Self-Adjusting Networks

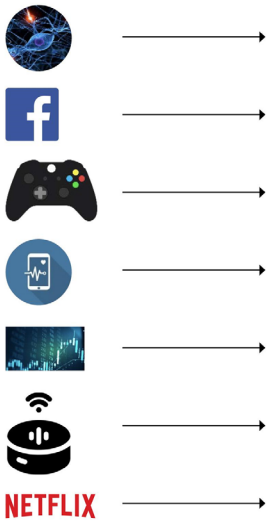
Stefan Schmid

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

(Folklore)

Trend:

Data-Centric Applications



Datacenters (“hyper-scale”)

+network

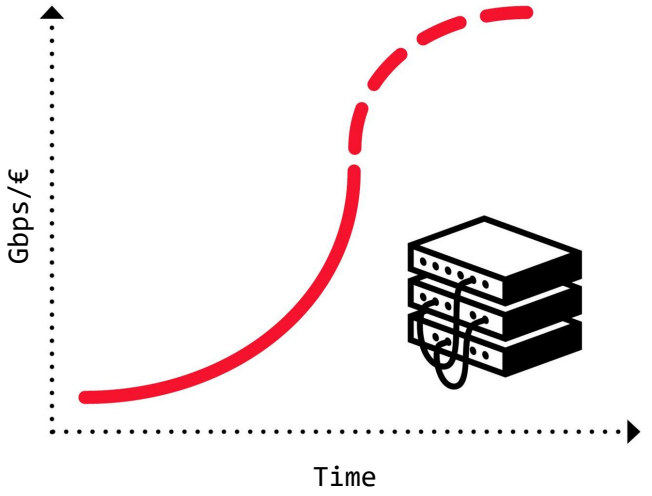
Interconnecting networks:
a **critical infrastructure**
of our digital society.

Source: Facebook

The Problem:

Huge Infrastructure, Inefficient Use

- ⇢ Network equipment reaching capacity limits
  - → Transistor density rates stalling
  - → "End of **Moore's Law** in networking" [1]
- ⇢ Hence: more equipment, larger networks
- ⇢ Resource intensive and: **inefficient**

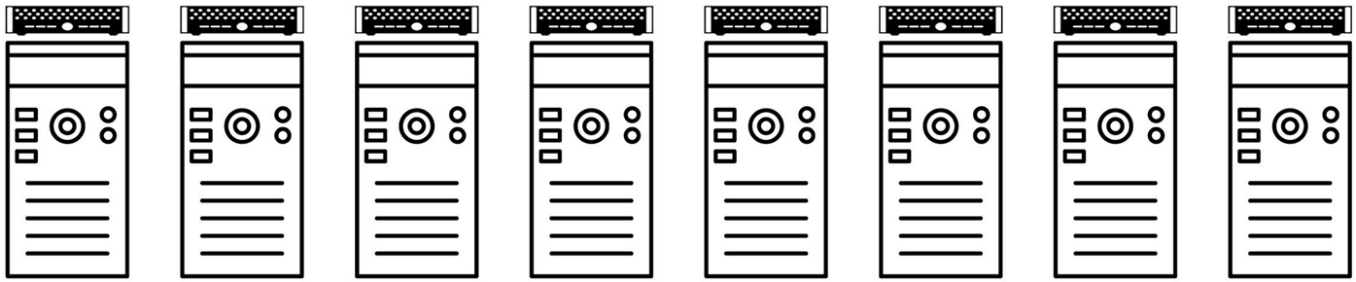


Annoying for companies,
opportunity for researchers

Root Cause:

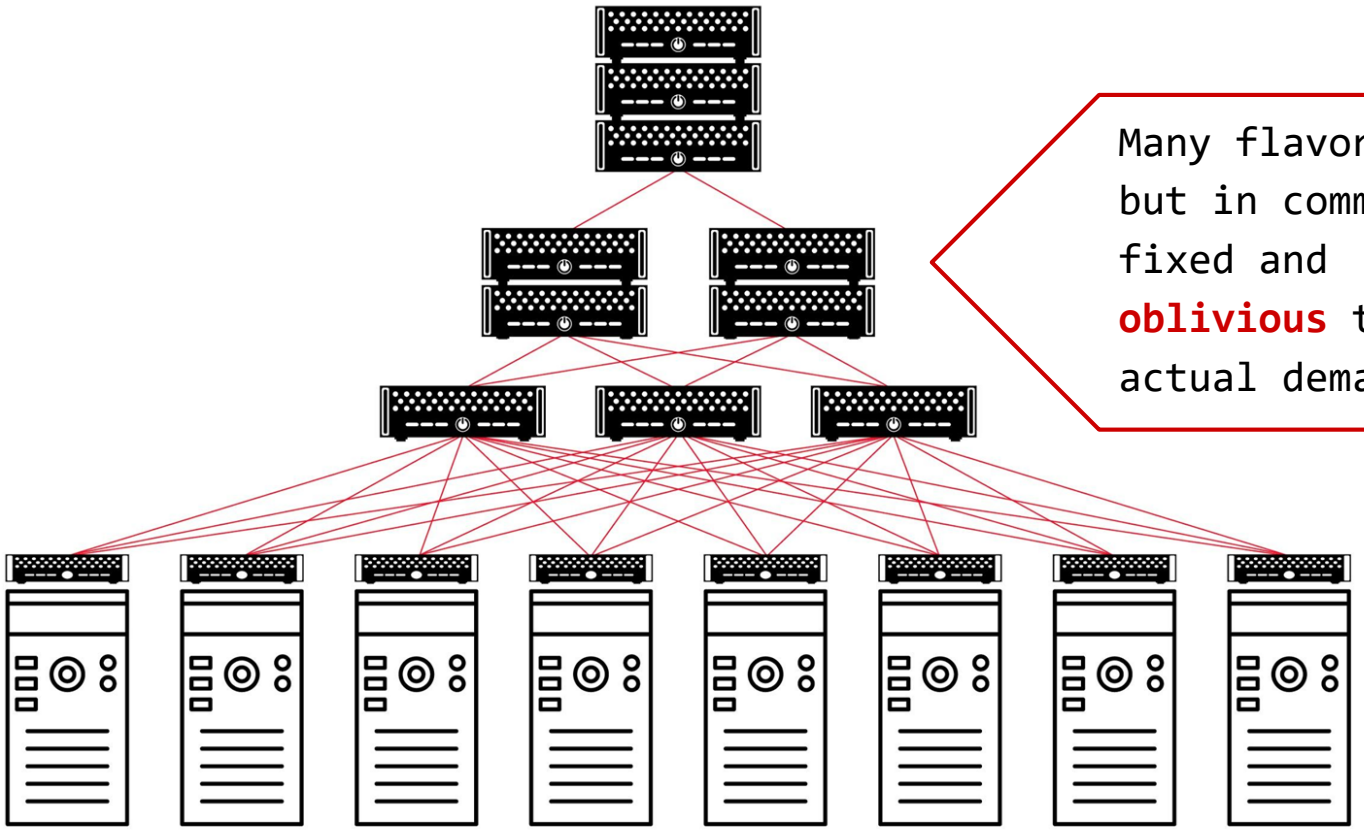
Fixed and Demand-Oblivious Topology

How to interconnect?



Root Cause:

Fixed and Demand-Oblivious Topology



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

Root Cause:

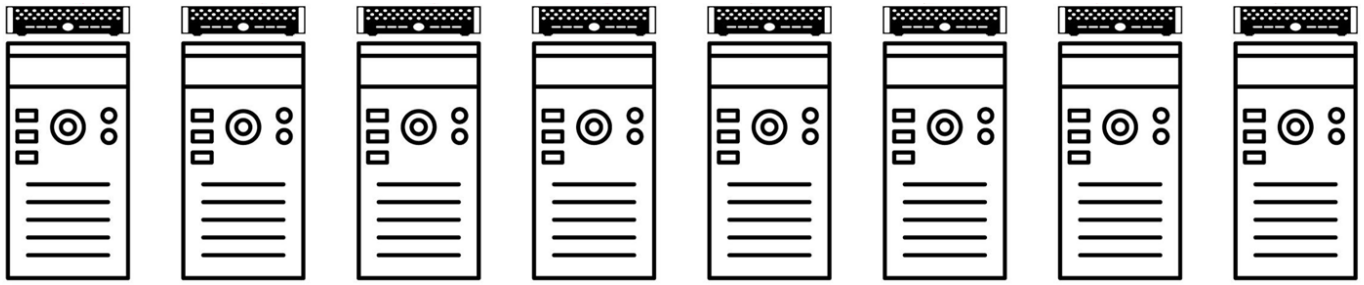
Fixed and Demand-Oblivious Topology

Highway which ignores actual traffic: frustrating!

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

Our Vision:

Flexible and Demand-Aware Topologies



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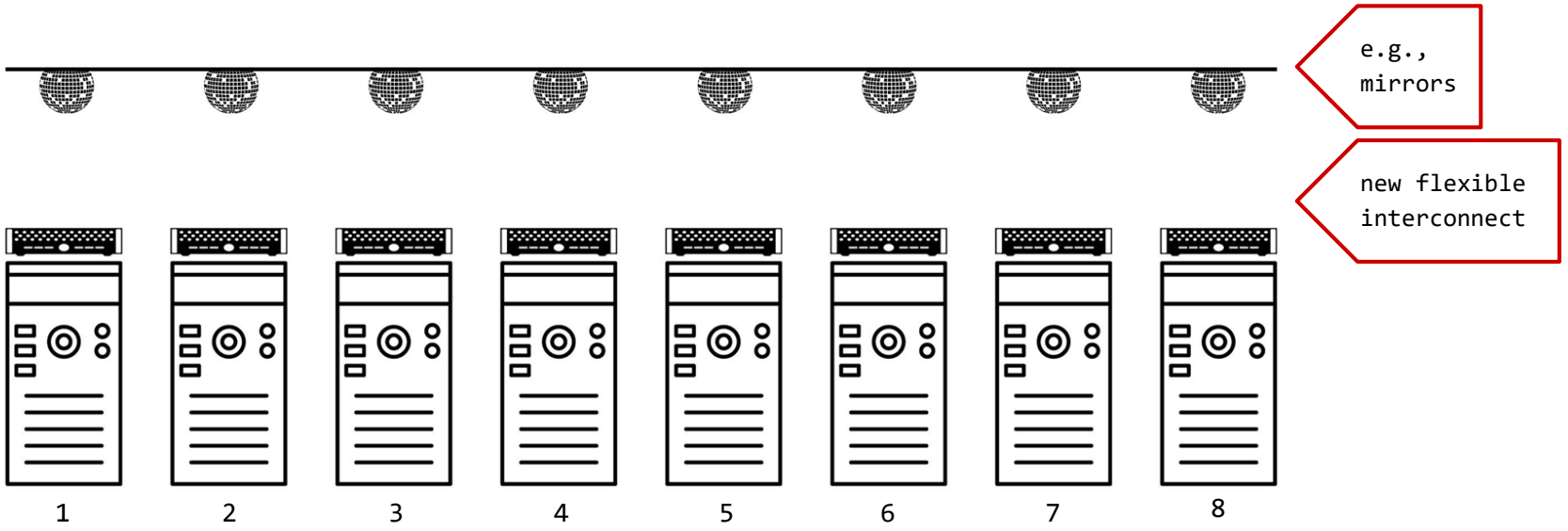
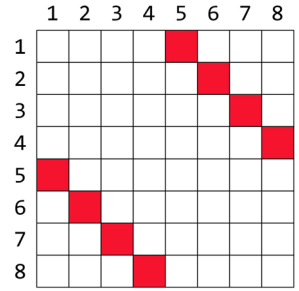
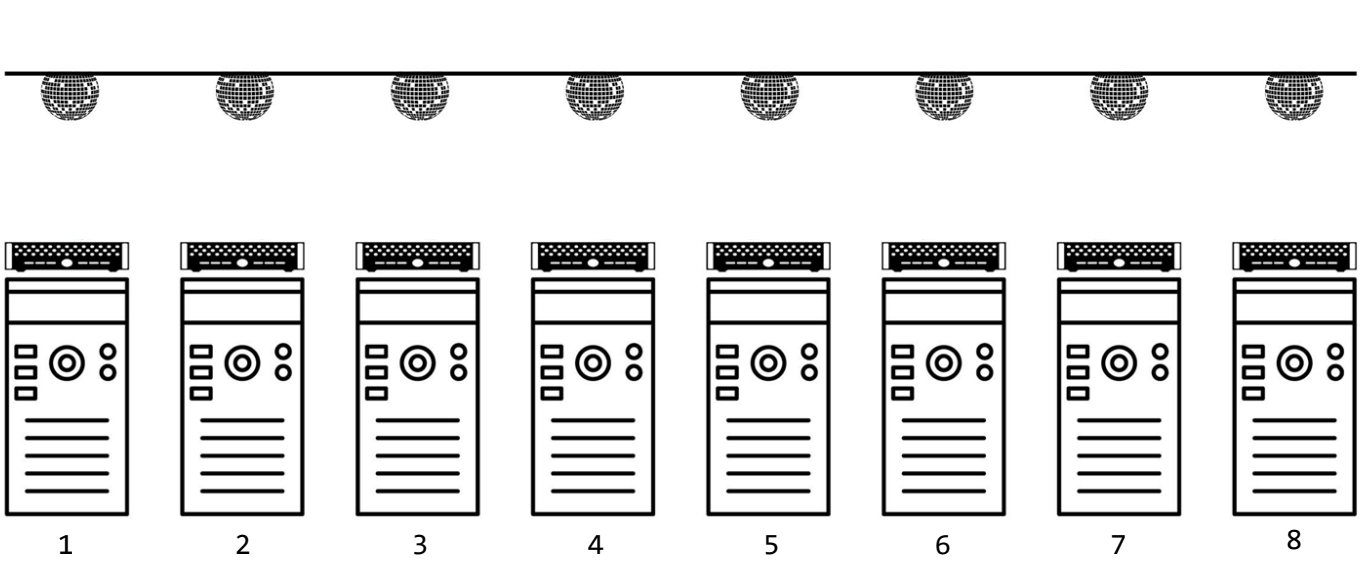


