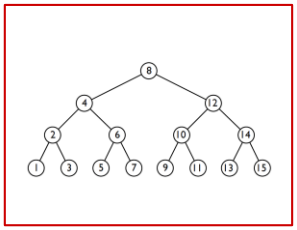

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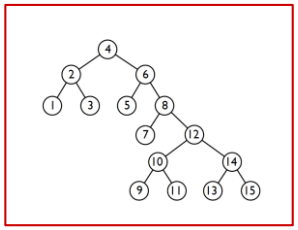

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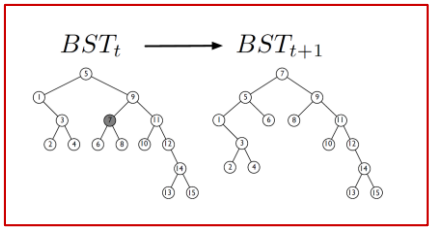

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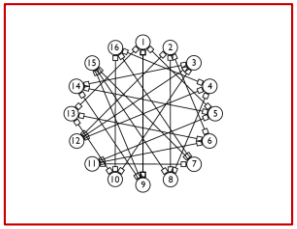
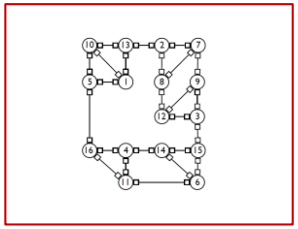
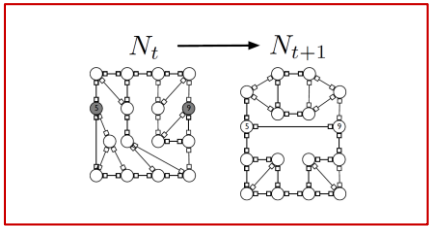




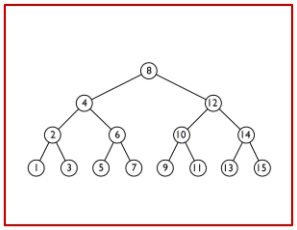


Similar **benefits**?

Our Approach:

Connection to Datastructures & Coding

Traditional BST
(Worst-case coding)



Demand-aware BST
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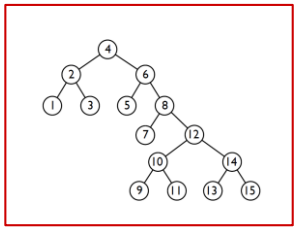

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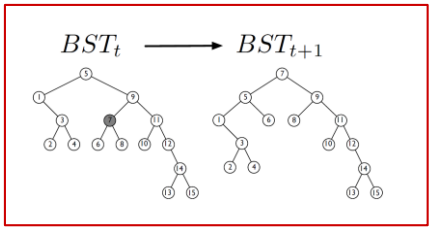
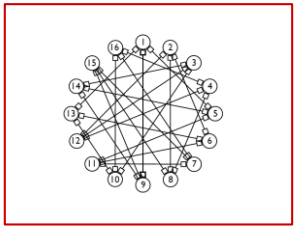
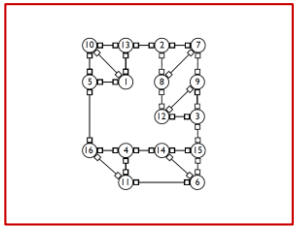
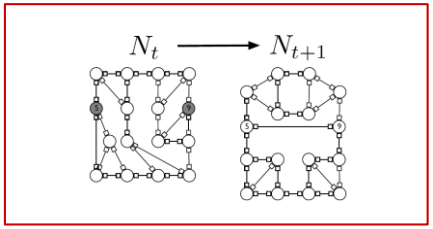


More than an analogy!

More structure: improved **access cost** / shorter **codes**







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Connection to Datastructures & Coding

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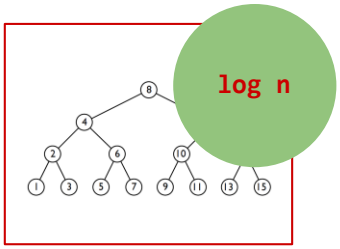
(Worst-case coding)



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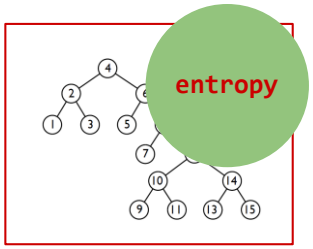
(Huffman coding)



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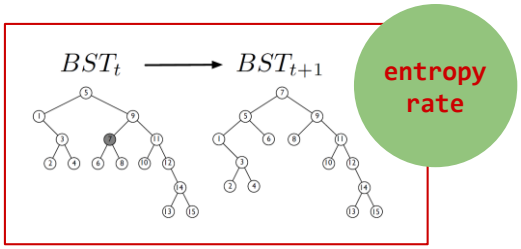
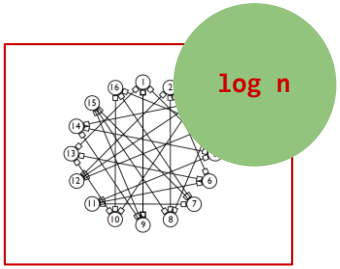
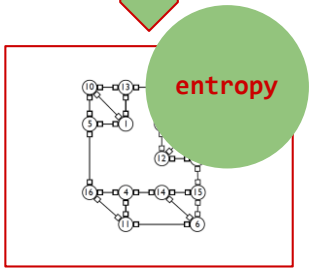
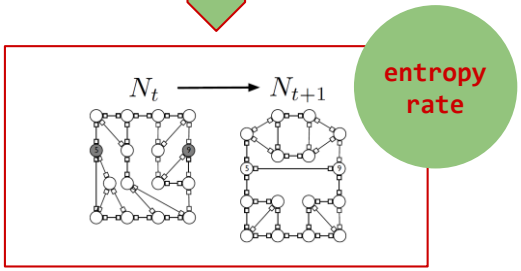








Reduced expected **route lengths**!

More than an analogy!

Generalize methodology:
... and transfer entropy bounds and algorithms of data-structures to networks.

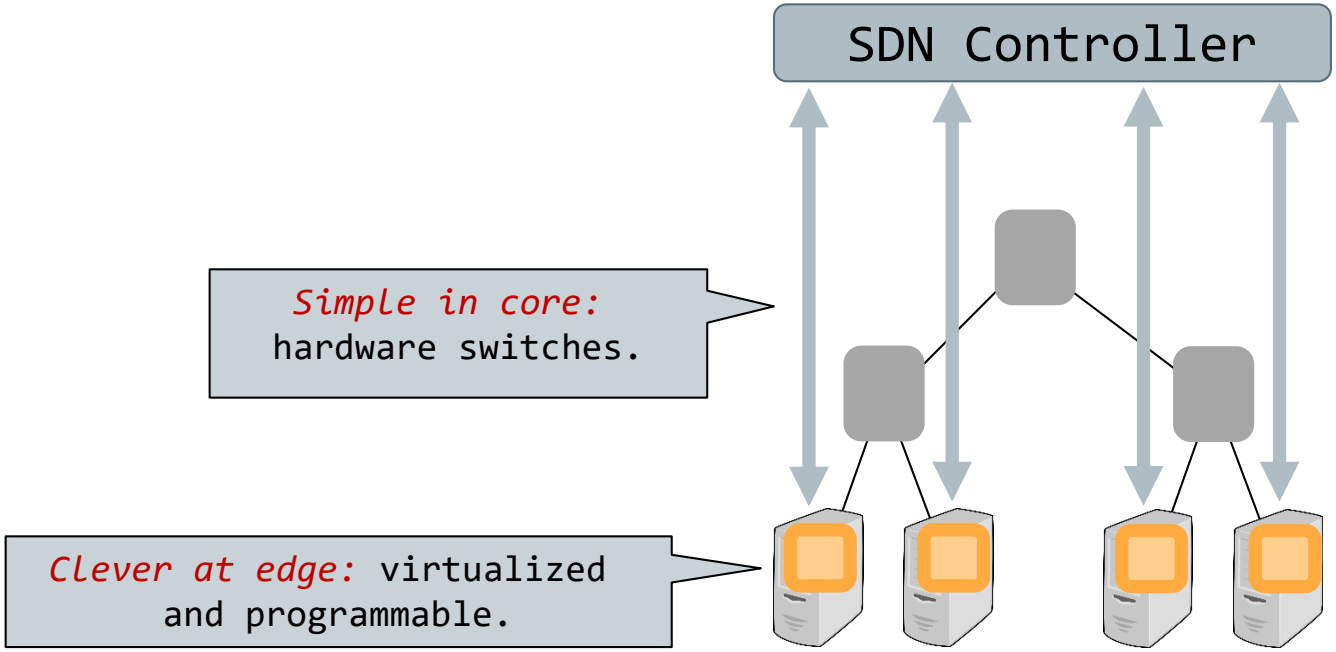
Results, e.g.:
Demand-aware networks of asymptotically optimal route lengths.

