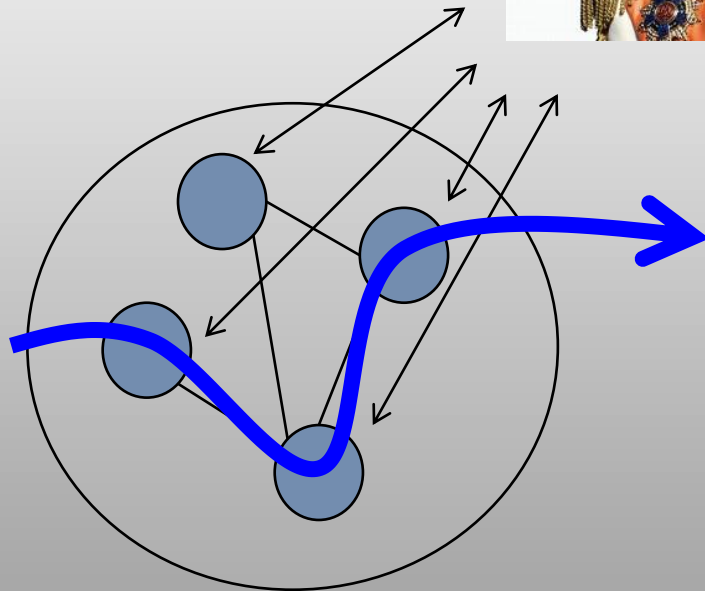


# Exploiting Locality in Distributed SDN Control

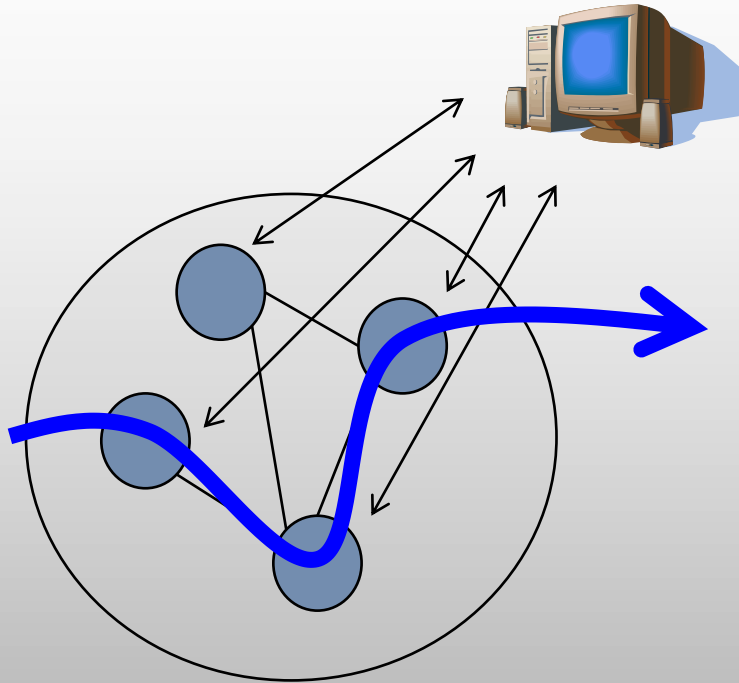
***Stefan Schmid (TU Berlin & T-Labs)***

Jukka Suomela (Uni Helsinki)

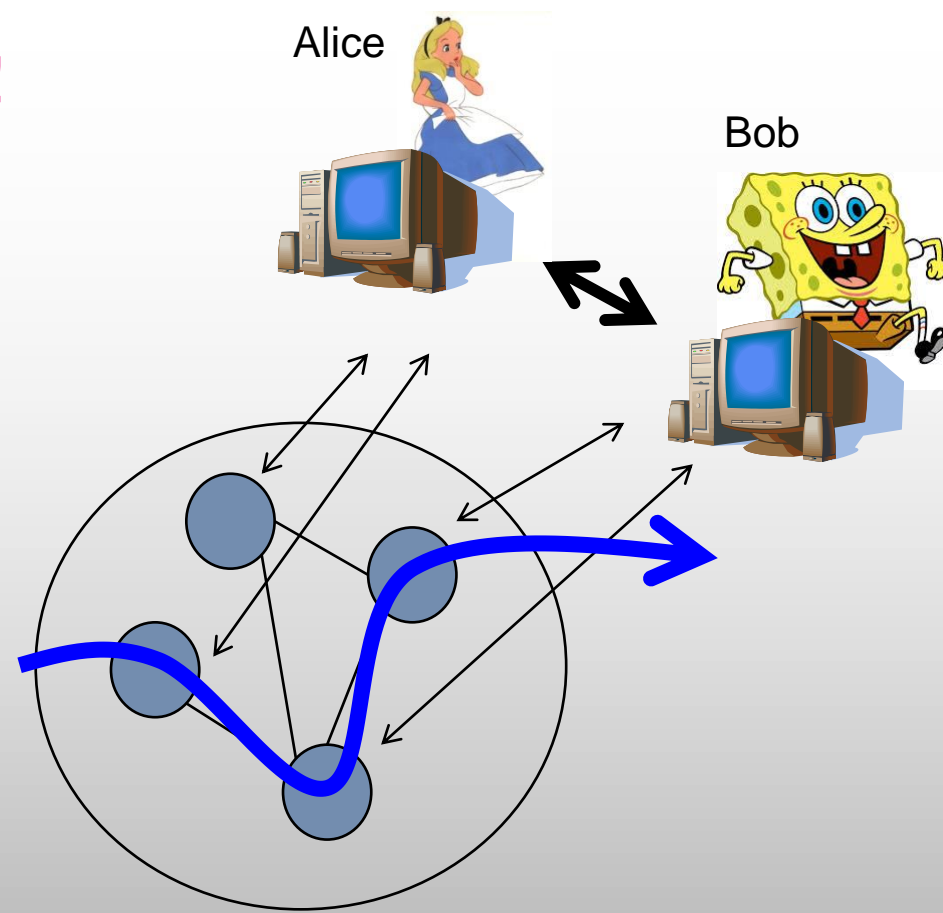
# My view of SDN before I met Marco and Dan...