Our Vision:

Flexible and Demand-Aware Topologies

demand matrix:



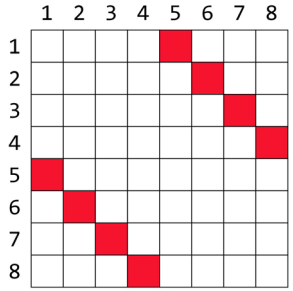


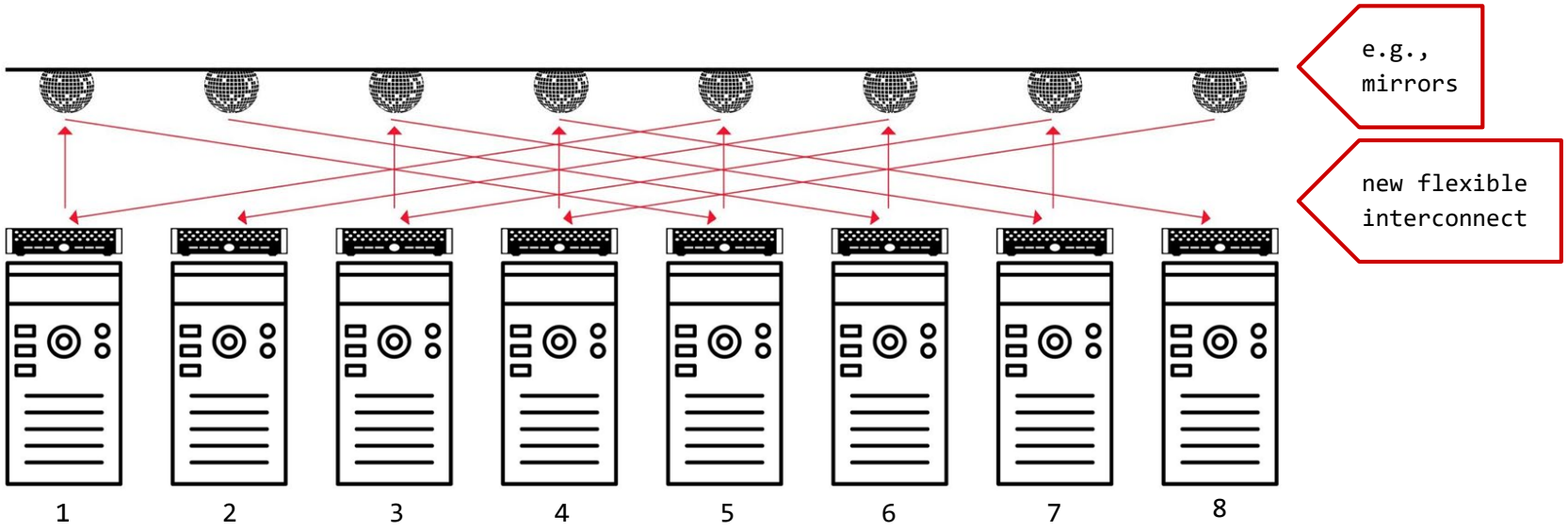
Our Vision:

Flexible and Demand-Aware Topologies

Matches demand

demand matrix:

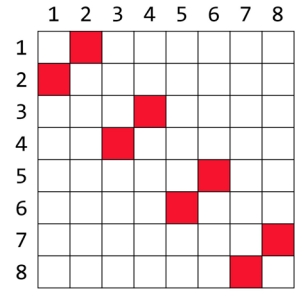


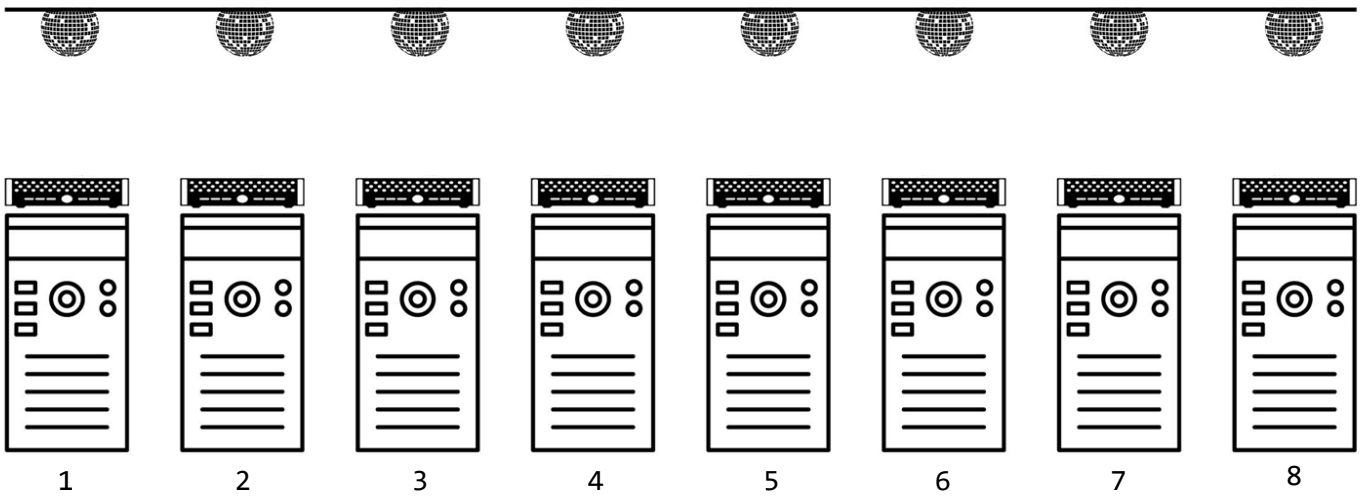


Our Vision:

Flexible and Demand-Aware Topologies

new demand:





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Flexible and Demand-Aware Topologies

Matches demand

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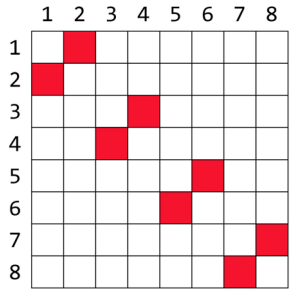
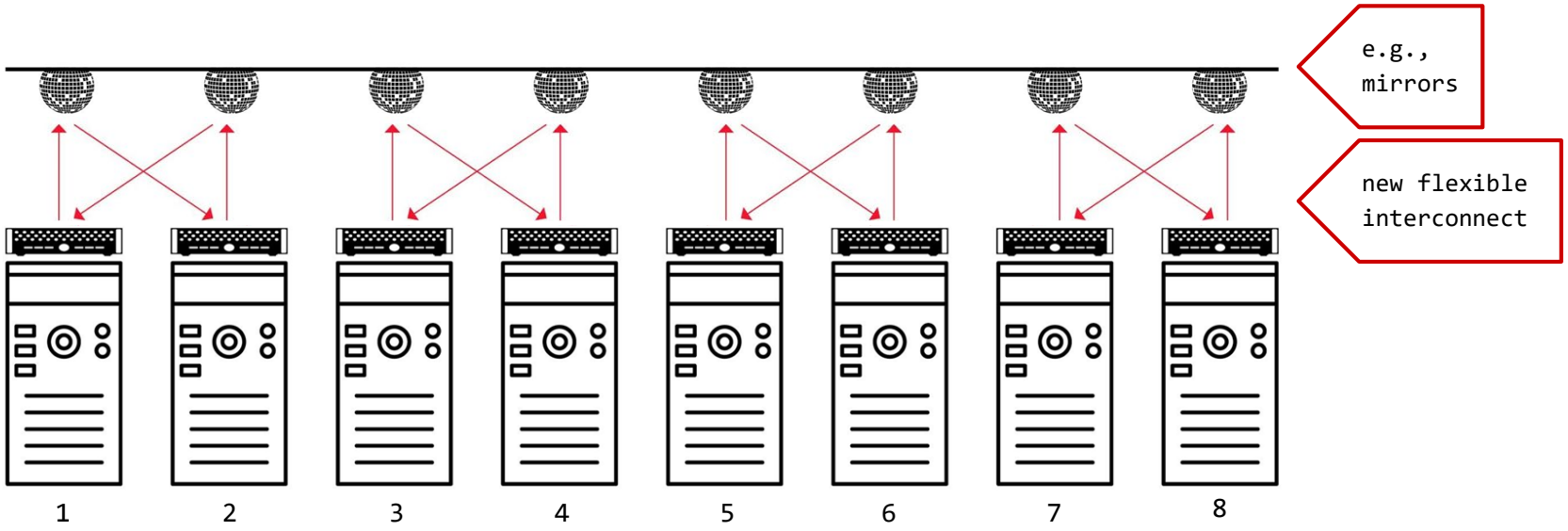


