Toward Self-* Networks

Stefan Schmid (Uni Vienna)

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

Passau, Germany

Inn, Donau, Ilz

Flexibilities: Along 3 Dimensions

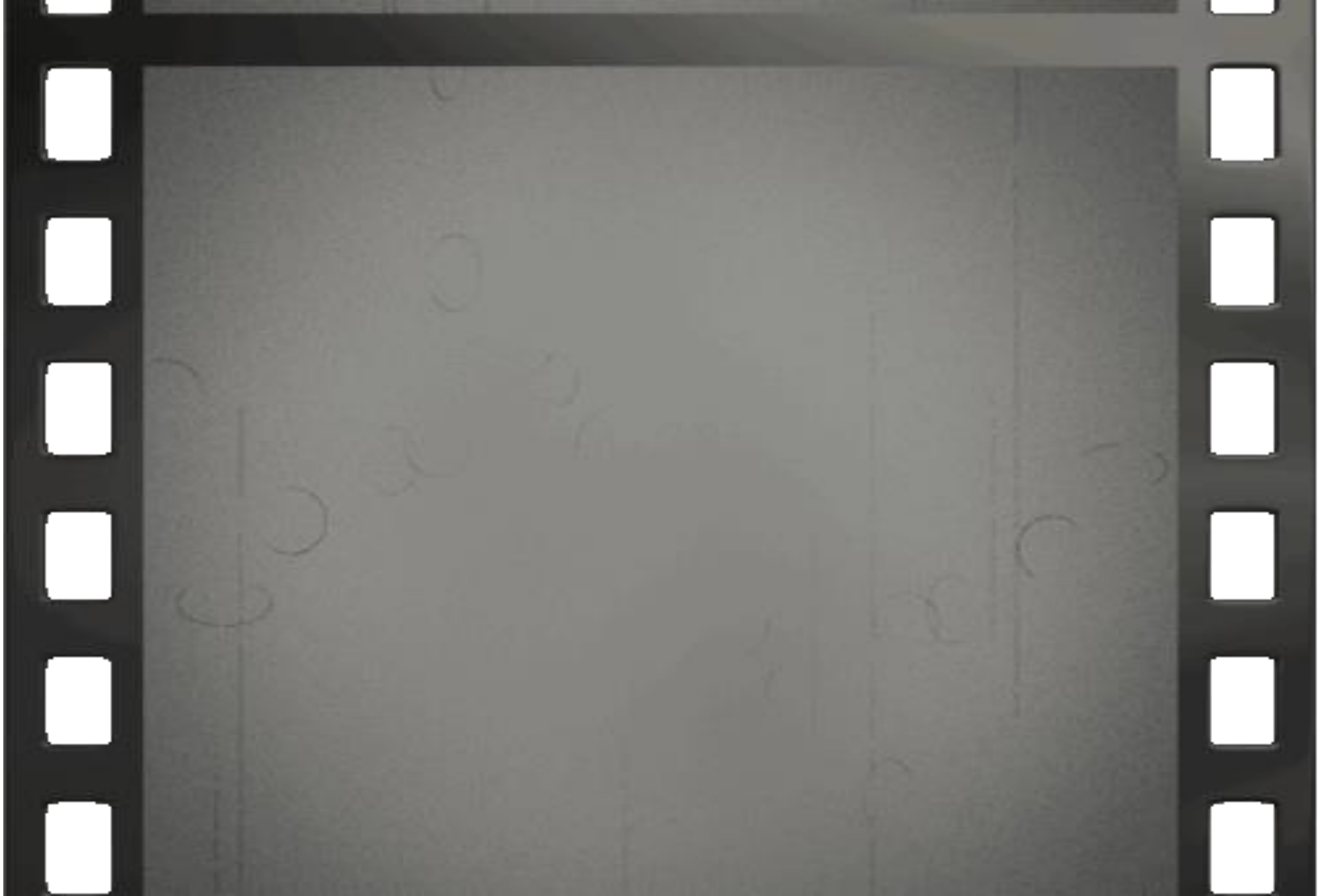
Enabler: SDN

Enabler: Virtualization

Enabler: Optics

u, Germany

Inn, Donau, Ilz



Rewinding the clock of the Internet…

Shortest path routing only

Indirect control: via weights only

Proprietary, blackbox implementations

Difficult and slow innovation

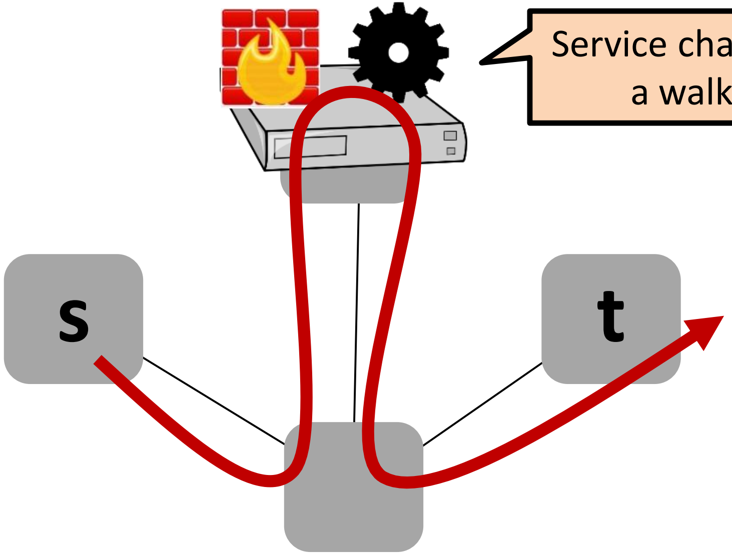
Kudos to: Pedro Casas

Opportunity: Flexible Routing

- **Direct control** over paths
  - Traditionally: indirect control ***via weights*** based on which ***shortest paths*** are computed

- More **general routes**
  - Beyond shortest paths, even ***beyond „paths“***
  - E.g., steer traffic through (virtualized) middleboxes to compose new services like ***service chains*** („**walk**“)

- General **match-action**
  - SDN allows to match ***L2-L4*** and route, e.g., HTTP traffic differently (e.g., to cache)

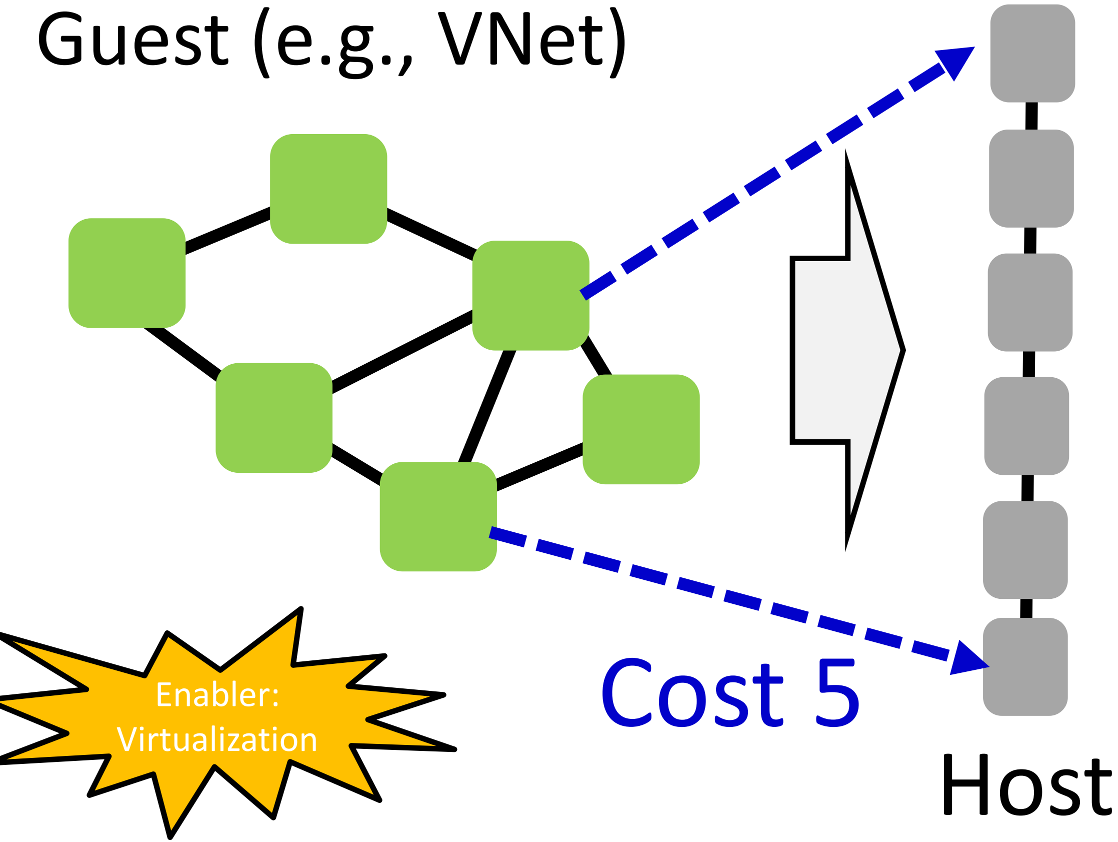


Service chaining: a walk!

Enabler: SDN

Charting the Algorithmic Complexity of Waypoint Routing. Amiri et al. ACM SIGCOMM CCR, 2018.

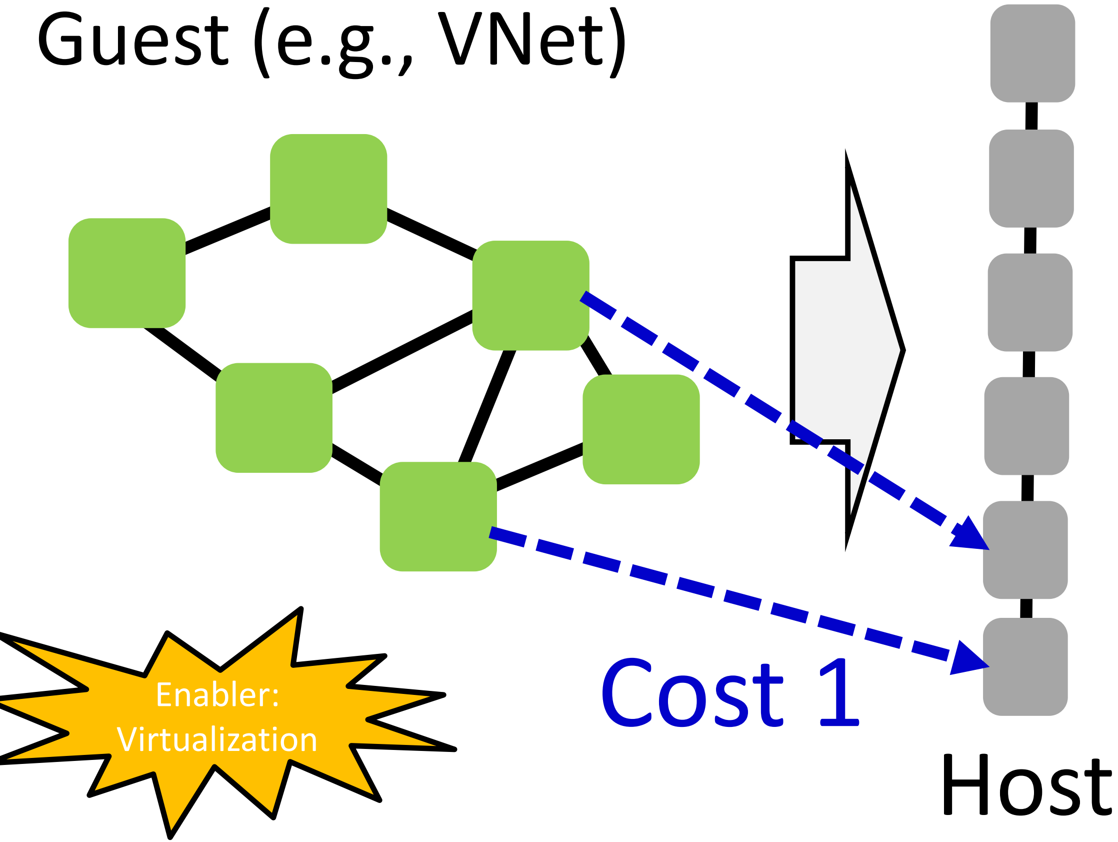
Opportunity: Flexible Embedding



- Flexibly **allocate** (virtualized) network functions or **map** (virtualized) communication partners…
- … to improve **utilization**, minimize **latency** and **load**, etc.

Charting the Complexity Landscape of Virtual Network Embeddings. Rost et al. IFIP Networking, 2018.

Opportunity: Flexible Embedding



- Flexibly **allocate** (virtualized) network functions or **map** (virtualized) communication partners…
- … to improve **utilization**, minimize **latency** and **load**, etc.

Charting the Complexity Landscape of Virtual Network Embeddings. Rost et al. IFIP Networking, 2018.

The Internet: Capable of Change on *All* Layers!

Application Layer ✓

Transport Layer ✓

Network Layer ✓

Link + Physical Layer ?

The Internet: Capable of Change on *All* Layers!

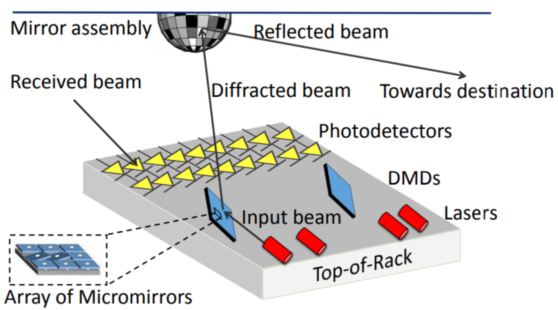
Application Layer ✓

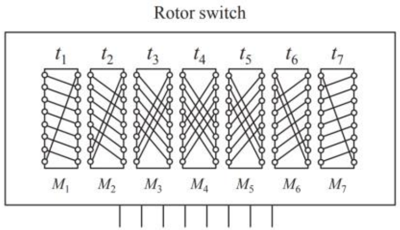
Transport Layer ✓

Network Layer ✓

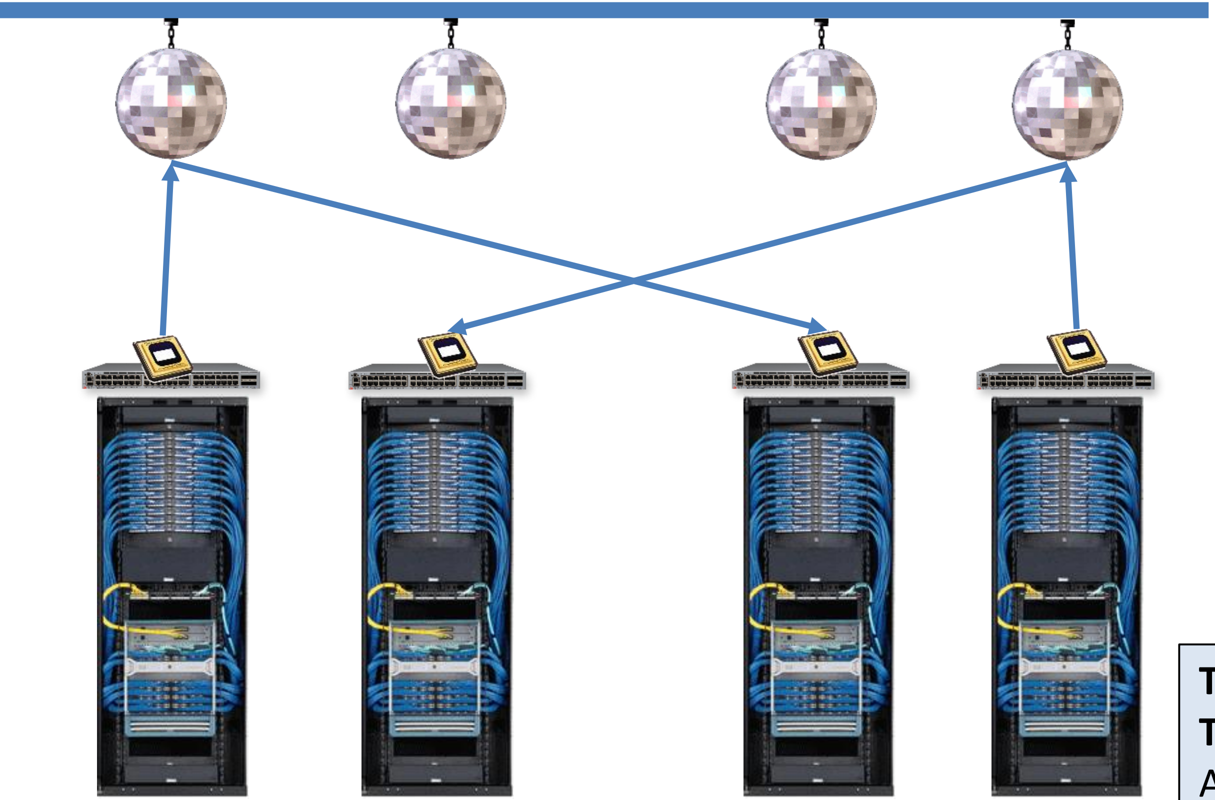
Link + Physical Layer ✓

Based on **free-space optics**, **60GHz** , **optical circuit switches**, **movable antennas** and **mirrors,** etc.





Opportunity: Flexible Topology Programming

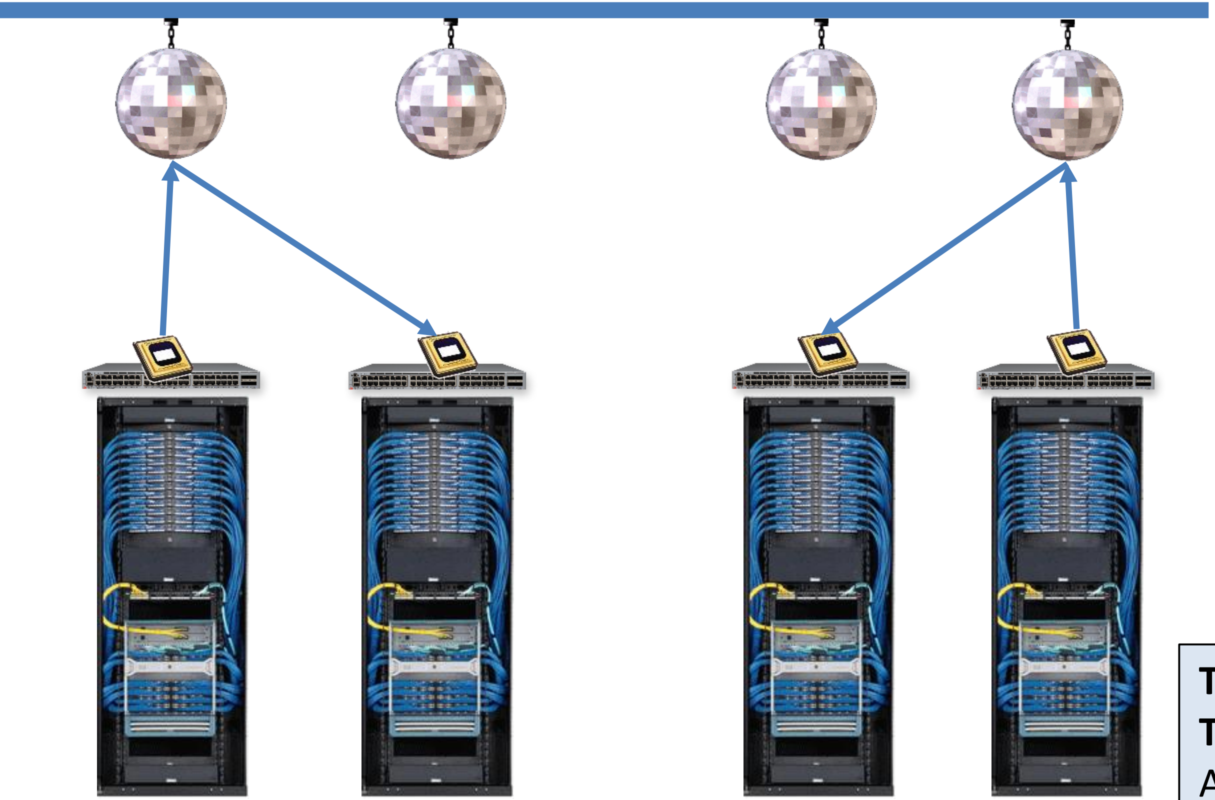


- **Reconfigure** networks towards needs

Enabler: Free-space optics

Toward Demand-Aware Networking: A Theory for Self-Adjusting Networks.
Avin et al. ACM SIGCOMM CCR, 2018.

Opportunity: Flexible Topology Programming



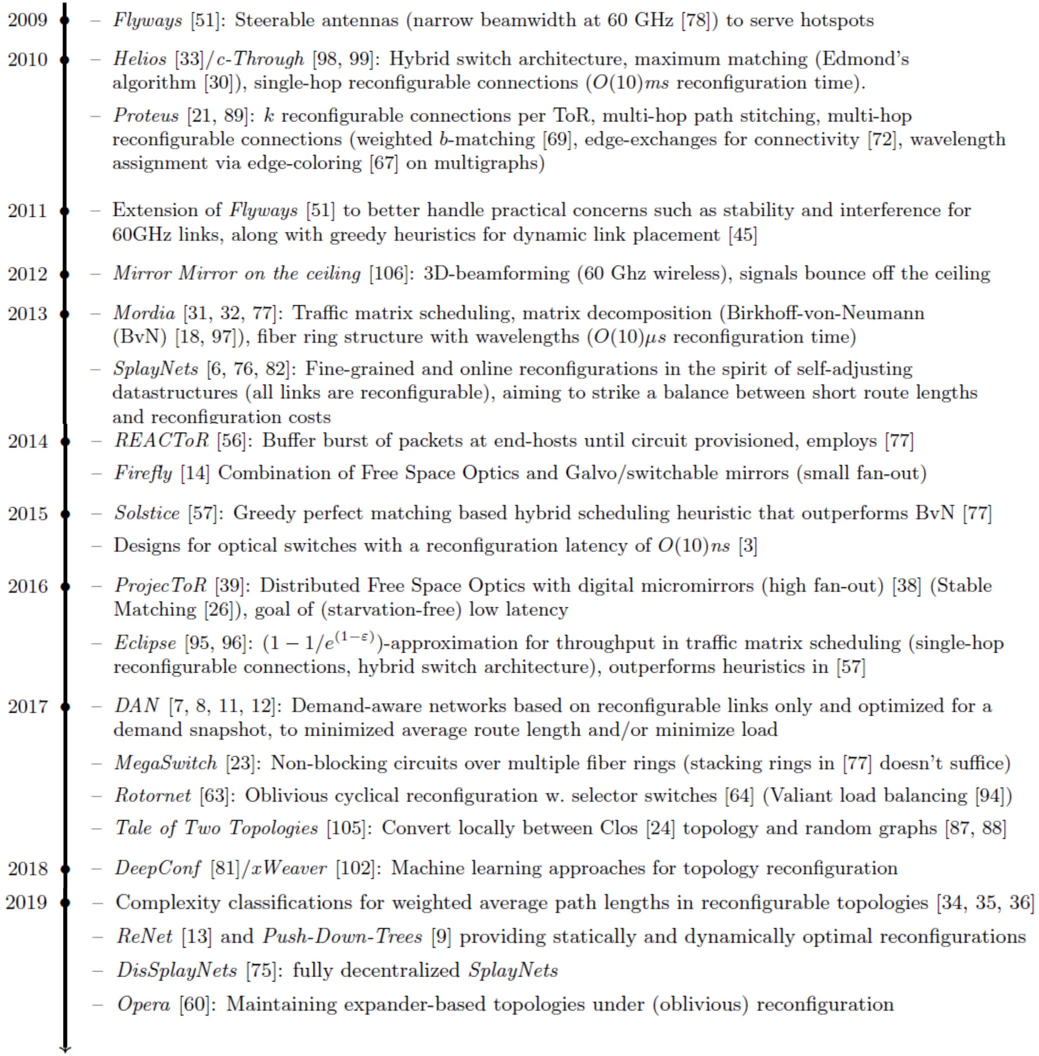
- **Reconfigure** networks towards needs

Enabler: Free-space optics

Toward Demand-Aware Networking: A Theory for Self-Adjusting Networks. Avin et al. ACM SIGCOMM CCR, 2018.

Timeline

Reconfiguration time: from milliseconds ***to microseconds*** (and decentralized).



- 2009
  - *Flyways* [51]: Steerable antennas (narrow beamwidth at 60 GHz [78]) to serve hotspots
- 2010
  - *Helios* [33]/*c-Through* [98, 99]: Hybrid switch architecture, maximum matching (Edmond's algorithm [30]), single-hop reconfigurable connections ($O(10)ms$ reconfiguration time).
  - *Proteus* [21, 89]: k reconfigurable connections per ToR, multi-hop path stitching, multi-hop reconfigurable connections (weighted b-matching [69], edge-exchanges for connectivity [72], wavelength assignment via edge-coloring [67] on multigraphs)
- 2011
  - Extension of *Flyways* [51] to better handle practical concerns such as stability and interference for 60GHz links, along with greedy heuristics for dynamic link placement [45]
- 2012
  - *Mirror Mirror on the ceiling* [106]: 3D-beamforming (60 Ghz wireless), signals bounce off the ceiling
- 2013
  - *Mordia* [31, 32, 77]: Traffic matrix scheduling, matrix decomposition (Birkhoff-von-Neumann (BvN) [18, 97]), fiber ring structure with wavelengths ($O(10)\mu s$ reconfiguration time)
  - *SplayNets* [6, 76, 82]: Fine-grained and online reconfigurations in the spirit of self-adjusting datastructures (all links are reconfigurable), aiming to strike a balance between short route lengths and reconfiguration costs
- 2014
  - *REACToR* [56]: Buffer burst of packets at end-hosts until circuit provisioned, employs [77]
  - *Firefly* [14] Combination of Free Space Optics and Galvo/switchable mirrors (small fan-out)
- 2015
  - *Solstice* [57]: Greedy perfect matching based hybrid scheduling heuristic that outperforms BvN [77]
  - Designs for optical switches with a reconfiguration latency of $O(10)ns$ [3]
- 2016
  - *ProjecToR* [39]: Distributed Free Space Optics with digital micromirrors (high fan-out) [38] (Stable Matching [26]), goal of (starvation-free) low latency
  - *Eclipse* [95, 96]: $(1-1/e^{(1-\varepsilon)})$-approximation for throughput in traffic matrix scheduling (single-hop reconfigurable connections, hybrid switch architecture), outperforms heuristics in [57]
- 2017
  - *DAN* [7, 8, 11, 12]: Demand-aware networks based on reconfigurable links only and optimized for a demand snapshot, to minimized average route length and/or minimize load
  - *MegaSwitch* [23]: Non-blocking circuits over multiple fiber rings (stacking rings in [77] doesn't suffice)
  - *Rotornet* [63]: Oblivious cyclical reconfiguration w. selector switches [64] (Valiant load balancing [94])
  - *Tale of Two Topologies* [105]: Convert locally between Clos [24] topology and random graphs [87, 88]
- 2018
  - *DeepConf* [81]/*xWeaver* [102]: Machine learning approaches for topology reconfiguration
- 2019
  - Complexity classifications for weighted average path lengths in reconfigurable topologies [34, 35, 36]
  - *ReNet* [13] and *Push-Down-Trees* [9] providing statically and dynamically optimal reconfigurations
  - *DisSplayNets* [75]: fully decentralized *SplayNets*
  - *Opera* [60]: Maintaining expander-based topologies under (oblivious) reconfiguration

Survey of Reconfigurable Data Center Networks. Foerster and Schmid. SIGACT News, 2019.

Opportunity

- Great **optimization opportunities**
- In principle flexibilities can be exploited „fast“: **open interfaces** (***bring your own algorithm***!)
- Also easier to **collect data**: programmable networks, **telemetry**

Challenge

- Operating networks may become more ***complex***, e.g.: **traversal** of firewall not mapped to „edge“
- Exploiting **online optimization** at runtime hard at ***human*** time scale: difficult algorithmic problems
- **Modelling** can be ***more difficult*** too: new components like **hypervisor** can affect performance

Challenge: Model vs Reality

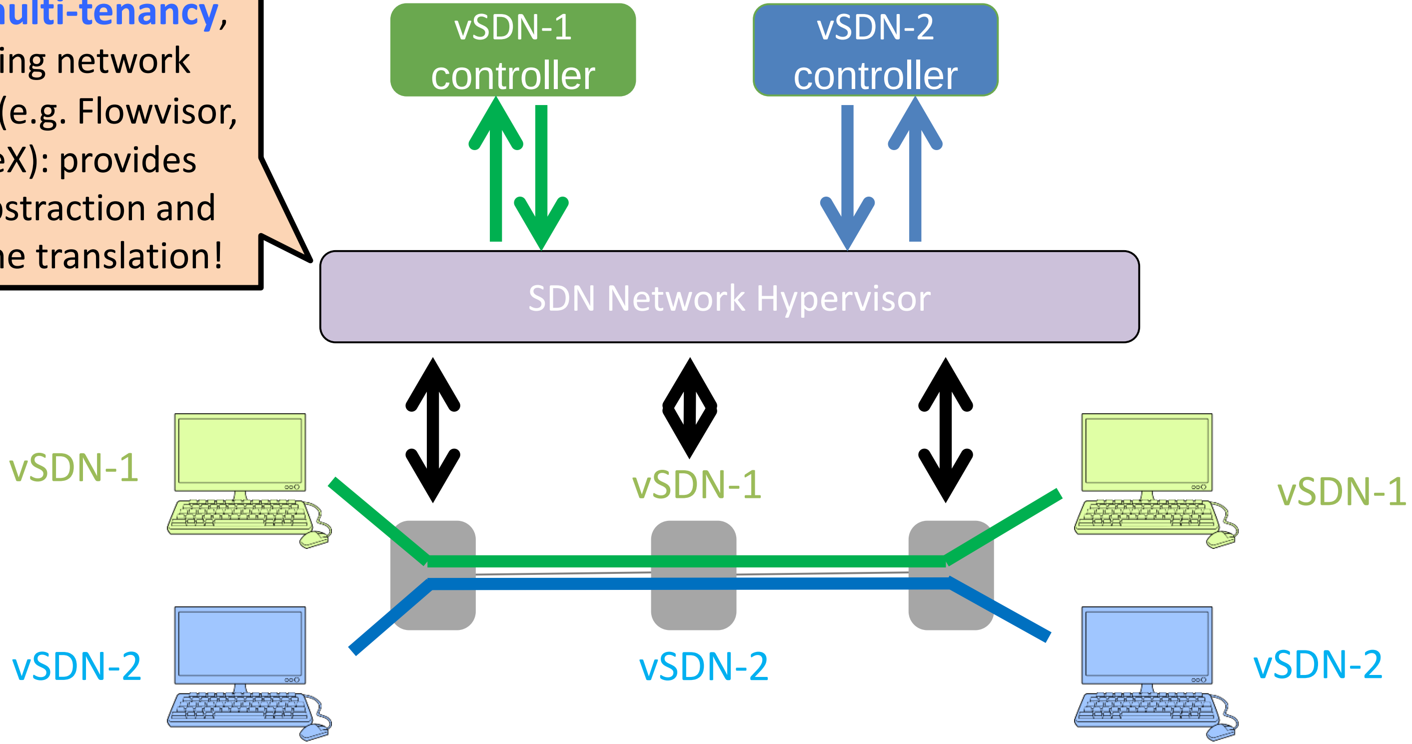
You: I invented a great new algorithm to route and embed service chains at low resource cost and providing minimal bandwidth guarantees!