# Logically Centralized, but Distributed!



VS



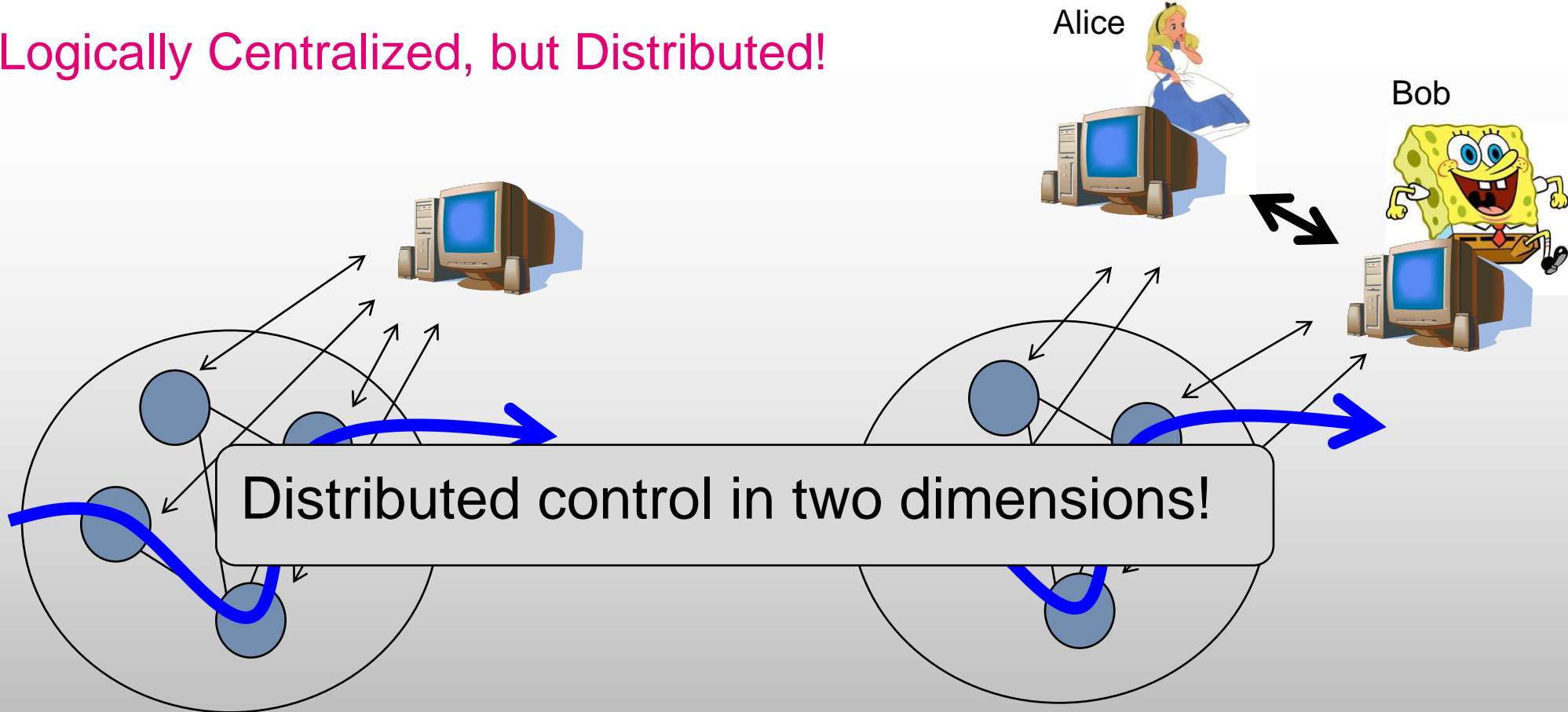
## Vision:

- Control becomes **distributed**
- Controllers become **near-sighted** (control part of network or flow space)

## Why:

- Enables **wide-area** SDN networks
- Administrative: Alice and Bob
  - Admin. domains, local provider footprint ...
- Optimization: Latency and load-balancing
  - **Latency** e.g., FIBIUM
  - Handling certain events **close to datapath** and **shield/load-balance** more global controllers (e.g., Kandoo)