Challenges of Software-Defined and Self-Driving Networks

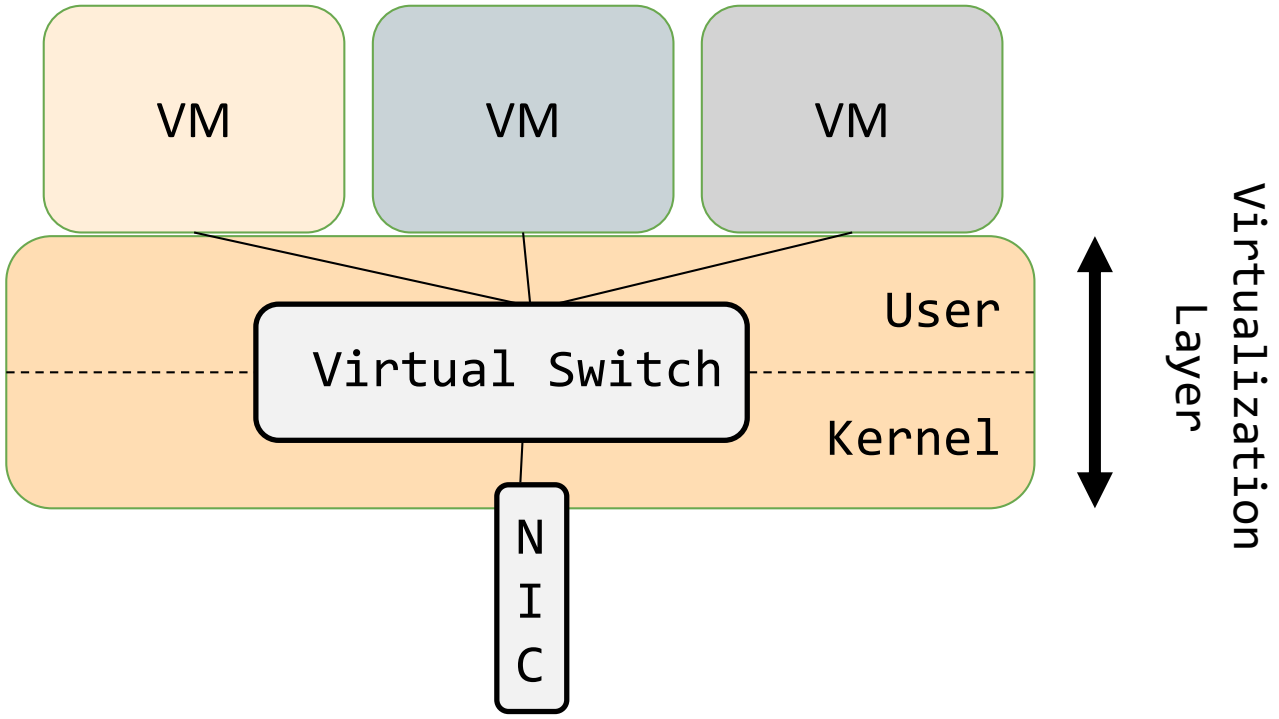
Example: Security

⇢ Trend: SDN deployed "*in software*"