Boss: So can I promise our customers a predictable performance?

You: hmm…

Recall Andi Blenk‘s Talk

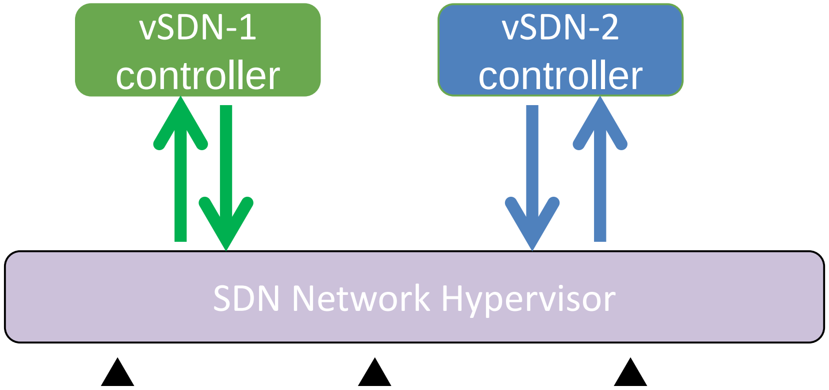
To enable **multi-tenancy**, take existing network **hypervisor** (e.g. Flowvisor, OpenVirteX): provides network abstraction and control plane translation!

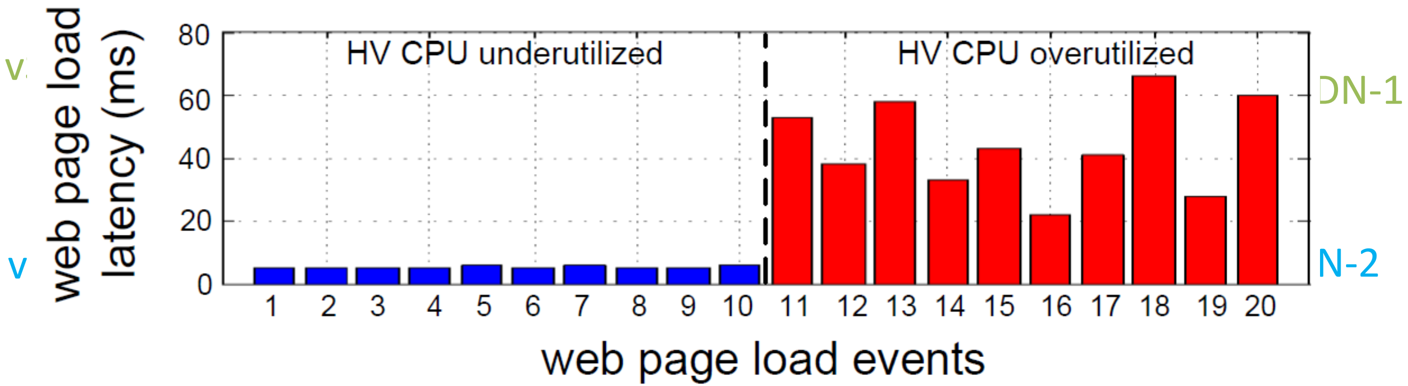


An Experiment: 2 vSDNs with bw guarantee!

Recall Andi Blenk‘s Talk

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!

First Conclusions

- Exploiting network flexibilities is non-trivial, especially if **fine-grained** and **fast** reactions are desired
- Also modelling such networked systems is challenging: details of **interference**, **demand**, etc. will only be available at runtime

Optimal operation of flexible networks ***too complex for humans***.

Let’s give up control: self-* networks!

Self-observing, self-adjusting, self-repairing, “self-driving”, …

It’s about automation!

Roadmap

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

- Challenges of desinging self-* networks

Roadmap

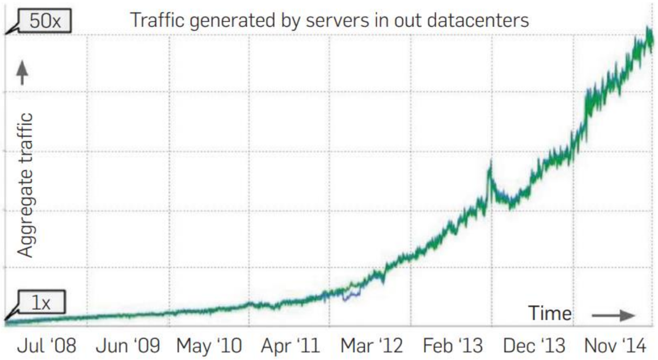
- Opportunities of self-* networks
  - **Example 1: Demand-aware, self-adjusting networks**
  - Example 2: Self-repairing networks
- Challenges of desinging self-* networks

Why Demand-Aware…?

Case study: datacenter networks

Explosive Growth of Demand…

Batch processing, web services, **distributed ML**, ….: ***data-centric applications*** are distributed and interconnecting network is ***critical***

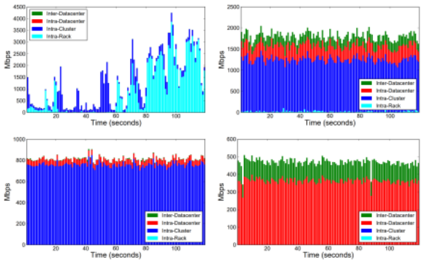


Source: Jupiter Rising. SIGCOMM 2015.

Aggregate server traffic in **Google's datacenter fleet**

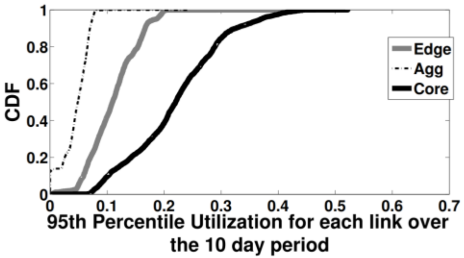
… But Much Structure!

Facebook



Inside the Social Network's (Datacenter) Network @ SIGCOMM 2015

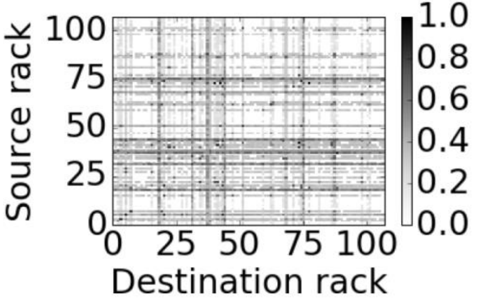
Benson et al.



Understanding Data Center Traffic Characteristics @ WREN 2009

Spatial (***sparse!***) and temporal **locality**

Microsoft

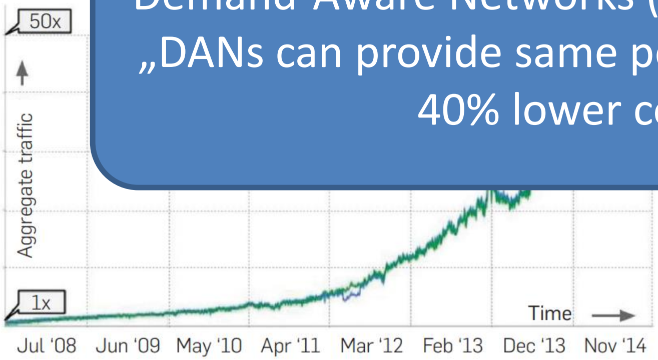


ProjecToR @ SIGCOMM 2016

Explosive Growth of Demand…

… But Much Structure!

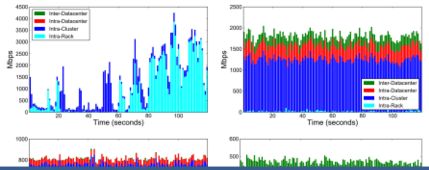
Batch processing, web services, **distributed ML**, …: ***data-centric applications*** are distributed and interconnecting network is ***critical***



Source: Jupiter Rising. SIGCOMM 2015.

Aggregate server traffic in **Google's datacenter fleet**

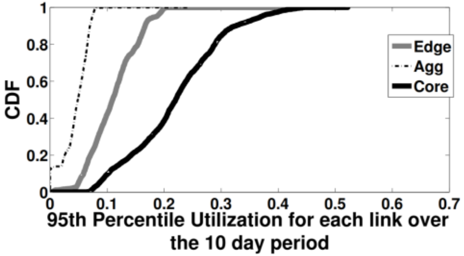
Facebook



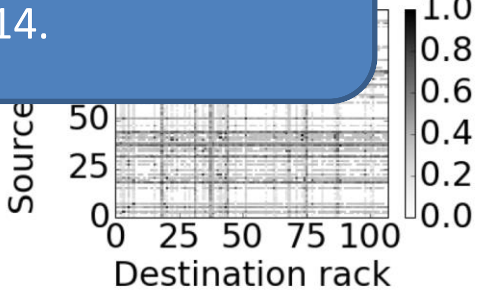
and

Demand-Aware Networks (DANs) can exploit this structure by adapting to it: „DANs can provide same performance as demand-oblivious networks at 25-40% lower costs." Firefly, SIGCOMM CCR, 2014.

Benson et al.



Understanding Data Center Traffic Characteristics @ WREN 2009



ProjecToR @ SIGCOMM 2016

Datacenter Networks

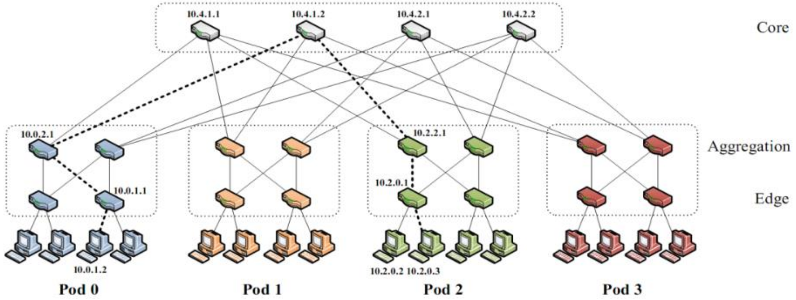
Traditionally: demand-**oblivious**:

Datacenter Networks

Traditionally: demand-**oblivious**:

Datacenter Networks

Traditional datacenter network

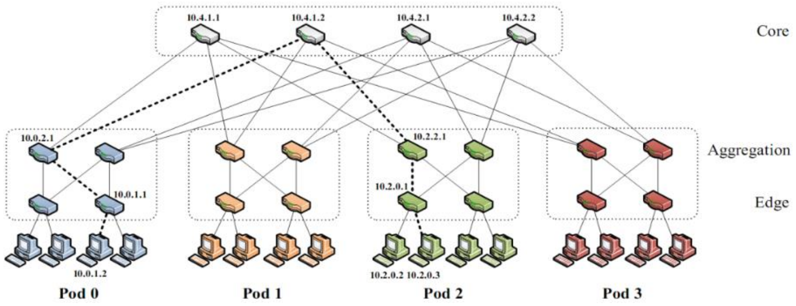


- Usually optimized ***for the "worst-case"*** (**all-to-all** communication)
- Example, fat-tree topologies: provide **full bisection bandwidth**

Traditionally: demand-**oblivious**:

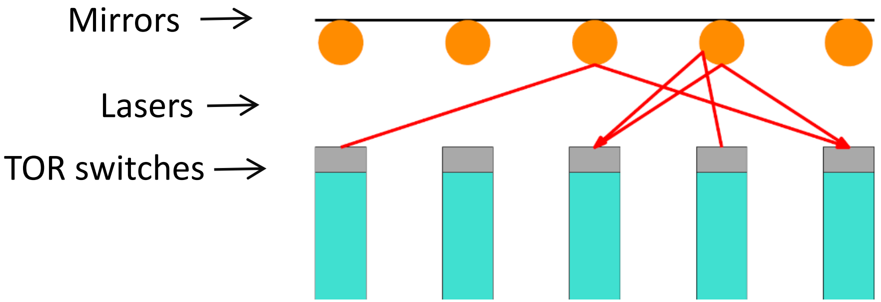
Datacenter Networks

Traditional datacenter network



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

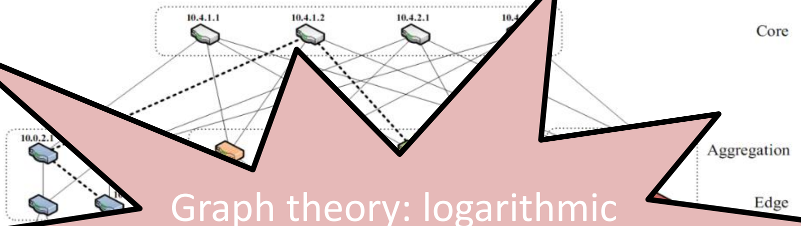
Reconfiguable datacenter network



- Optimized ***toward the workload*** it serves (e.g., **route length**)
- Statically or ***even dynamically***

Datacenter Networks

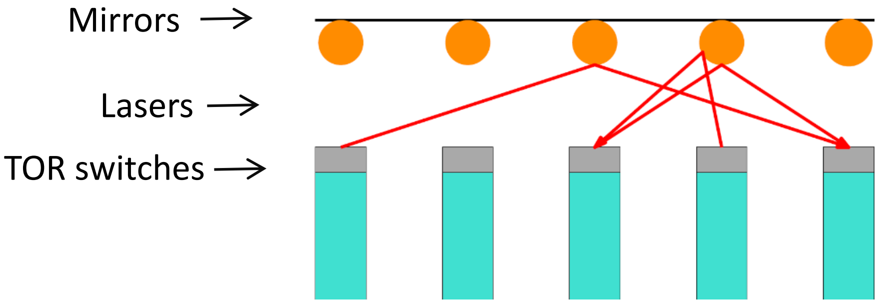
Traditional datacenter network



Graph theory: logarithmic route lengths in constant-degree datacenter networks.

- Usually
  case” (**to-** m cation,
- Example, fat- e topo gies: provide **full bi ection bandwidth**

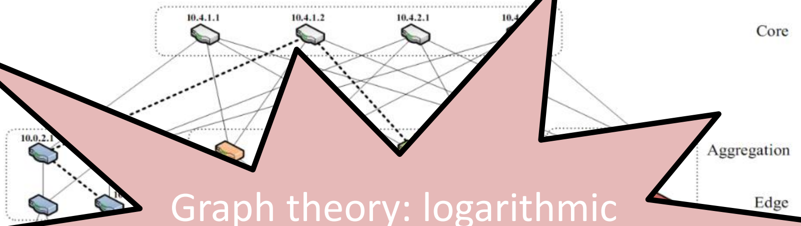
Reconfiguable datacenter network



- Optimized ***toward the workload*** it serves (e.g., **route length**)
- Statically or ***even dynamically***

Datacenter Networks

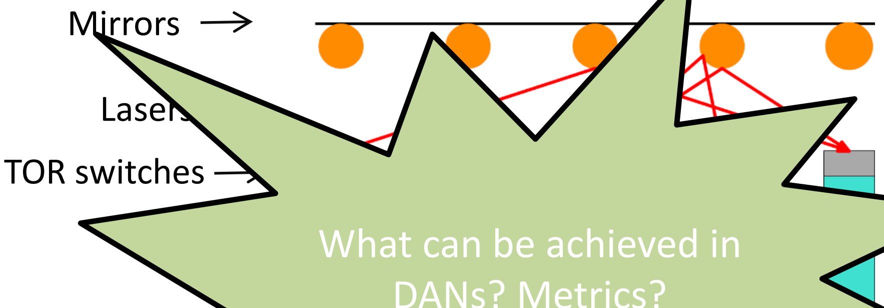
Traditional datacenter network



Graph theory: logarithmic route lengths in constant-degree datacenter networks.

- Usually ... *case"* (to- om cation
- Example, fat- e topo gies: provide **full bi ection bandwidth**

Reconfiguable datacenter network



What can be achieved in DANs? Metrics?

- Opti ed ***ur work d*** it serves (e.g **ute le th**)
- Statically or ***even dynamically***

DAN Design: New Types of Problems

Input: Workload

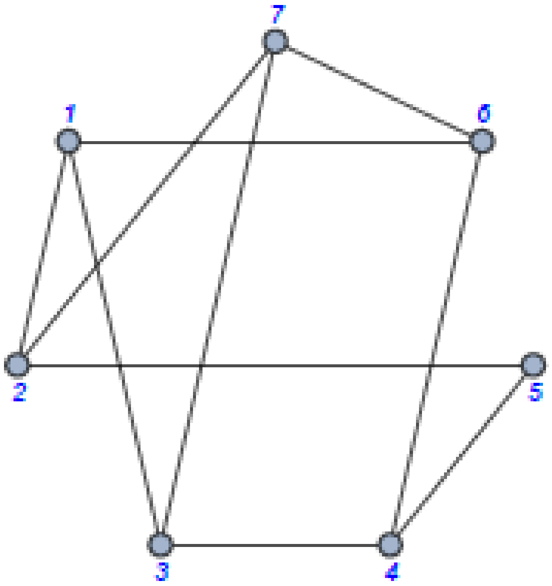
Destinations

Sources

$$
\begin{array}{c|ccccccc|}
 & 1 & 2 & 3 & 4 & 5 & 6 & 7 \\
\hline
1 & 0 & \frac{2}{65} & \frac{1}{13} & \frac{1}{65} & \frac{1}{65} & \frac{2}{65} & \frac{3}{65} \\
2 & \frac{2}{65} & 0 & \frac{1}{65} & 0 & 0 & 0 & \frac{2}{65} \\
3 & \frac{1}{13} & \frac{1}{65} & 0 & \frac{2}{65} & 0 & 0 & \frac{1}{13} \\
4 & \frac{1}{65} & 0 & \frac{2}{65} & 0 & \frac{4}{65} & 0 & 0 \\
5 & \frac{1}{65} & 0 & \frac{3}{65} & \frac{4}{65} & 0 & 0 & 0 \\
6 & \frac{2}{65} & 0 & 0 & 0 & 0 & 0 & \frac{3}{65} \\
7 & \frac{3}{65} & \frac{2}{65} & \frac{1}{13} & 0 & 0 & \frac{3}{65} & 0 \\
\hline
\end{array}
$$

design

Output: DAN



Demand matrix: joint distribution

… of ***constant degree*** (**scalability**)

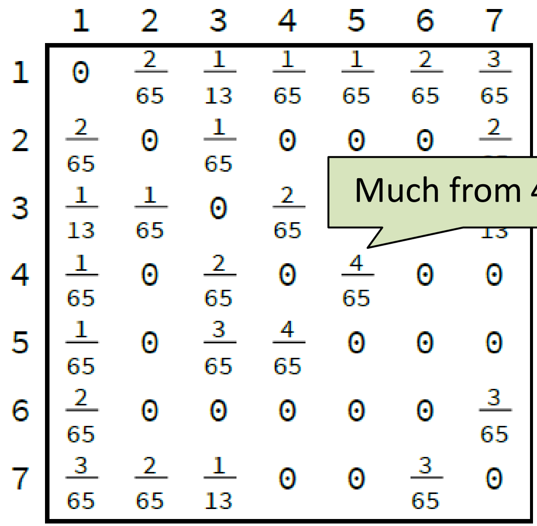
DAN Design: New Types of Problems

Input: Workload

Output: DAN

Destinations

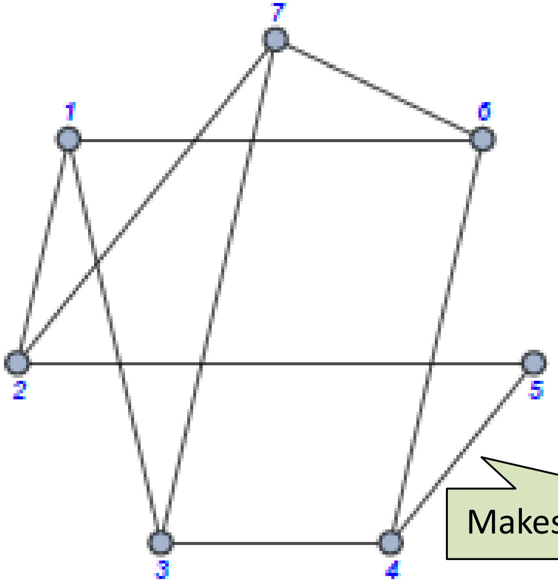
Sources



	1	2	3	4	5	6	7
1	0	$\frac{2}{65}$	$\frac{1}{13}$	$\frac{1}{65}$	$\frac{1}{65}$	$\frac{2}{65}$	$\frac{3}{65}$
2	$\frac{2}{65}$	0	$\frac{1}{65}$	0	0	0	2
3	$\frac{1}{13}$	$\frac{1}{65}$	0	$\frac{2}{65}$			13
4	$\frac{1}{65}$	0	$\frac{2}{65}$	0	$\frac{4}{65}$	0	0
5	$\frac{1}{65}$	0	$\frac{3}{65}$	$\frac{4}{65}$	0	0	0
6	$\frac{2}{65}$	0	0	0	0	0	$\frac{3}{65}$
7	$\frac{3}{65}$	$\frac{2}{65}$	$\frac{1}{13}$	0	0	$\frac{3}{65}$	0

Much from 4 to 5.

design



Makes sense to add link!

Demand matrix: joint distribution

… of ***constant degree*** (**scalability**)

DAN Design: New Types of Problems

Input: Workload

Destinations

1 communicates to many.

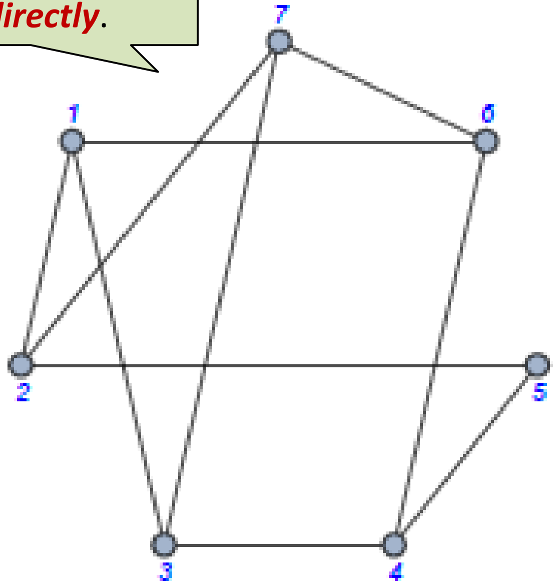
Sources

$$\begin{array}{c|ccccccc} & & & & & & 6 & 7 \\ \hline 1 & 0 & \frac{2}{65} & \frac{1}{13} & \frac{1}{65} & \frac{1}{65} & \frac{2}{65} & \frac{3}{65} \\ 2 & \frac{2}{65} & 0 & \frac{1}{65} & 0 & 0 & 0 & \frac{2}{65} \\ 3 & \frac{1}{13} & \frac{1}{65} & 0 & \frac{2}{65} & 0 & 0 & \frac{1}{13} \\ 4 & \frac{1}{65} & 0 & \frac{2}{65} & 0 & \frac{4}{65} & 0 & 0 \\ 5 & \frac{1}{65} & 0 & \frac{3}{65} & \frac{4}{65} & 0 & 0 & 0 \\ 6 & \frac{2}{65} & 0 & 0 & 0 & 0 & 0 & \frac{3}{65} \\ 7 & \frac{3}{65} & \frac{2}{65} & \frac{1}{13} & 0 & 0 & \frac{3}{65} & 0 \end{array}$$

design

Output: DAN

Bounded degree: route to 7 ***indirectly***.



Demand matrix: joint distribution

… of ***constant degree*** (**scalability**)

DAN Design: New Types of Problems

Input: Workload

Destinations

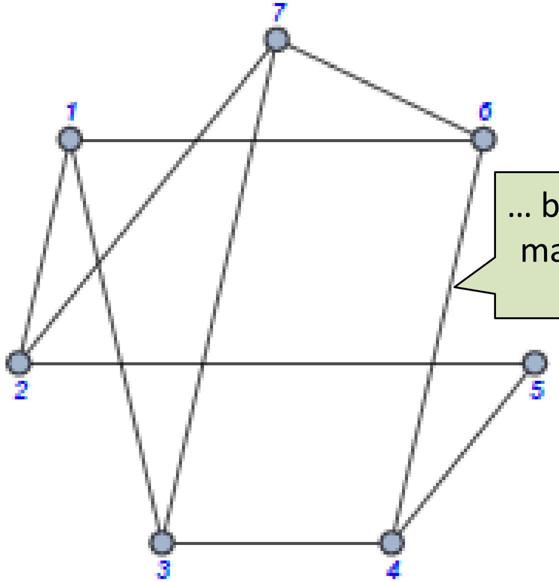
Sources

$$
\begin{array}{c|ccccccc}
 & 1 & 2 & 3 & 4 & 5 & 6 & 7 \\
\hline
1 & 0 & \frac{2}{65} & \frac{1}{13} & \frac{1}{65} & \frac{1}{65} & \frac{2}{65} & \frac{3}{65} \\
2 & \frac{2}{65} & 0 & \frac{1}{65} & 0 & 0 & 0 & \frac{2}{65} \\
3 & \frac{1}{13} & \frac{1}{65} & 0 & \frac{2}{65} & 0 & 0 & \frac{1}{13} \\
4 & \frac{1}{65} & 0 & \frac{2}{65} & 0 & \frac{4}{65} & 0 & 0 \\
5 & \frac{1}{65} & 0 & \frac{3}{65} & \frac{4}{65} & 0 & \text{[illegible]} & \text{[illegible]} \\
6 & \frac{2}{65} & 0 & 0 & 0 & 0 & \text{[illegible]} & \text{[illegible]} \\
7 & \frac{3}{65} & \frac{2}{65} & \frac{1}{13} & 0 & 0 & \frac{3}{65} & 0
\end{array}
$$

4 and 6 don't communicate…

design

Output: DAN



… but "extra" link still makes sense: ***not a subgraph***.

Demand matrix: joint distribution

… of ***constant degree*** (**scalability**)

More Formally: DAN Design Problem

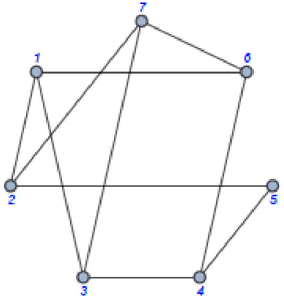
Input:

$\mathcal{D}[\mathbf{p}(\mathbf{i},\mathbf{j})]$: joint **distribution**, $\boldsymbol{\Delta}$

$$
\begin{array}{cc}
 & \text{Y} \\
\text{X} &
\begin{array}{c|ccccccc|}
 & 1 & 2 & 3 & 4 & 5 & 6 & 7 \\
\hline
1 & 0 & \frac{2}{65} & \frac{1}{13} & \frac{1}{65} & \frac{1}{65} & \frac{2}{65} & \frac{3}{65} \\
2 & \frac{2}{65} & 0 & \frac{1}{65} & 0 & 0 & 0 & \frac{2}{65} \\
3 & \frac{1}{13} & \frac{1}{65} & 0 & \frac{2}{65} & 0 & 0 & \frac{1}{13} \\
4 & \frac{1}{65} & 0 & \frac{2}{65} & 0 & \frac{4}{65} & 0 & 0 \\
5 & \frac{1}{65} & 0 & \frac{3}{65} & \frac{4}{65} & 0 & 0 & 0 \\
6 & \frac{2}{65} & 0 & 0 & 0 & 0 & 0 & \frac{3}{65} \\
7 & \frac{3}{65} & \frac{2}{65} & \frac{1}{13} & 0 & 0 & \frac{3}{65} & 0 \\
\hline
\end{array}
\end{array}
$$

Output:

N: DAN



Bounded degree
$\Delta=3$

Objective:

Expected Path Length (EPL):
Demand-weighted route length

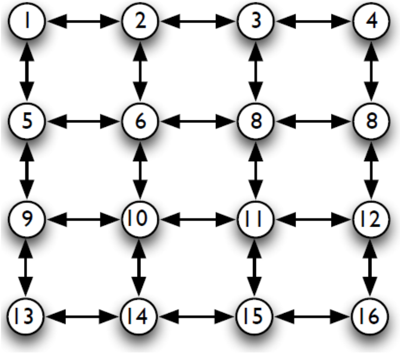
$$\mathrm{EPL}(\mathcal{D},\mathrm{N}) = \sum_{(\mathrm{u},\mathrm{v})\in\mathcal{D}} \mathrm{p}(\mathrm{u},\mathrm{v}) \cdot \mathrm{d}_{\mathrm{N}}(\mathrm{u},\mathrm{v})$$

Path length ***on DAN N***.