# Logically Centralized, but Distributed!



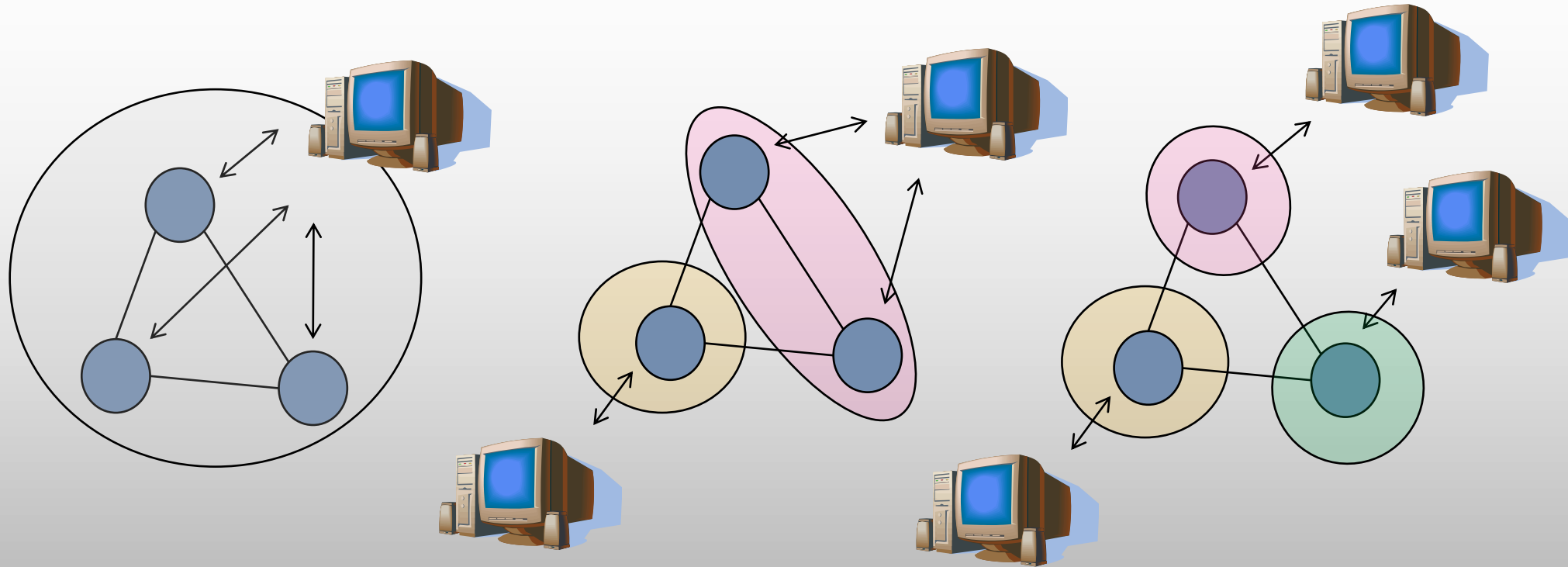
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# 1<sup>st</sup> Dimension of Distribution: Flat SDN Control (“Divide Network”)

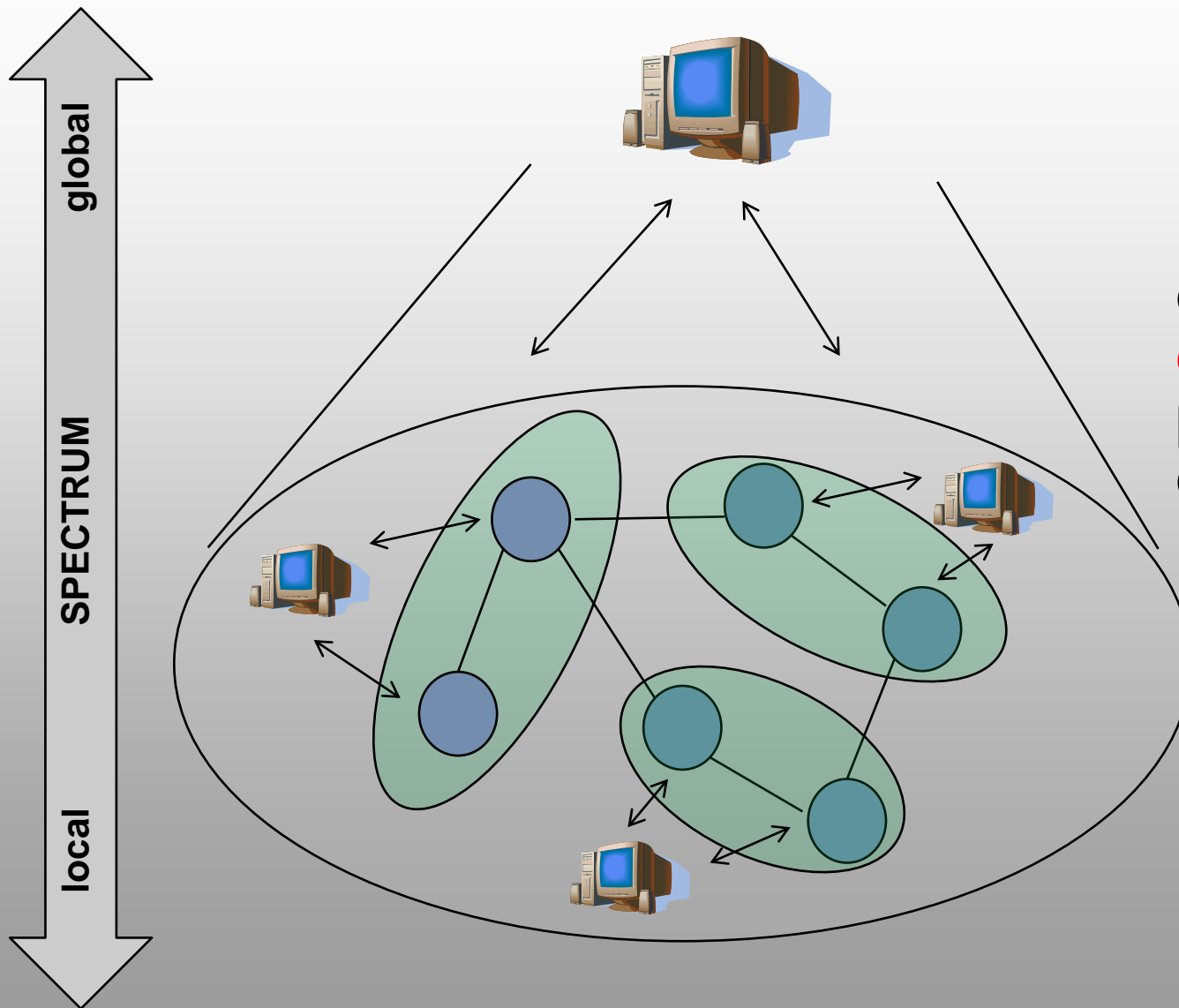


e.g., small network

e.g., routing control platform

e.g., SDN router (*FIBIUM*)

# 2<sup>nd</sup> Dimension of Distribution: Hierarchical SDN Control (“Flow Space”)



e.g., handle **frequent events** close to data path, shield global controllers (*Kandoo*)

# Questions Raised

- How to control a network if I have “**local view**” only?
- How to design distributed control plane (if I can), and how to divide it among controllers?
- Where to place controllers? (see Brandon!)
- Which tasks can be solved locally, which tasks need global control?
- ...