⇢ E.g., virtual switches in datacenters



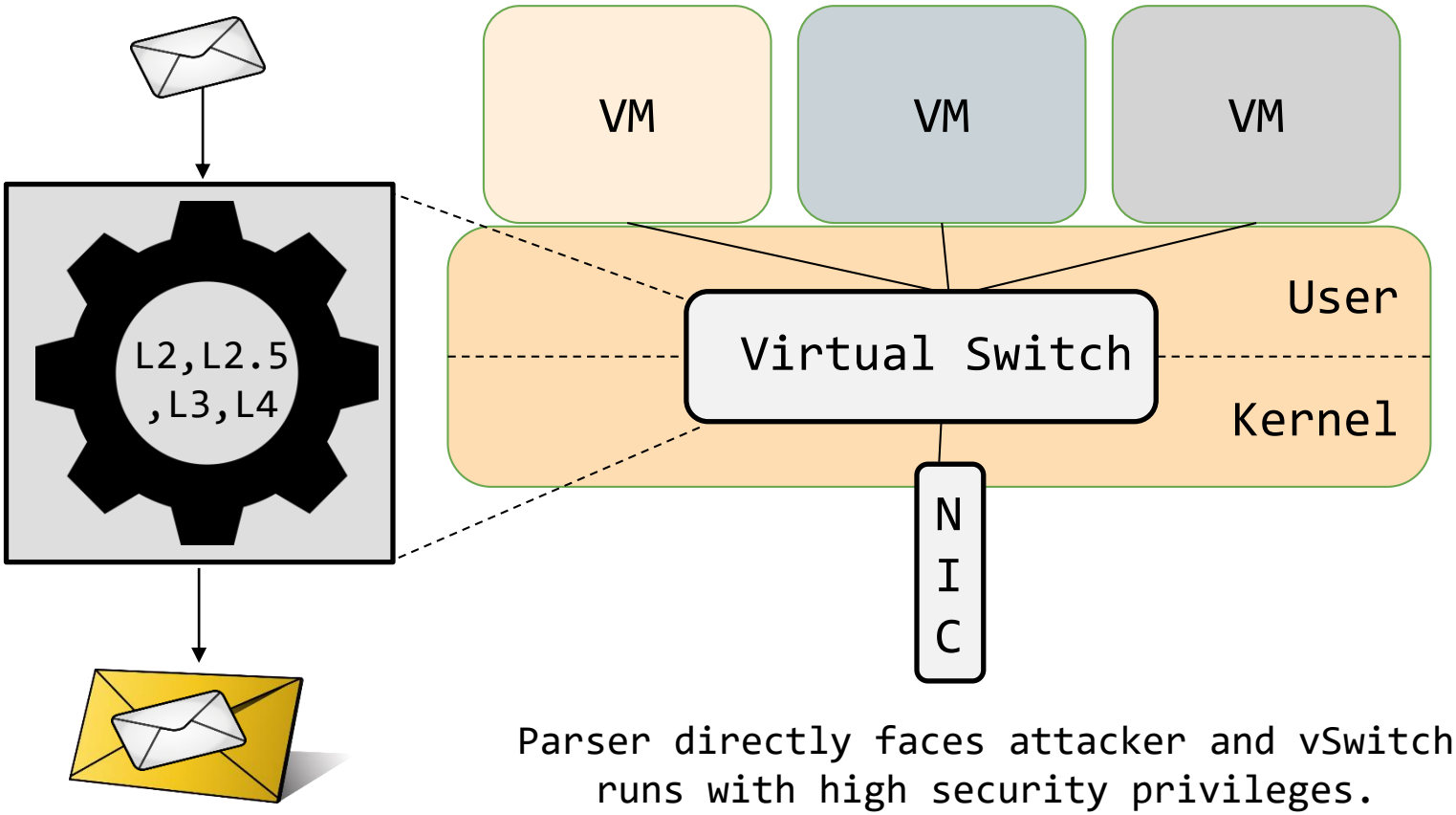
Virtual Switches



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

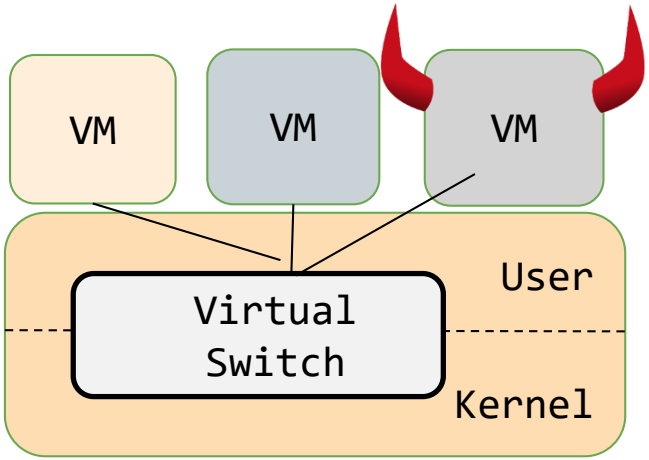
Complexity: Parsing

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



Parser directly faces attacker and vSwitch runs with high security privileges.

Bears Risks!



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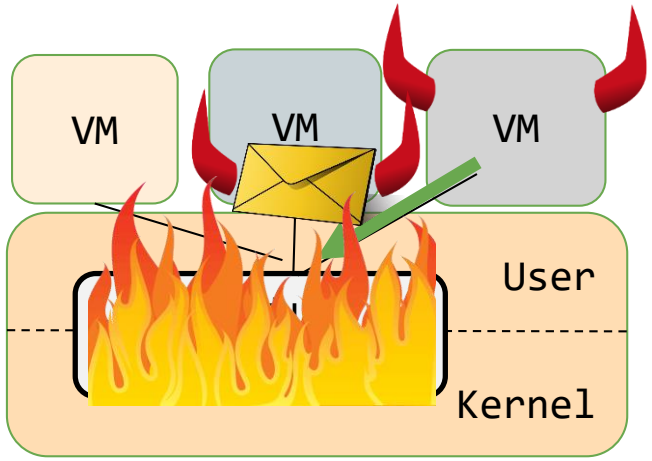

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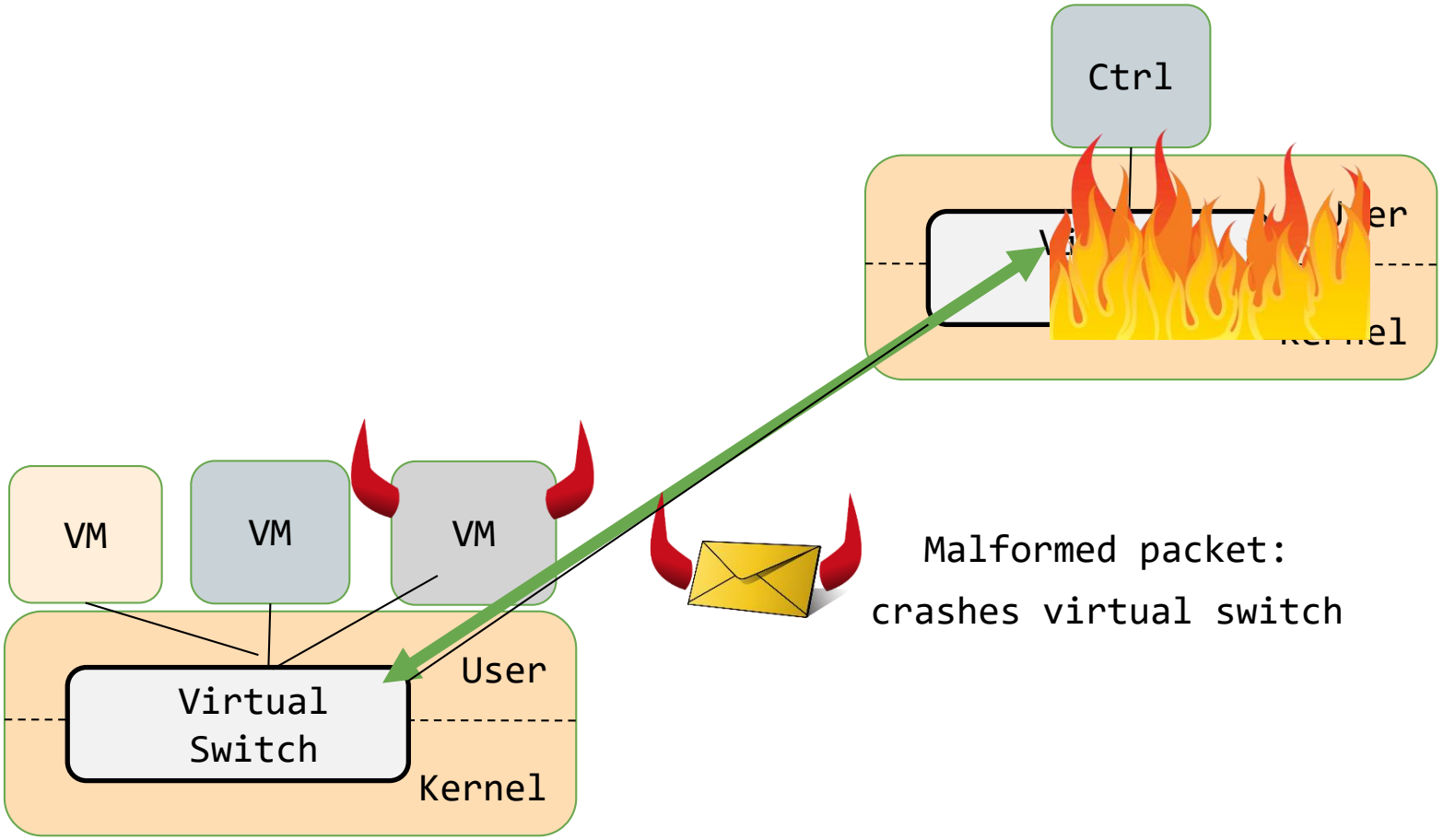
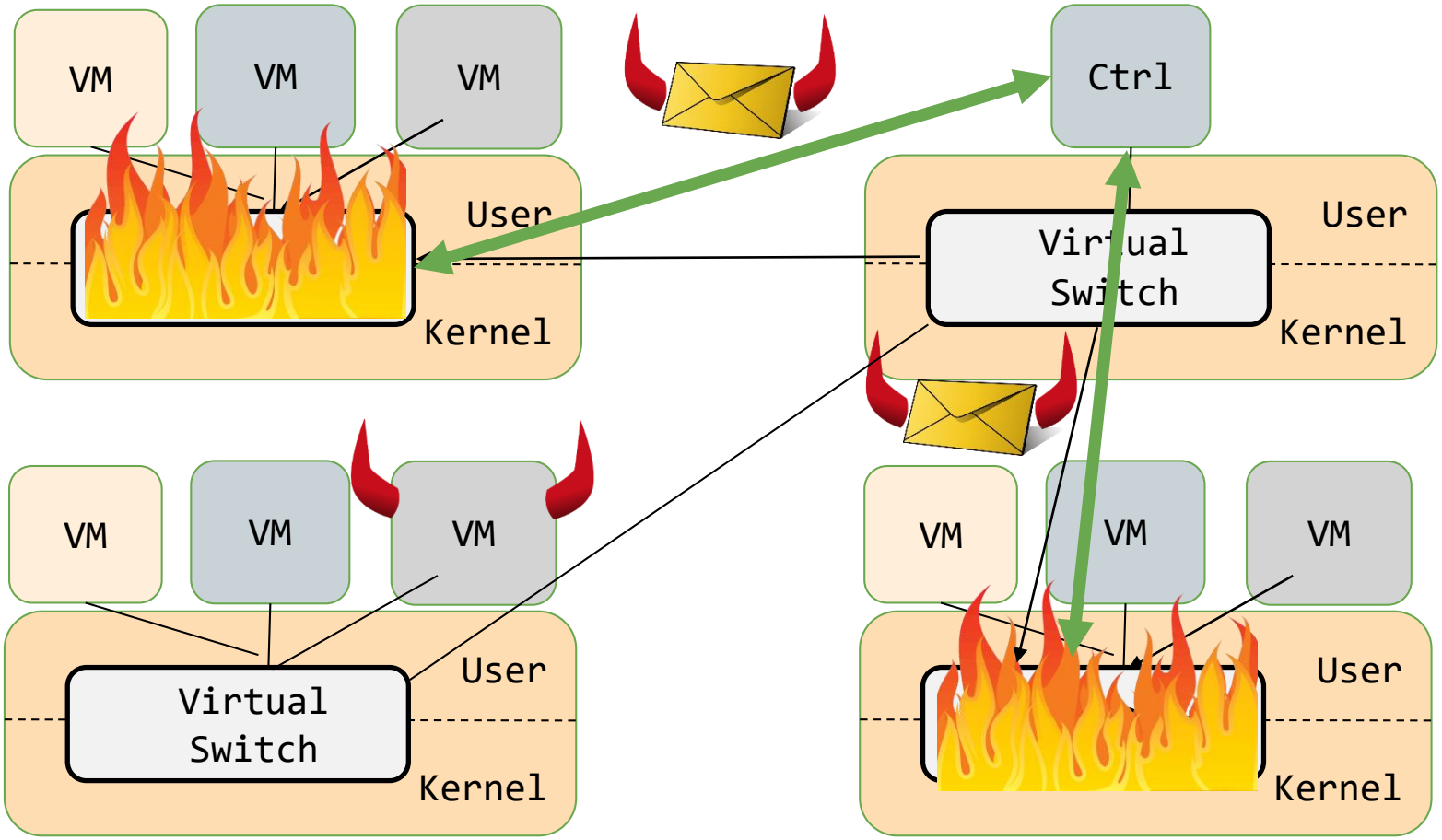