Frequency

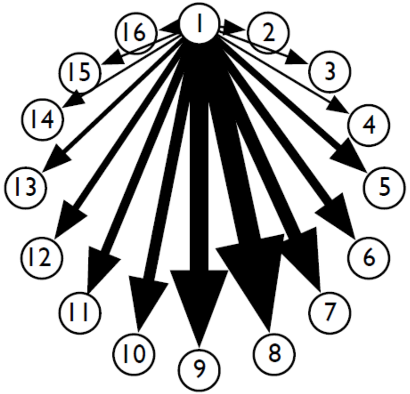
Sometimes, DANs can be much better!

Example 1: low-degree demand



- Already low degree: degree-4 DAN can serve this ***at cost 1*** .

Example 2: high-degree but **skewed demand**



- If sufficiently skewed: constant-degree DAN can serve it at cost ***O(1)***

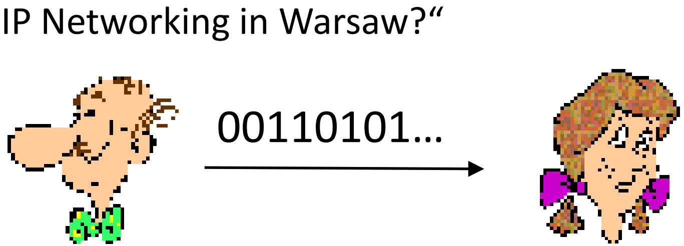
So on what does it depend?

So on what does it depend?

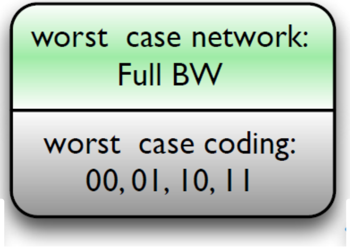
We argue (but still don‘t know!): on the **“entropy” of the demand**!

?

An Analogy to Coding



if demand ***arbitrary*** and ***unknown***



worst case network:
Full BW

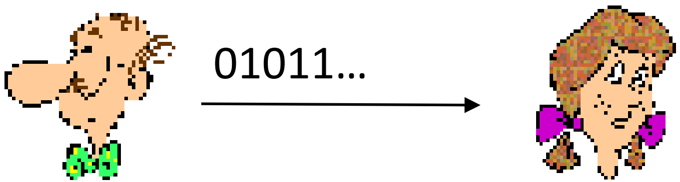
worst case coding:
00, 01, 10, 11

log diameter

log # bits / symbol

„Coming to IFIP Networking in Warsaw?“

An Analogy to Coding



if demand ***arbitrary*** and ***unknown***

worst case network:
Full BW

log diameter

worst case coding:
00, 01, 10, 11

log # bits / symbol

DAN!

if demand ***known*** and ***fixed***

static
Demand-Aware Nets

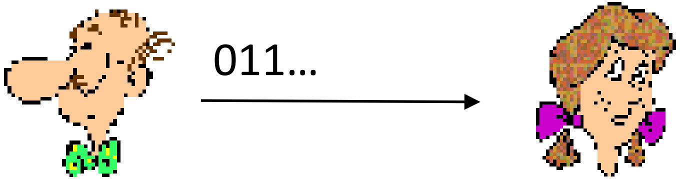
entropy?

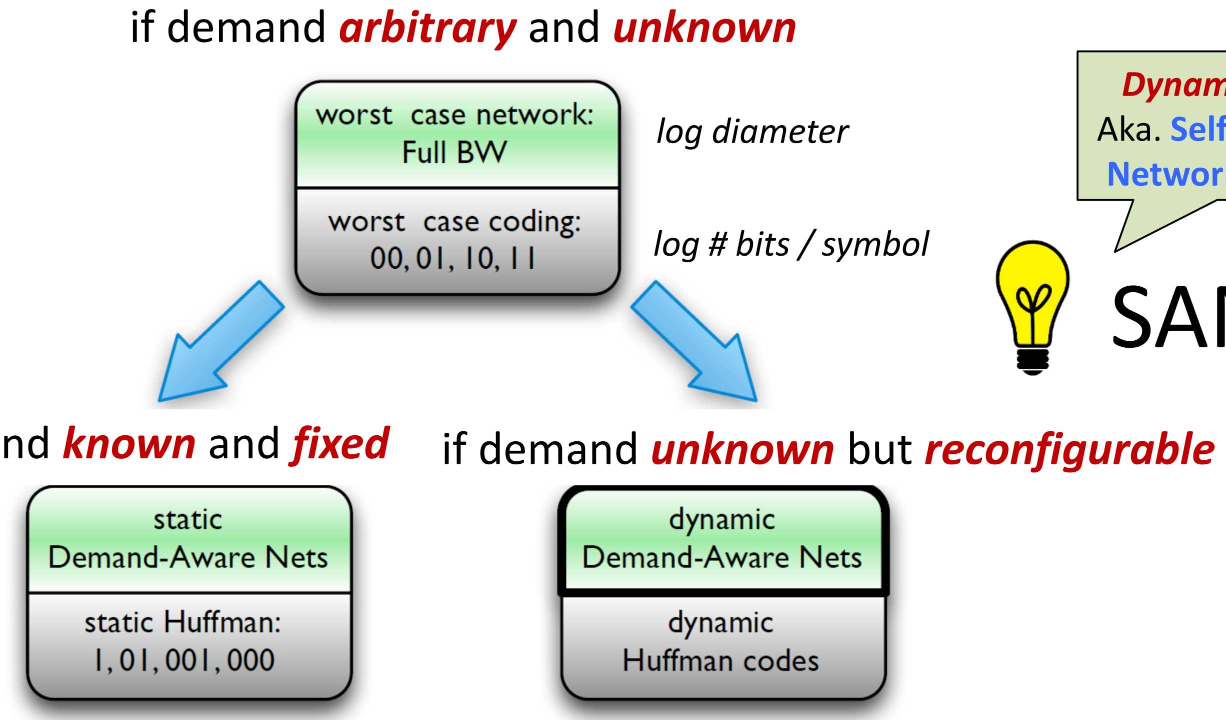
static Huffman:
1, 01, 001, 000

entropy / symbol

„Coming to IFIP Networking in Warsaw?“

An Analogy to Coding





if demand ***arbitrary*** and ***unknown***

worst case network:
Full BW

log diameter

worst case coding:
00, 01, 10, 11

log # bits / symbol

DAN!

Dynamic DANs:
Aka. **Self-Adjusting Networks** (SANs)!

SAN!

if demand ***known*** and ***fixed***

entropy?

static
Demand-Aware Nets

entropy / symbol

static Huffman:
1, 01, 001, 000

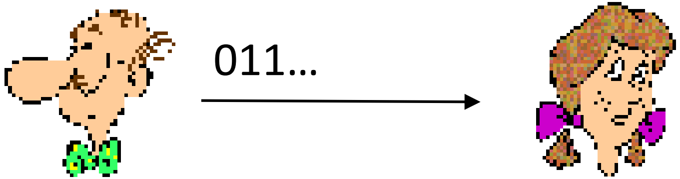
if demand ***unknown*** but ***reconfigurable***

dynamic
Demand-Aware Nets

dynamic
Huffman codes

„Coming to IFIP Networking in Warsaw?“

An Analogy to Coding



if demand ***arbitrary*** and ***unknown***

worst case network:
Full BW

log diameter

worst case coding:
00, 01, 10, 11

log # bits / symbol

Dynamic DANs:
Aka. **Self-Adjusting Networks** (SANs)!

DAN!

SAN!

if demand ***known*** and ***fixed***

static
Demand-Aware Nets

static Huffman:
1, 01, 001, 000

Can exploit
spatial locality!

if demand ***unknown*** but ***reconfigurable***

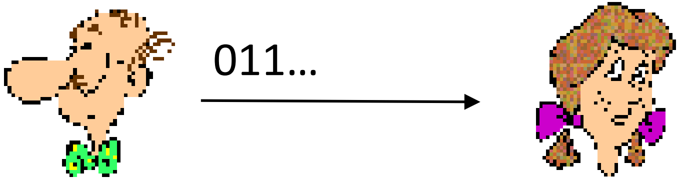
dynamic
Demand-Aware Nets

dynamic
Huffman codes

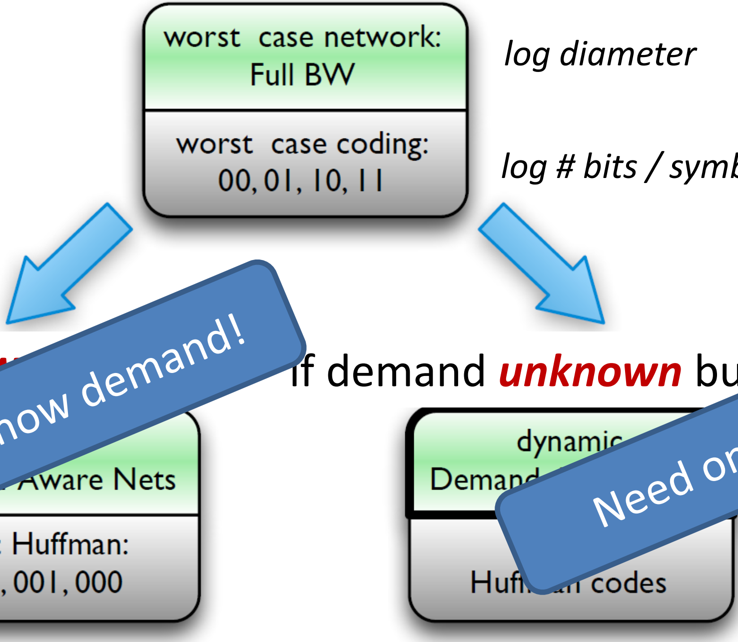
Additionally exploit
temporal locality!

An Analogy to Coding

„Coming to IFIP Networking in Warsaw?“



if demand ***arbitrary*** and ***unknown***



worst case network:
Full BW

worst case coding:
00, 01, 10, 11

log diameter

log # bits / symbol

Dynamic DANs:
Aka. **Self-Adjusting Networks** (SANs)!

DAN!

SAN!

if demand ***know***

if demand ***unknown*** but ***r***

Aware Nets

static Huffman:
1, 01, 001, 000

dynamic
Demand

Huf codes

Can exploit
spati

Additionally exploit ***temporal locality***!

„Cheating“: need to know demand!

Need online algorithms!

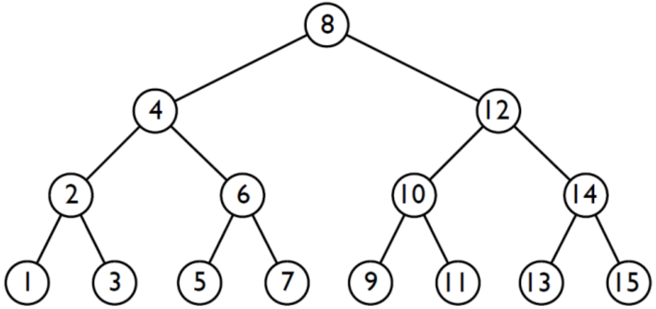
Analogous to *Datastructures*: Oblivious…

- Traditional, **fixed** BSTs do not rely on any assumptions on the demand
- Optimize for the **worst-case**
- Example **demand**:

  1,…,1,3,…,3,5,…,5,7,…,7,…,log(n),…,log(n)

  many *many* *many* *many* *many*
- Items stored at ***O(log n)*** from the root, **uniformly** and **independently** of their frequency

Corresponds to ***max possible demand***!

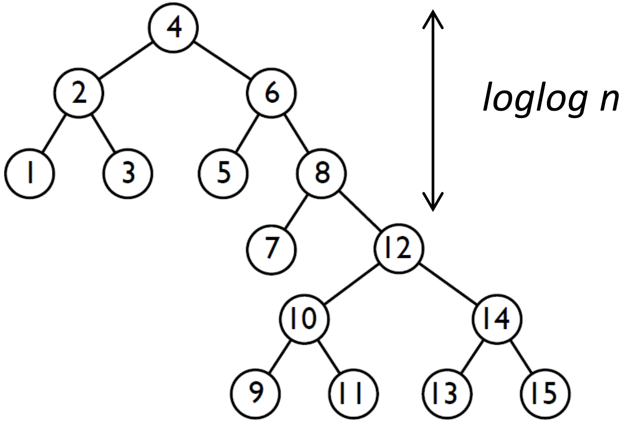


Many requests for leaf 1…

… then for leaf 3…

… Demand-Aware …

- **Demand-aware fixed** BSTs can take advantage of ***spatial locality*** of the demand
- E.g.: place frequently accessed elements close to the root
- E.g., **Knuth/Mehlhorn/Tarjan** trees
- Recall example **demand**: 1,…,1,3,…,3,5,…,5,7,…,7,…,log(n),…,log(n)
  - Amortized cost ***O(loglog n)***

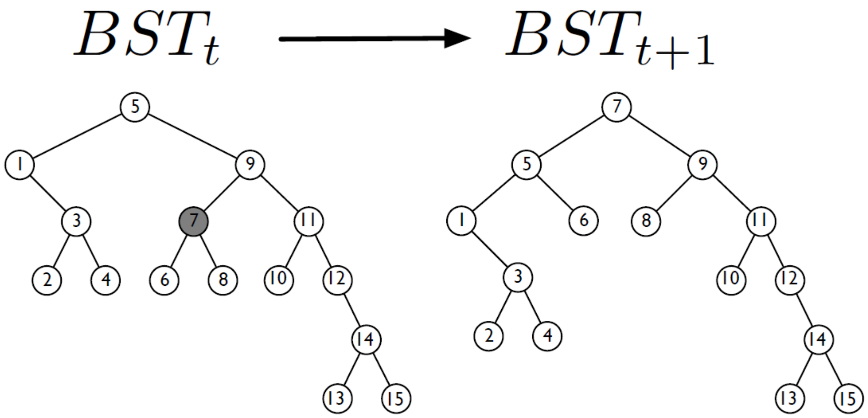


Amortized cost corresponds to ***empirical entropy of demand***!

… Self-Adjusting!

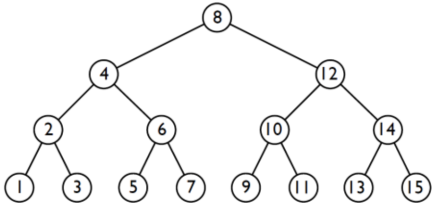
- **Demand-aware reconfigurable** BSTs can additionally take advantage of ***temporal locality***

- By moving accessed element to the root: amortized cost is ***constant***, i.e., O(1)
  - Recall example **demand**: 1,…,1,3,…,3,5,…,5,7,…,7,…,log(n),…,log(n)



Datastructures

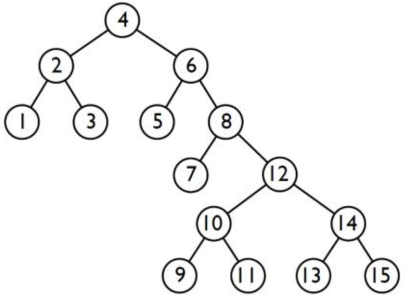
Oblivious



Lookup

O(log n)

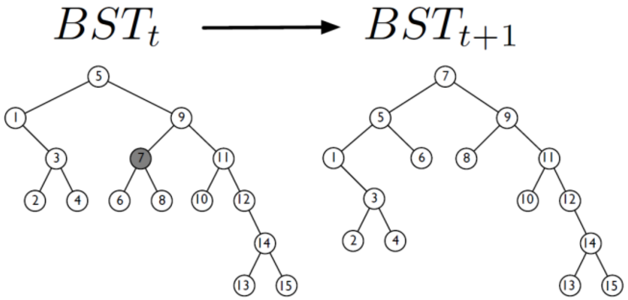
Demand-Aware



Exploit **spatial locality**:

empirical entropy O(loglog n)

Self-Adjusting

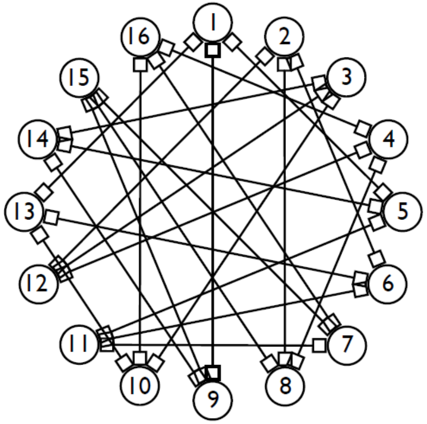


Exploit **temporal locality** as well:

O(1)

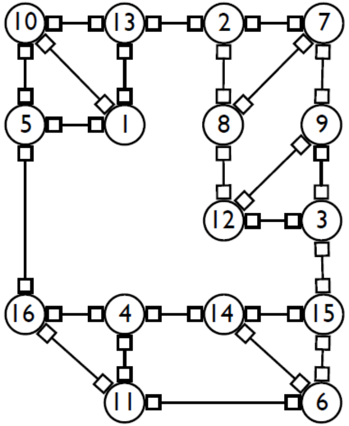
Analogously for Networks

Oblivious



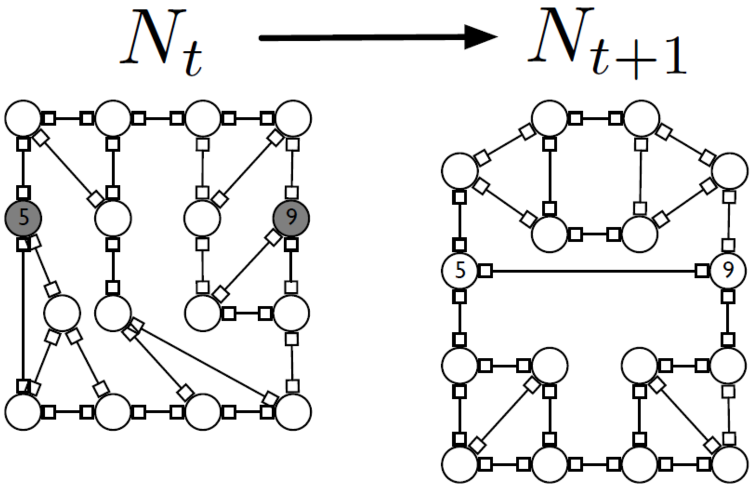
Const degree
(e.g., **expander**):
route lengths ***O(log n)***

DAN



Exploit **spatial locality**

SAN



Exploit **temporal locality** as well

Avin, S.: Toward Demand-Aware Networking: A Theory for Self-Adjusting Networks. **SIGCOMM CCR** 2018.

Intuition: Entropy Lower Bound

Lower Bound Idea:
Leverage Coding or Datastructure

Destinations

Sources

	1	2	3	4	5	6	7
1	0	$\frac{2}{65}$	$\frac{1}{13}$	$\frac{1}{65}$	$\frac{1}{65}$	$\frac{2}{65}$	$\frac{3}{65}$
2	$\frac{2}{65}$	0	$\frac{1}{65}$	0	0	0	$\frac{2}{65}$
3	$\frac{1}{13}$	$\frac{1}{65}$	0	$\frac{2}{65}$	0	0	$\frac{1}{13}$
4	$\frac{1}{65}$	0	$\frac{2}{65}$	0	$\frac{4}{65}$	0	0
5	$\frac{1}{65}$	0	$\frac{3}{65}$	$\frac{4}{65}$	0	0	0
6	$\frac{2}{65}$	0	0	0	0	0	$\frac{3}{65}$
7	$\frac{3}{65}$	$\frac{2}{65}$	$\frac{1}{13}$	0	0	$\frac{3}{65}$	0

- DAN just for a ***single (source) node 1***: cannot do better than Δ-ary **Huffman tree** (or a **biased BST**) for its destinations

- How good can this tree be?

Entropy lower bound on EPL known for binary trees, e.g. ***Mehlhorn*** 1975 for BST

Lower Bound Idea:
Leverage Coding or Datastructure

An optimal “**ego-tree**“ for this source!

Destinations

Sources

	1	2	3	4	5	6	7
1	0	$\frac{2}{65}$	$\frac{1}{13}$	$\frac{1}{65}$	$\frac{1}{65}$	$\frac{2}{65}$	$\frac{3}{65}$
2	$\frac{2}{65}$	0	$\frac{1}{65}$	0	0	0	$\frac{2}{65}$
3	$\frac{1}{13}$	$\frac{1}{65}$	0	$\frac{2}{65}$	0	0	$\frac{1}{13}$
4	$\frac{1}{65}$	0	$\frac{2}{65}$	0	$\frac{4}{65}$	0	0
5	$\frac{1}{65}$	0	$\frac{3}{65}$	$\frac{4}{65}$	0	0	0
6	$\frac{2}{65}$	0	0	0	0	0	$\frac{3}{65}$
7	$\frac{3}{65}$	$\frac{2}{65}$	$\frac{1}{13}$	0	0	$\frac{3}{65}$	0

- DAN just for a ***single (source) node 1***: cannot do better than Δ-ary **Huffman tree** (or a **biased BST**) for its destinations
- How good can this tree be?

Entropy lower bound on EPL known for binary trees, e.g. ***Mehlhorn*** 1975 for BST

So: Entropy of the *Entire* Demand

sources

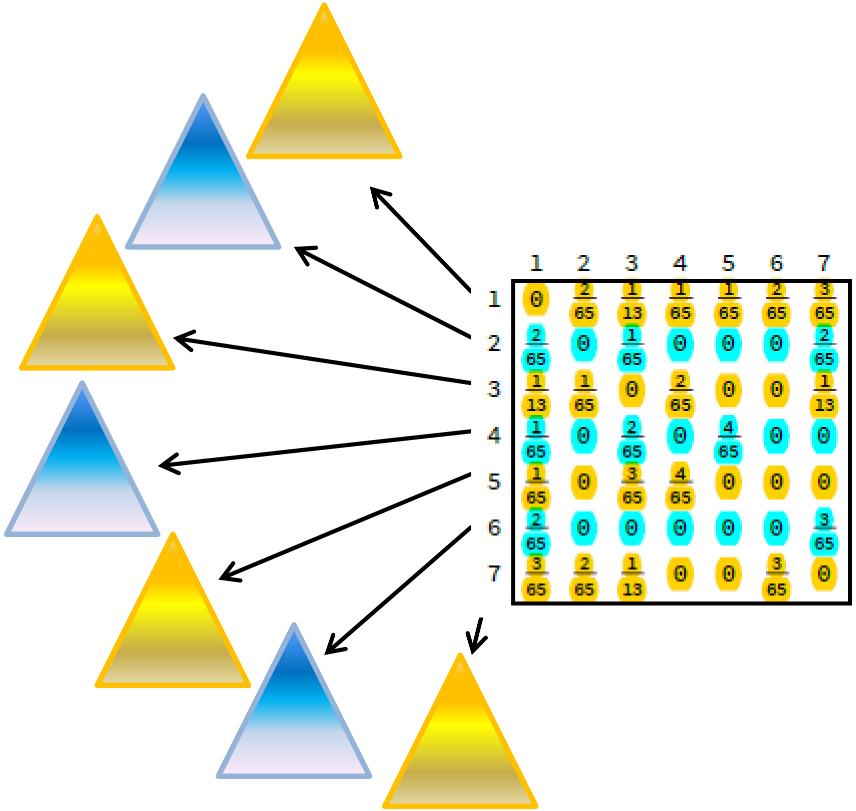
destinations

- **Proof idea** (EPL=$\Omega(H_\Delta(Y|X))$):

entropy

degree

- Compute **ego-tree** for each source node
- Take ***union*** of all **ego-trees**
- Violates ***degree restriction*** but valid lower bound



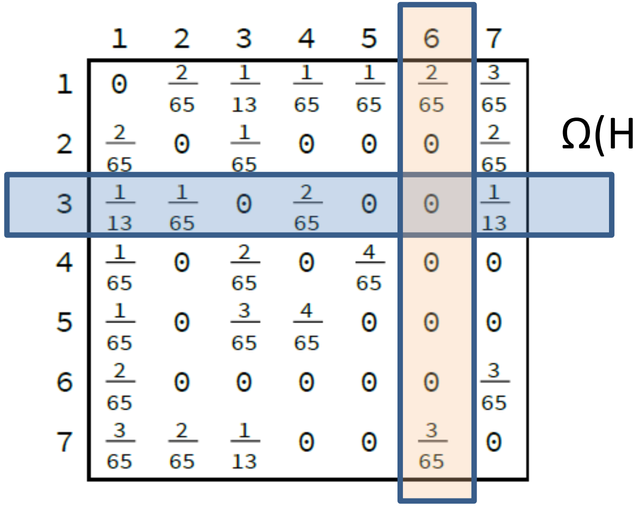
$$\begin{array}{c|ccccccc} & 1 & 2 & 3 & 4 & 5 & 6 & 7 \\ \hline 1 & 0 & \frac{2}{65} & \frac{1}{13} & \frac{1}{65} & \frac{1}{65} & \frac{2}{65} & \frac{3}{65} \\ 2 & \frac{2}{65} & 0 & \frac{1}{65} & 0 & 0 & 0 & \frac{2}{65} \\ 3 & \frac{1}{13} & \frac{1}{65} & 0 & \frac{2}{65} & 0 & 0 & \frac{1}{13} \\ 4 & \frac{1}{65} & 0 & \frac{2}{65} & 0 & \frac{4}{65} & 0 & 0 \\ 5 & \frac{1}{65} & 0 & \frac{3}{65} & \frac{4}{65} & 0 & 0 & 0 \\ 6 & \frac{2}{65} & 0 & 0 & 0 & 0 & 0 & \frac{3}{65} \\ 7 & \frac{3}{65} & \frac{2}{65} & \frac{1}{13} & 0 & 0 & \frac{3}{65} & 0 \end{array}$$

Entropy of the *Entire* Demand: Sources *and* Destinations

Do this in **both dimensions**:

EPL ≥ $\Omega(\max\{H_\Delta(Y|X), H_\Delta(X|Y)\})$

$\Omega(H_\Delta(X|Y))$



$$\begin{array}{c|ccccccc}
 & 1 & 2 & 3 & 4 & 5 & 6 & 7 \\
\hline
1 & 0 & \frac{2}{65} & \frac{1}{13} & \frac{1}{65} & \frac{1}{65} & \frac{2}{65} & \frac{3}{65} \\
2 & \frac{2}{65} & 0 & \frac{1}{65} & 0 & 0 & 0 & \frac{2}{65} \\
3 & \frac{1}{13} & \frac{1}{65} & 0 & \frac{2}{65} & 0 & 0 & \frac{1}{13} \\
4 & \frac{1}{65} & 0 & \frac{2}{65} & 0 & \frac{4}{65} & 0 & 0 \\
5 & \frac{1}{65} & 0 & \frac{3}{65} & \frac{4}{65} & 0 & 0 & 0 \\
6 & \frac{2}{65} & 0 & 0 & 0 & 0 & 0 & \frac{3}{65} \\
7 & \frac{3}{65} & \frac{2}{65} & \frac{1}{13} & 0 & 0 & \frac{3}{65} & 0
\end{array}$$