Exploiting Locality in Distributed SDN Control

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**ABSTRACT**  
Large SDN networks will be partitioned in multiple controller domains; each controller is responsible for one domain, and the controllers of adjacent domains may need to communicate to enforce global policies. This paper studies the implications of the local network view of the controllers. In particular, we establish a connection to the field of local algorithms and distributed computing, and discuss lessons for the design of a distributed control plane. We show that existing local algorithms can be used to develop efficient coordination protocols in which each controller only needs to respond to events that take place in its local neighborhood. However, while existing algorithms can be used, SDN networks also suggest a new approach to the study of locality in distributed computing. We introduce the so-called *supported locality model* of distributed computing. The new model is more expressive than the classical models that are commonly used in the design and analysis of distributed algorithms, and it is a better match with the features of SDN networks.

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This paper highlights that there is a lot of potential for interactions between the two areas, the distributed control of SDN networks and local algorithms. On the one hand, we argue that there are many recent results related to local algorithms that are relevant in the efficient management and operation of SDN networks. On the other hand, we identify properties of SDN networks which raise additional and new challenges in the design of local algorithms. We describe a disparity between the features of SDN networks and the standard models of distributed systems that are used in the design and analysis of local algorithms. Indeed, there are many tasks that can be solved efficiently in real-world SDN networks, yet they do not admit a local algorithm in the traditional sense. We suggest a new model of distributed computing that separates the relatively static network structure (e.g., physical network equipment) and dynamic inputs (e.g., current traffic pattern).

**1.1 Running Examples**  
We begin our exploration of the interactions between distributed SDN control and local algorithms with two scenarios that we will use as running examples.

**Example 1. Link assignment.** Consider an Internet Service Provider with a number of Points-of-Presence  $v \in V$ , and a number of customers  $u \in U$ . For each customer, there are multiple redundant connections between the customer's site and the operator's network. We can represent the connections between the customer sites and the access routers in the operator's network as a bipartite graph  $G = (U \cup V, E)$ , where an edge  $(u, v) \in E$  indicates that there is a network link from customer site  $u$  to the access router in point-of-presence  $v$ .



$V$ : operator's backbone network  
 $U$ : point-of-presence  
 $E$ : redundant links  
customer sites

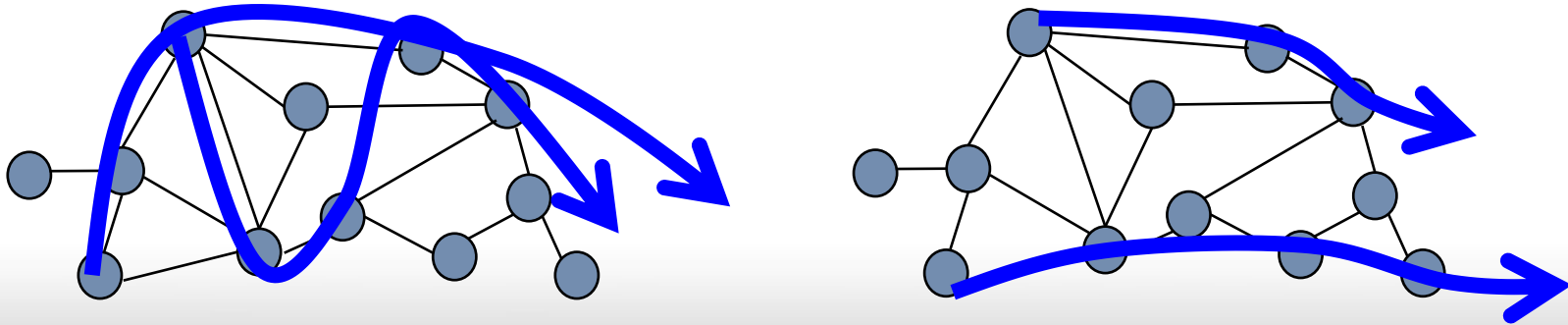
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## Our paper:

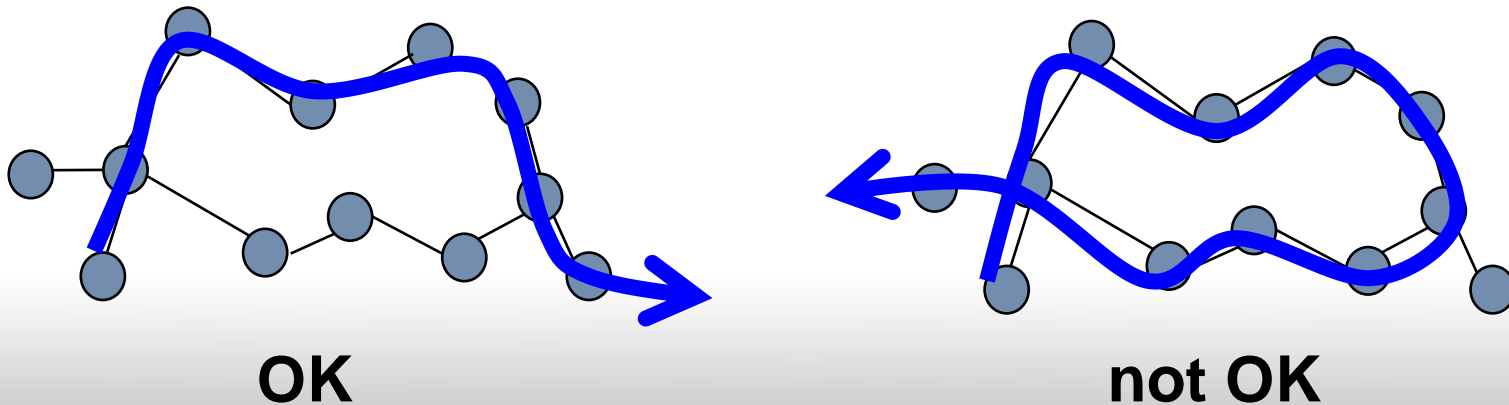
- Review and apply lessons to SDN from distributed computing and **local algorithms**\* (**emulation** framework to make some results applicable)
- Study of **case studies**: (1) a *load balancing* application and (2) ensuring *loop-free forwarding* set
- First insights on what can be computed and verified locally (and **how**), and what cannot
- \* Local algorithms = distributed algorithms with constant radius (“control infinite graphs in **finite time**”)