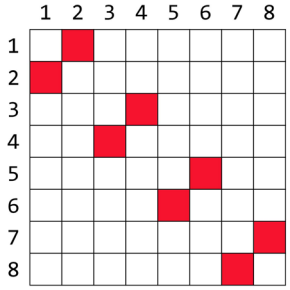


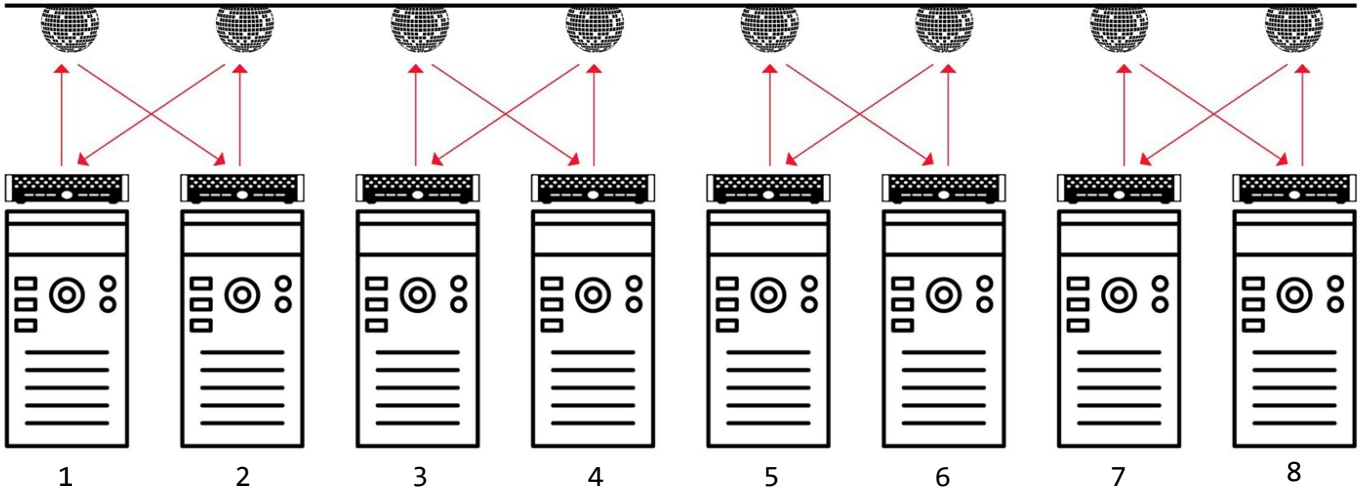
Our Vision:

Flexible and Demand-Aware Topologies

Self-Adjusting Networks

new demand:



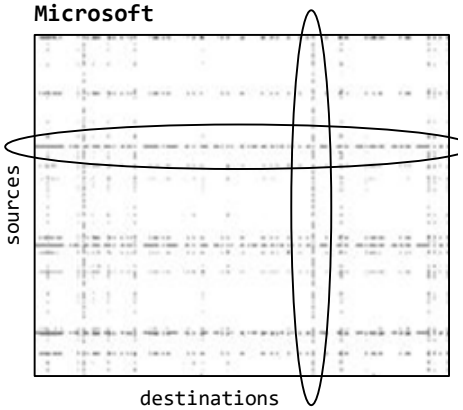


Our Motivation:

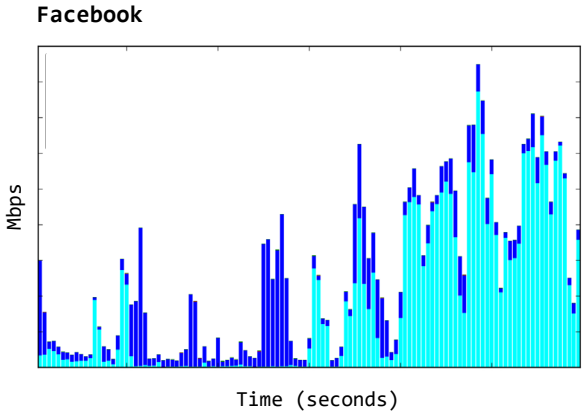
Much Structure in the Demand

Empirical studies:

traffic matrices sparse and skewed

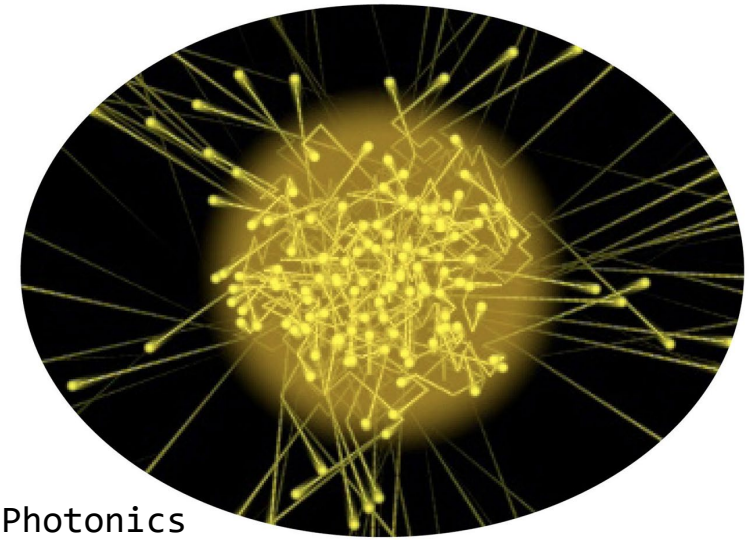


traffic bursty over time



My hypothesis: can be exploited.

Sounds Crazy? Emerging Enabling Technology.



Photonics

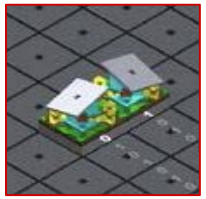
H2020:
“Photonics one of only five key enabling technologies for future prosperity.”

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 year's ACM **SIGCOMM** workshop

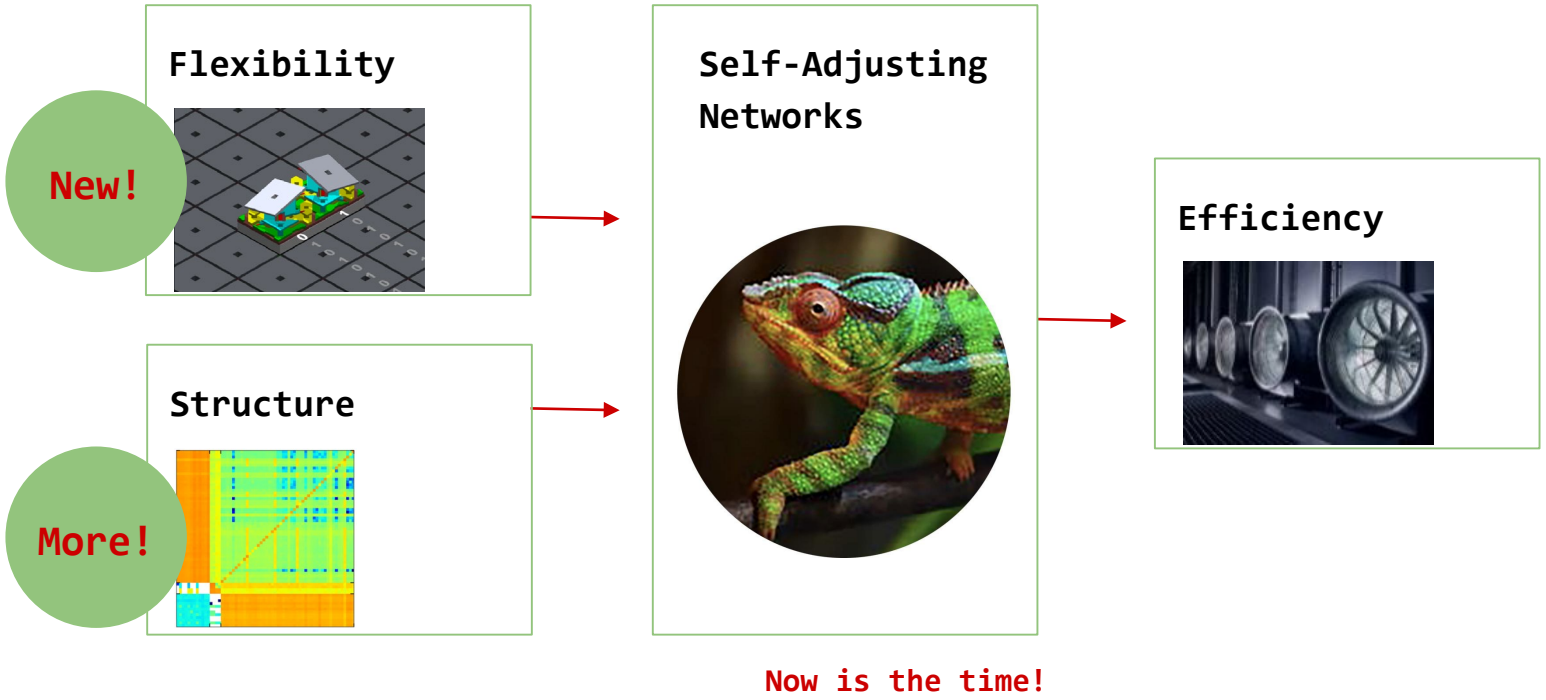


Prototype 1

Prototype 2

Prototype 3

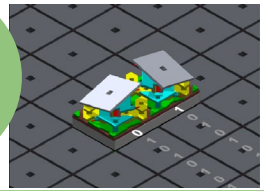
The Big Picture



The Big Picture

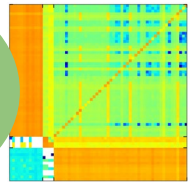
New!

Flexibility



More!

Structure



Self-Adjusting Networks

Now is the time!

Efficiency

Our goal: Develop the theoretical **foundations** of demand-aware, self-adjusting networks.

Unique Position:

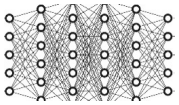
Demand-Aware, Self-Adjusting Systems

Everywhere, but mainly in software

Algorithmic trading

NETFLIX

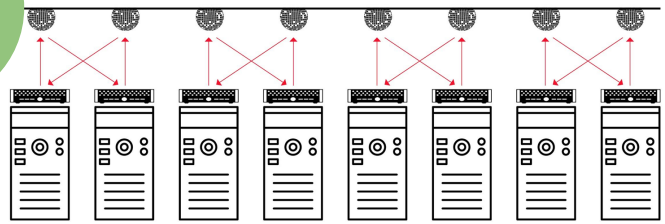
Recommender systems



Neural networks

VS

Our focus: in hardware



Question 1:

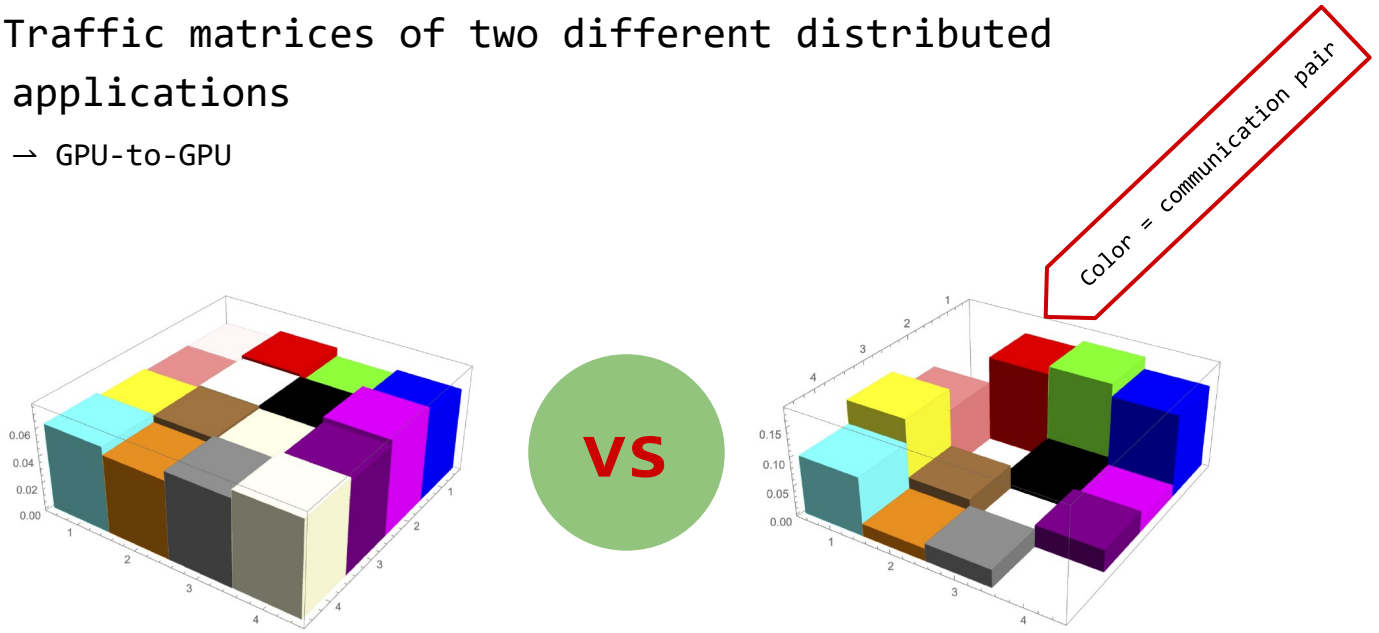
How to Quantify such “Structure” in the Demand?