Ctrl
VM
VM
VM
User
Virtual
Switch
Kernel
Malformed packet:
crashes virtual switch

Bears Risks!


VM
VM
VM
User
Kernel
Ctrl
User
Virtual Switch
Kernel
VM
VM
VM
User
Virtual Switch
Kernel
VM
VM
VM
User
Kernel

Limits of Automation?

⇢ What should not or cannot be automated?

⇢ Can networks detect themselves, when the need “help from the operator”?

Conclusion

⇢ A vision: self-driving networks

⇢ Example 1: policy-compliant networks

- ⇀ self-verifying
- ⇀ self-repairing

⇢ Example 2: demand-aware topologies

⇢ On both fronts: tip of the iceberg!

⇀ E.g., self-adjusting networks further supported by telemetry (data) and AI (e.g., prediction)

Thank you!

References

AalWiNes: A Fast and Quantitative What-If Analysis Tool for MPLS Networks
Peter Gjøl Jensen, Morten Konggaard, Dan Kristiansen, Stefan Schmid, Bernhard Clemens Schrenk, and Jiri Srba.
16th ACM International Conference on emerging Networking EXperiments and Technologies (**CoNEXT**), Barcelona, Spain, December 2020.

Latte: Improving the Latency of Transiently Consistent Network Update Schedules
Mark Glavind, Niels Christensen, Jiri Srba, and Stefan Schmid.
38th International Symposium on Computer Performance, Modeling, Measurements and Evaluation (**PERFORMANCE**) and ACM Performance Evaluation Review (**PER**), Milan, Italy, November 2020.

On the Complexity of Traffic Traces and Implications
Chen Avin, Manya Ghobadi, Chen Griner, and Stefan Schmid.
ACM **SIGMETRICS** and ACM Performance Evaluation Review (**PER**), Boston, Massachusetts, USA, June 2020.

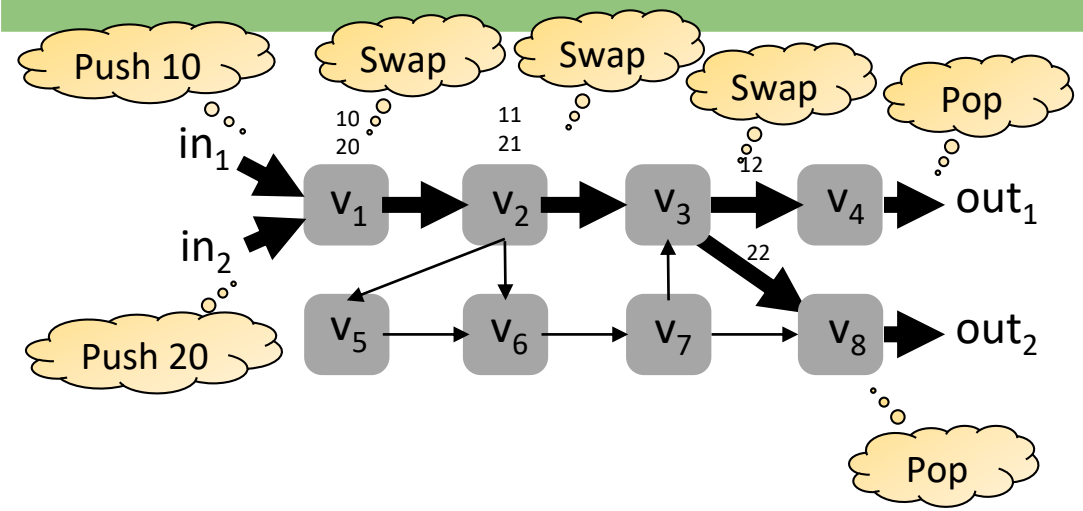
Toward Demand-Aware Networking: A Theory for Self-Adjusting Networks (Editorial)
Chen Avin and Stefan Schmid.
ACM SIGCOMM Computer Communication Review (**CCR**), October 2018.

Taking Control of SDN-based Cloud Systems via the Data Plane (Best Paper Award)
Kashyap Thimmaraju, Bhargava Shastry, Tobias Fiebig, Felicitas Hetzelt, Jean-Pierre Seifert, Anja Feldmann, and Stefan Schmid.
ACM Symposium on SDN Research (**SOSR**), Los Angeles, California, USA, March 2018.