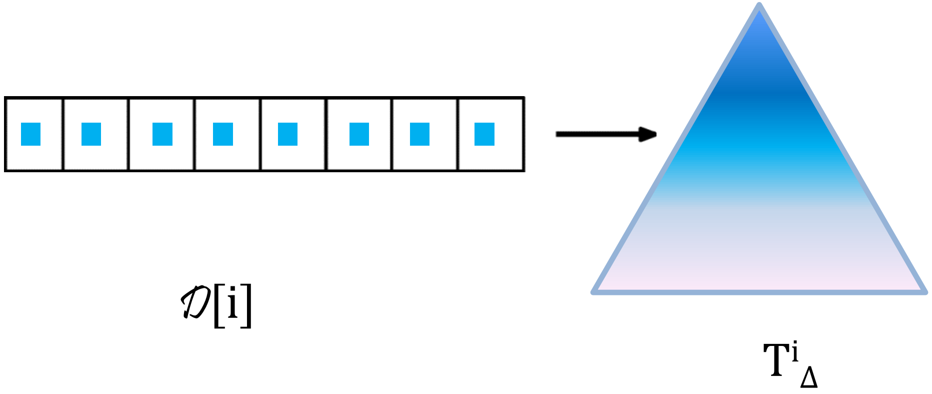
$\Omega(H_\Delta(Y|X))$

$\mathcal{D}$

Intuition: Reaching Entropy Limit in Datacenters

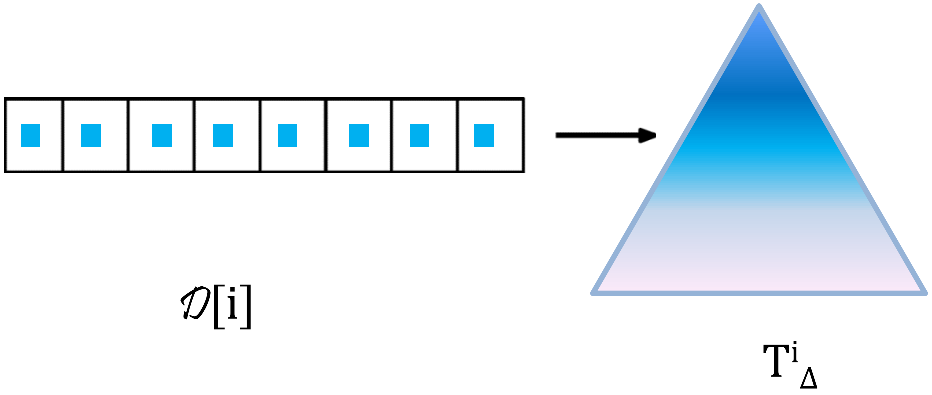
Ego-Trees Revisited

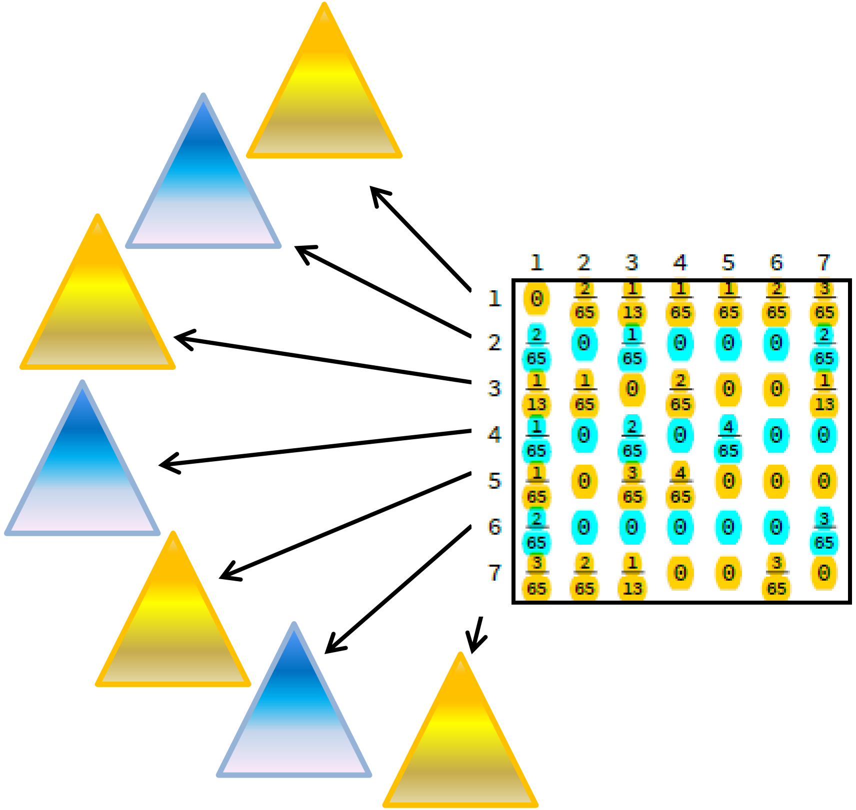
- ego-tree: optimal tree for a row (= given source)



Ego-Trees Revisited

- ego-tree: optimal tree for a row (= given source)



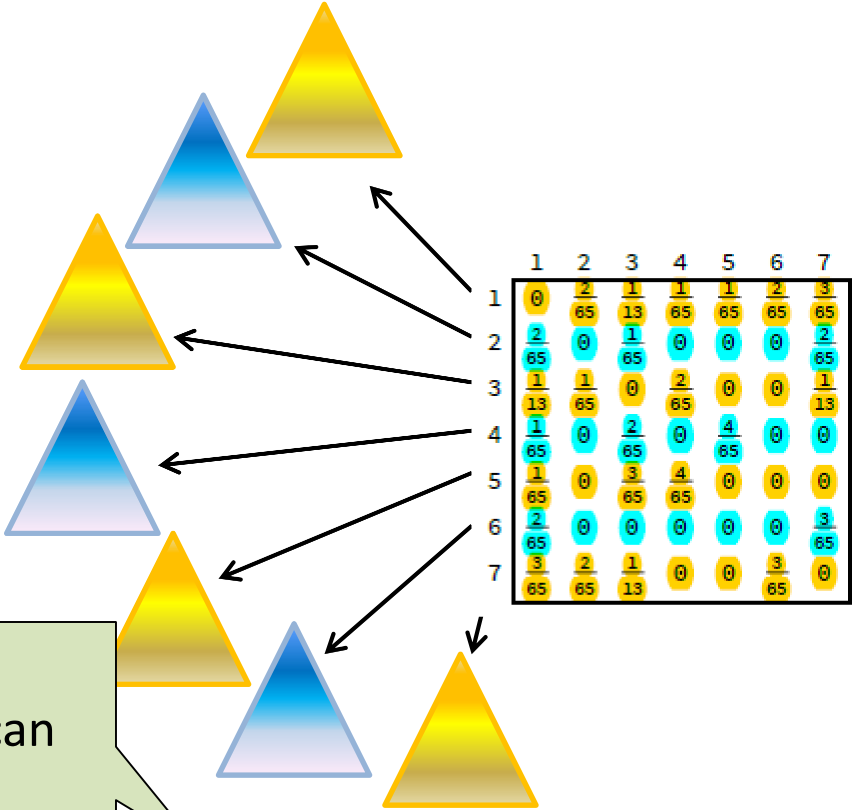


	1	2	3	4	5	6	7
1	0	$\frac{2}{65}$	$\frac{1}{13}$	$\frac{1}{65}$	$\frac{1}{65}$	$\frac{2}{65}$	$\frac{3}{65}$
2	$\frac{2}{65}$	0	$\frac{1}{65}$	0	0	0	$\frac{2}{65}$
3	$\frac{1}{13}$	$\frac{1}{65}$	0	$\frac{2}{65}$	0	0	$\frac{1}{13}$
4	$\frac{1}{65}$	0	$\frac{2}{65}$	0	$\frac{4}{65}$	0	0
5	$\frac{1}{65}$	0	$\frac{3}{65}$	$\frac{4}{65}$	0	0	0
6	$\frac{2}{65}$	0	0	0	0	0	$\frac{3}{65}$
7	$\frac{3}{65}$	$\frac{2}{65}$	$\frac{1}{13}$	0	0	$\frac{3}{65}$	0

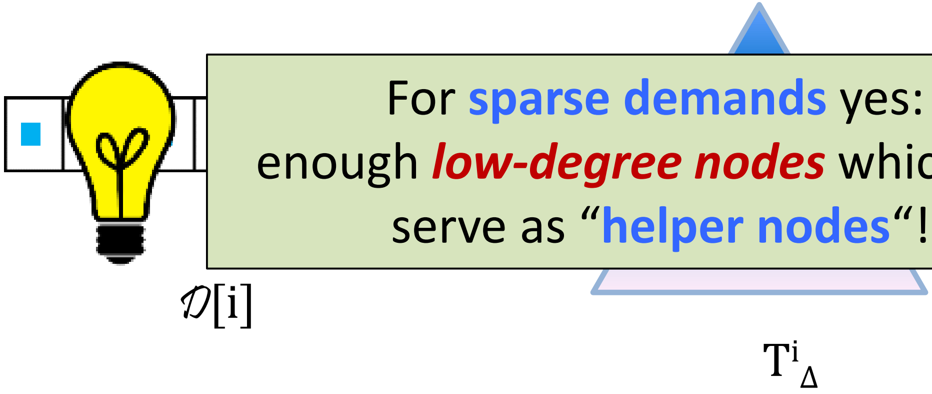
Can we merge the trees ***without distortion*** and ***keep degree low***?

Ego-Trees Revisited

- ego-tree: optimal tree for a row (= given source)



$$\begin{array}{c|ccccccc}
 & 1 & 2 & 3 & 4 & 5 & 6 & 7 \\
\hline
1 & 0 & \frac{2}{65} & \frac{1}{13} & \frac{1}{65} & \frac{1}{65} & \frac{2}{65} & \frac{3}{65} \\
2 & \frac{2}{65} & 0 & \frac{1}{65} & 0 & 0 & 0 & \frac{2}{65} \\
3 & \frac{1}{13} & \frac{1}{65} & 0 & \frac{2}{65} & 0 & 0 & \frac{1}{13} \\
4 & \frac{1}{65} & 0 & \frac{2}{65} & 0 & \frac{4}{65} & 0 & 0 \\
5 & \frac{1}{65} & 0 & \frac{3}{65} & \frac{4}{65} & 0 & 0 & 0 \\
6 & \frac{2}{65} & 0 & 0 & 0 & 0 & 0 & \frac{3}{65} \\
7 & \frac{3}{65} & \frac{2}{65} & \frac{1}{13} & 0 & 0 & \frac{3}{65} & 0
\end{array}$$

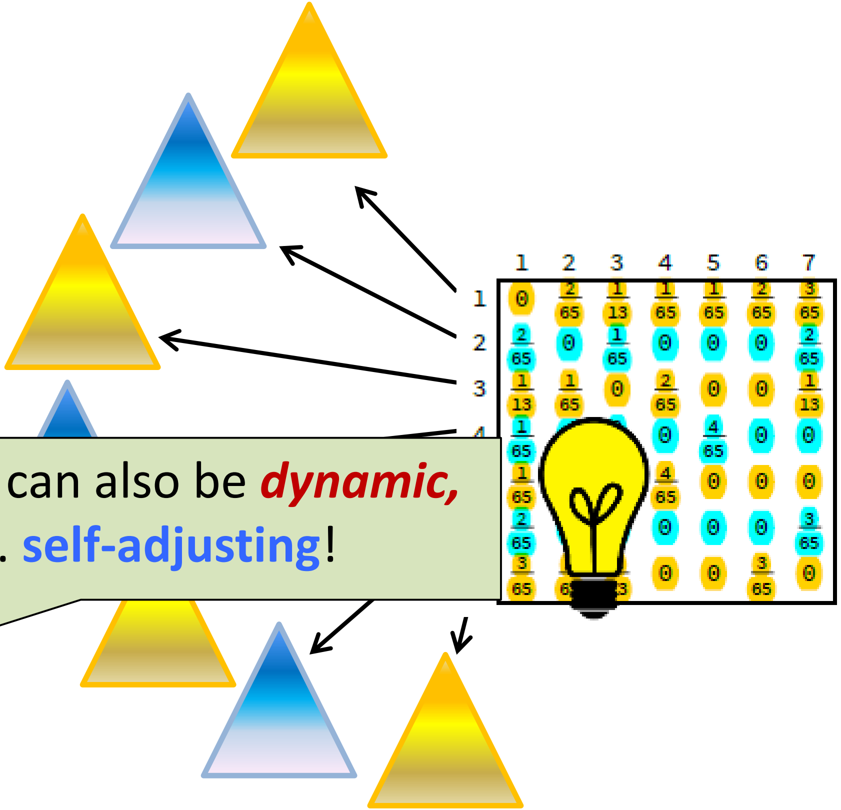


For **sparse demands** yes:
enough ***low-degree nodes*** which can
serve as “**helper nodes**“!

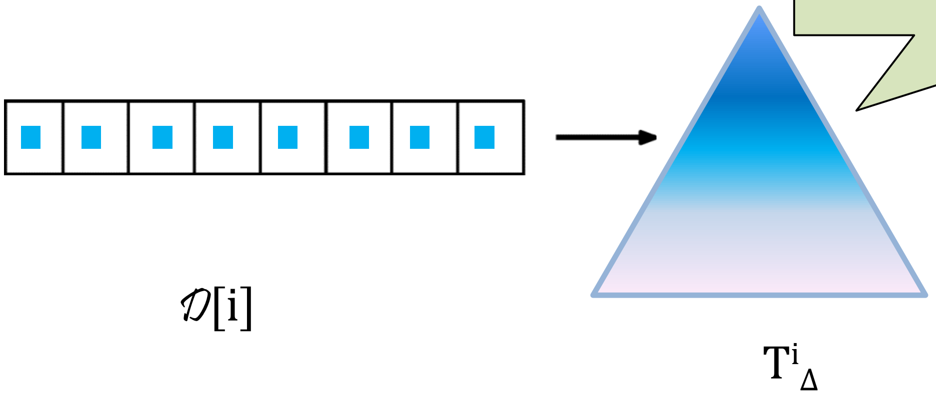
Can we merge the trees ***without distortion*** and ***keep degree low***?

Ego-Trees Revisited

- ego-tree: optimal tree for a row (= given source)



Ego-tree can also be ***dynamic,*** i.e. **self-adjusting**!



Can we merge the trees ***without distortion*** and ***keep degree low***?

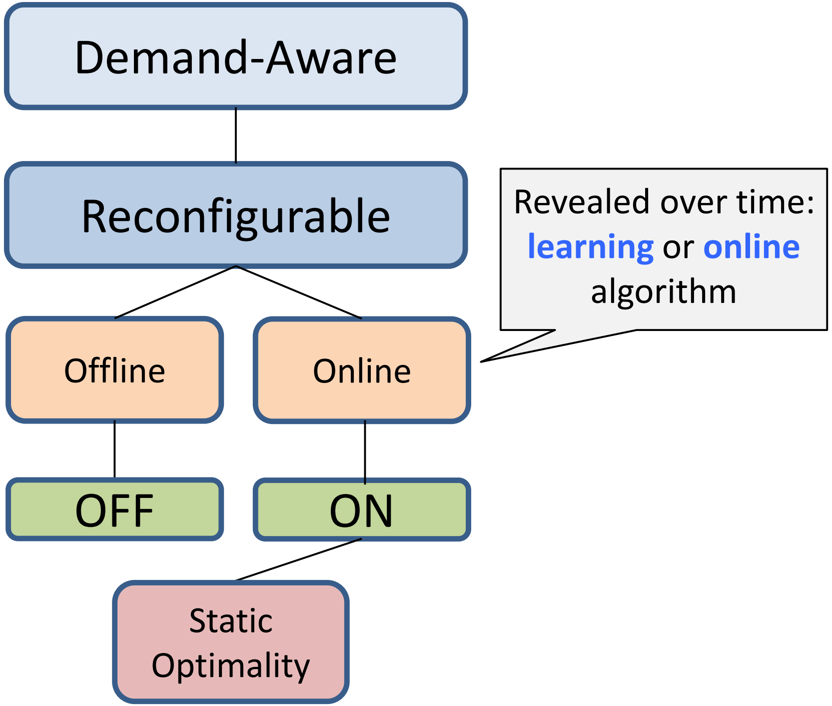
Other metrics for self-adjusting networks?

A Taxonomy: Reconfigurable Networks

Static Optimality:

“***Not worse than static*** which knows demand ahead of time!”

ρ = Cost(ON)/Cost(STAT*) is constant.



Demand-Aware

Reconfigurable

Offline

Online

OFF

ON

Static Optimality

Revealed over time: **learning** or **online** algorithm

Awareness

Topology

Input

Algorithm

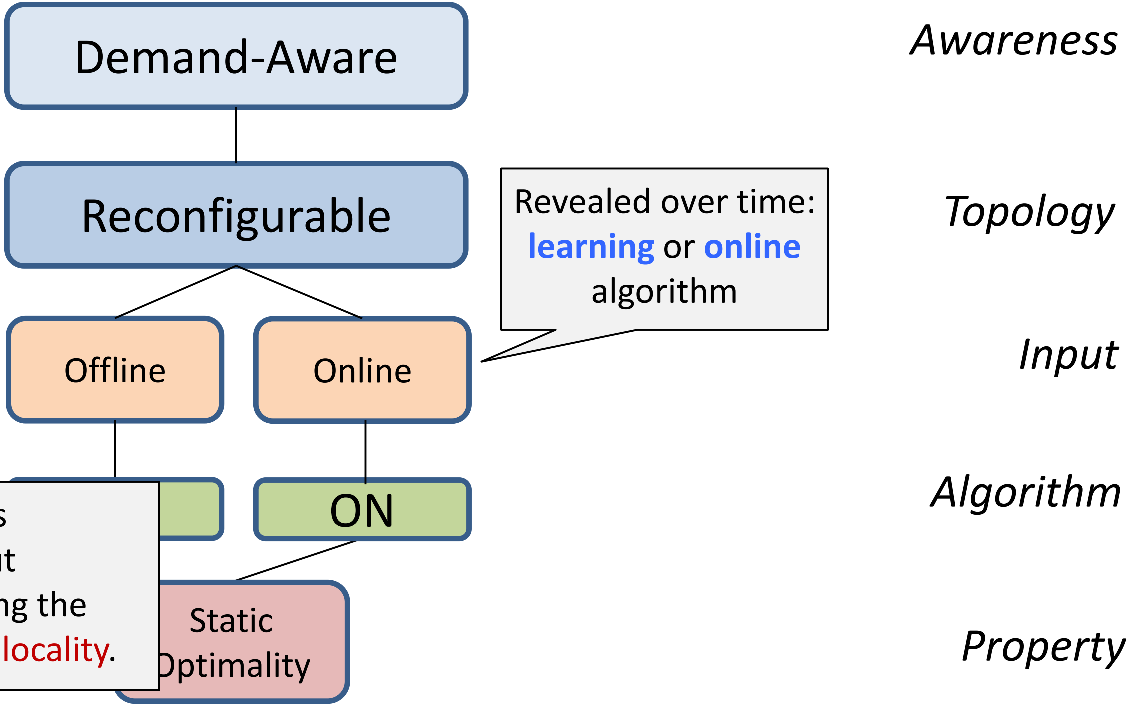
Property

A Taxonomy: Reconfigurable Networks

Static Optimality:

“***Not worse than static*** which knows demand ahead of time!”

ρ = Cost(ON)/Cost(STAT*) is constant.



Demand-Aware

Reconfigurable

Offline

Online

ON

Static Optimality

Revealed over time: **learning** or **online** algorithm

Awareness

Topology

Input

Algorithm

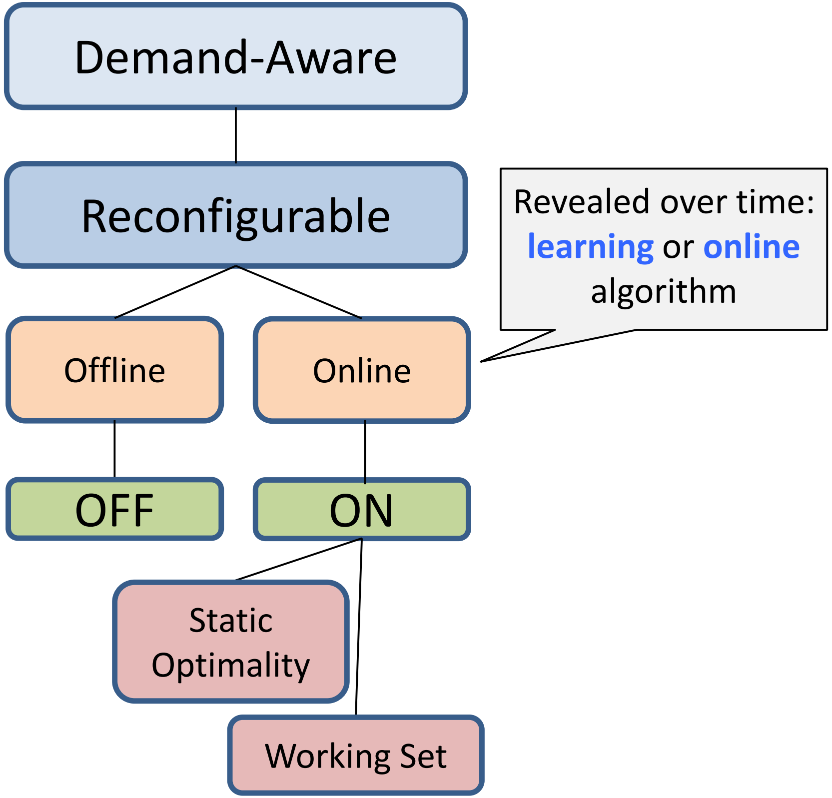
Property

Note: may be ***<<1***. ON has advantage of adjusting, but the disadvantage of not knowing the workload. E.g. if much temporal locality.

A Taxonomy: Reconfigurable Networks

Working Set Property:

"***Topological distance*** between nodes ***proportional to how recently they communicated***!"



Demand-Aware

Reconfigurable

Offline

Online

Revealed over time: **learning** or **online** algorithm

OFF

ON

Static Optimality

Working Set

Awareness

Topology

Input

Algorithm

Property

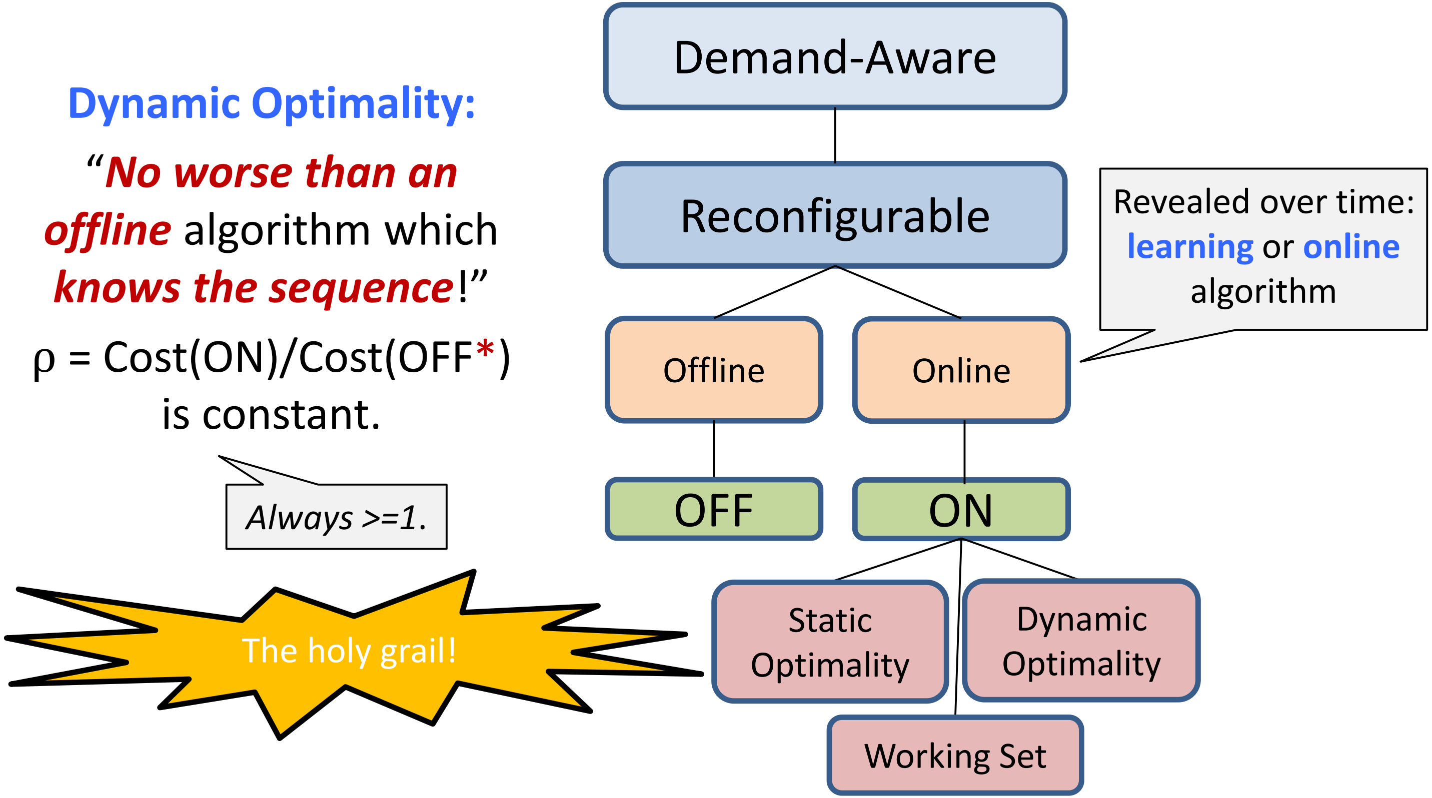
A Taxonomy: Reconfigurable Networks

Dynamic Optimality:

"***No worse than an offline*** algorithm which ***knows the sequence***!"

ρ = Cost(ON)/Cost(OFF*) is constant.

Always >=1.



Revealed over time: **learning** or **online** algorithm

Awareness

Topology

Input

Algorithm

Property

So: How *much* structure/entropy is there?

How to ***measure*** it?
How to distinguish between **temporal** and **non-temporal** structure?
More ***tricky***!

Often only intuitions in the literature…

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

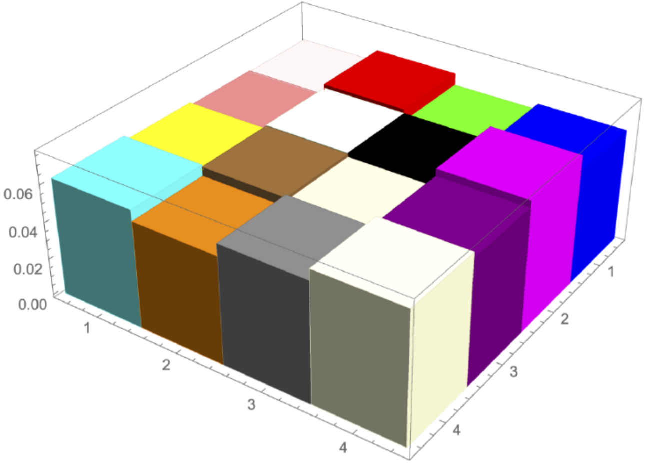
“only a few ToRs switches are hot and most of their traffic goes to a few other ToRs”

“over 90% bytes flow in elephant flows”

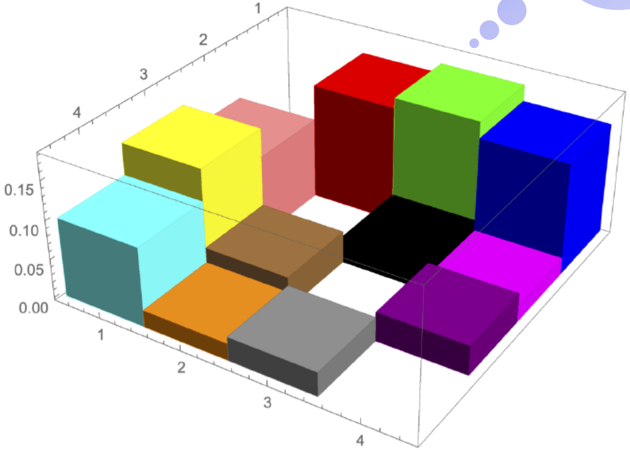
… and it *is* intuitive!

Non-temporal Structure

Color = comm. pair



VS



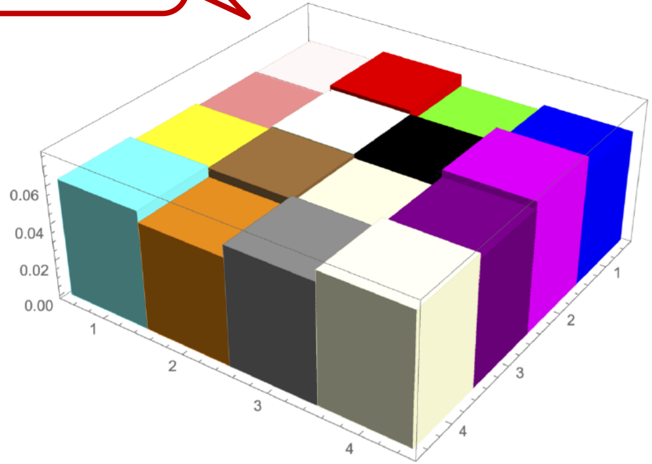
Traffic matrix of two different **distributed ML** applications (GPU-to-GPU):

Which one has *more structure*?

… and it *is* intuitive!

Non-temporal Structure

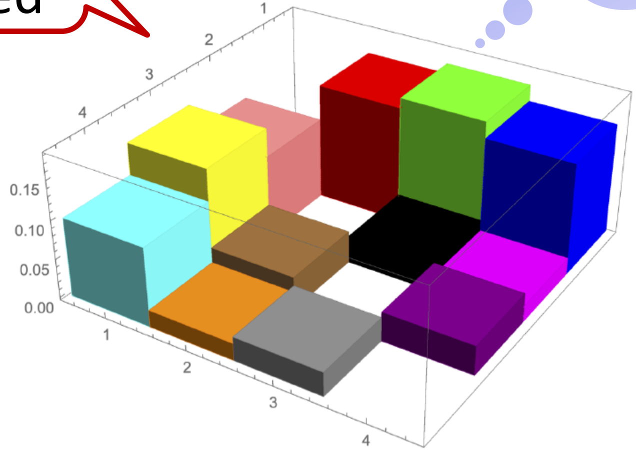
More uniform



VS

More skewed

Color = comm. pair

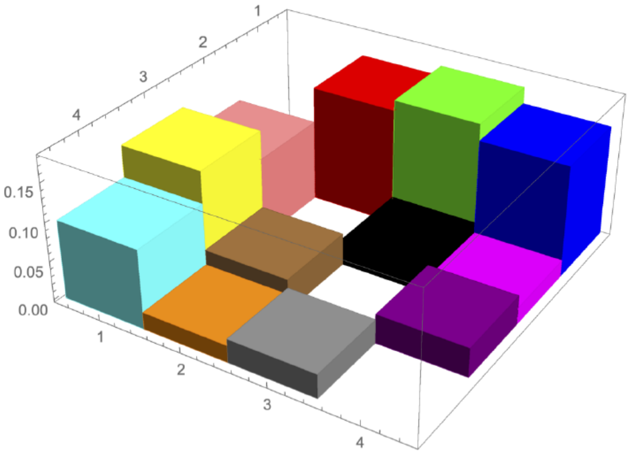


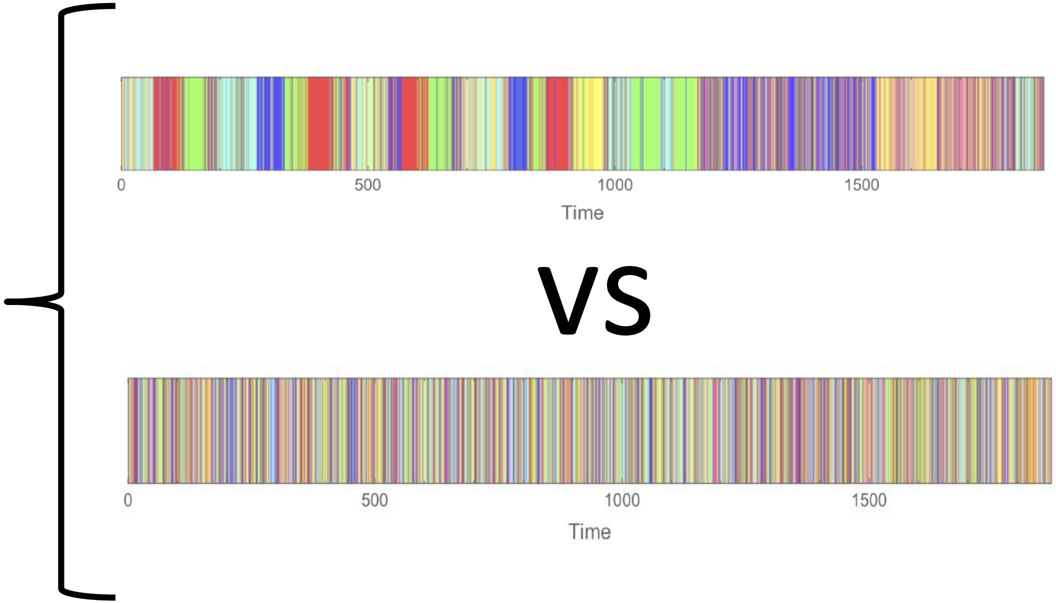
Traffic matrix of two different **distributed ML** applications (GPU-to-GPU):

Which one has *more structure*?