Intuition:

Which demand has more structure?

⇢ Traffic matrices of two different distributed ML applications

→ GPU-to-GPU



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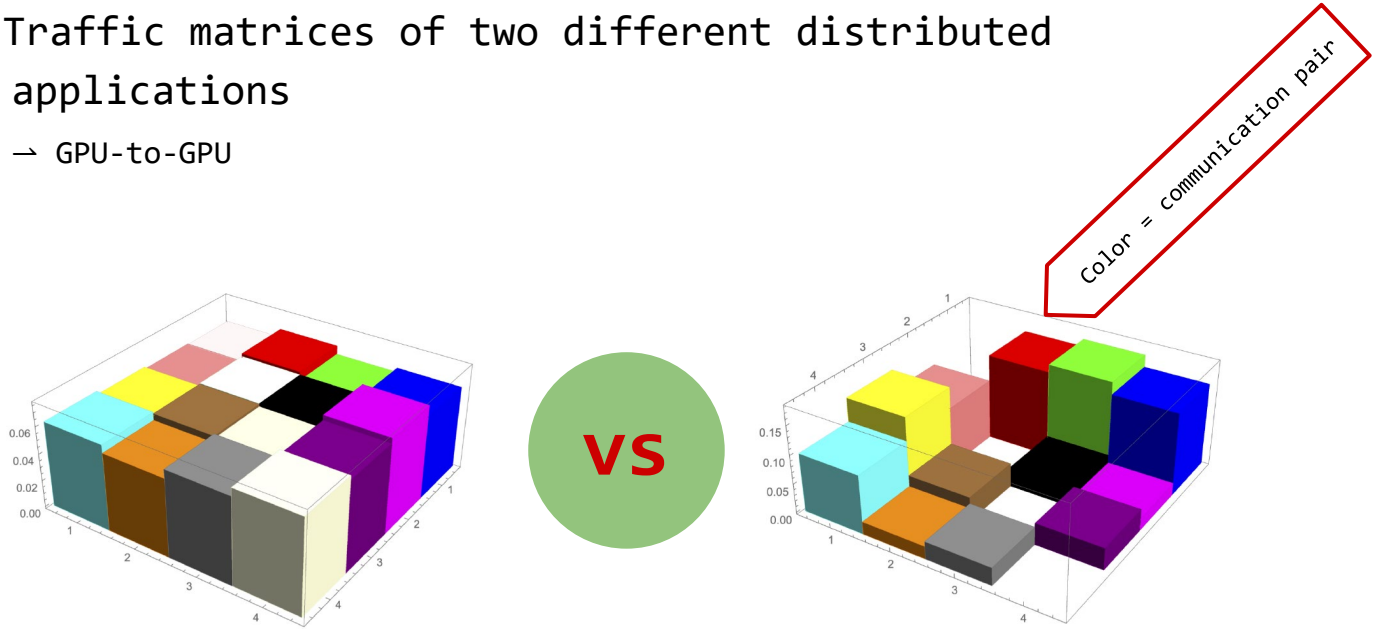


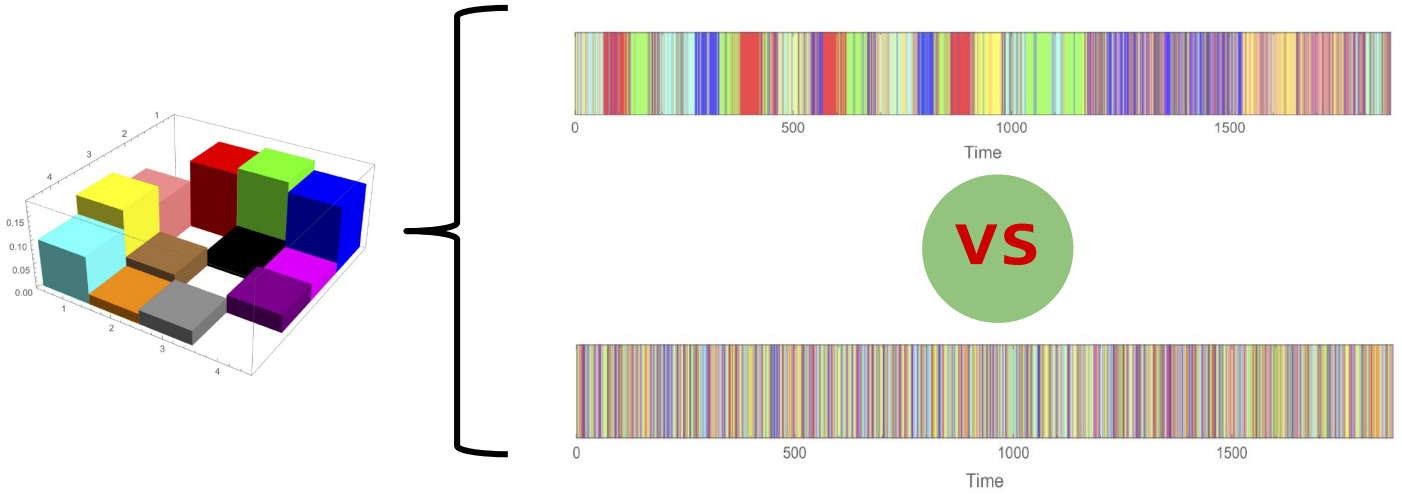
More uniform **More structure**

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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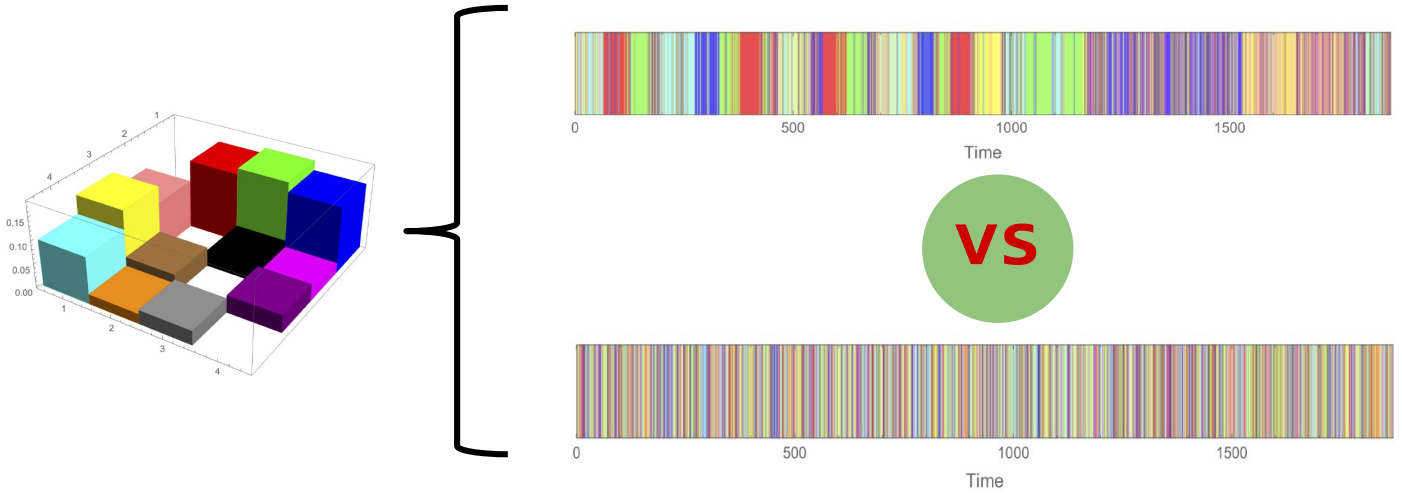
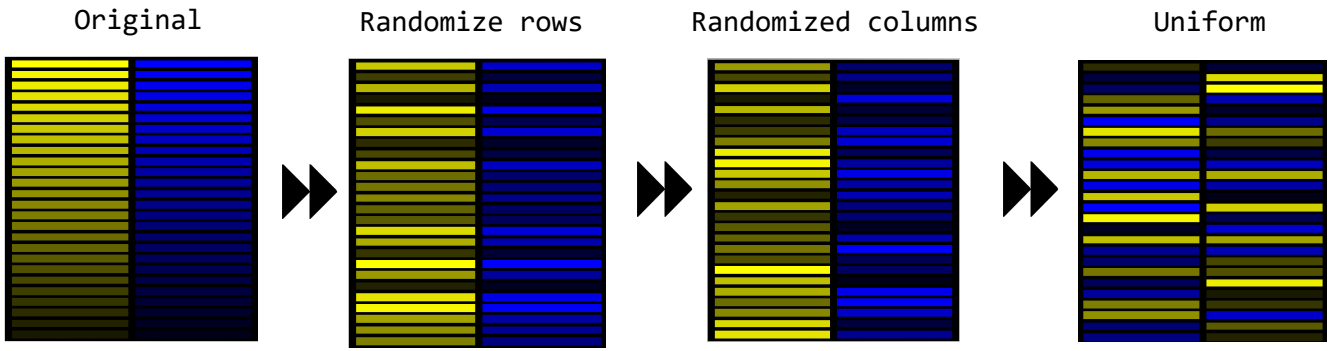


Systematically?