Backup Slides

Case Study:

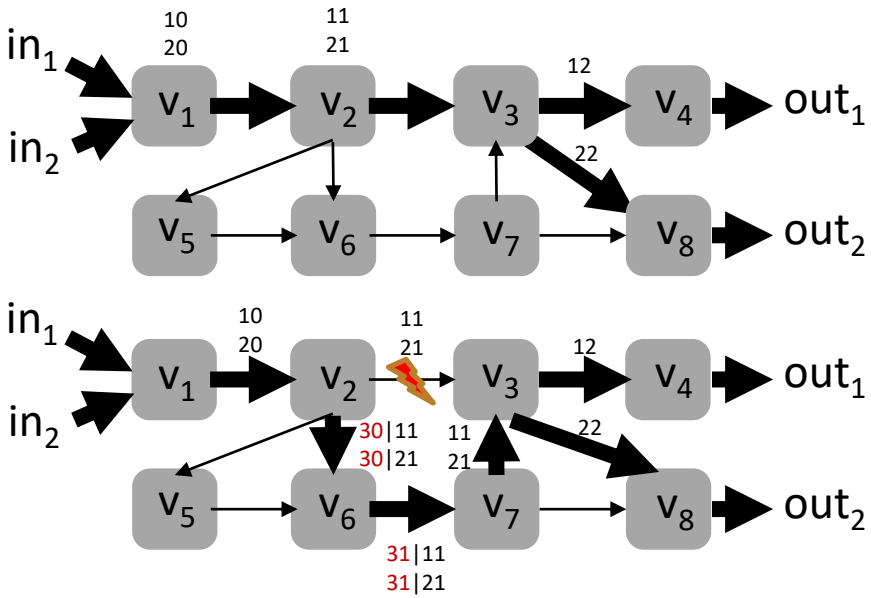
MPLS Networks



Original Routing

Case Study:

MPLS Networks

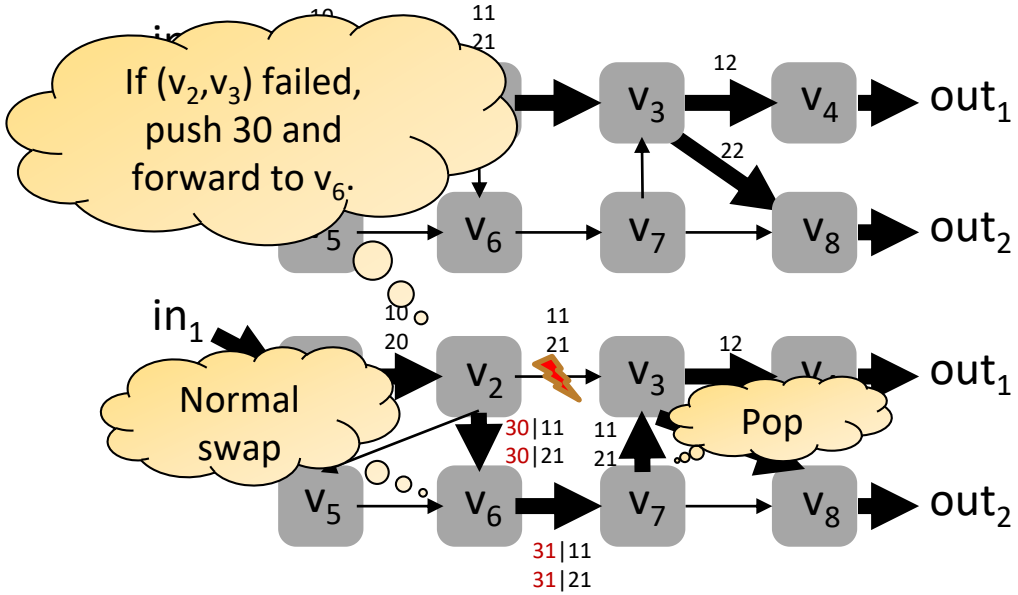


Original Routing

One failure: push 30: route around (v_2, v_3)

Case Study:

MPLS Networks



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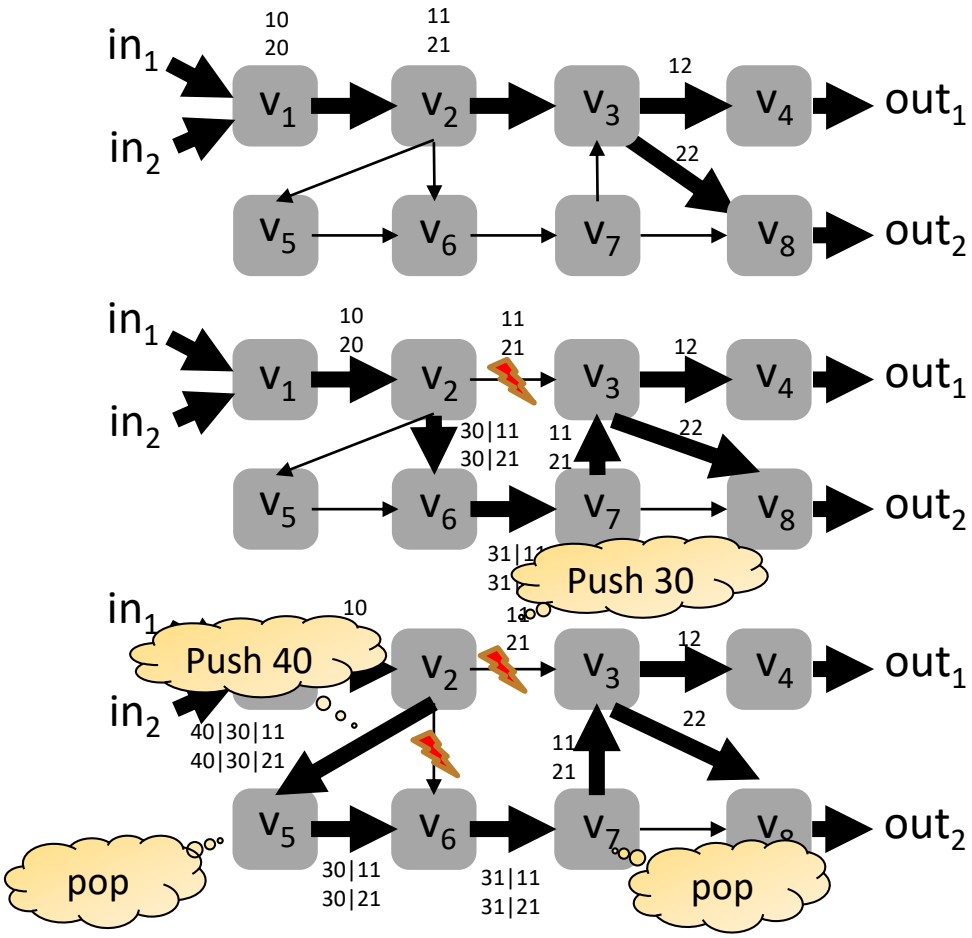


Original Routing

One failure: push 30: route around (v_2,v_3)

Two failures: first push 30: route around (v_2,v_3)