… and it *is* intuitive!

Temporal Structure



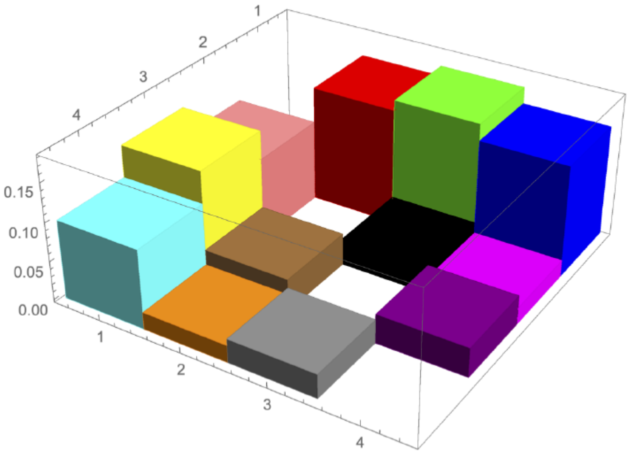


Two different ways to generate *same traffic matrix* (same non-temporal structure):

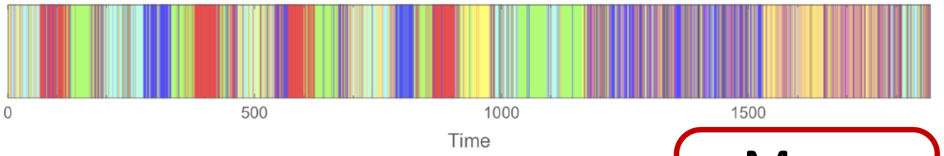
Which one has *more structure*?

… and it *is* intuitive!

Temporal Structure

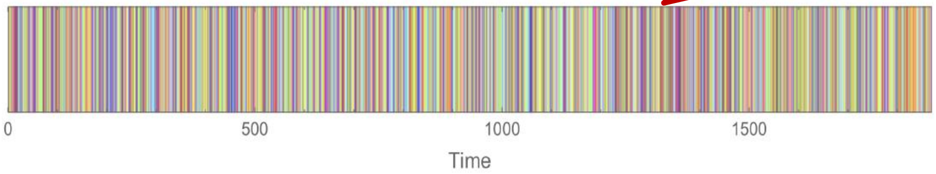


More bursty



VS

More random



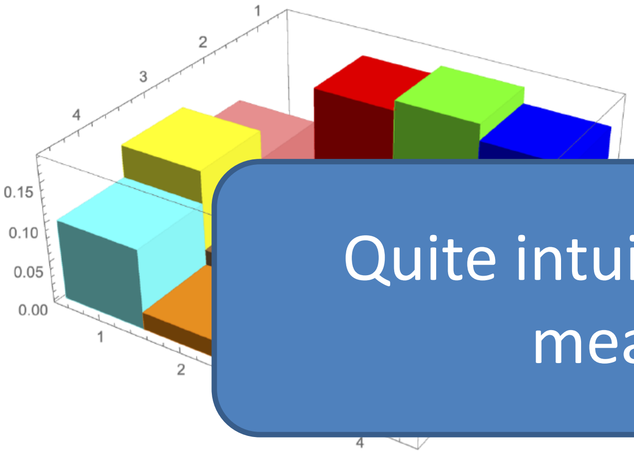
Two different ways to generate *same traffic matrix* (same non-temporal structure):

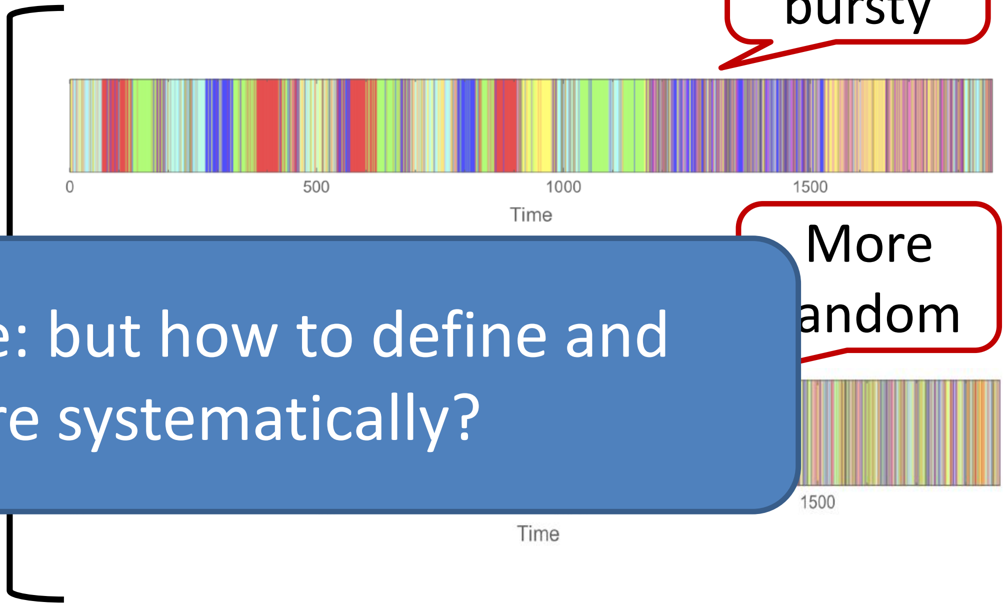
Which one has *more structure*?

… and it *is* intuitive!

Temporal Structure

More bursty





More andom

Quite intuitive: but how to define and measure systematically?

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

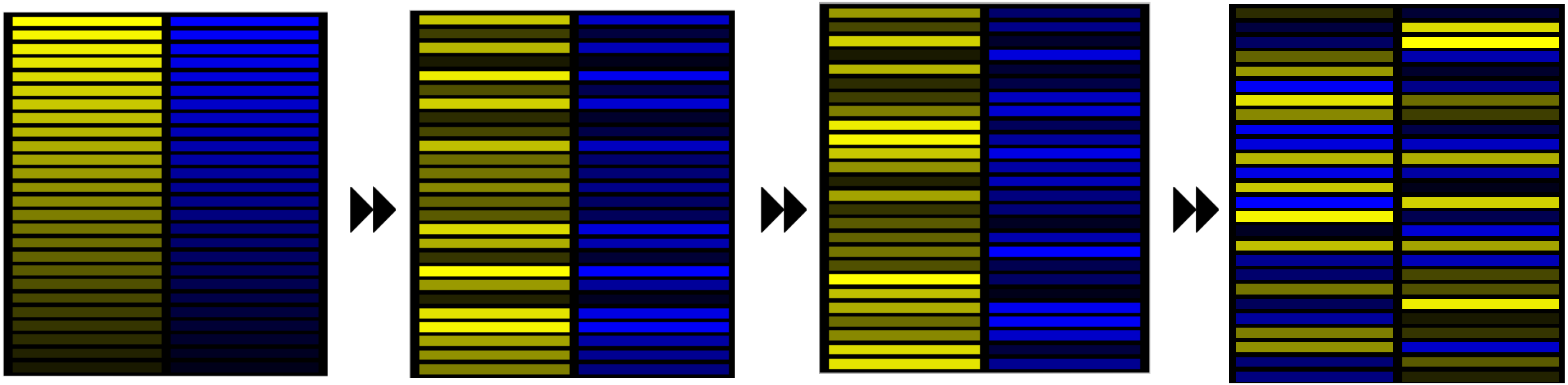
Which one has *more structure*?

The Trace Complexity

- An **information-theoretic**: what is the entropy (rate) of a traffic trace?

- Systematic „**shuffle&compress**“ methodology
  - Remove structure by iterative *randomization*
  - Difference of compression *before and after* randomization: structure

The Trace Complexity



Original src-dst trace

Randomize rows

Randomized columns

Uniform trace

Increasing complexity (systematically randomized)

More structure (compresses better)

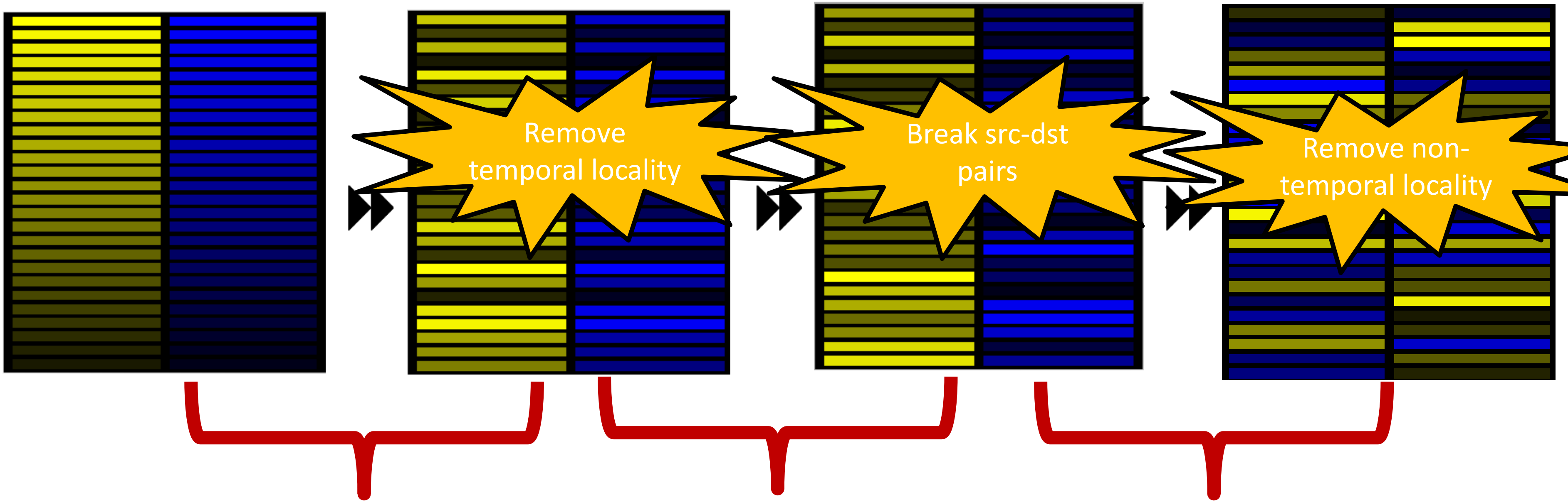
The Trace Complexity

Original src-dst trace

Randomize rows

Randomized columns

Uniform trace



Remove temporal locality

Break src-dst pairs

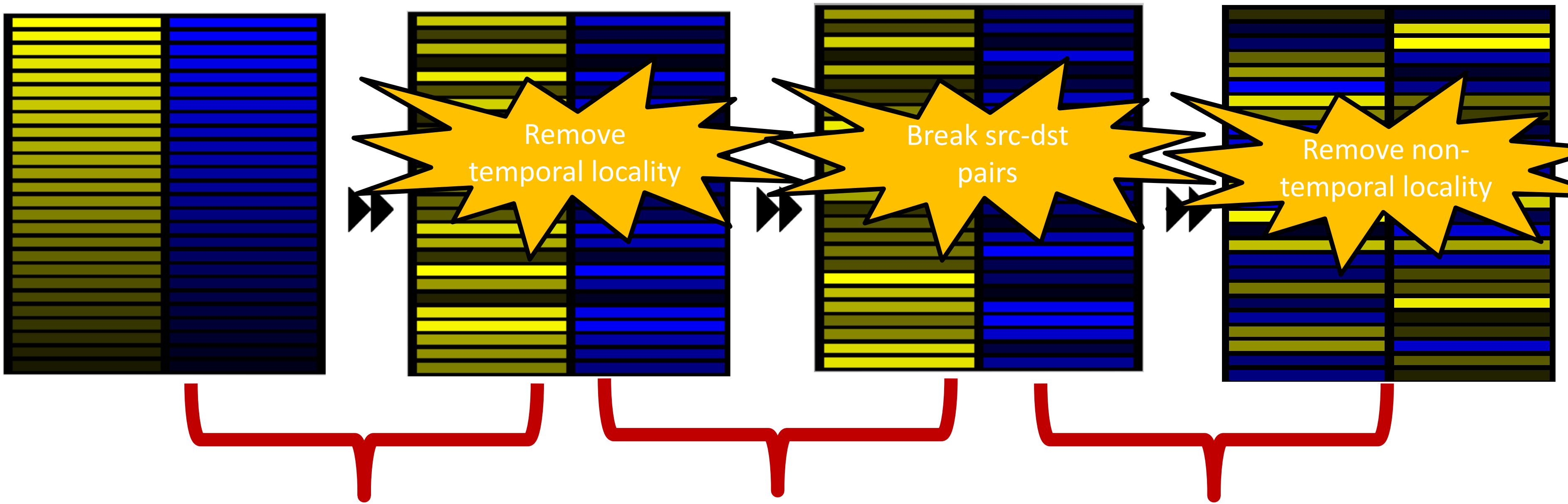
Remove non-temporal locality

Difference in compression?

Difference in compression?

Difference in compression?

The Trace Complexity



Original src-dst trace

Randomize rows

Randomized columns

Uniform trace

Remove temporal locality

Break src-dst pairs

Remove non-temporal locality

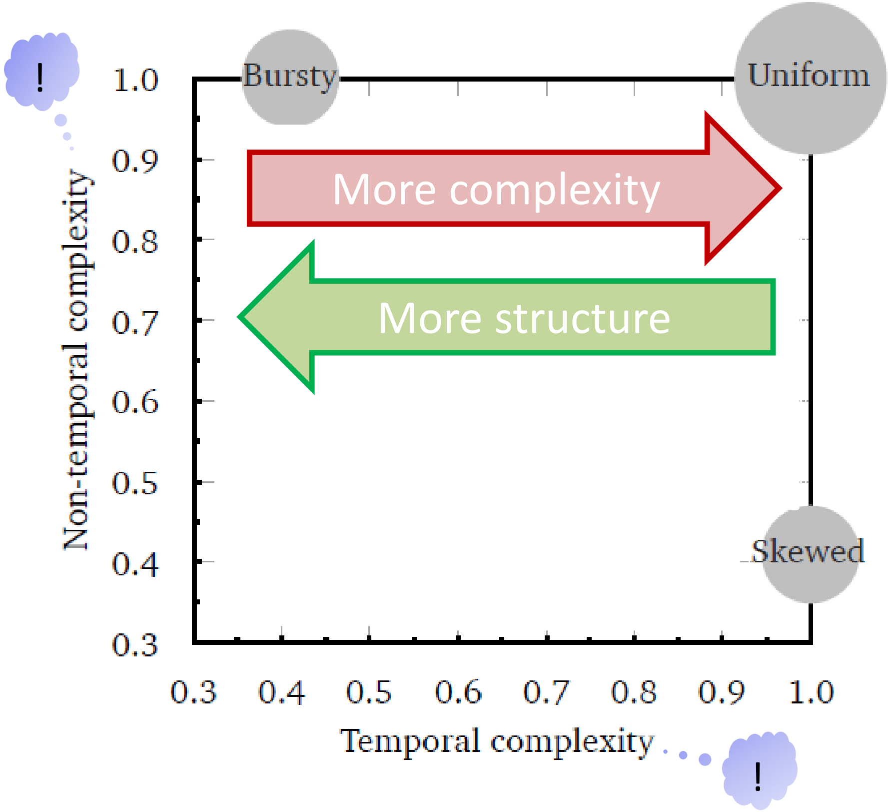
Difference in compression?

Difference in compression?

Difference in compression?

Can be used to define a „complexity map“!

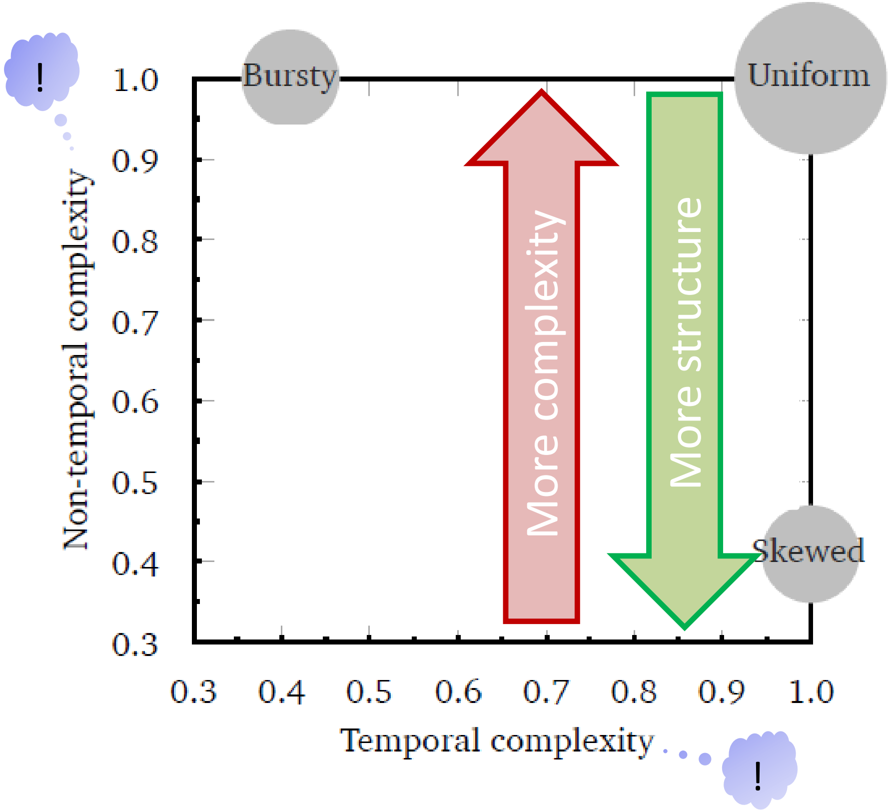
The Complexity Map



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

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

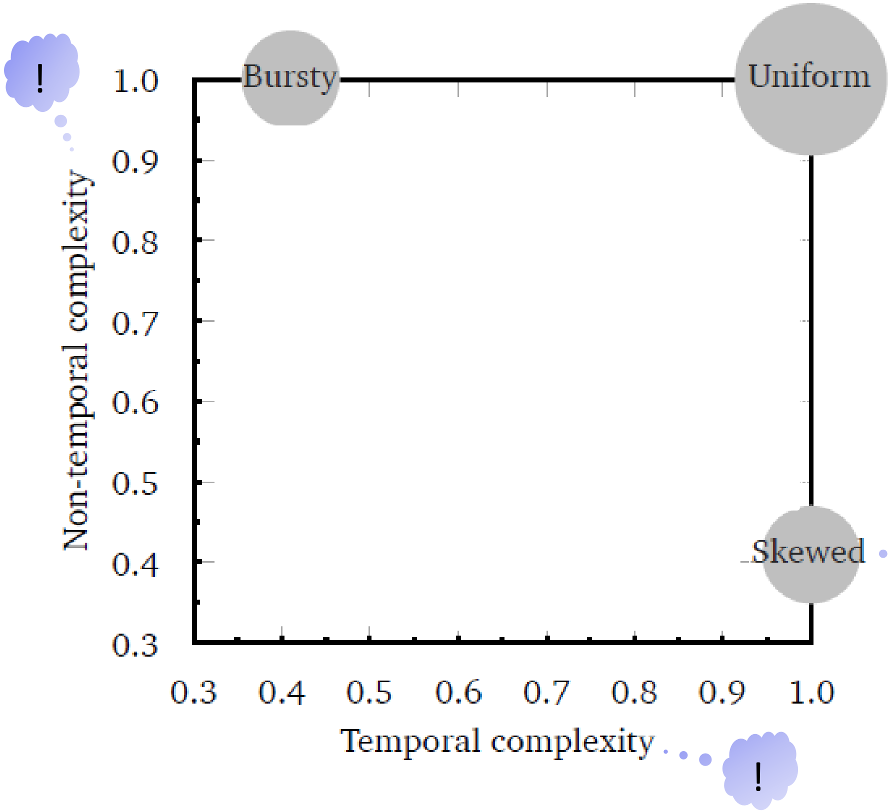
The Complexity Map



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

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

The Complexity Map

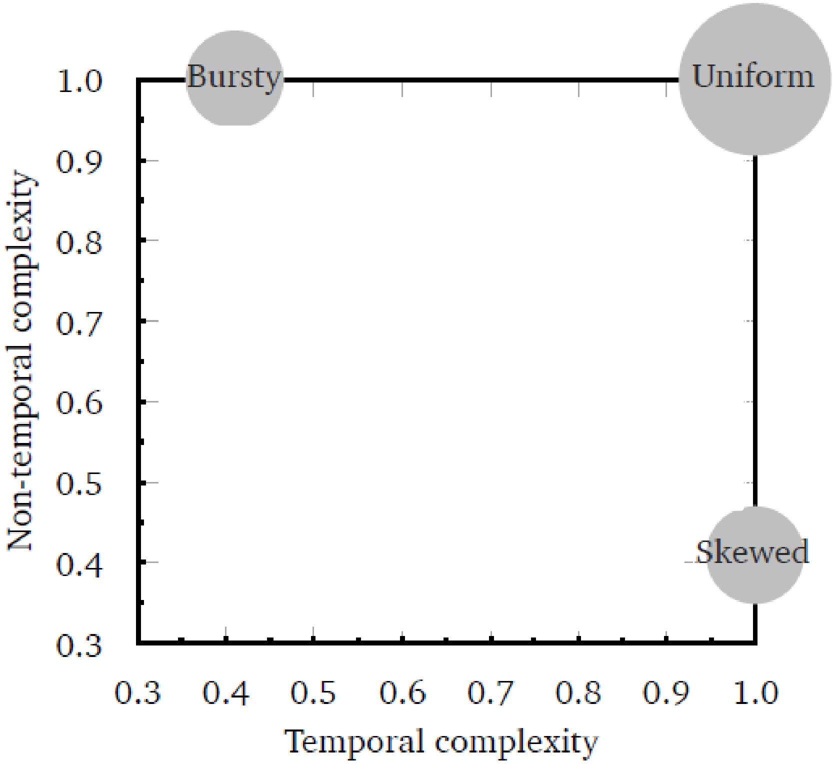


Size = product of entropy

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

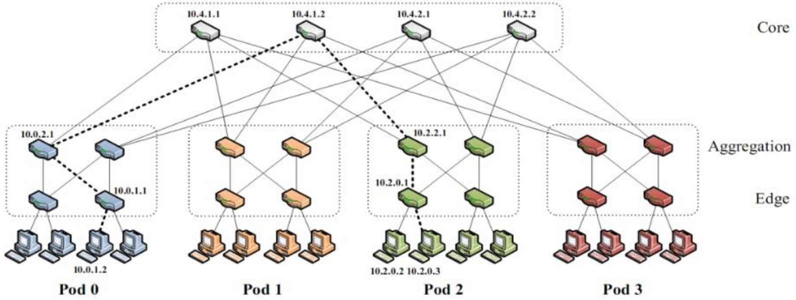
Measuring the Complexity of Packet Traces.
Avin, Ghobadi, Griner, Schmid. ArXiv 2019.

The Complexity Map

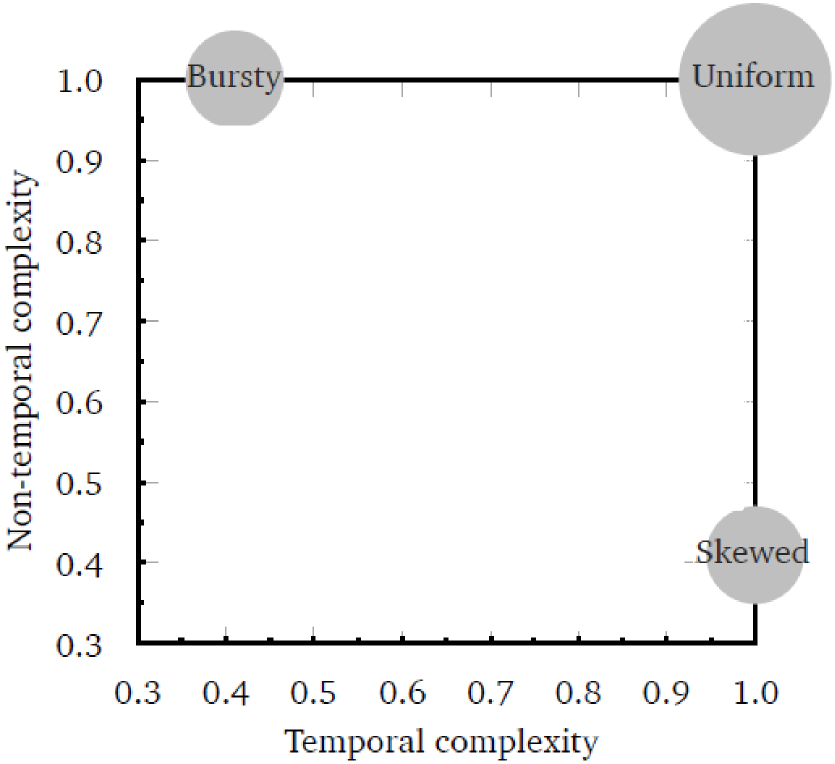


Uniform: Today’s datacenters

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

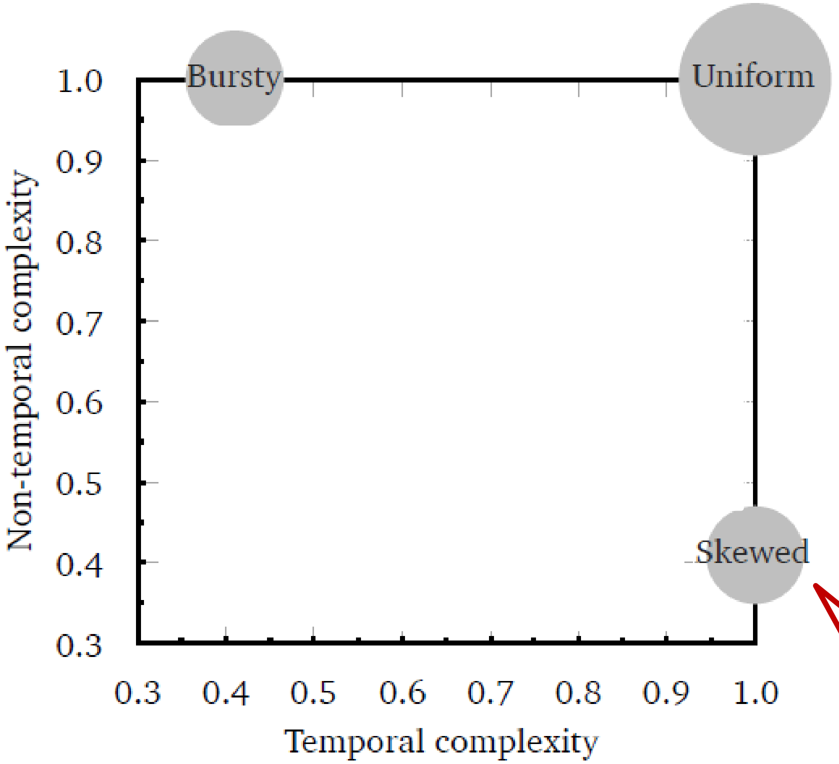


The Complexity Map



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

The Complexity Map

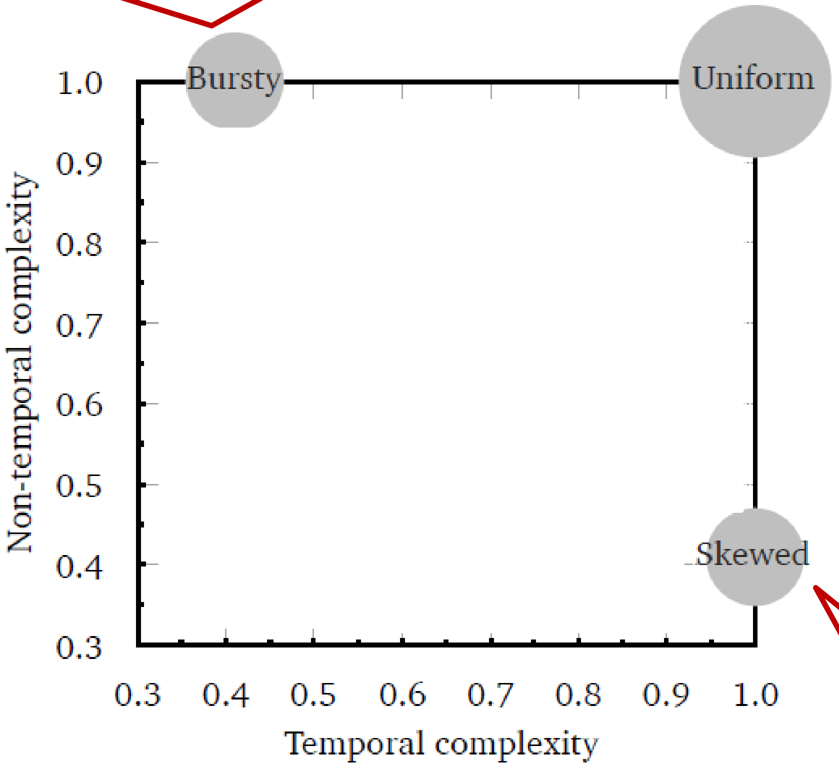


Good in the worst case ***but***: cannot leverage different **temporal** and **non-temporal** structures of traffic traces!