Trace Complexity:

A Systematic “Shuffle&Compress” Approach



Increasing complexity (systematically randomized)

More structure (compresses better)

Trace Complexity:

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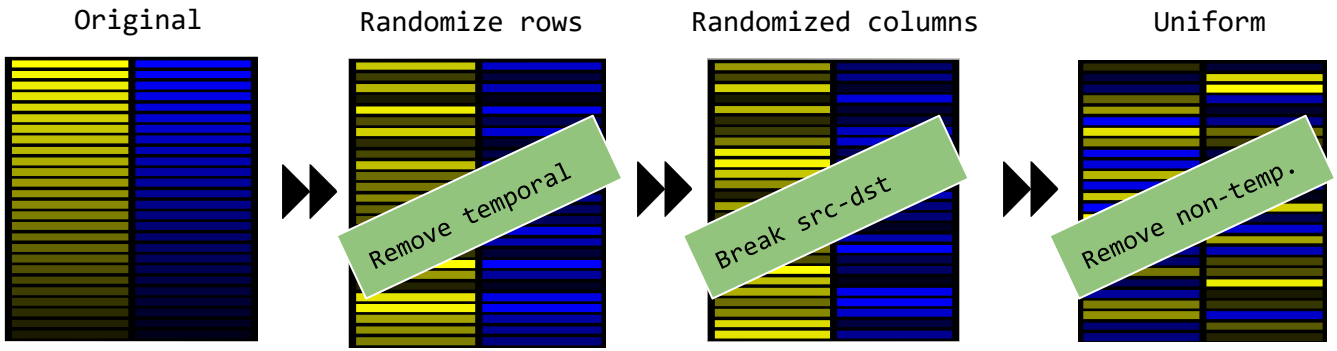

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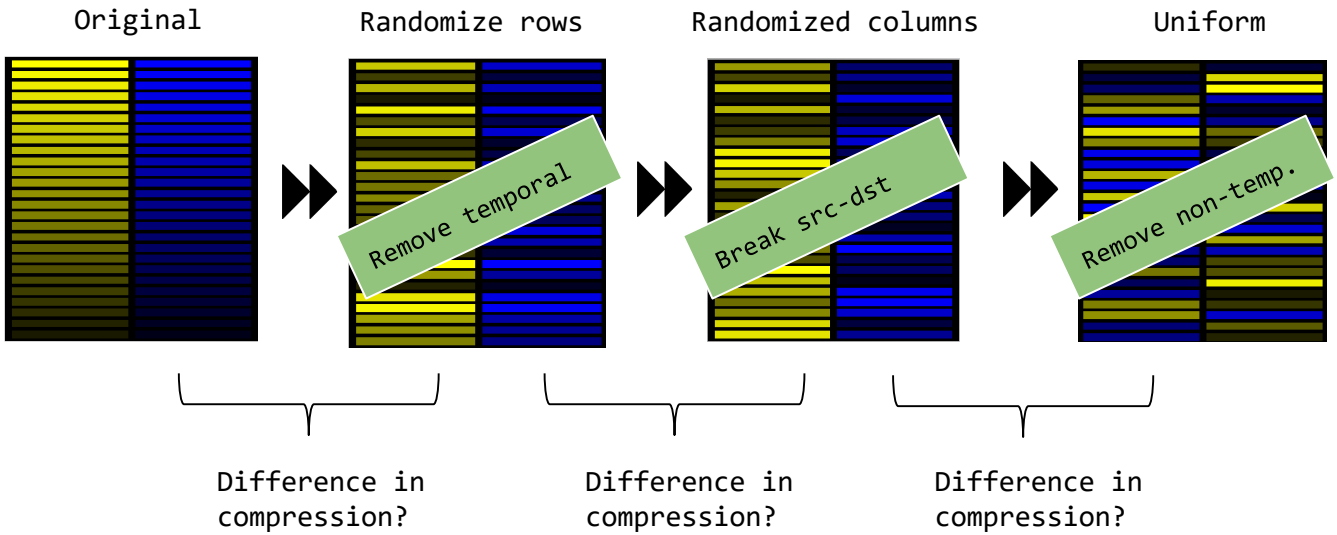

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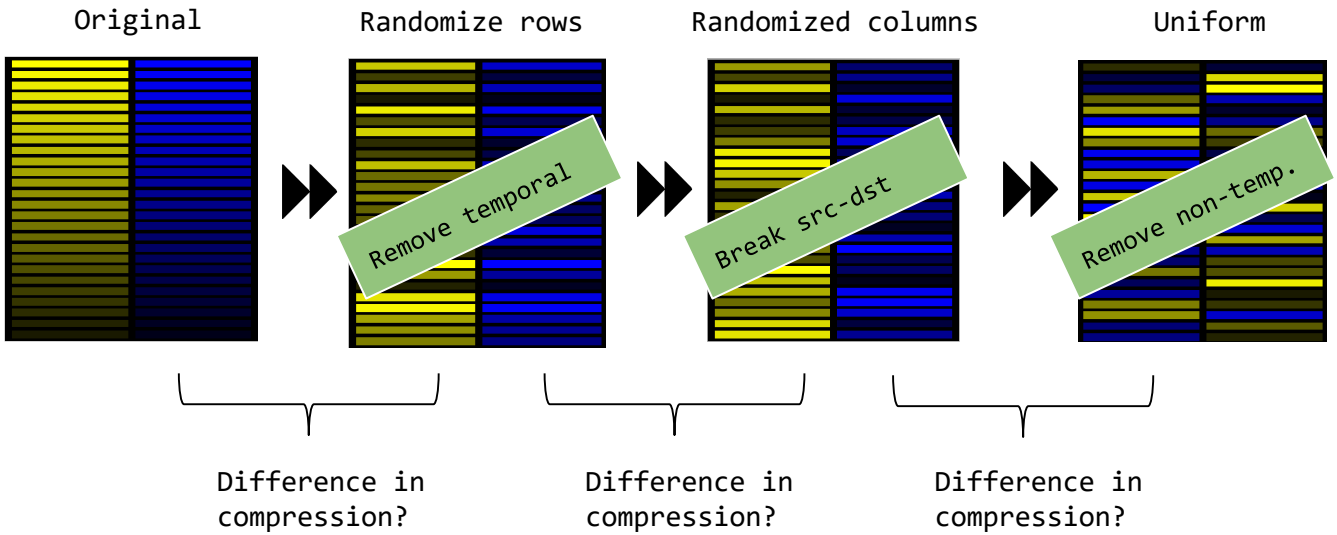
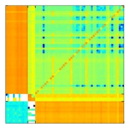
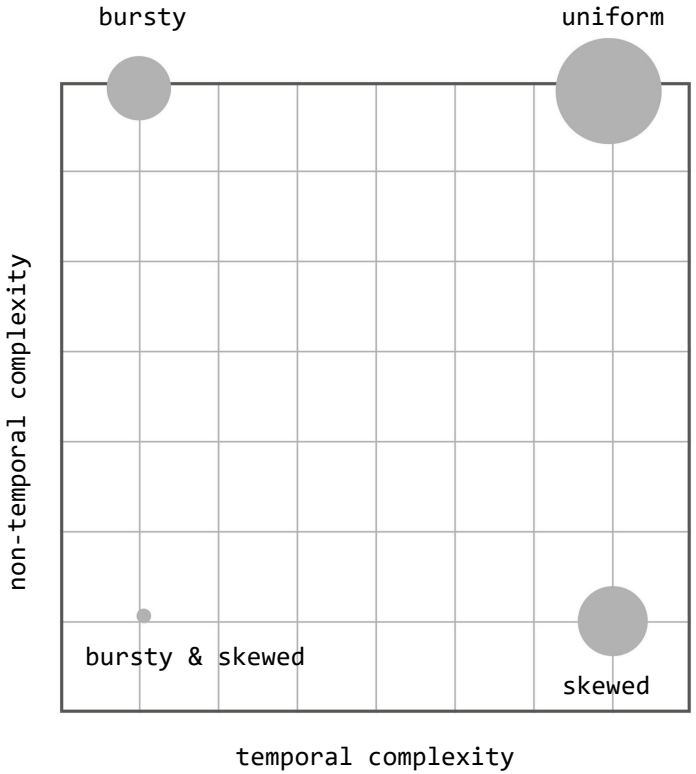


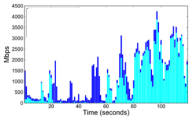
Can be used to define a “Complexity Map”!

Our Methodology:

Complexity Map



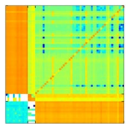


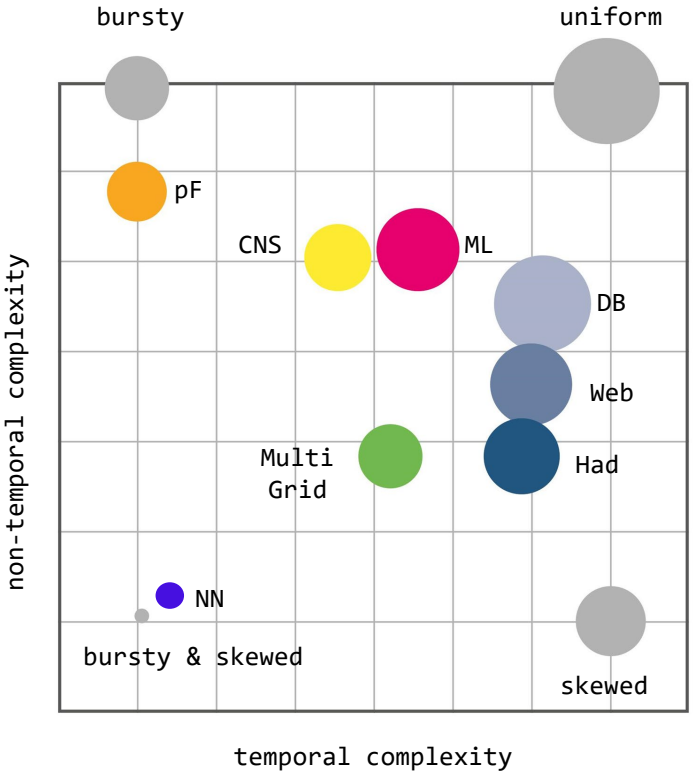


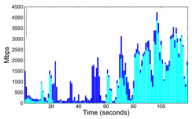
Our **approach**: iterative **randomization and compression** of trace to identify dimensions of structure.

Our Methodology:

Complexity Map





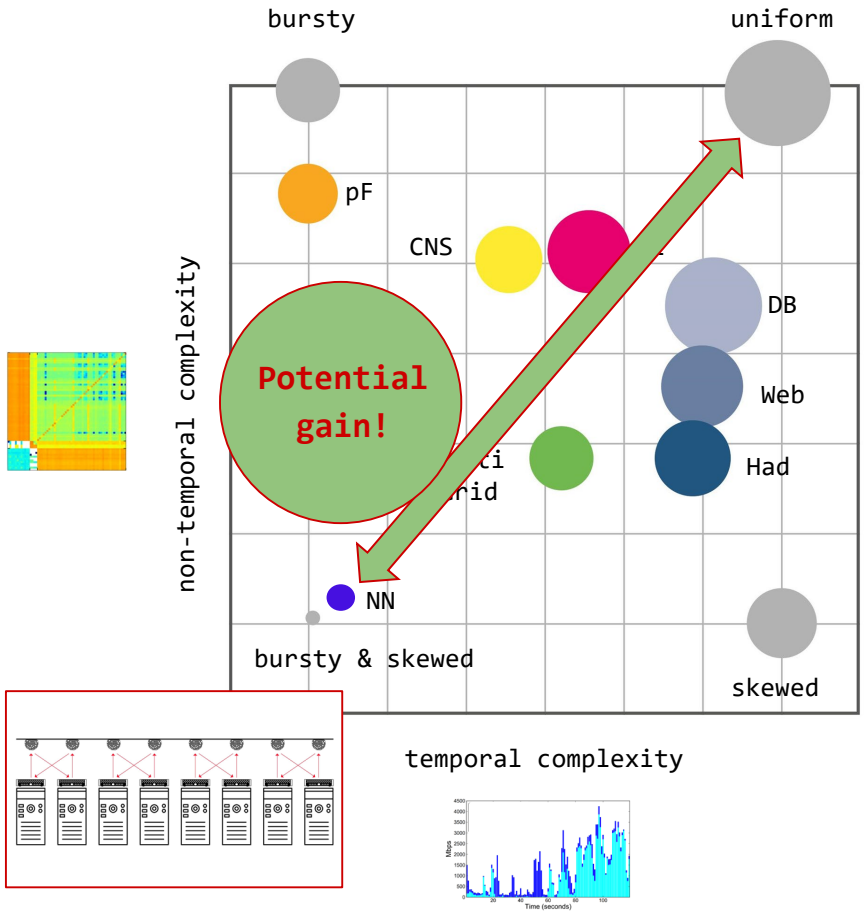


Our **approach**: iterative **randomization and compression** of trace to identify dimensions of structure.