# Generic SDN Tasks: Load-Balancing and Ensuring Loop-free Paths

## SDN for TE and Load-Balancing: Re-Route Flows



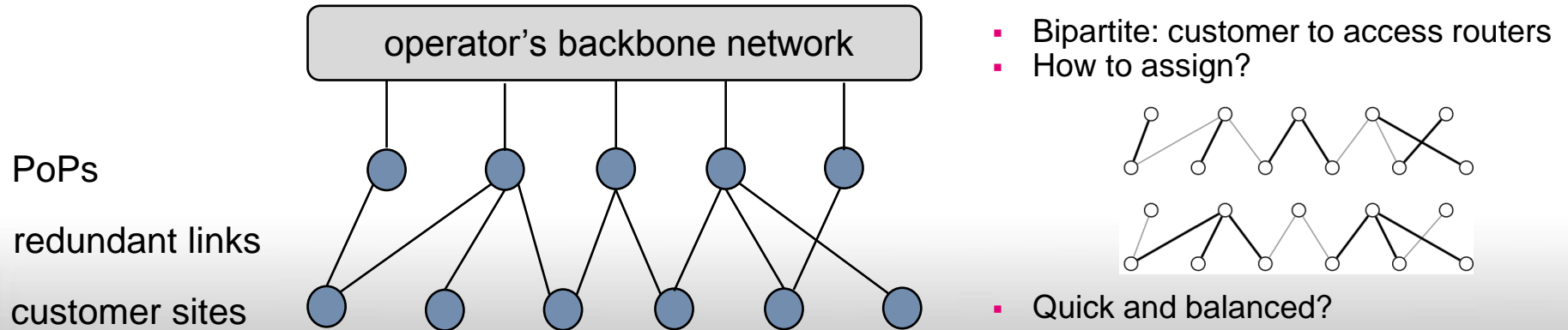
## Compute and Ensure Loop-Free Forwarding Set



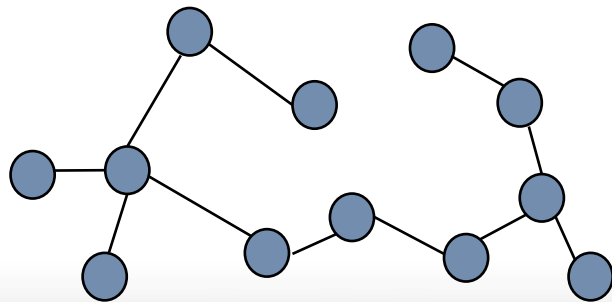


# Concrete Tasks

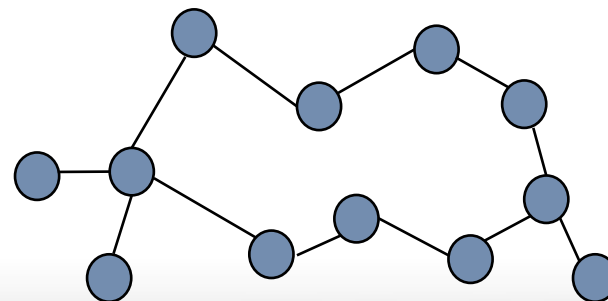
## SDN Task 1: Link Assignment („Semi-Matching Problem“)