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

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

nplexity Map



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

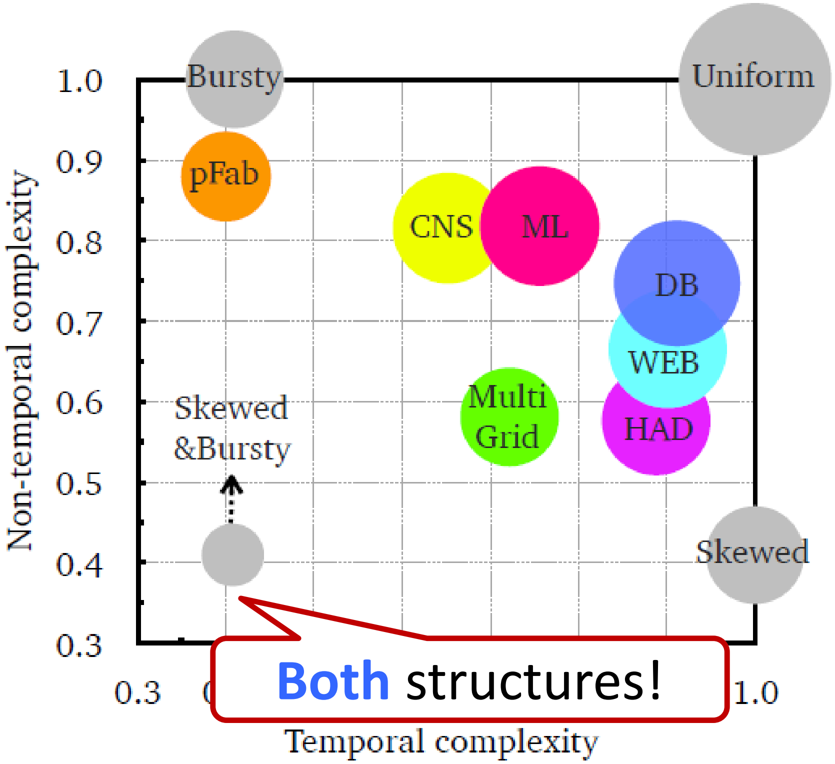
Non-temporal structure could be exploited already with ***static demand-aware networks***!

The Complexity Map

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

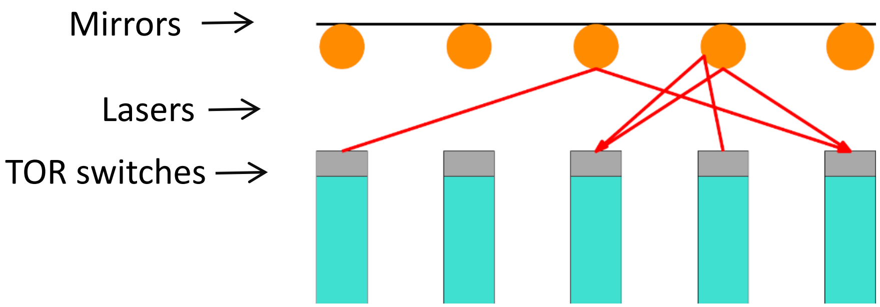
- **Facebook** clusters: DB, WEB, HAD
- **HPC** workloads: CNS, Multigrid
- Distributed **Machine Learning** (ML)
- Synthetic traces like **pFabric**

The Complexity Map



Both structures!

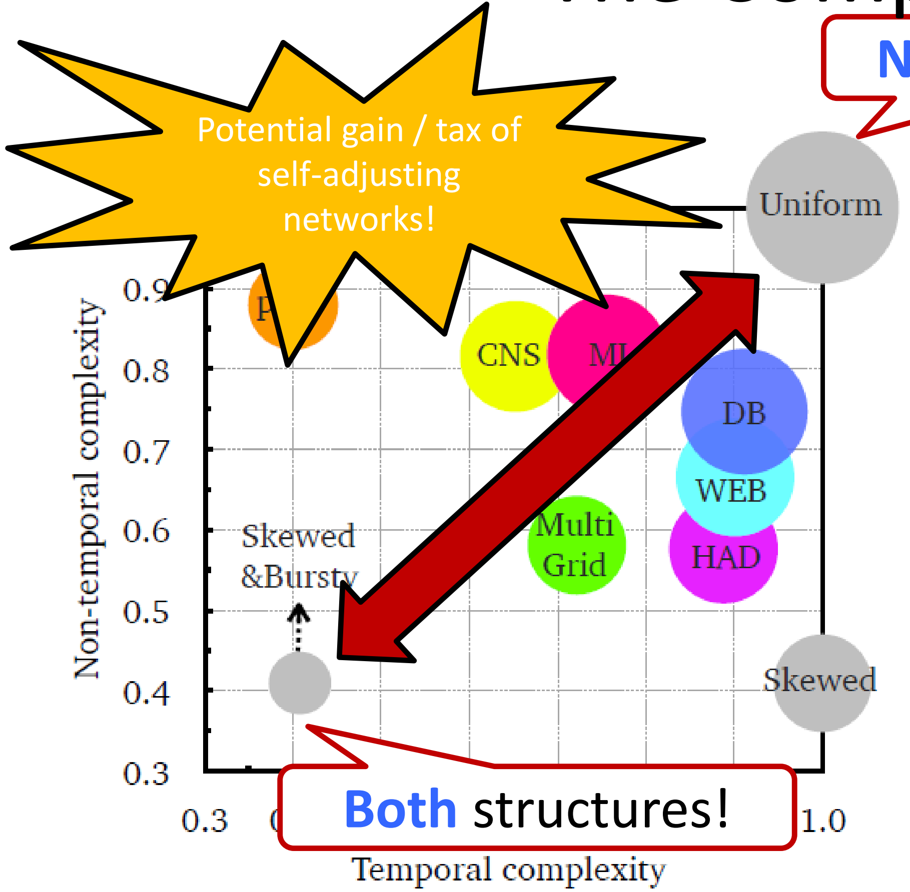
Goal: Design **self-adjusting networks** which leverage ***both*** dimensions of structure!


Mirrors →

Lasers →

TOR switches →

The Complexity Map

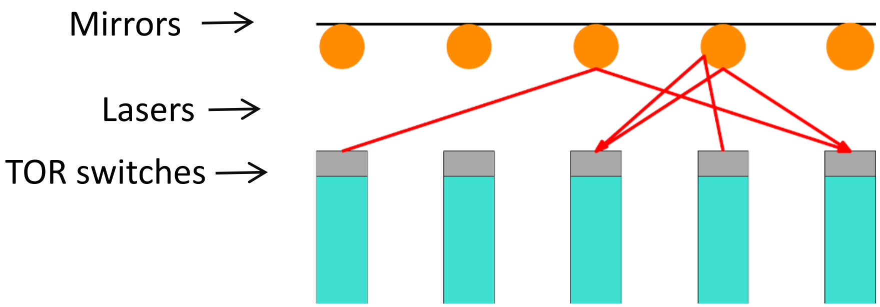


Potential gain / tax of self-adjusting networks!

No structure!

Both structures!

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

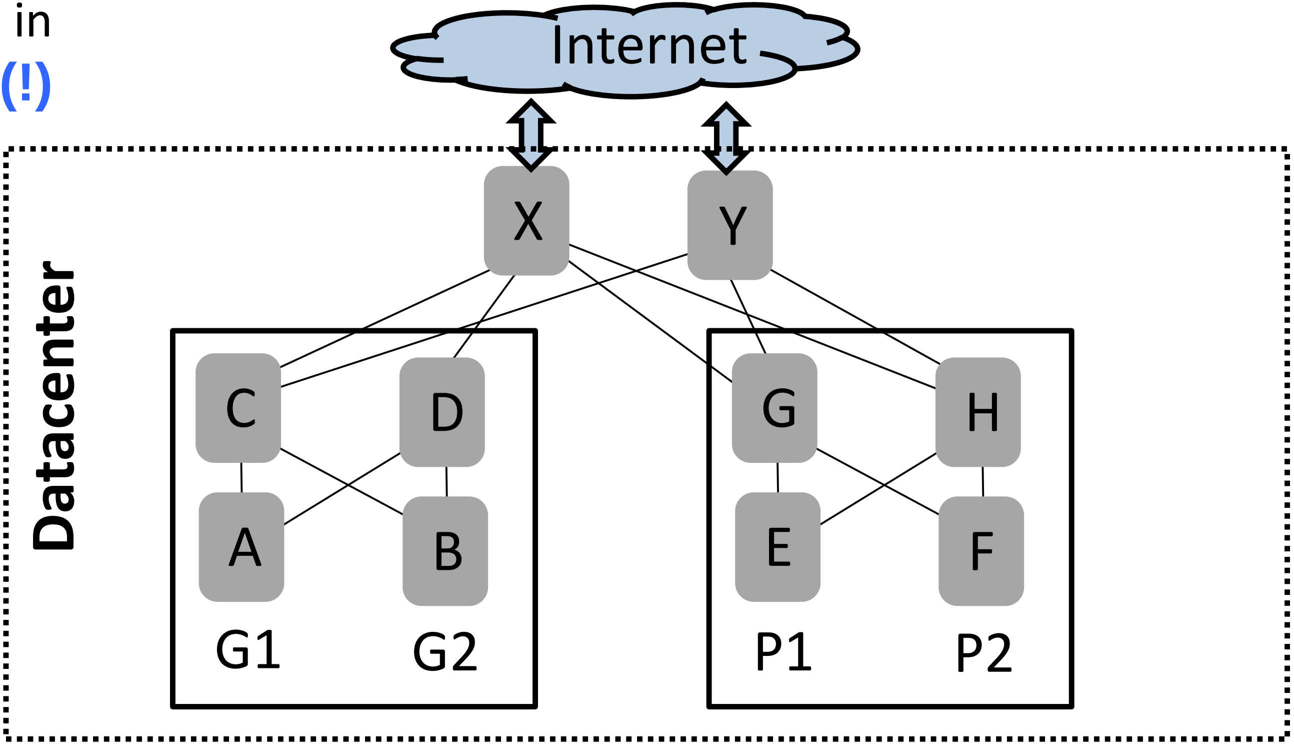


Roadmap

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

Reasoning About Failures is Hard

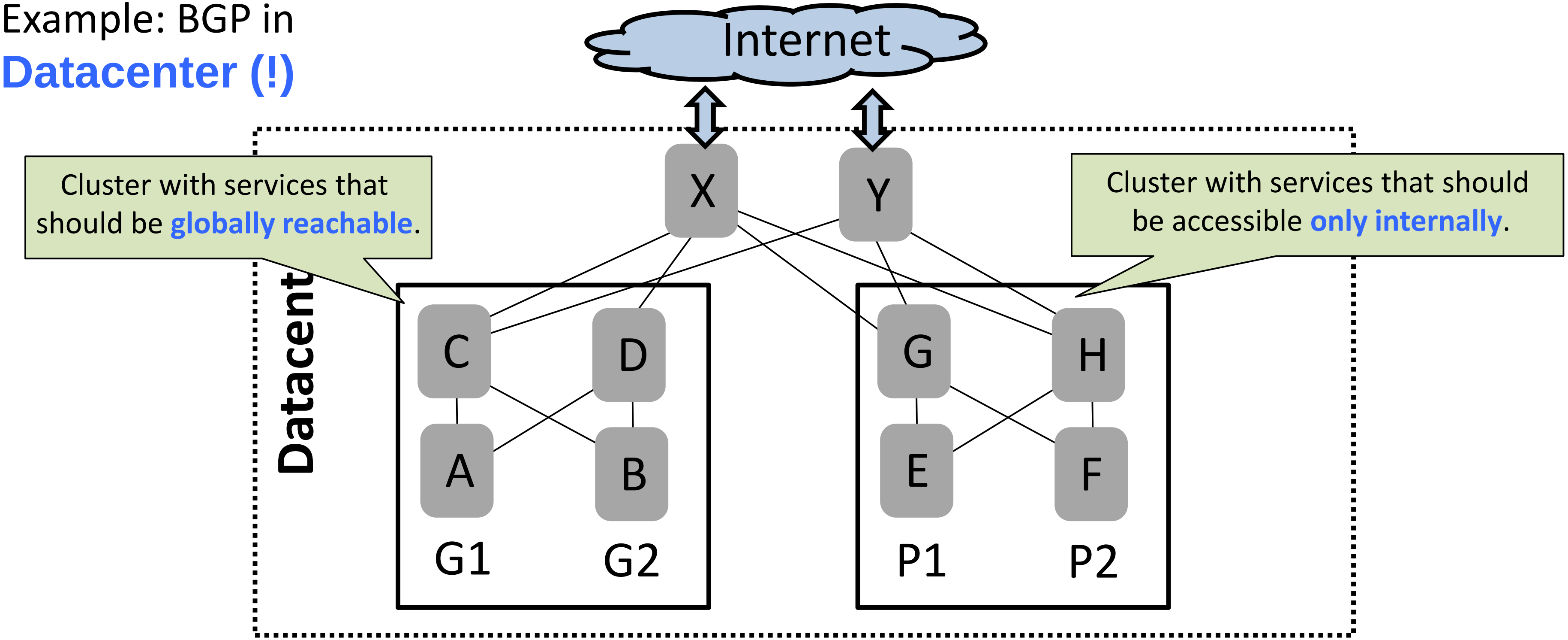
Example: BGP in
Datacenter (!)



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

Reasoning About Failures is Hard

Example: BGP in
Datacenter (!)



Cluster with services that should be **globally reachable**.

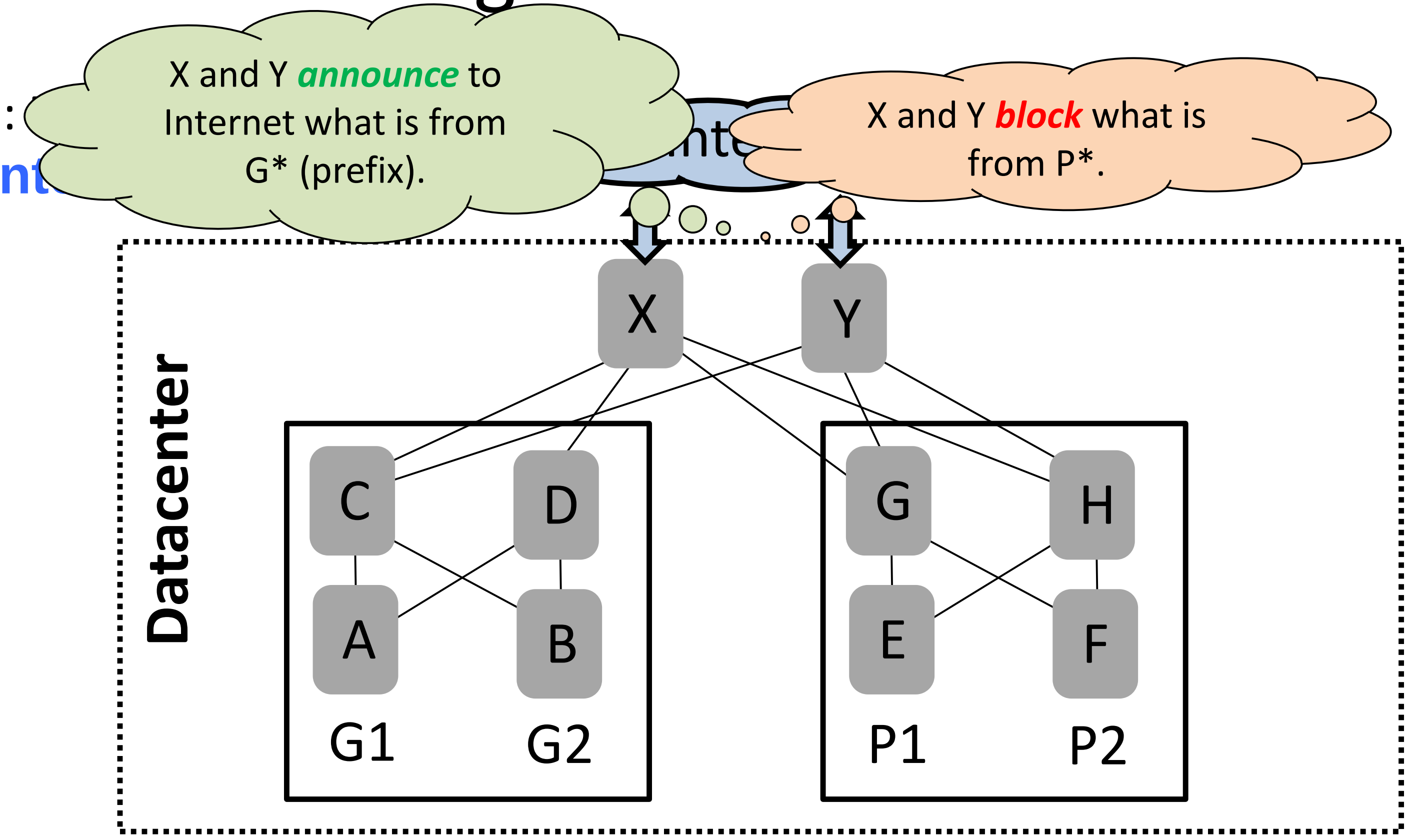
Cluster with services that should be accessible **only internally**.

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

Reasoning About Failures is Hard

Example:

Datacent



X and Y ***announce*** to Internet what is from G* (prefix).

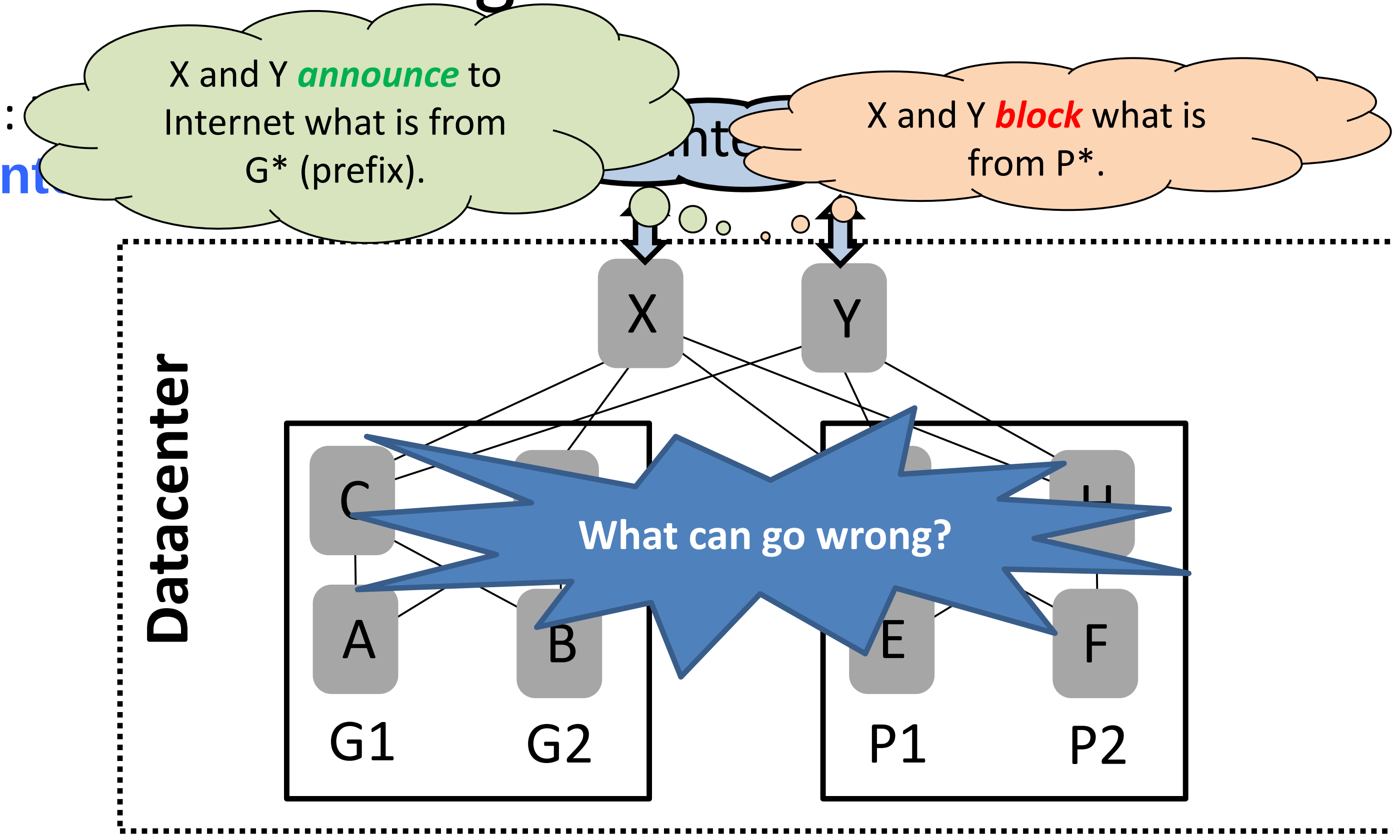
X and Y ***block*** what is from P*.

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

Reasoning About Failures is Hard

Example:

Datacent

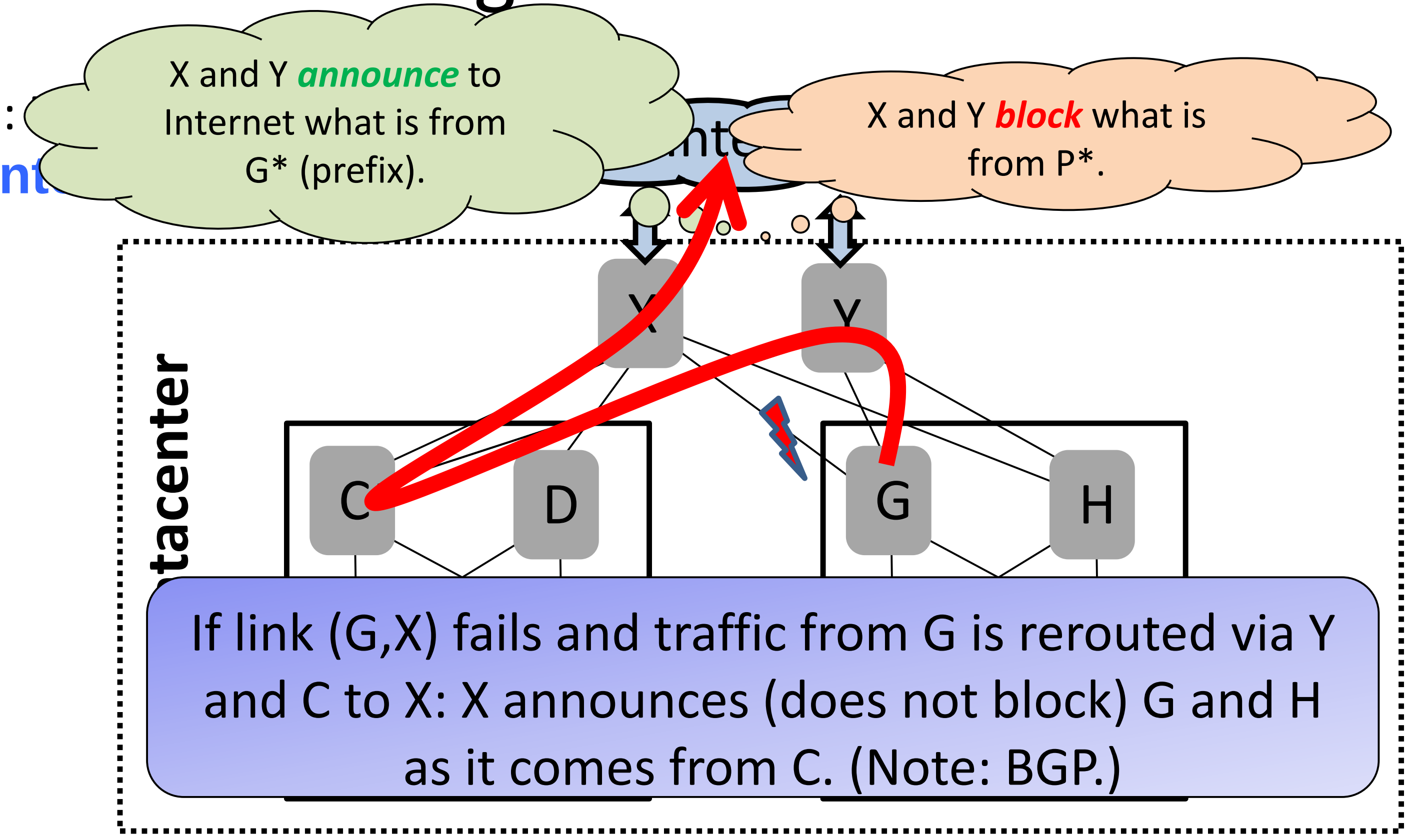


Credits: Beckett et al. (SIGCOMM 2016): Bridging Network-wide Objectives and Device-level Configurations.

Reasoning About Failures is Hard

Example:

Datacent



X and Y ***announce*** to Internet what is from G* (prefix).

X and Y ***block*** what is from P*.

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.)

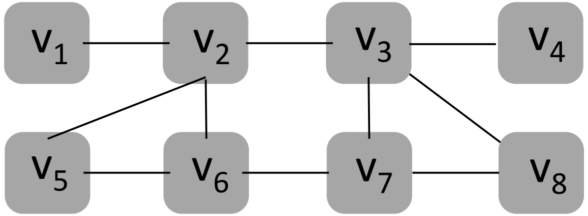
Credits: Beckett et al. (SIGCOMM 2016): Bridging Network-wide Objectives and Device-level Configurations.

Managing Complex Networks is Hard for Humans

Another Case for Automation!