Different structures!

Our Methodology:

Complexity Map



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

Different structures!

Question 2:

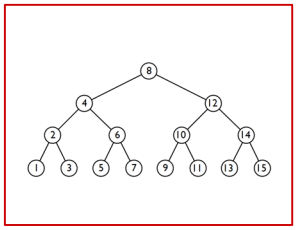
Given This Structure, What Can Be Achieved? Metrics and Algorithms?

A first insight: entropy of the demand.

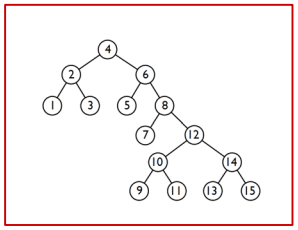
Our Approach:

Connection to Datastructures

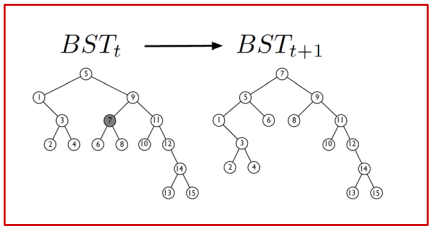
Traditional BST



Demand-aware BST



Self-adjusting BST

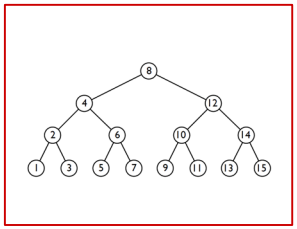


More structure: improved **access cost**

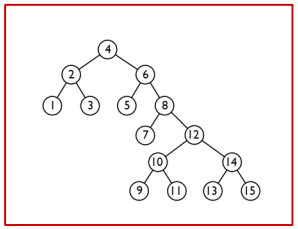
Our Approach:

Connection to Datastructures & Coding

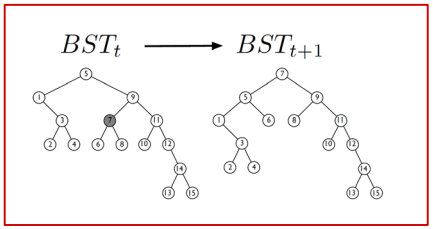
Traditional BST
(Worst-case coding)



Demand-aware BST
(Huffman coding)



Self-adjusting BST
(Dynamic Huffman coding)



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

Our Approach:

Connection to Datastructures & Coding

Traditional BST
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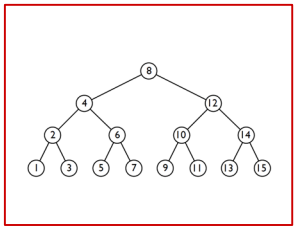

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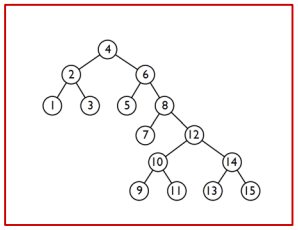

Self-adjusting BST
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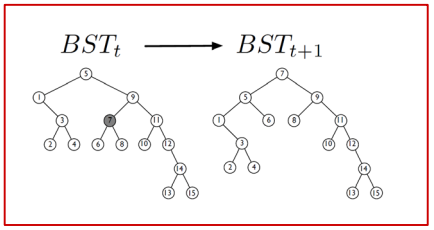
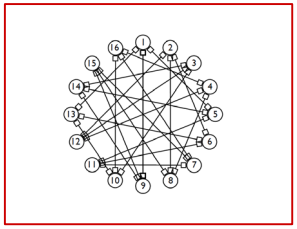
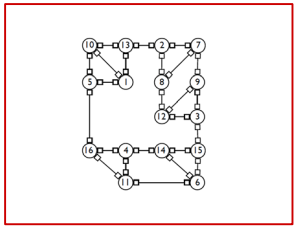
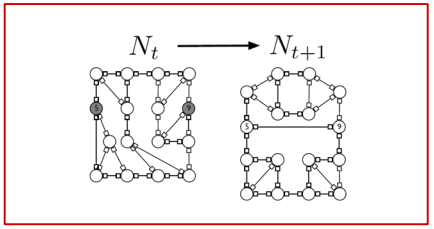


More structure: improved **access cost** / shorter **codes**





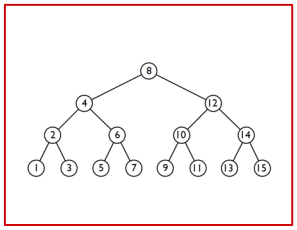


Similar **benefits**?

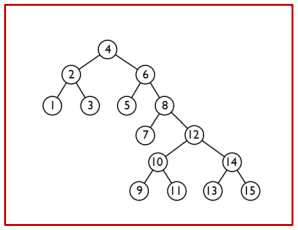
Our Approach:

Connection to Datastructures & Coding

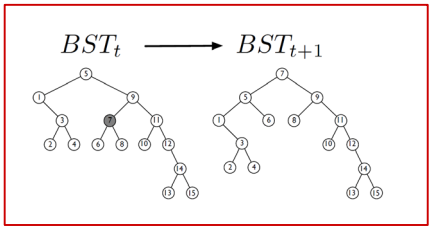
Traditional BST
(Worst-case coding)



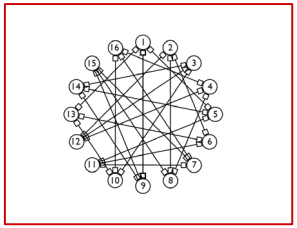
Demand-aware BST
(Huffman coding)

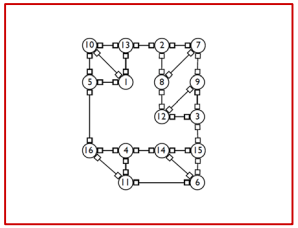


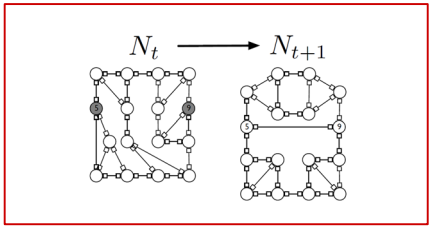
Self-adjusting BST
(Dynamic Huffman coding)



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







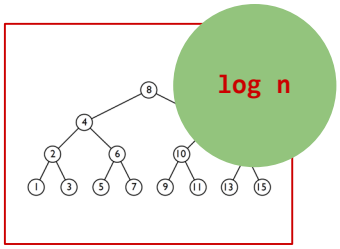
Similar **benefits**?

More than an analogy!

Our Approach:

Connection to Datastructures & Coding

Traditional BST
(Worst-case coding)



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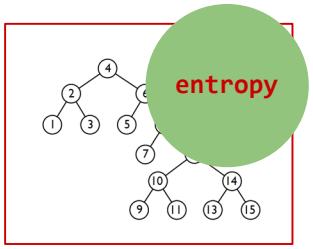

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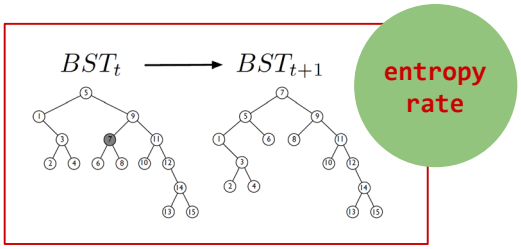

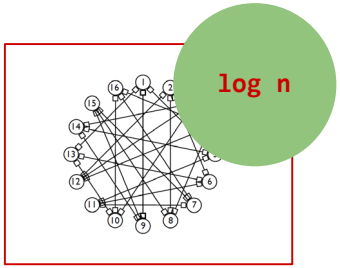

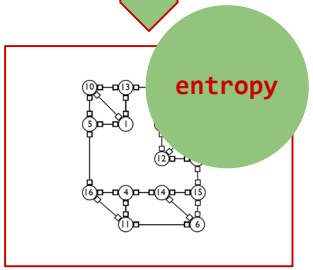

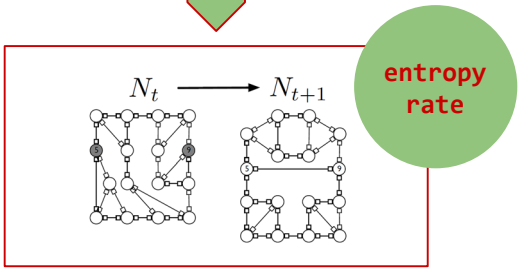

Reduced expected **route lengths**!

More than an analogy!

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

First result:
Demand-aware networks of asymptotically optimal route lengths.

Our Approach:

Connection to Datastructures & Coding

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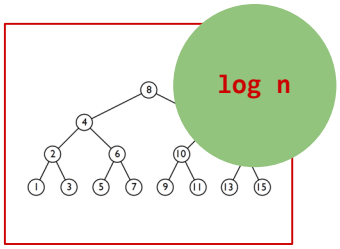

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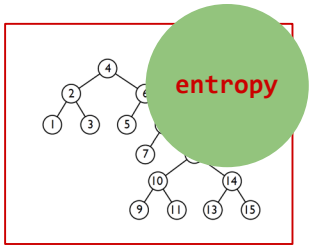

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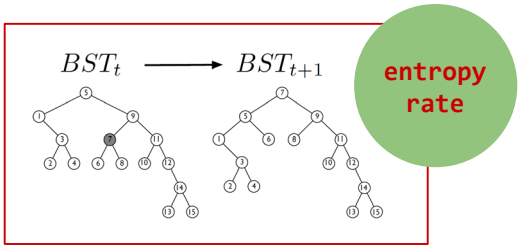

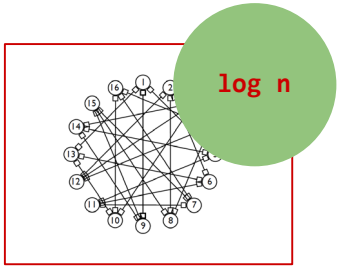

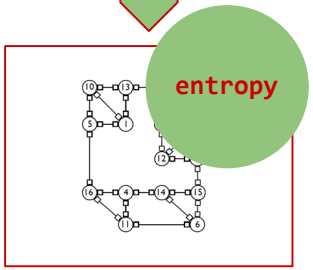

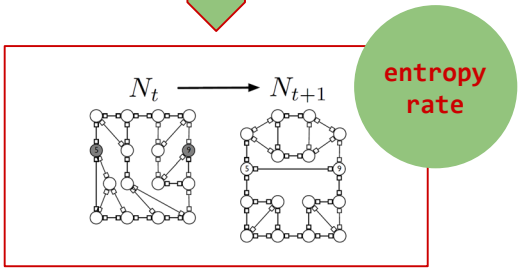

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Generalize methodology:
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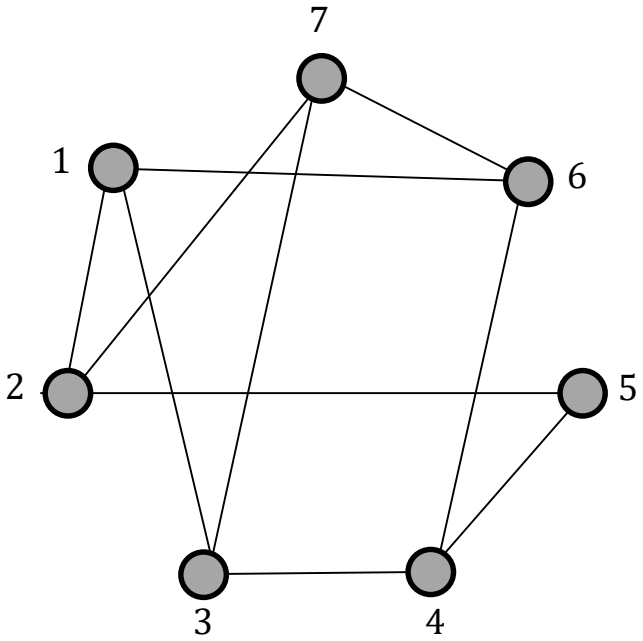
Demand-aware networks of asymptotically optimal route lengths.