Push recursively

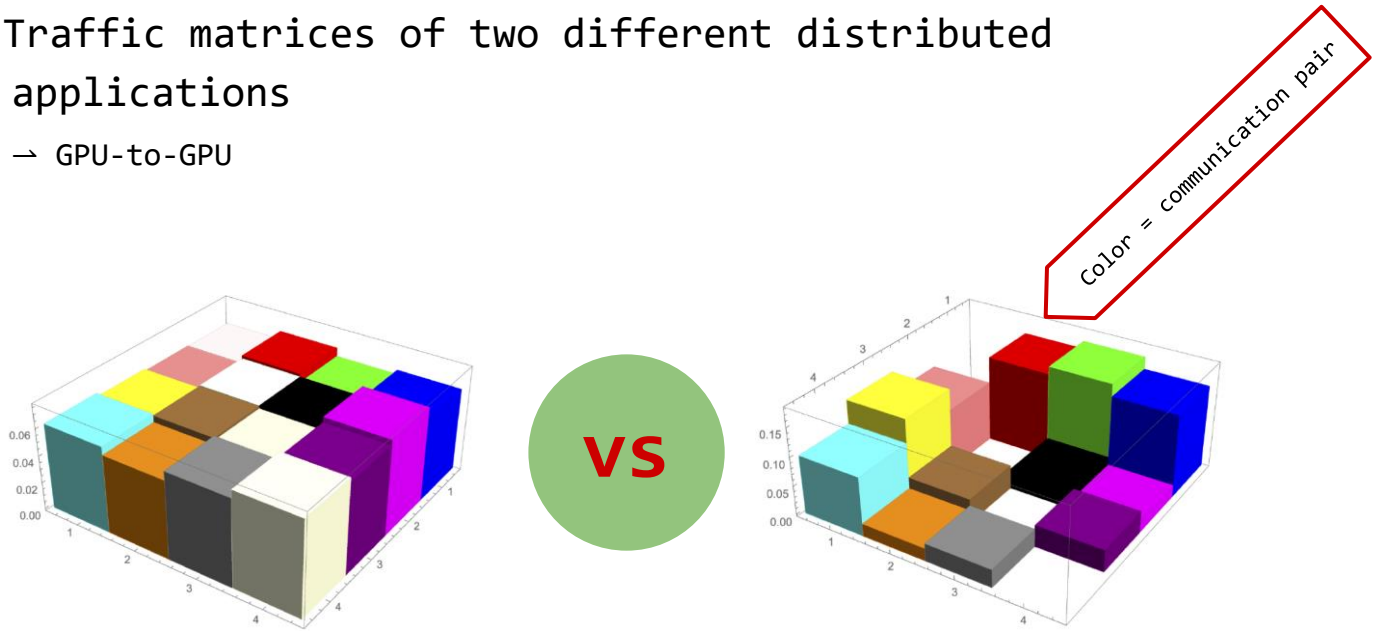
40: route around (v_2,v_6)

Intuition

Which demand has more structure?

⇢ Traffic matrices of two different distributed ML applications

→ GPU-to-GPU



Intuition

Which demand has more structure?

⇢ Traffic matrices of two different distributed ML applications

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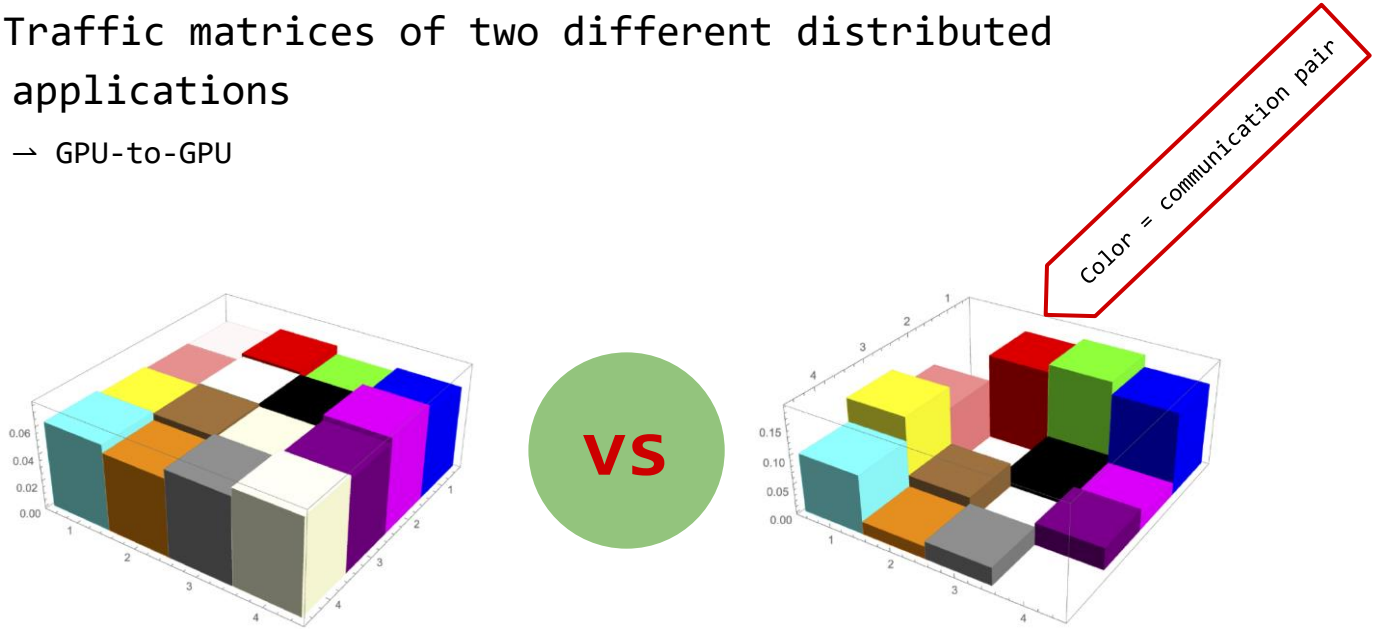


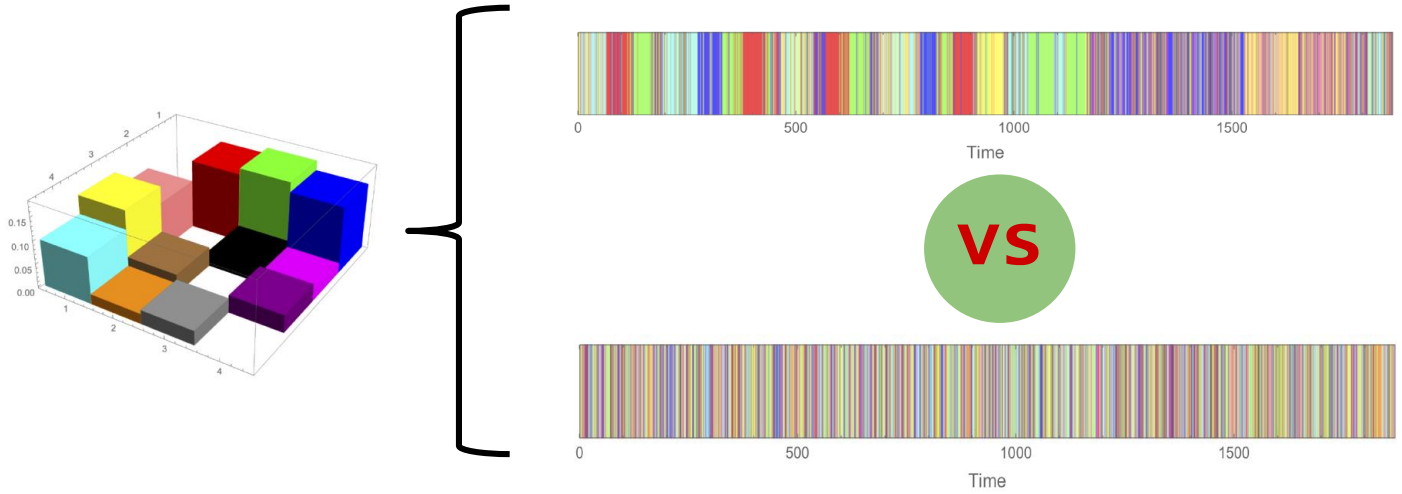
More uniform **More structure**

Intuition

Spatial vs temporal structure

⇢ Two different ways to generate same traffic matrix:
  ⇀ Same non-temporal structure

⇢ Which one has more structure?