Case Study: Self-Repairing MPLS Networks

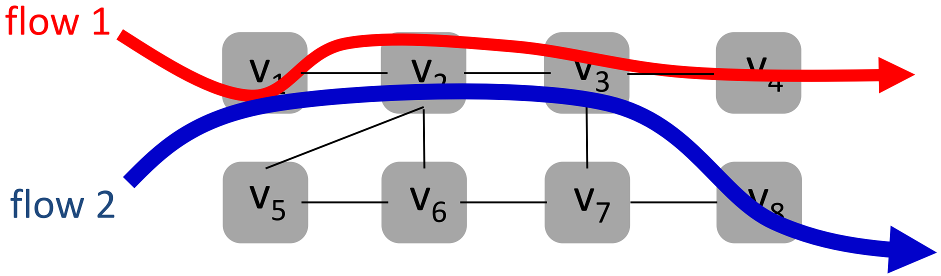
- MPLS: forwarding based on **top label** of label **stack**



Default routing of
two flows

Case Study: Self-Repairing MPLS Networks

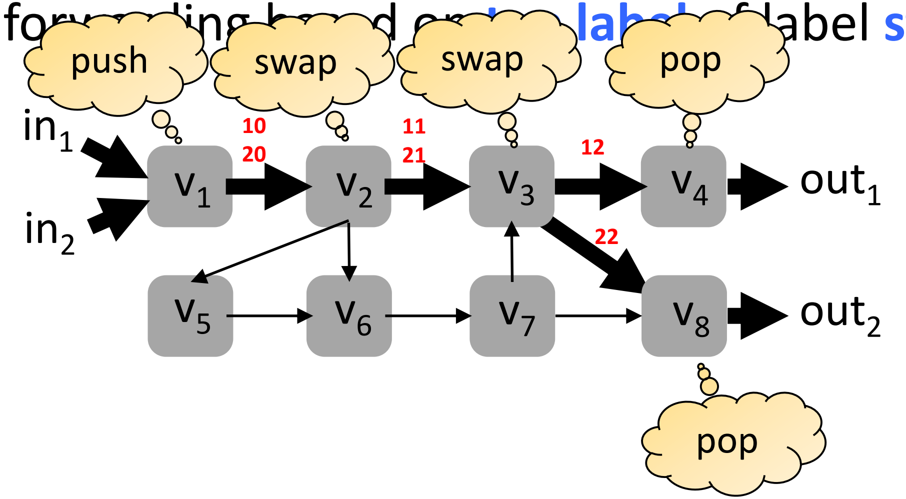
- MPLS: forwarding based on **top label** of label **stack**



Default routing of two flows

Case Study: Self-Repairing MPLS Networks

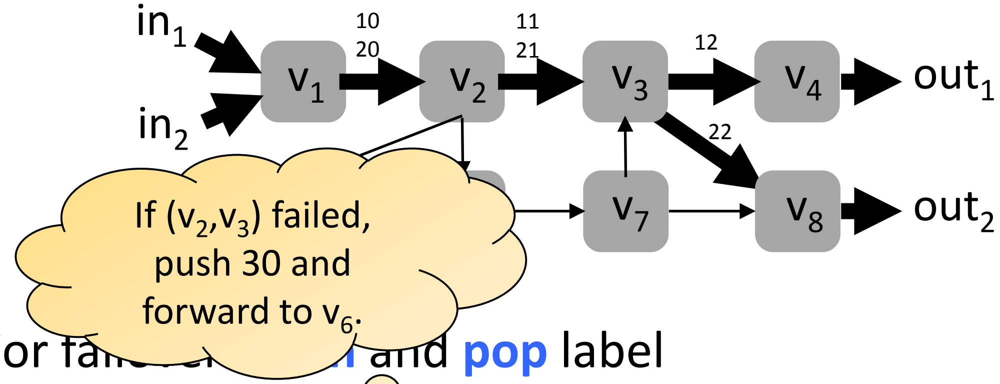
- MPLS: forwarding based on **top label** of label **stack**



Default routing of two flows

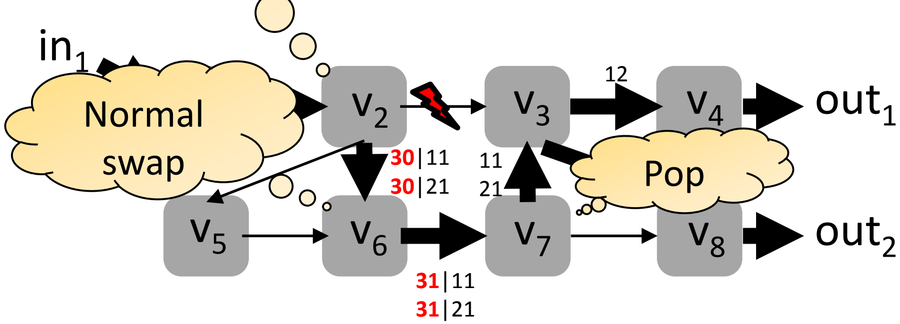
Fast Reroute Around *1 Failure*

- MPLS: forwarding based on **top label** of label **stack**



Default routing of two flows

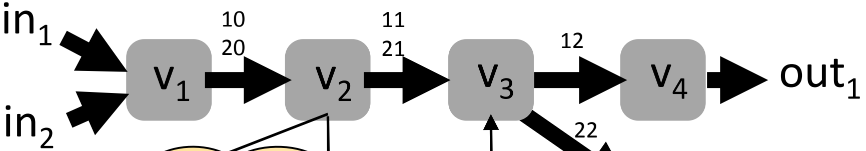
- For fa [illegible] and **pop** label



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

Fast Reroute Around *1 Failure*

- MPLS: forwarding based on **top label** of label **stack**

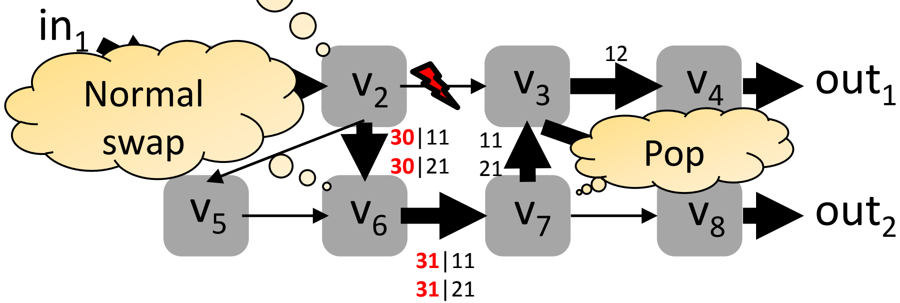


Default routing of two flows

If (v$_2$,v$_3$
push
forward to v$_6$.

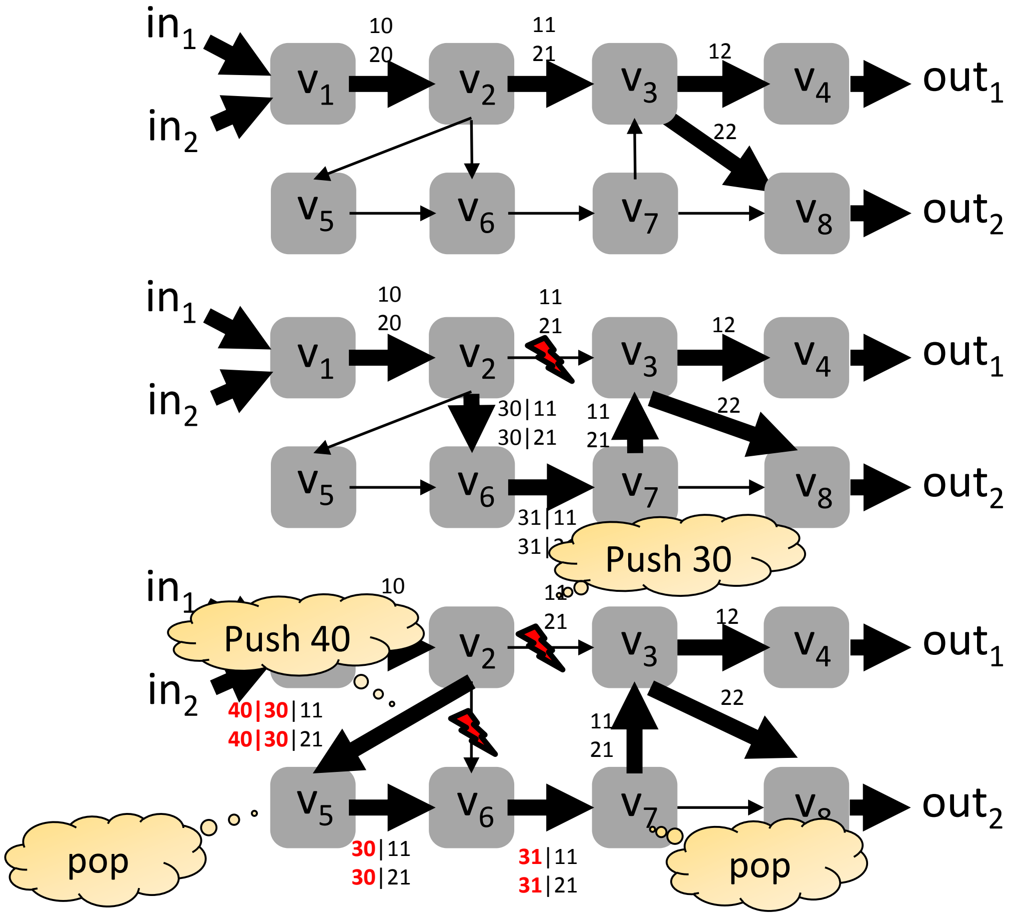
What about multiple link failures?

- For fa and **pop** label



One failure: push 30: route around (v$_2$,v$_3$)

2 Failures: Push *Recursively*



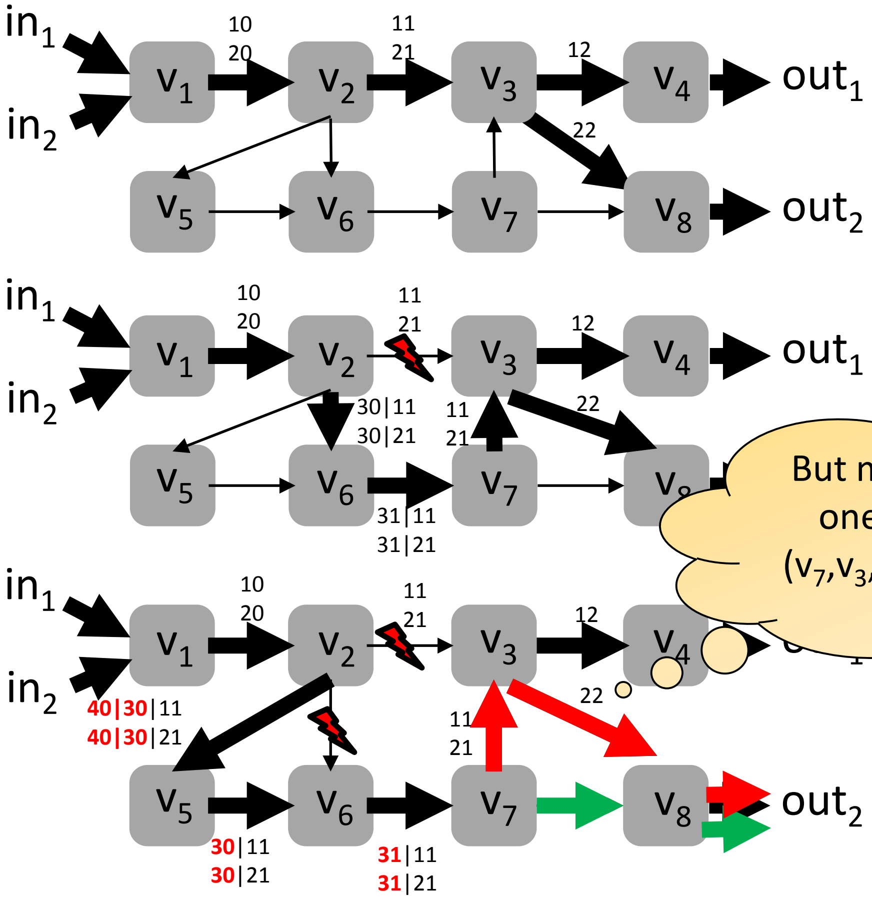
Original Routing

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)

2 Failures: Push *Recursively*



Original Routing

One failure: push 30:

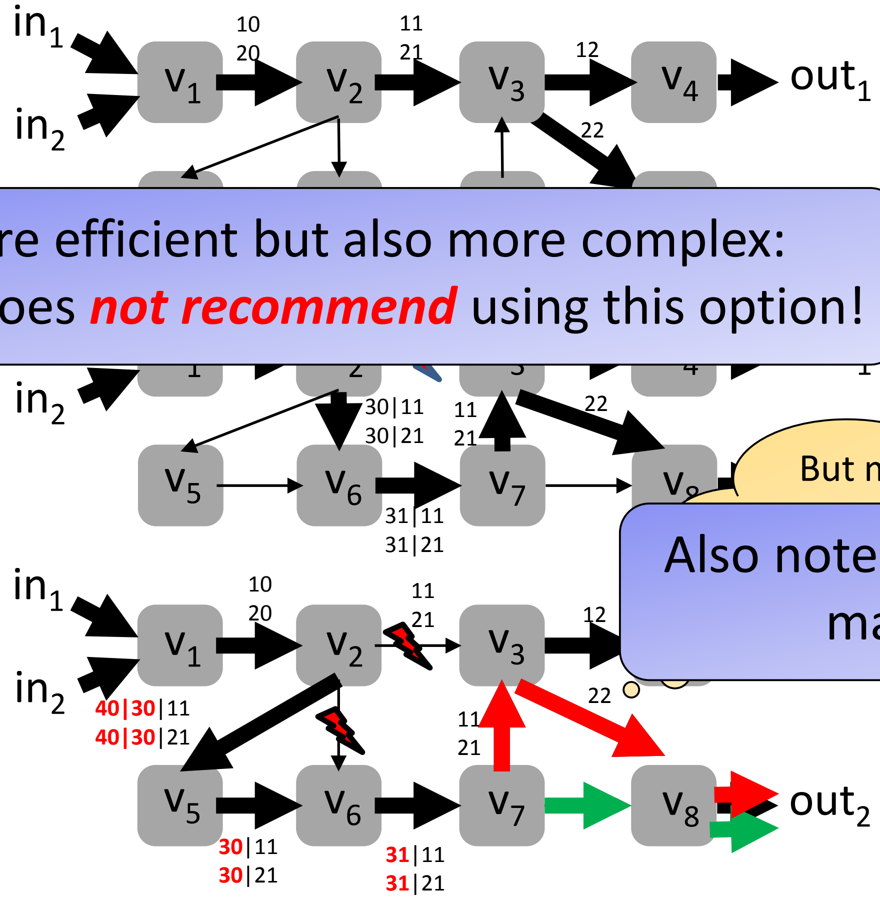
)

But masking links one-by-one can be inefficient: (v_7,v_3,v_8) could be shortcut to (v_7,v_8).

30: route around (v_2,v_3)

Push recursively 40: route around (v_2,v_6)

2 Failures: Push *Recursively*



Original Routing

More efficient but also more complex:
Cisco does ***not recommend*** using this option!

One failure: push 30:

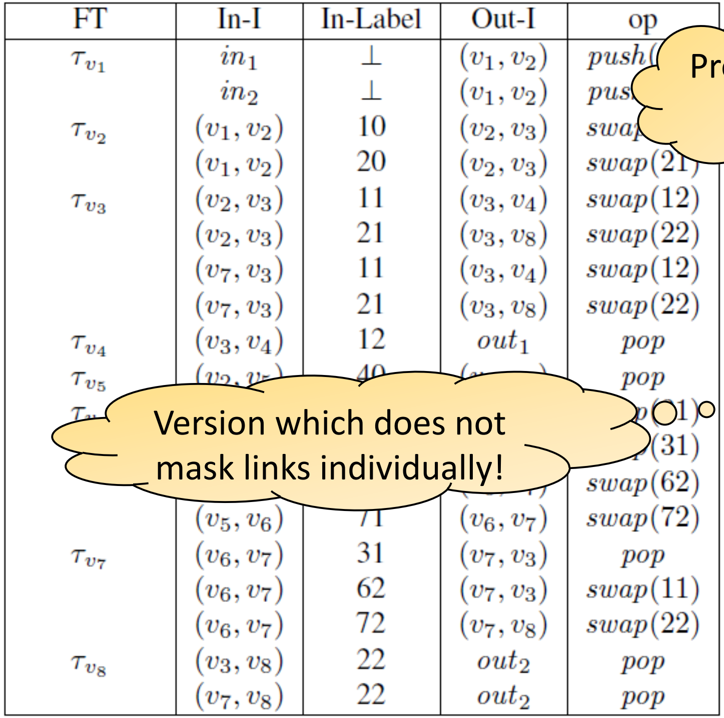
But masking links one-by-

Also note: due to push, ***header size*** may grow arbitrarily!

around (v_2,v_3)

Push recursively 40:
route around (v_2,v_6)

Reasoning About Low-Level Rules is Hard



FT	In-I	In-Label	Out-I	op
τ_{v_1}	in_1	$\bot$	(v_1, v_2)	[illegible]
	in_2	$\bot$	(v_1, v_2)	[illegible]
τ_{v_2}	(v_1, v_2)	10	(v_2, v_3)	[illegible]
	(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	[illegible]	pop
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]	$swap(62)$
	(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

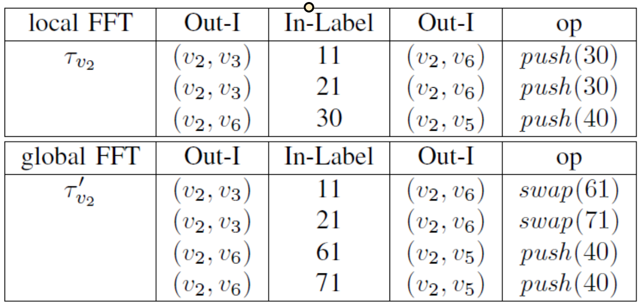
Protected link

Alternative link

Label

Version which does not mask links individually!

Flow Table



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)	$push(40)$

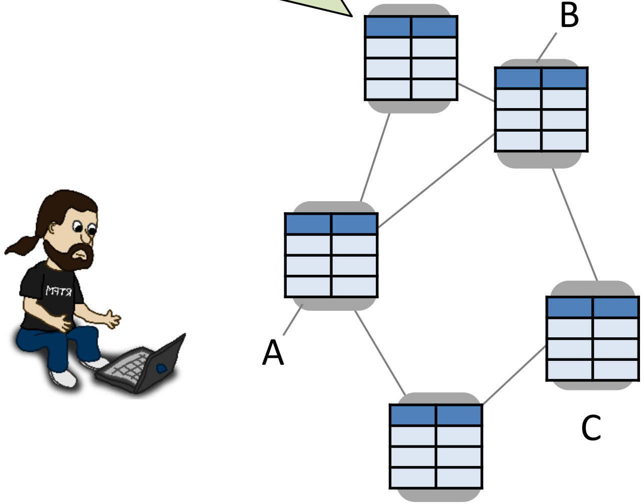
global FFT	Out-I	In-Label	Out-I	op
τ'_{v_2}	(v_2, v_3)	11	(v_2, v_6)	$swap(61)$
	(v_2, v_3)	21	(v_2, v_6)	$swap(71)$
	(v_2, v_6)	61	(v_2, v_5)	$push(40)$
	(v_2, v_6)	71	(v_2, v_5)	$push(40)$

Failover Tables

Tables for our example

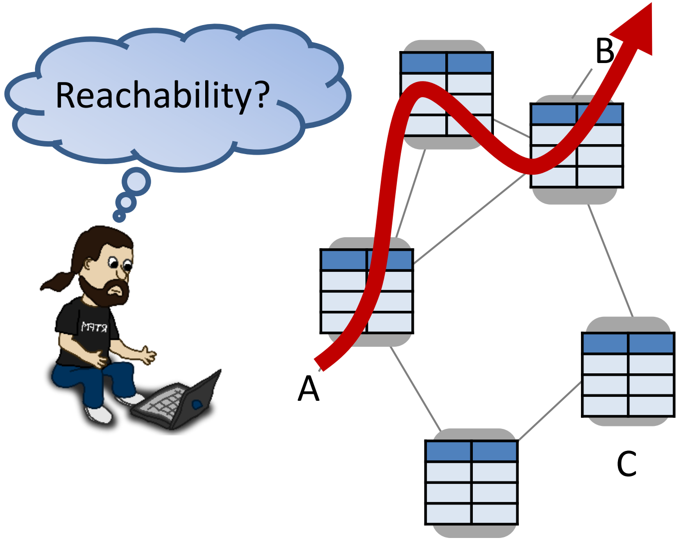
MPLS Tunnels in Today‘s ISP Networks

Responsibilities of a Sysadmin



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

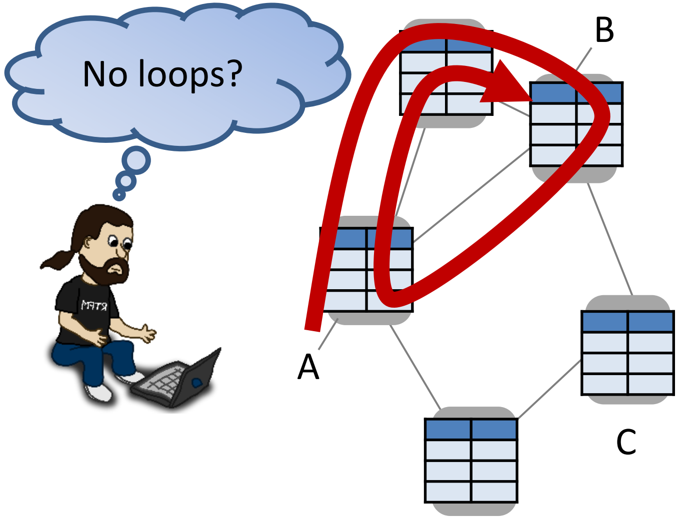
Responsibilities of a Sysadmin



Sysadmin responsible for:

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

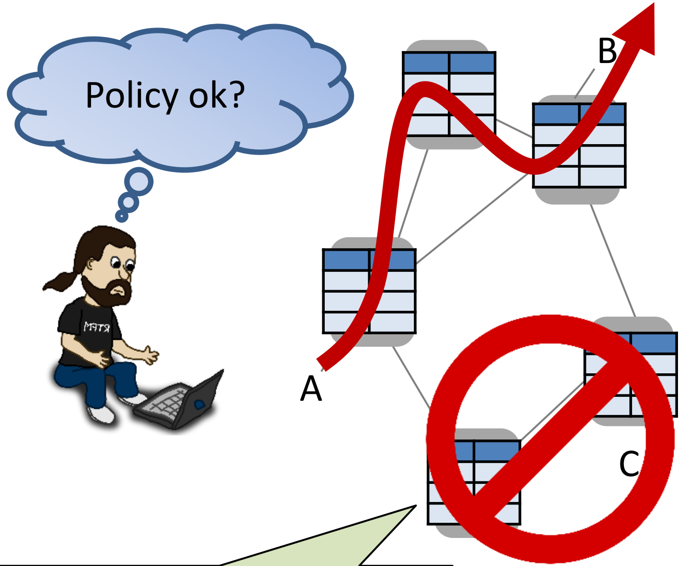
Responsibilities of a Sysadmin



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

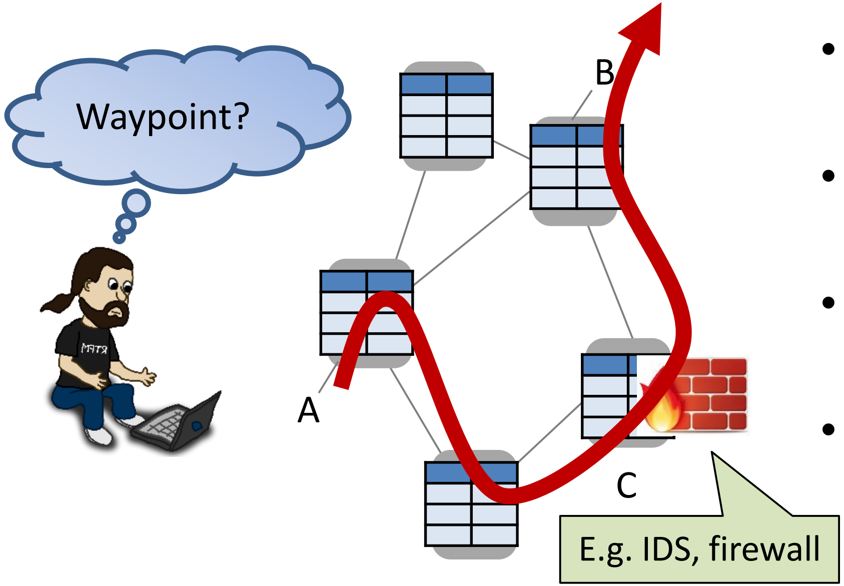


E.g. ***NORDUnet***: no traffic via Iceland (expensive!). Or no traffic through ***route reflectors***.

Sysadmin responsible for:

- **Reachability:** Can traffic from ingress port A reach egress port B?
- **Loop-freedom:** Are the routes implied by the forwarding rules loop-free?
- **Policy:** Is it ensured that traffic from A to B never goes via C?

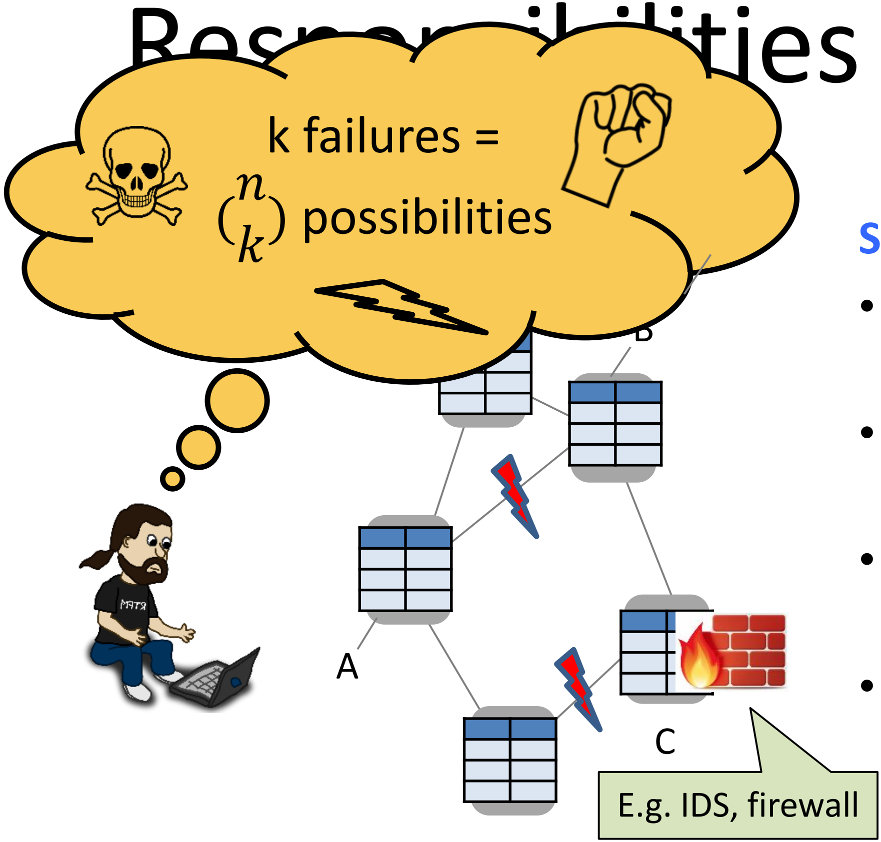
Responsibilities of a Sysadmin



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?
- **Policy:** Is it ensured that traffic from A to B never goes via C?
- **Waypoint enforcement:** Is it ensured that traffic from A to B is always routed via a node C?

Responsibilities of a Sysadmin



k failures = $\binom{n}{k}$ possibilities

E.g. IDS, firewall

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?
- **Policy:** Is it ensured that traffic from A to B never goes via C?
- **Waypoint enforcement:** Is it ensured that traffic from A to B is always routed via a node C?

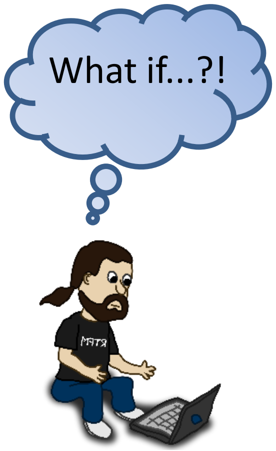
… and everything even under multiple failures?!

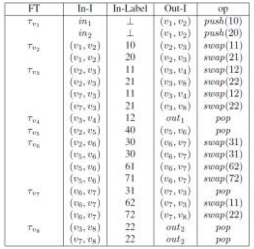
Can we automate such tests
or even self-repair?

Can we automate such tests or even self-repair?

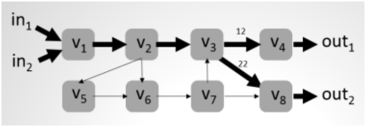
Yes! Encouraging: sometimes even ***fast***:
What-if Analysis Tool for MPLS and SR

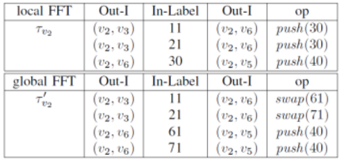
Leveraging Automata-Theoretic Approach





FT	In-I	In-Label	Out-I	op
τ_{v_1}	in_1	$\bot$	(v_1, v_2)	$push(10)$
	in_2	$\bot$	(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

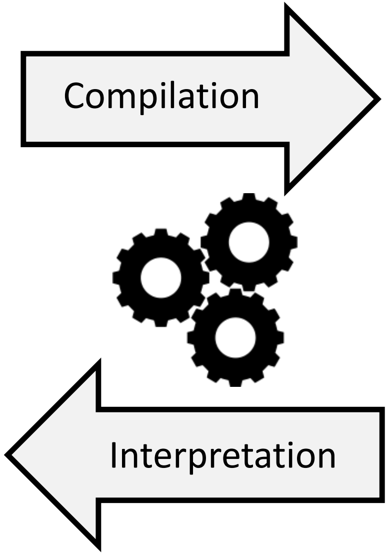




local FFT	Out-I	In-Label	Out-I	op
τ_{v_2}	(v_2, v_3)	11	(v_2, v_6)	$push(30)$
	(v_2, v_3)	21	(v_2, v_6)	$push(30)$
	(v_2, v_6)	30	(v_2, v_5)	$push(40)$

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.



Compilation

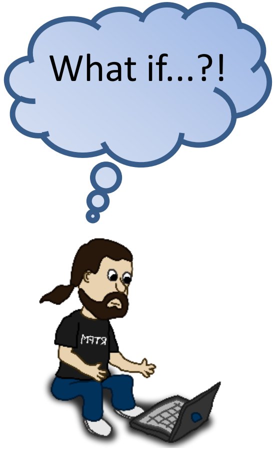
Interpretation

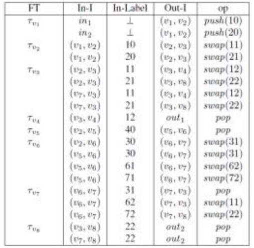
$$pX \Longrightarrow qXX$$
$$pX \Longrightarrow qYX$$
$$qY \Longrightarrow rYY$$
$$rY \Longrightarrow r$$
$$rX \Longrightarrow pX$$

Pushdown Automaton
and **Prefix Rewriting Systems** Theory

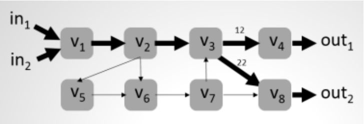
Leveraging Autom oach

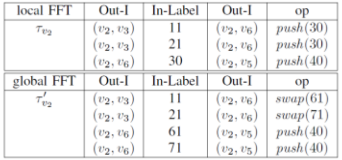
Use cases: Sysadmin ***issues queries*** to test certain properties, or do it on a ***regular basis*** automatically!





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)	$swap(22)$
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

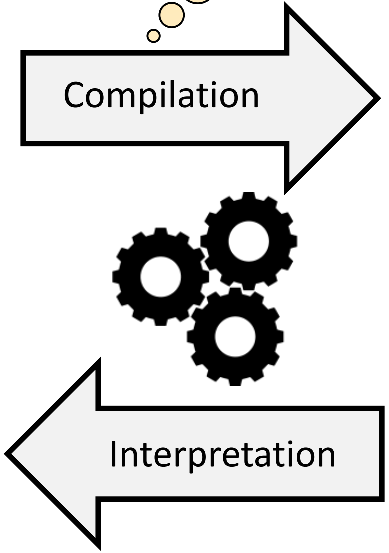




local FFT	Out-I	In-Label	Out-I	op
τ_{v_2}	(v_2, v_3)	11	(v_2, v_6)	$push(30)$
	(v_2, v_3)	21	(v_2, v_6)	$push(30)$
	(v_2, v_6)	30	(v_2, v_5)	$push(40)$

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.