An Example:

Constant-Degree Demand-Aware Network

Sources \ Destinations	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



$$\mathrm{ERL}(\mathcal{D},\mathrm{N}) = \sum_{(u,v)\in\mathcal{D}} p(u,v)\cdot d_N(u,v)$$

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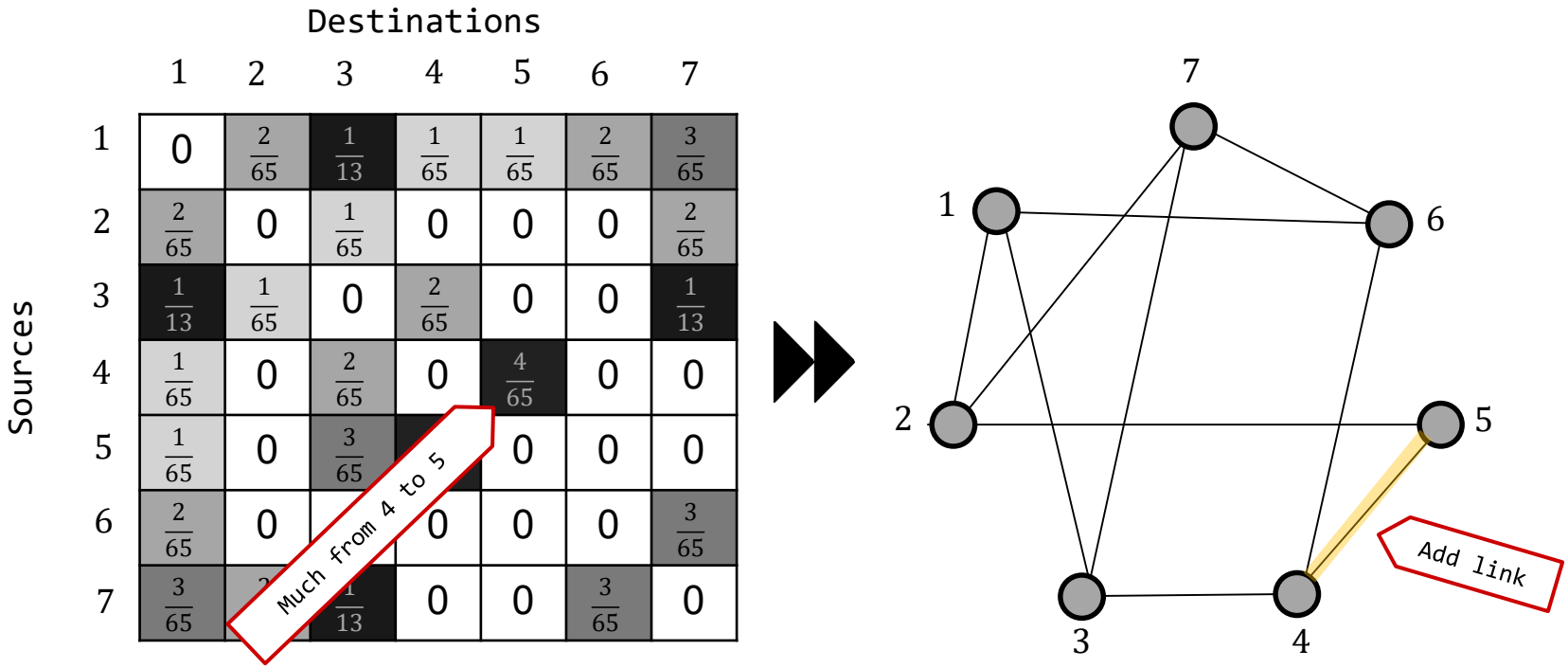
Constant-Degree Demand-Aware Network



$$\mathrm{ERL}(\mathcal{D},N) = \sum_{(u,v)\in\mathcal{D}} p(u,v)\cdot d_N(u,v)$$

An Example:

Constant-Degree Demand-Aware Network

Communicated with many

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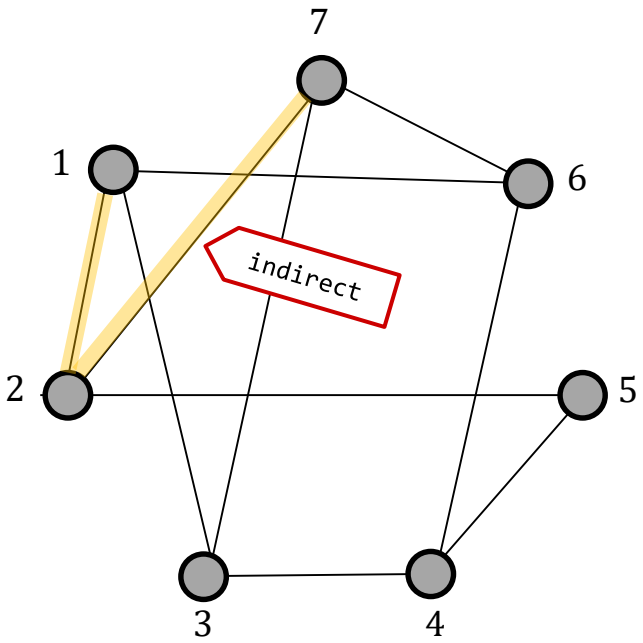
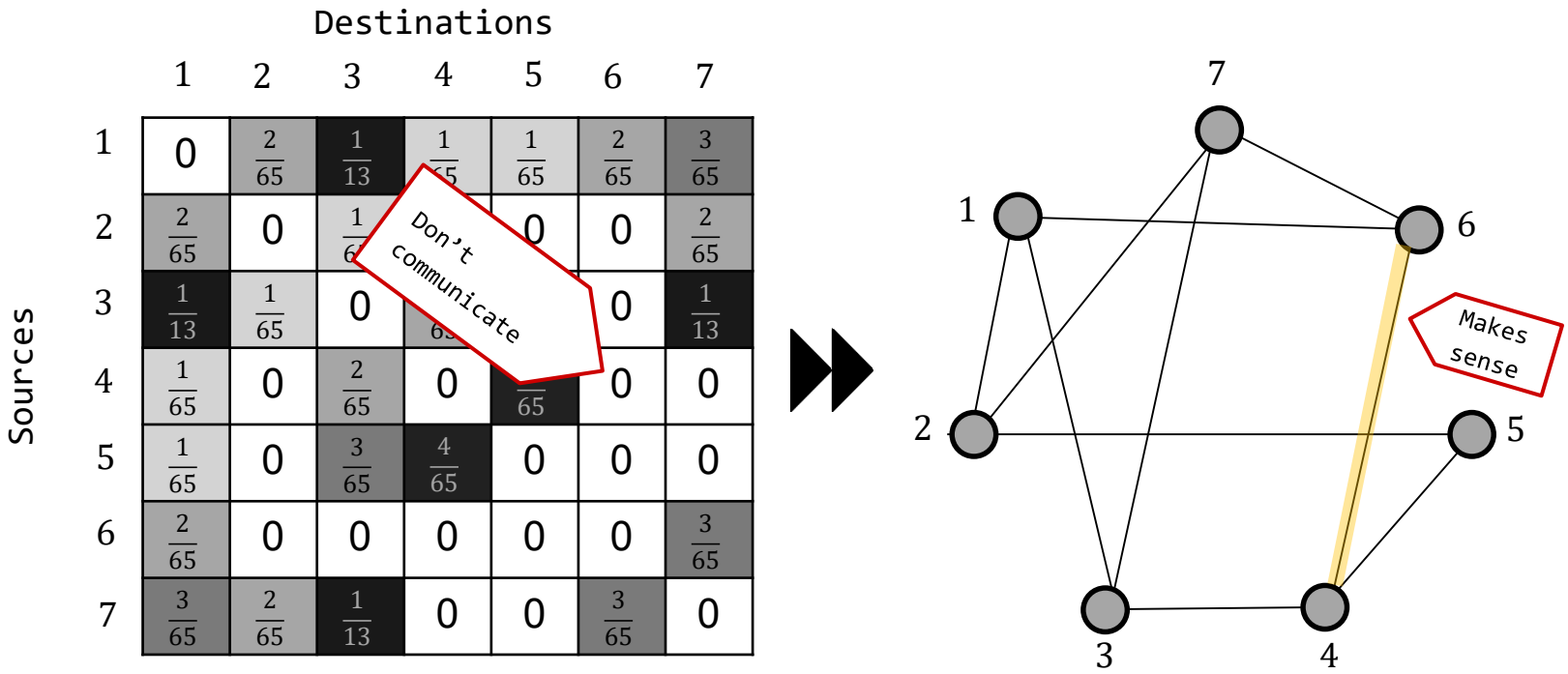
5	$\frac{1}{65}$	0	$\frac{3}{65}$	$\frac{4}{65}$	0	0	0
6	$\frac{2}{65}$	0	0	0	0	0	$\frac{3}{65}$
7	$\frac{3}{65}$	$\frac{2}{65}$	$\frac{1}{13}$	0	0	$\frac{3}{65}$	0



$$\mathrm{ERL}(\mathcal{D},N) = \sum_{(u,v)\in\mathcal{D}} p(u,v)\cdot d_N(u,v)$$

An Example:

Constant-Degree Demand-Aware Network



$$\mathrm{ERL}(\mathcal{D},\mathrm{N}) = \sum_{(u,v)\in\mathcal{D}} p(u,v)\cdot d_N(u,v)$$

From Static Coding:

Entropy Lower Bound

Destinations

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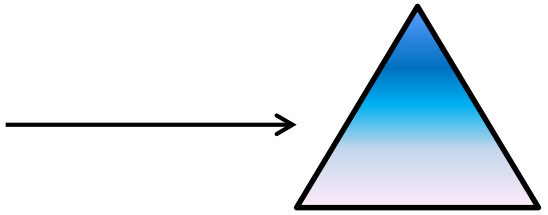
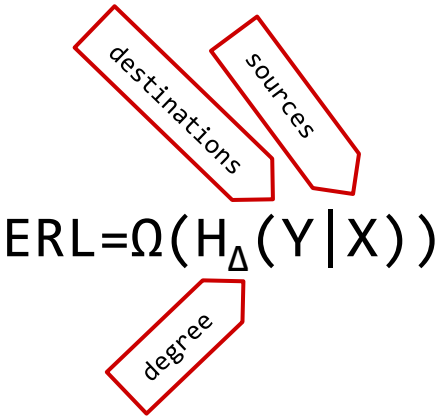
6	$\frac{2}{65}$	0	0	0	0	0	$\frac{3}{65}$
	$\frac{3}{65}$	$\frac{2}{65}$	$\frac{1}{13}$	0	0	$\frac{3}{65}$	0