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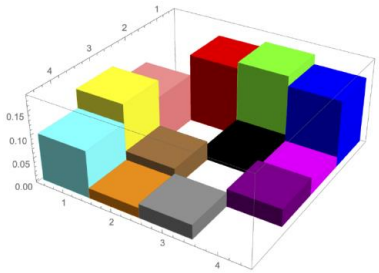
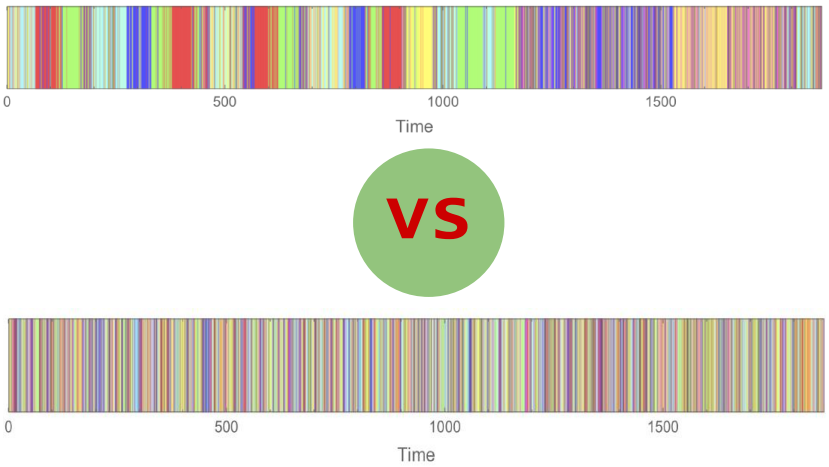


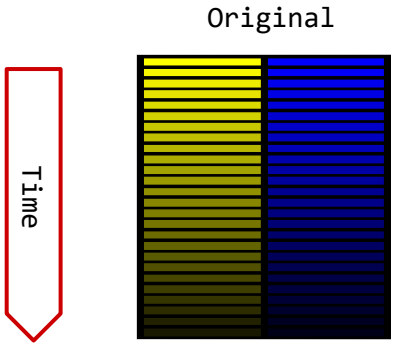


Systematically?

Trace Complexity

Information-Theoretic Approach

“Shuffle&Compress”



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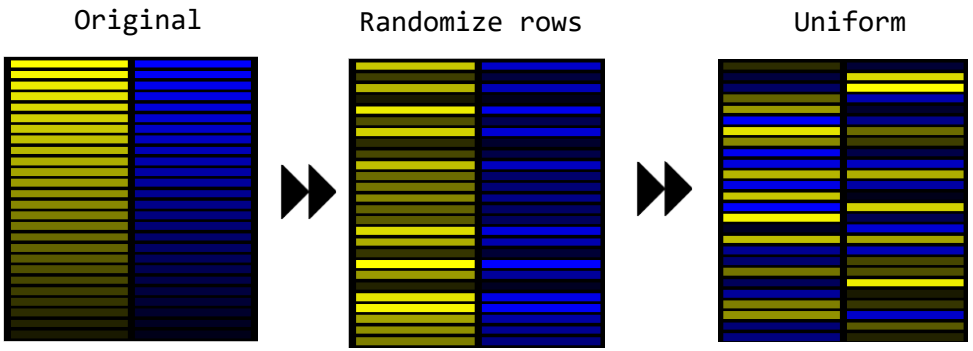
“Shuffle&Compress”



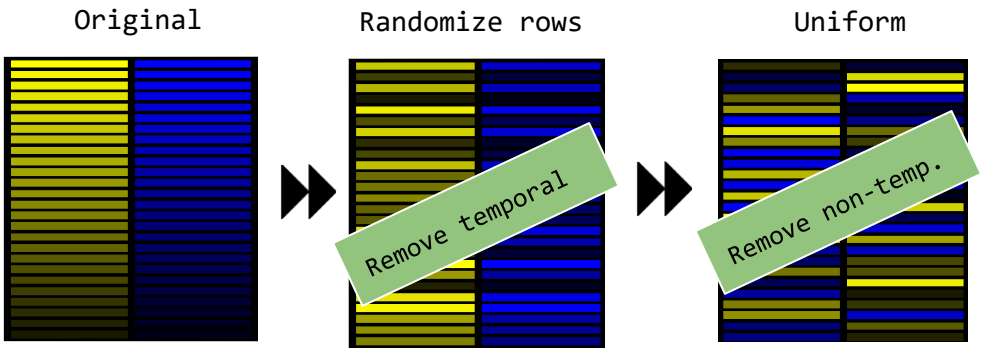
Increasing complexity (systematically randomized)

More structure (compresses better)

Trace Complexity

Information-Theoretic Approach

“Shuffle&Compress”