Compilation

Interpretation

$$\mathrm{pX} \Rightarrow \mathrm{qXX}$$

$$pX \Rightarrow qYX$$

$$qY \Rightarrow rYY$$

$$rY \Rightarrow r$$

$$rX \Rightarrow pX$$

Pushdown Automaton and **Prefix Rewriting Systems** Theory

Mini-Tutorial: A Network Model

- Network: a 7-tuple

Links

Outgoing interfaces

$$N = (V, E, I_v^{in}, I_v^{out}, \lambda_v, L, \delta_v^F)$$

Nodes

Incoming interfaces

Set of labels in packet header

Mini-Tutorial: A Network Model

- Network: a 7-tuple

$$N = (V, E, I_v^{in}, I_v^{out}, \lambda_v, L, \delta_v^F)$$

Interface function

Interface function: maps outgoing interface to next hop node and incoming interface to previous hop node

$$\lambda_v : I_v^{in} \cup I_v^{out} \rightarrow V$$

That is: $(\lambda_v(in), v) \in E$ and $(v, \lambda_v(out)) \in E$

Mini-Tutorial: A Network Model

- Network: a 7-tuple

$$N = (V, E, I_v^{in}, I_v^{out}, \lambda_v, L, \delta_v^F)$$

Routing function

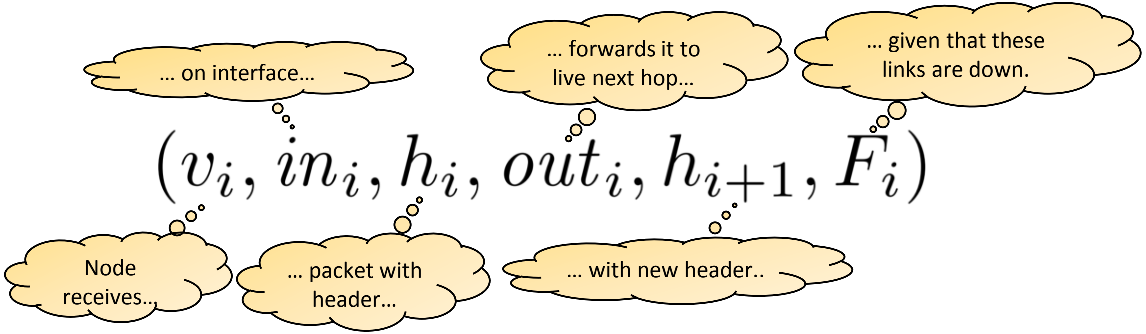
Routing function: for each set of failed links $F \subseteq E$, the routing function

$$\delta_v^F : I_v^{in} \times L^* \rightarrow 2^{(I^{out} \times L^*)}$$

defines, for all incoming interfaces and packet headers, outgoing interfaces together with modified headers.

Routing in Network

Packet routing sequence can be represented using **sequence of tuples**:



... on interface...

... forwards it to live next hop...

... given that these links are down.

$$(v_i, in_i, h_i, out_i, h_{i+1}, F_i)$$

Node receives...

... packet with header...

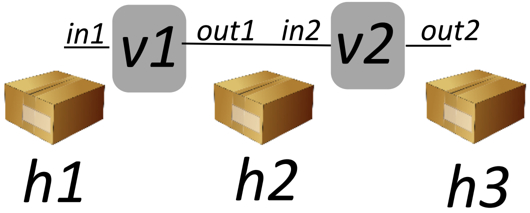
... with new header..

- Example: **routing** (in)finite sequence of tuples

$$(v_1, in_1, h_1, out_1, h_2, F_1),$$

$$(v_2, in_2, h_2, out_2, h_3, F_2),$$

$$\ldots$$



Example Rules:
Regular Forwarding on Top-Most Label

Push:

Push label on stack

$$(v, in)\ell \rightarrow (v, out, 0)\ell'\ell \text{ if } \tau_v(in, \ell) = (out, push(\ell'))$$

Swap:

Swap top of stack

$$(v, in)\ell \rightarrow (v, out, 0)\ell' \text{ if } \tau_v(in, \ell) = (out, swap(\ell'))$$

Pop:

Pop top of stack

$$(v, in)\ell \rightarrow (v, out, 0) \text{ if } \tau_v(in, \ell) = (out, pop)$$

Example *Failover* Rules

Emumerate all rerouting options

Failover-Push:

$$(v, out, i)\ell \rightarrow (v, out', i+1)\ell'\ell \text{ for every } i,\ 0 \leq i < k,$$
$$\text{where } \pi_v(out, \ell) = (out', push(\ell'))$$

Failover-Swap:

$$(v, out, i)\ell \rightarrow (v, out', i+1)\ell' \text{ for every } i,\ 0 \leq i < k,$$
$$\text{where } \pi_v(out, \ell) = (out', swap(\ell')),$$

Failover-Pop:

$$(v, out, i)\ell \rightarrow (v, out', i+1) \text{ for every } i,\ 0 \leq i < k,$$
$$\text{where } \pi_v(out, \ell) = (out', pop).$$

Example rewriting sequence:

$$(v_1, in_1)h_1\bot \rightarrow (v_1, out, 0)h\bot \rightarrow (v_1, out', 1)h'\bot \rightarrow (v_1, out'', 2)h''\bot \rightarrow \ldots \rightarrow (v_1, out_1, i)h_2\bot$$

Try default

Try first backup

Try second backup

A Complex and Big Formal Language!
Why Polynomial Time?!

k failures = $\binom{n}{k}$ possibilities

- 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 Push-Down Automata (PDA) is computationally non-trivial and sometimes even **undecidable**!

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 Push-Down Automata (PDA) is computationally non-trivial and sometimes even **undecidable**!

This is ***not*** how we will use the PDA!

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 Push-Down Automata (PDA) is computationally non-trivial and sometimes even **undecidable**!

The words in our language are sequences of pushdown stack symbols, not the labels of transitions.

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

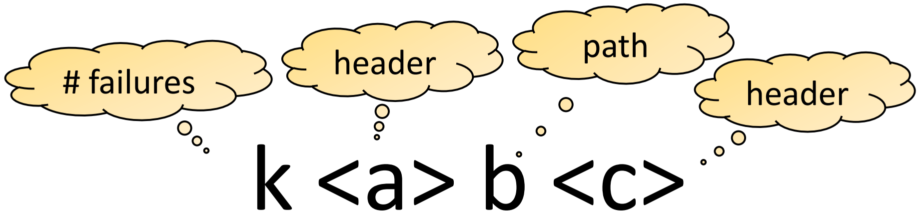
Tool and Query Language

Part 1: Parses query and constructs Push-Down System (PDS)

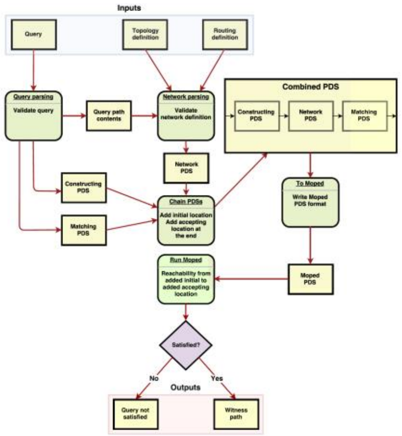
- In Python 3

Part 2: Reachability analysis of constructed PDS

- Using ***Moped*** tool



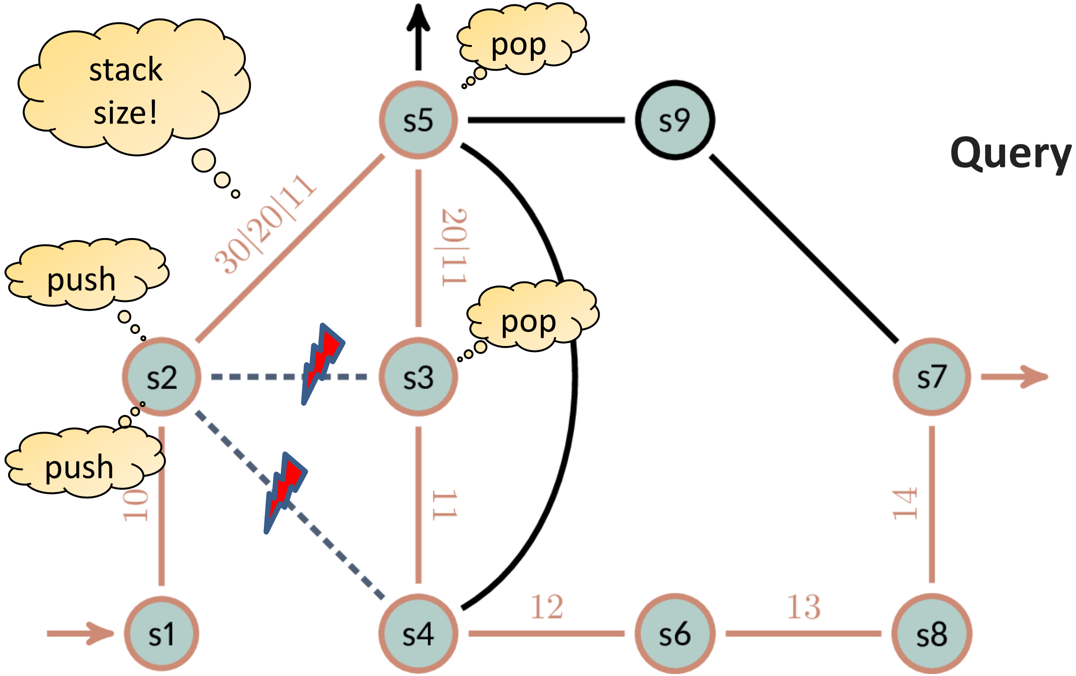
Regular query language



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?



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

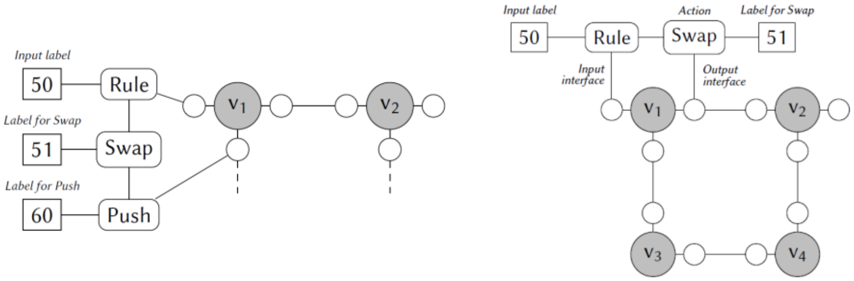
YES!

(Gives witness!)

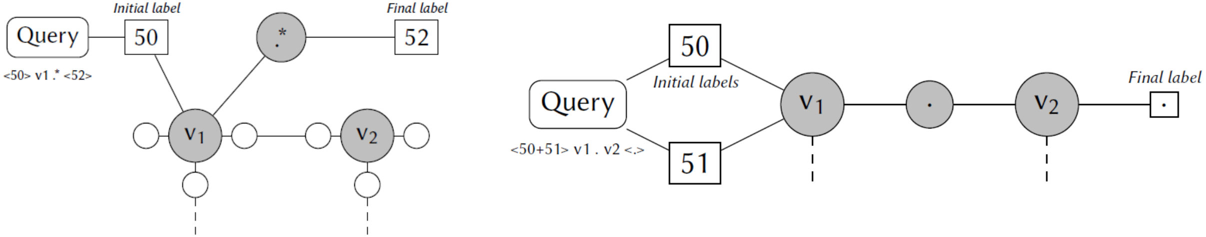
Formal methods are nice (give guarantees!)… But what about ML…?!

Speed Up Further and Synthesize: Deep Learning (s. talk by Fabien Geyer)

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



Network topologies and MPLS rules



Network topologies and query

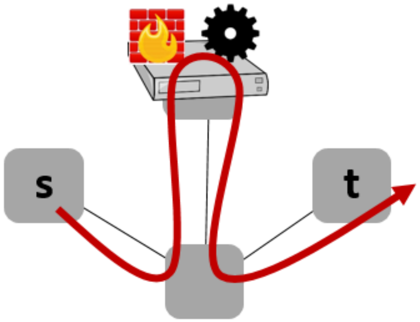
Roadmap

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

- Challenges of desinging self-* networks

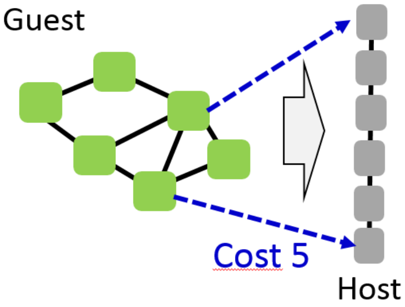
Challenge 1: Hard Problems

- Optimization problems are often **NP-hard**: hard *even for computers*!



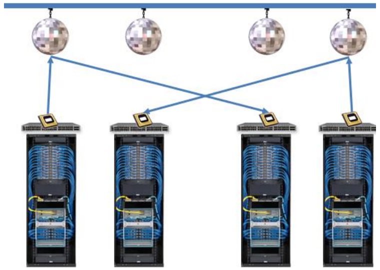
Waypoint routing:

disjoint paths



Embedding:

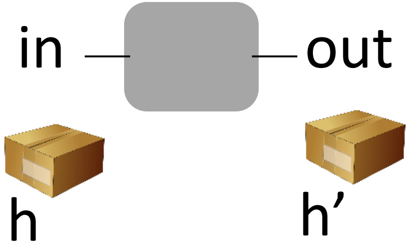
Minimum Lin. Arrangment



Topology design:

Graph spanners

It can get worse…: intractable!



Rules match the header **h**
of packets arriving at ***in***,
and define to which port ***out*** to
forward as well as new header **h’**.

(Simplified) MPLS rules:

prefix rewriting

in x L → out x ***OP***

where ***OP*** **=** ***{swap,push,pop}***

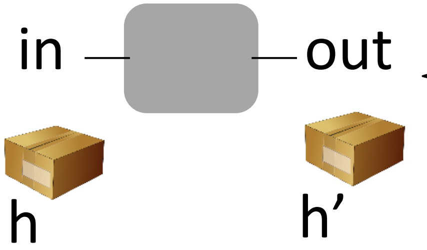
vs

Rules of general networks (e.g., SDN):

arbitrary header rewriting

in x L → out x L**

It can get worse…: intractable!



Rules match the header **h**
of packets arriving at ***in***,
and define to which port ***out*** to
forward as well as new header **h’**.

(Simplified) MPLS rules:

prefix rew

*t x **OP***

wh OP = {swap,push,pop}

Polynomial time

VS

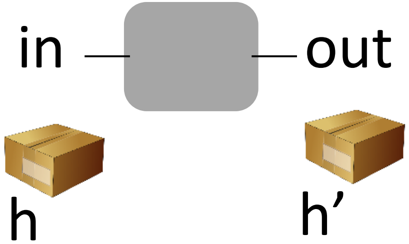
Rules of general network g., SDN):

arbitrary h iting

*i → out x L**

Undecidable!

It can get worse…: intractable!



Rules match the header **h**
of packets arriving at ***in***,
and define to which port ***out*** to
forward as well as new header **h’**.

What is a good tradeoff between generality and performance?

(Simpl

pr

Polynom

t x **O**

wh OP = {swap,push,pop}

i → *out x L**

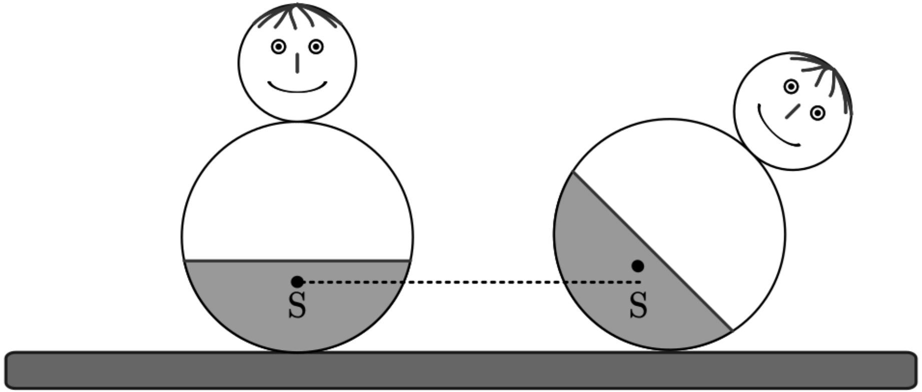
Challenge 2: Realizing Limits?

- 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 3: 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*.



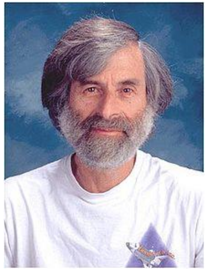
„Stehaufmännchen“

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)



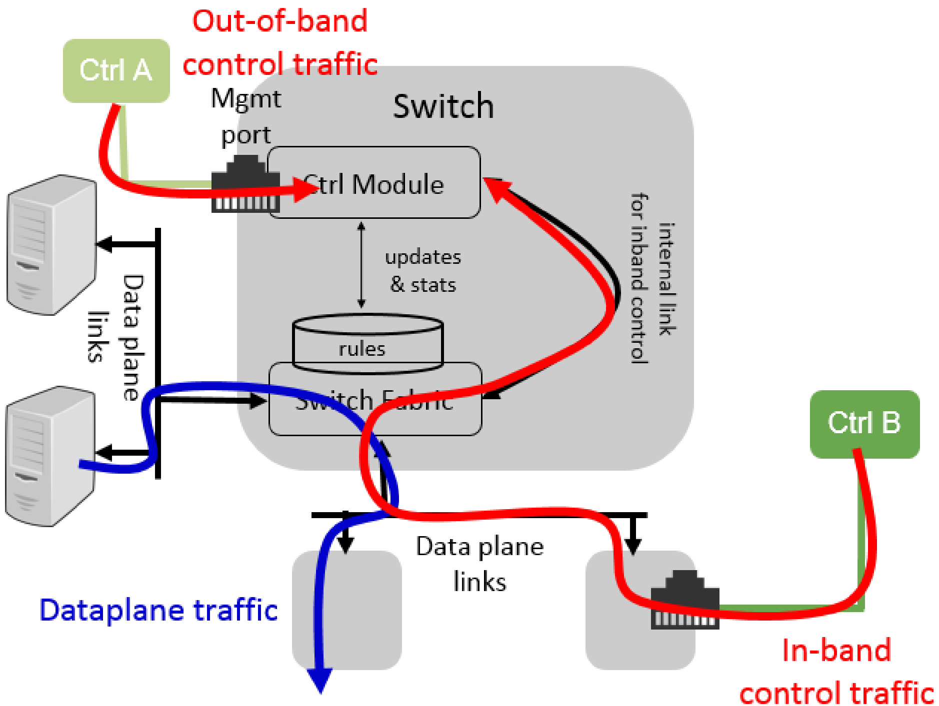
Some notable works by **Perlman** toward self-stabilizing Internet, e.g., self-stabilizing spanning trees.

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

E.g., Self-Stabilizing SDN Control?

- Distributed SDN control plane which **self-organizes management** of switches?

- Especially challenging: **inband control** (how to distinguish traffic?)



Challenge 4: Uncertainties

- How to deal with **uncertainties**?
- How to maintain flexibilities?
- Use of principles from robotics? E.g., **empowerment**?

Empowering Self-Driving Networks. Kalmbach et al. ACM SIGCOMM 2018 Workshop on Self-Driving Networks (SDN), 2018.

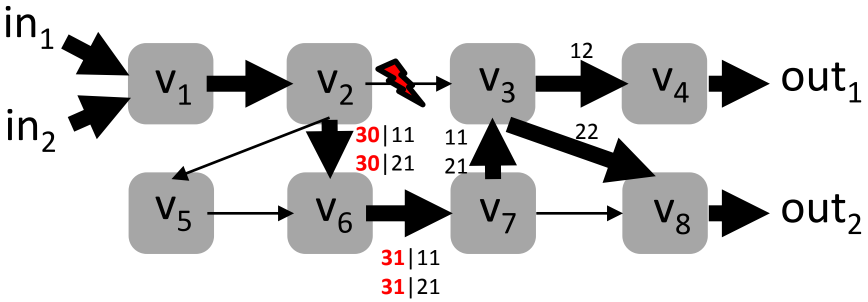
Conclusion

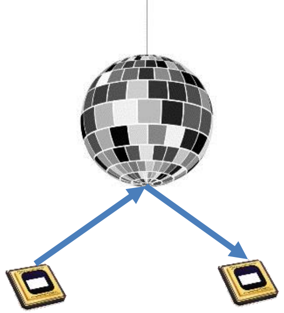
- **Flexibilities** in networks: great opportunities for **optimization** and **automation**

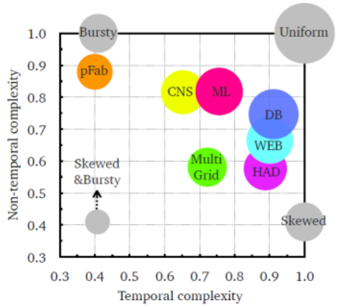
- **Demand-aware** and **self-adjusting** networks: beating the routing lower bounds of oblivious networks, ***reaching entropy bounds***

- Potential of **self-repairing** networks, self-stabilizing networks, etc.

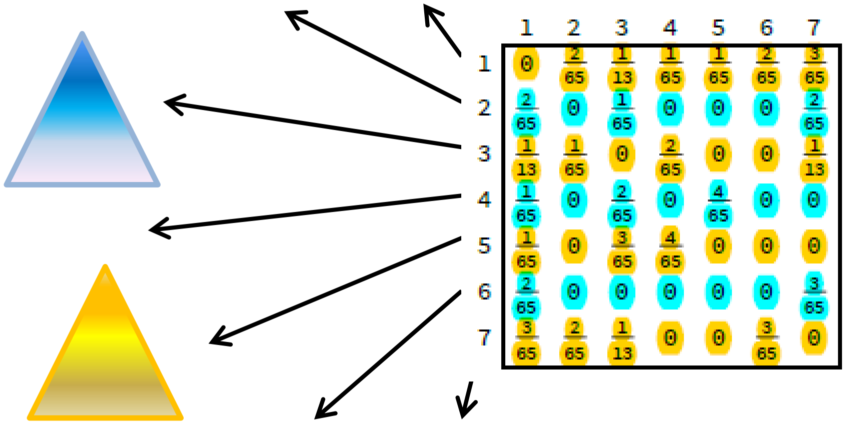
- Much work ahead: ***tradeoff*** generality vs efficiency? How to self-monitor and **fall-back** if needed? Use of **formal methods** and ML?



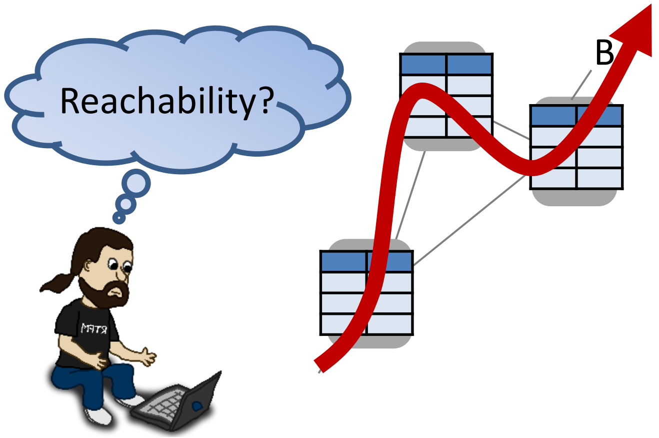




Thank you! Questions?



$$\begin{array}{c|ccccccc}
 & 1 & 2 & 3 & 4 & 5 & 6 & 7 \\
\hline
1 & 0 & \frac{2}{65} & \frac{1}{13} & \frac{1}{65} & \frac{1}{65} & \frac{2}{65} & \frac{3}{65} \\
2 & \frac{2}{65} & 0 & \frac{1}{65} & 0 & 0 & 0 & \frac{2}{65} \\
3 & \frac{1}{13} & \frac{1}{65} & 0 & \frac{2}{65} & 0 & 0 & \frac{1}{13} \\
4 & \frac{1}{65} & 0 & \frac{2}{65} & 0 & \frac{4}{65} & 0 & 0 \\
5 & \frac{1}{65} & 0 & \frac{3}{65} & \frac{4}{65} & 0 & 0 & 0 \\
6 & \frac{2}{65} & 0 & 0 & 0 & 0 & 0 & \frac{3}{65} \\
7 & \frac{3}{65} & \frac{2}{65} & \frac{1}{13} & 0 & 0 & \frac{3}{65} & 0
\end{array}$$



Further Reading

Flexibilities and Complexity

On The Impact of the Network Hypervisor on Virtual Network Performance
Andreas Blenk, Arsany Basta, Wolfgang Kellerer, and Stefan Schmid.
IFIP Networking, Warsaw, Poland, May 2019.
Adaptable and Data-Driven Softwarized Networks: Review, Opportunities, and Challenges (Invited Paper)
Wolfgang Kellerer, Patrick Kalmbach, Andreas Blenk, Arsany Basta, Martin Reisslein, and Stefan Schmid.
Proceedings of the IEEE (**PIEEE**), 2019.
Efficient Distributed Workload (Re-)Embedding
Monika Henzinger, Stefan Neumann, and Stefan Schmid.
ACM/IFIP **SIGMETRICS/PERFORMANCE**, Phoenix, Arizona, USA, June 201
Parametrized Complexity of Virtual Network Embeddings: Dynamic & Linear Programming Approximations
Matthias Rost, Elias Döhne, and Stefan Schmid.
ACM SIGCOMM Computer Communication Review (**CCR**), January 2019.
Charting the Complexity Landscape of Virtual Network Embeddings (Best Paper Award)
Matthias Rost and Stefan Schmid.
IFIP Networking, Zurich, Switzerland, May 2018.
Tomographic Node Placement Strategies and the Impact of the Routing Model
Yvonne Anne Pignolet, Stefan Schmid, and Gilles Tredan.
ACM **SIGMETRICS**, Irvine, California, USA, June 2018. hmid.
ACM/IEEE Symposium on Architectures for Networking and Communications Systems (**ANCS**), Ithaca, New York, USA, July 2018.

Further Reading

Demand-Aware and Self-Adjusting Networks

Survey of Reconfigurable Data Center Networks: Enablers, Algorithms, Complexity
Klaus-Tycho Foerster and Stefan Schmid.
SIGACT News, June 2019.
Toward Demand-Aware Networking: A Theory for Self-Adjusting Networks (Editorial)
Chen Avin and Stefan Schmid.
ACM SIGCOMM Computer Communication Review (**CCR**), October 2018.
Demand-Aware Network Design with Minimal Congestion and Route Lengths
Chen Avin, Kaushik Mondal, and Stefan Schmid.
38th IEEE Conference on Computer Communications (**INFOCOM**), Paris, France, April 2019.
Documents: paper pdf, bibtex bib
Distributed Self-Adjusting Tree Networks
Bruna Peres, Otavio Augusto de Oliveira Souza, Olga Goussevskaia, Chen Avin, and Stefan Schmid.
38th IEEE Conference on Computer Communications (**INFOCOM**), Paris, France, April 2019.
Efficient Non-Segregated Routing for Reconfigurable Demand-Aware Networks
Thomas Fenz, Klaus-Tycho Foerster, Stefan Schmid, and Anaïs Villedieu.
IFIP Networking, Warsaw, Poland, May 2019.
DaRTree: Deadline-Aware Multicast Transfers in Reconfigurable Wide-Area Networks
Long Luo, Klaus-Tycho Foerster, Stefan Schmid, and Hongfang Yu.
IEEE/ACM International Symposium on Quality of Service (**IWQoS**), Phoenix, Arizona, USA, June 2019.
Demand-Aware Network Designs of Bounded Degree
Chen Avin, Kaushik Mondal, and Stefan Schmid.
31st International Symposium on Distributed Computing (**DISC**), Vienna, Austria, October 2017.
SplayNet: Towards Locally Self-Adjusting Networks
Stefan Schmid, Chen Avin, Christian Scheideler, Michael Borokhovich, Bernhard Haeupler, and Zvi Lotker.
IEEE/ACM Transactions on Networking (**TON**), Volume 24, Issue 3, 2016. Early version: IEEE **IPDPS** 2013.
Characterizing the Algorithmic Complexity of Reconfigurable Data Center Architectures
Klaus-Tycho Foerster, Monia Ghobadi, and Stefan Schmid.
ACM/IEEE Symposium on Architectures for Networking and Communications Systems (**ANCS**), Ithaca, New York, USA, July 2018.

Further Reading

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.
14th International Conference on emerging Networking EXperiments and Technologies (**CoNEXT**), Heraklion, Greece, December 2018.
Polynomial-Time What-If Analysis for Prefix-Manipulating MPLS Networks
Stefan Schmid and Jiri Srba.
37th IEEE Conference on Computer Communications (**INFOCOM**), Honolulu, Hawaii, USA, April 2018.
Renaissance: A Self-Stabilizing Distributed SDN Control Plane
Marco Canini, Iosif Salem, Liron Schiff, Elad Michael Schiller, and Stefan Schmid.
38th IEEE International Conference on Distributed Computing Systems (**ICDCS**), Vienna, Austria, July 2018.
Empowering Self-Driving Networks
Patrick Kalmbach, Johannes Zerwas, Peter Babarczi, Andreas Blenk, Wolfgang Kellerer, and Stefan Schmid.
ACM SIGCOMM 2018 Workshop on Self-Driving Networks (**SDN**), Budapest, Hungary, August 2018.
DeepMPLS: Fast Analysis of MPLS Configurations using Deep Learning
Fabien Geyer and Stefan Schmid.
IFIP Networking, Warsaw, Poland, May 2019.