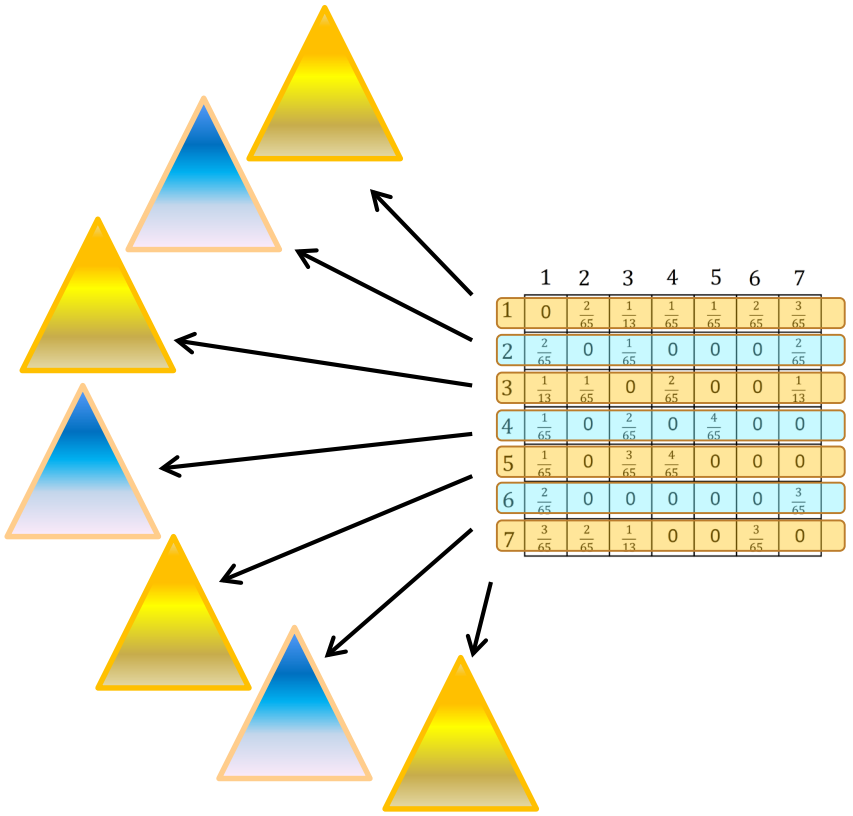
Huffman tree:
“ego-tree”

From Static Coding:

Entropy Lower Bound



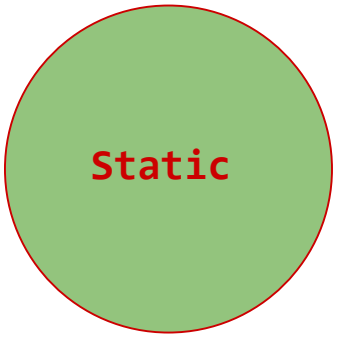
$$ERL=\Omega(H_{\Delta}(Y|X))$$

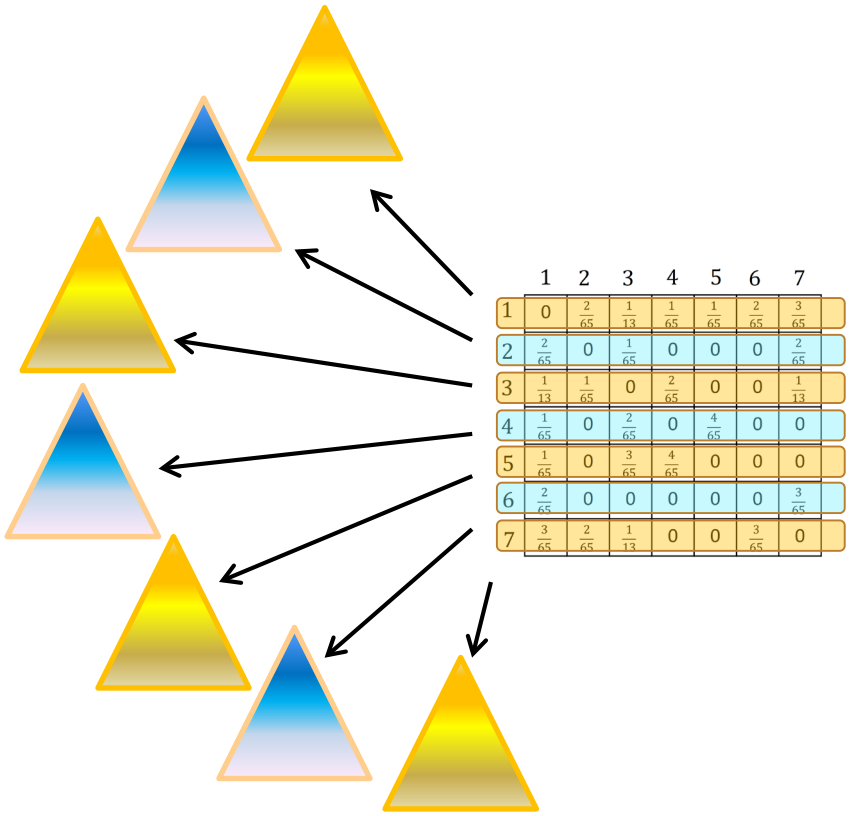


From Static Coding:

Upper Bound and Algo

- Idea for algorithm:
  - union of trees
  - reduce degree
- Ok for sparse demands
  - helper nodes





What about dynamic case?

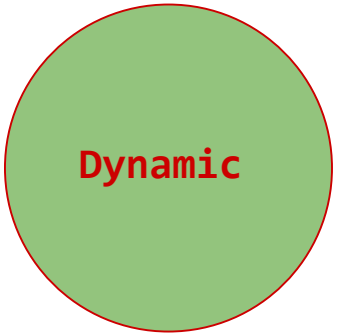
From Dynamic Coding:

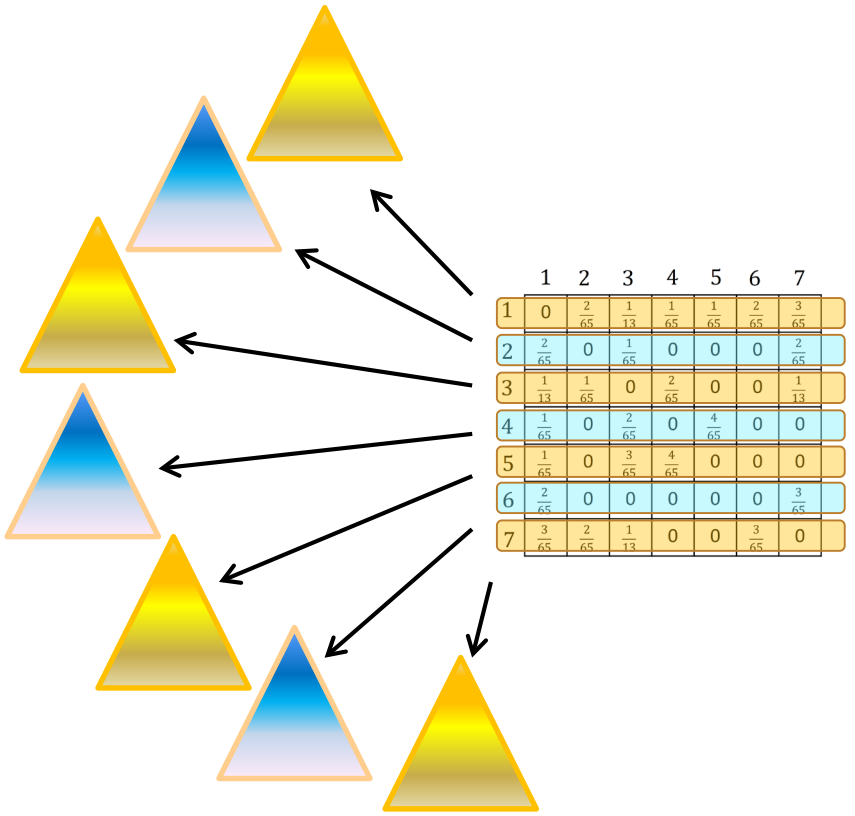
Dynamic Setting

⇢ Dynamic the same:

→ union of **dynamic ego-trees**

⇢ E.g., SplayNets





Future Work

so far scratched surface

to do ☺

Notion of self-adjusting networks opens a **large uncharted field** with many questions:

- → By how much can load be lowered, **energy** reduced, quality-of-service improved, etc. in demand-aware networks?
- → How to **model** reconfiguration costs?
- → How to render these networks **robust?**
- → Impact on **other layers**?
- → How to design **scalable** control planes?

Challenges:

Domain 1 Models and metrics	**Domain 2** Algorithms	**Domain 3** Integration

Requires knowledge in networking, distributed systems, algorithms, performance evaluation.

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so far

scratched surface

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Monika Henzinger (University of Vienna)

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Even bigger picture:

Flexible Networks

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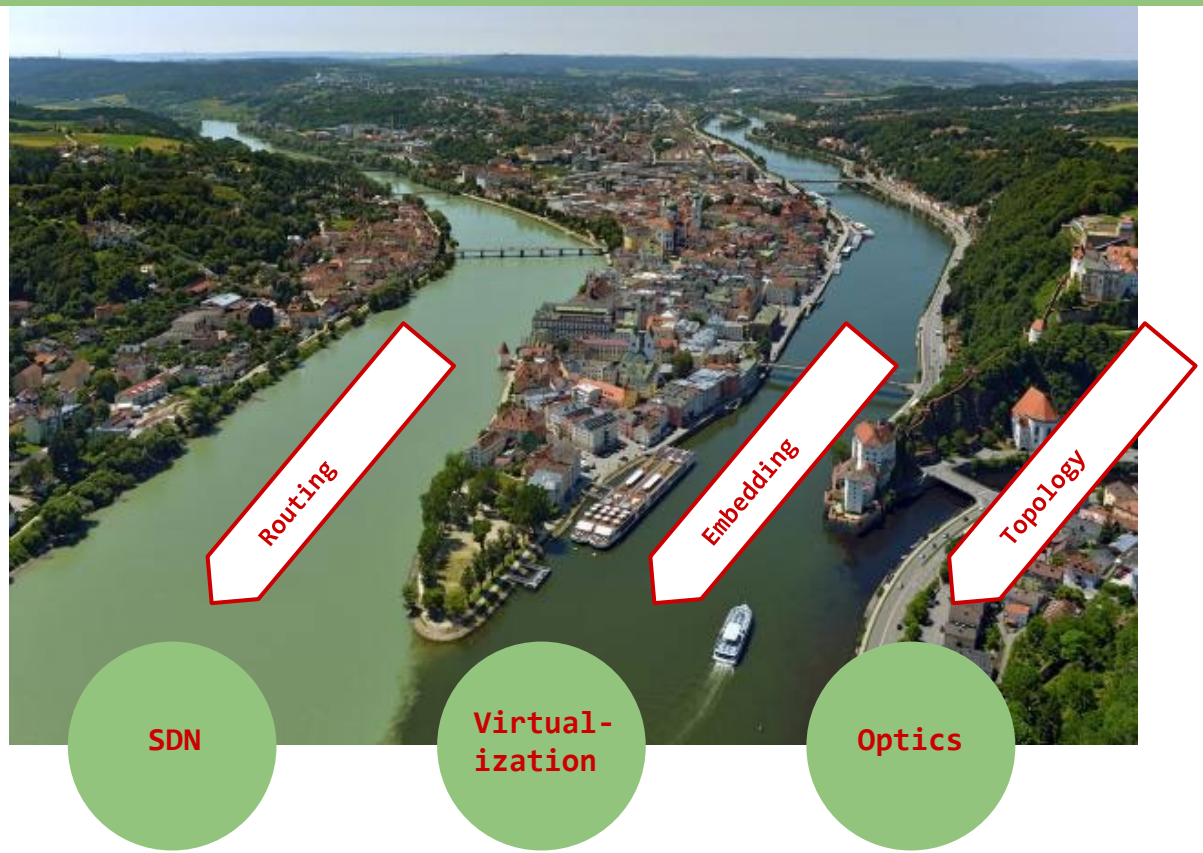
Flexible Networks



Contributors

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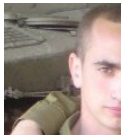
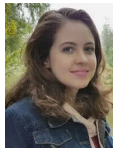


Khen Griner



Bruna Peres

et al.!

Funding:

German-Israeli Foundation for Scientific Research and Development

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