## SDN Task 2: Spanning Tree Verification



OK

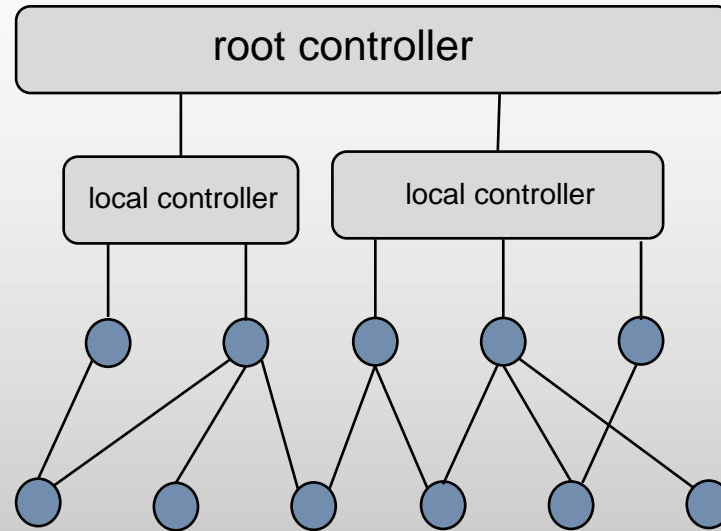


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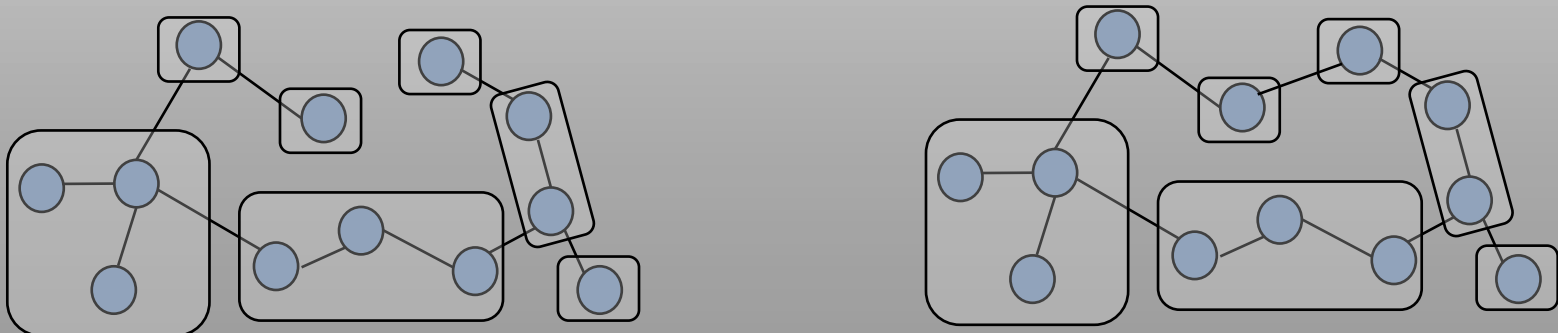
**Both tasks are trivial under global control...!**

# ... but not for distributed control plane!

- Hierarchical control:

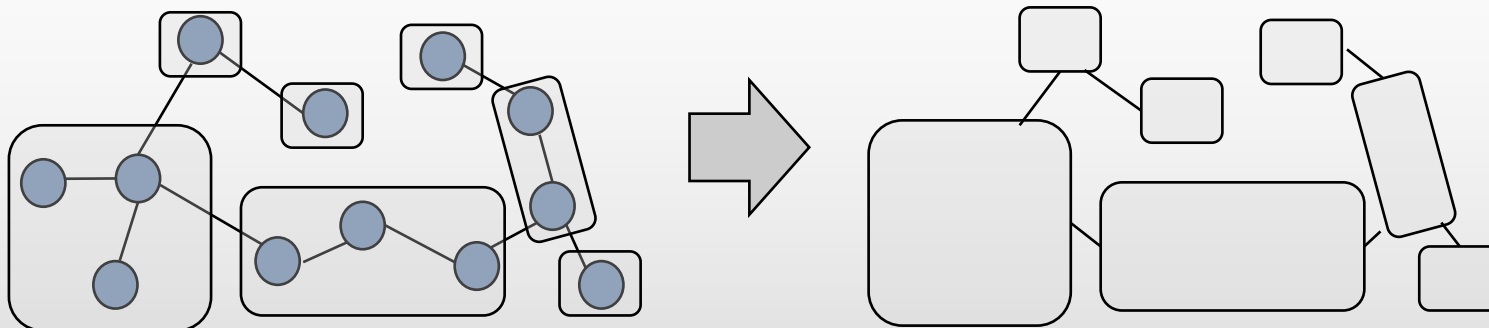


- Flat control:

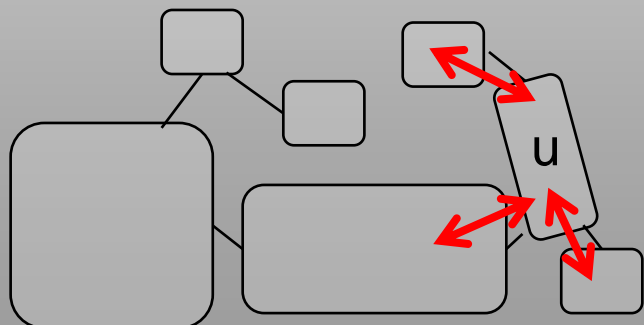
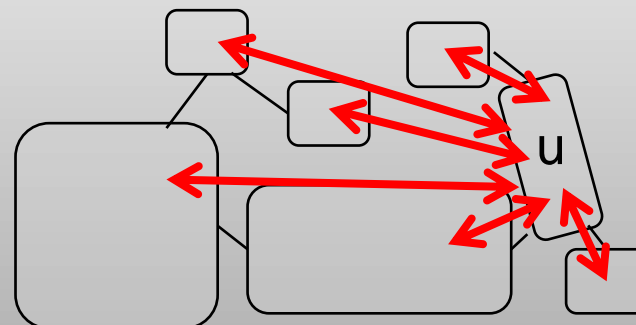


# Local vs Global: Minimize Interactions Between Controllers

Useful abstraction and terminology: The “controllers graph”



**Global task:** inherently need to respond to events occurring at all devices.

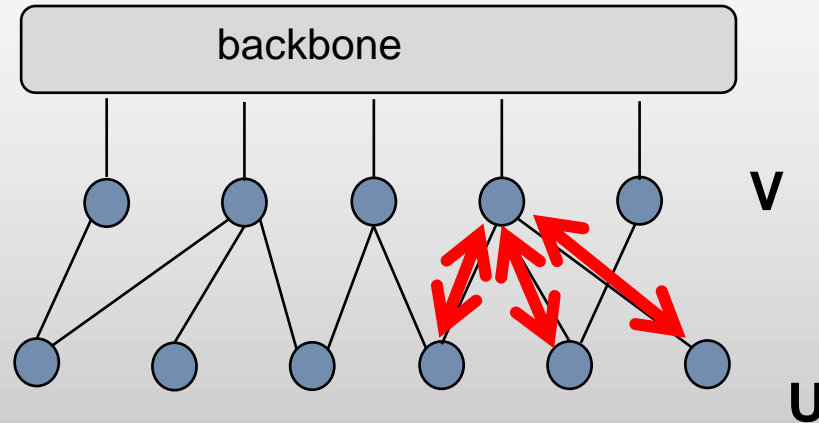


**Local task:** sufficient to respond to events occurring in vicinity!

Objective: **minimize interactions** (number of involved controllers and communication)

# Take-home 1: Go for Local Approximations!

A semi-matching problem:



## Semi-matching

If a customer  $u$  connects to a POP with  $c$  clients connected to it, the customer  $u$  costs  $c$ .