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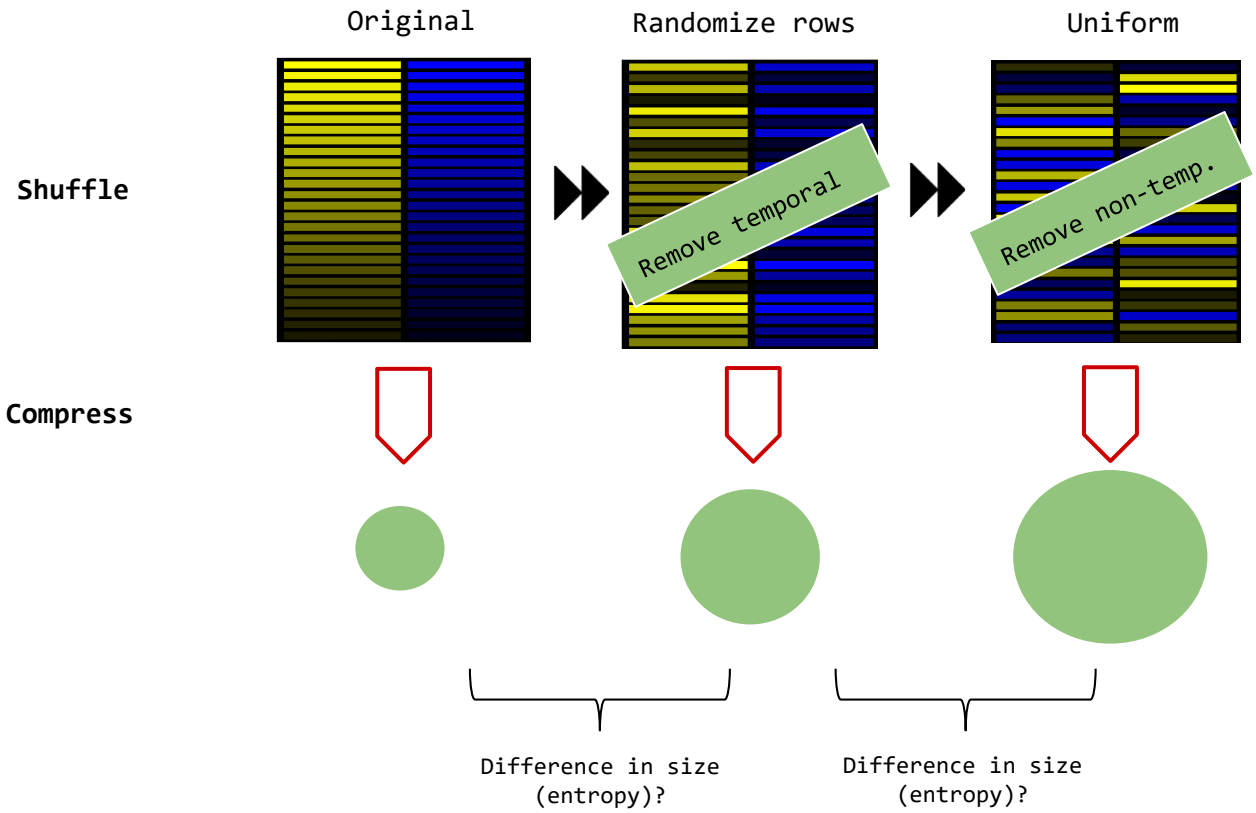
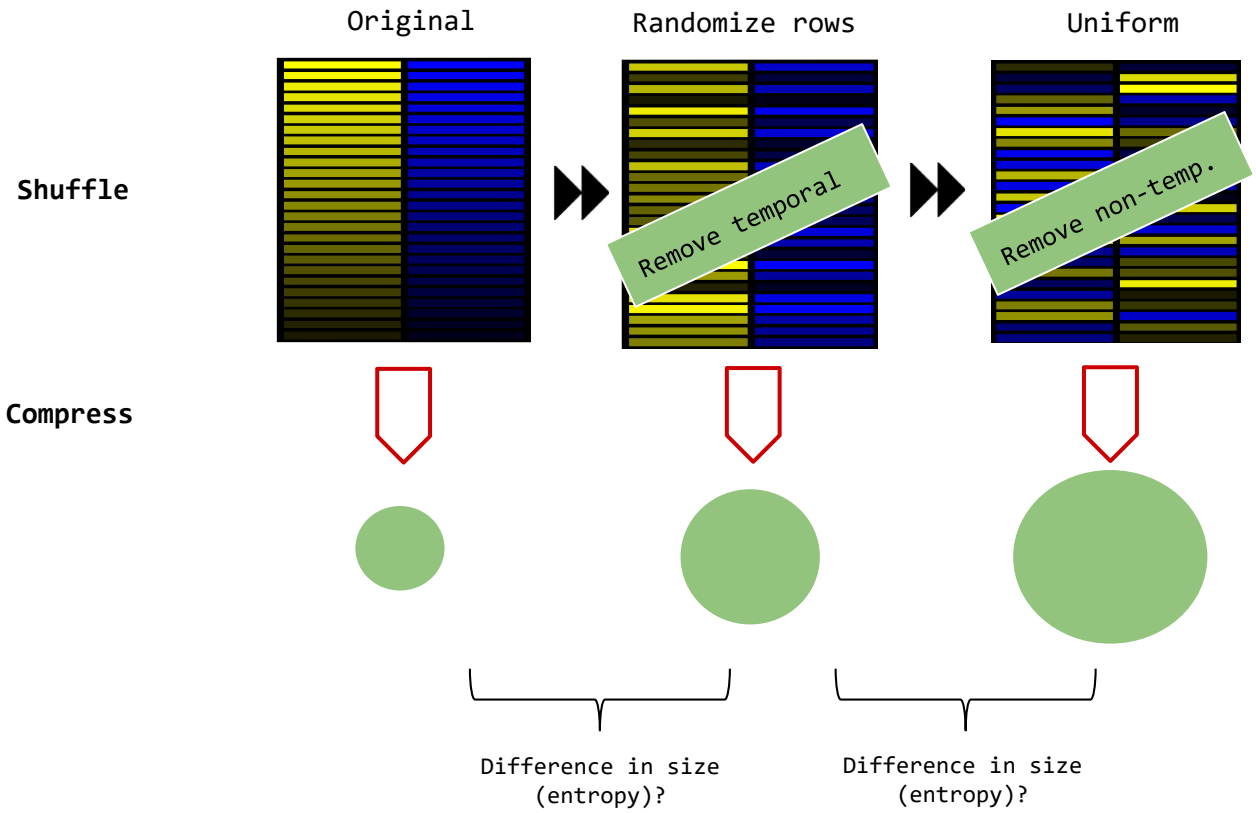


Trace Complexity

Information-Theoretic Approach

“Shuffle&Compress”

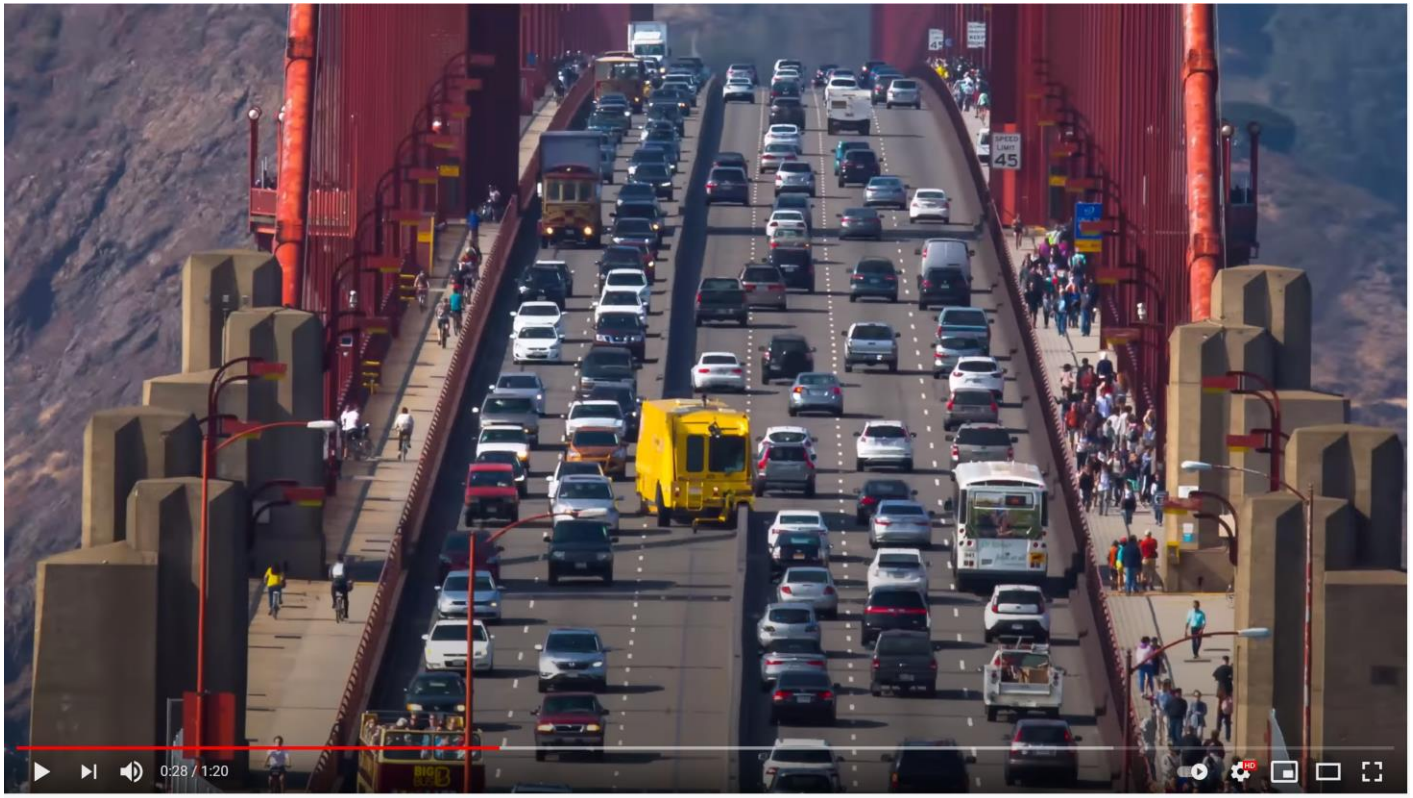


Can be used to define 2-dimensional complexity map!

Bonus Material

Hogwarts Stair

Bonus Material



Golden Gate Zipper

Bonus Material

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Reconfigurable Optical Networks Will Move Supercomputer Data 100X Faster

Newly designed HPC network cards and software that reshapes topologies on-the-fly will be key to success

By **Michelle Hampson**

Photo illustration: Shutterstock

In HPC