Minimize the average cost of customers!

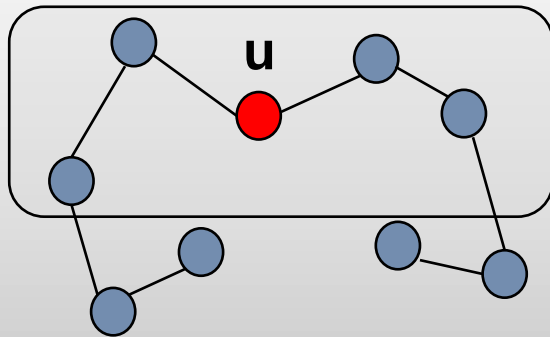
**The bad news:** Generally the problem is **inherently global** e.g.,



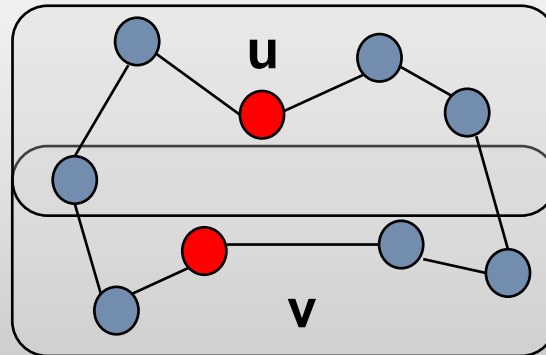
**The good news:** **Near-optimal semi-matchings** can be found efficiently and **locally**! Runtime independent of graph size and local communication only. (How? Paper! 😊)

# Take-home 2: Verification is Easier than Computation

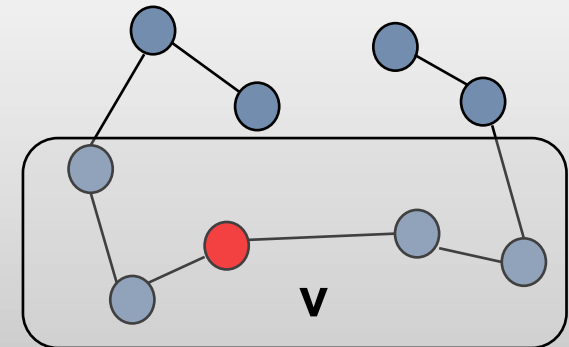
**Bad news:** Spanning tree computation (and even verification!) is an inherently global task.



OK



not OK



OK

2-hop local views of controllers  $u$  and  $v$ : in the three examples, **cannot distinguish** the local view of a good instance from the local view of the bad instance.

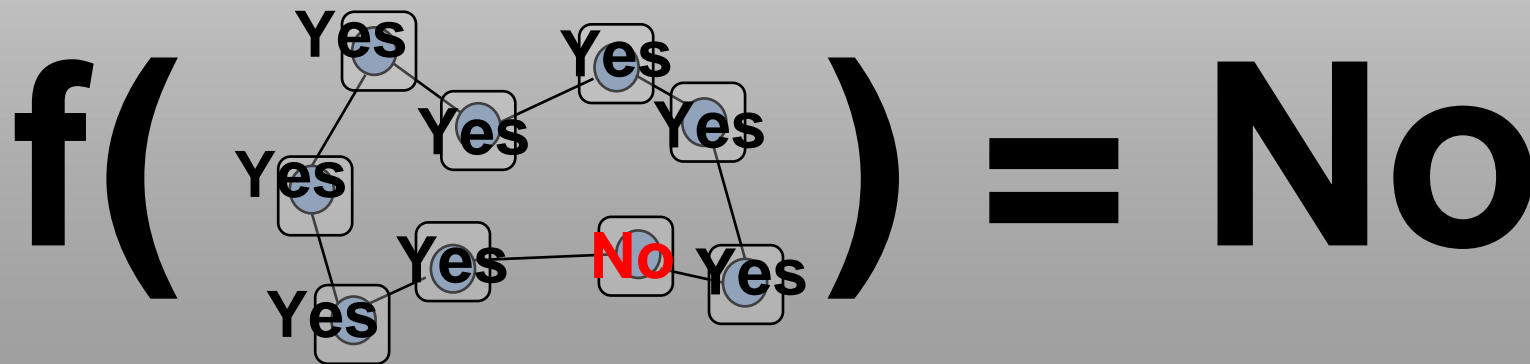
**Good news:** However, at least verification can be made local, with **minimal additional information** / local communication between controllers (**proof labels**)!

# Proof Labeling Schemes

**Idea:** For verification, it is often sufficient if at least one controller notices **local inconsistency**: it can then trigger **global re-computation!**

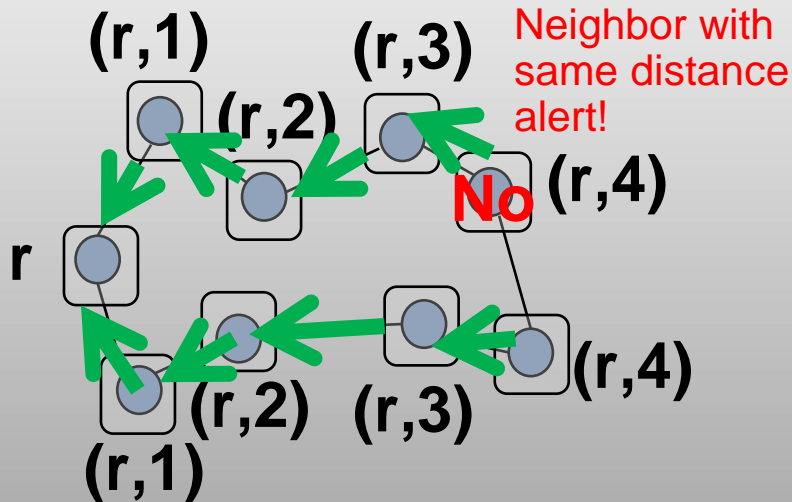
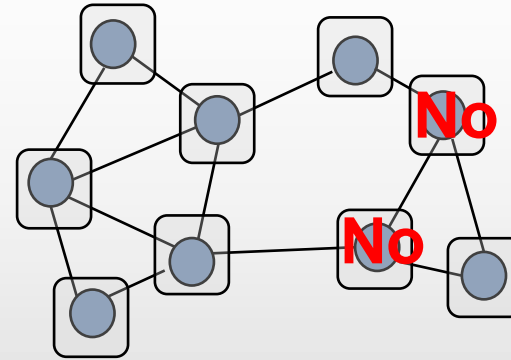
## Requirements:

- Controllers exchange minimal amount of information (“**proofs labels**”)
- Proof labels are **small** (an “SMS”)
- Communicate only with controllers **with incident domains**
- **Verification**: if property not true, *at least one* controller will notice...
- ... and raise alarm (re-compute labels)



# Examples

**Euler Property:** Hard to compute Euler tour (“each edge exactly once”), but easy to verify! **0-bits (= no communication)** : output whether degree is even.



**Spanning Tree Property:** Label encodes root node plus distance & direction to root. At least one node notices that root/distance not consistent! Requires  **$O(\log n)$  bits.**

**Any (Topological) Property:**  **$O(n^2)$  bits.**

Maybe also known from databases: efficient ancestor query! Given two  $\log(n)$  labels.

# Take-home 3: Not Purely Local, Pre-Processing Can Help!

**Idea:** If network changes happen at **different time scales** (e.g., **topology vs traffic**), pre-processing “(relatively) static state” (e.g., topology) can improve the performance of local algorithms (e.g., no need for symmetry breaking)!

Local problems often face two challenges: **optimization** and **symmetry breaking**. The latter may be **overcome** by pre-processing.

## Example: Local Matchings

(M1) Maximal matching (only because of symm!)

(M2) Maximal matching on bicolored graph ← bipartite (like PoP assignment)

(M3) Maximum matching (symm+opt!)

(M4) Maximum matching on bicolored graph

(M5) Fractional maximum matching ← packing LP

\* impossible, approx ok, easy

### Optimization:

(M1, M2): only need to find feasible solution!

(M1, M2, M3): need to find optimal solution!

### Symmetry breaking:

(M1, M3): require symmetry breaking

(M2, M4): symmetry already broken

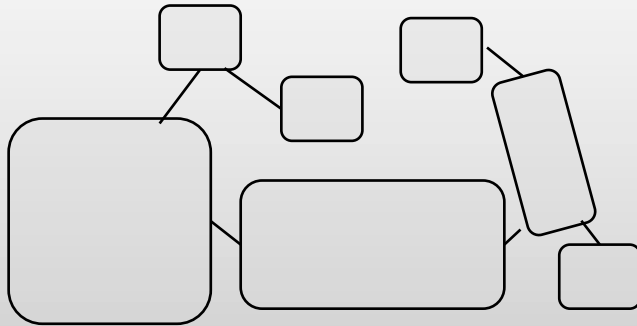
(M5): symmetry trivial

E.g., (M1) is simpler if graph can be pre-colored! Or *Dominating Set* (1. distance-2 coloring then 2. greedy [5]), *MaxCut*, ... The “**supported locality model**”. 😊



# Take-home >3: How to Design Control Plane

- Make your controller graph **low-degree** if you can!
- ...



Problem	Approx. factor
Matching	$1 + \epsilon$ $(\Delta + 1)/2$
Weighted matching	$2 + \epsilon$
Simple 2-matching	$2 + \epsilon$
Semi-matching	$O(1)$
Edge cover	2
Vertex cover	2
	6
	$4 + \epsilon$
	3
	$2 + \epsilon$
	2
Dominating set	$\Delta + 1$ $2\lceil \Delta/2 \rceil + 1$ $(\Delta + 1)/2$ $O(1)$ $O(A \log \Delta)$
Domatic partition	$(\delta + 1)/2$
Edge domin. set	$4 - 2/\Delta$

## Exploiting Locality in Distributed SDN Control

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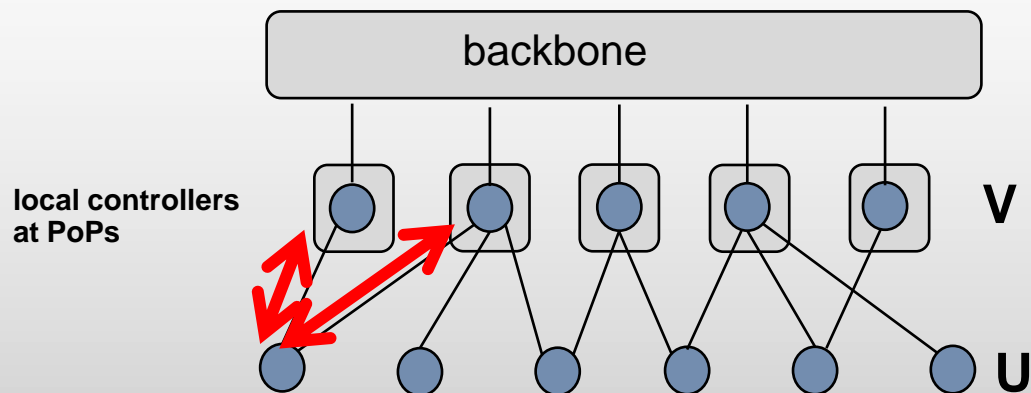
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# Conclusion

- **Local algorithms** provide insights on how to design and operate distributed control plane. Not always literally, requires **emulation!** (No communication over customer site!)
- **Take-home message 1:** Some tasks like **matching** are inherently global if they need to be solved optimally. But efficient **almost-optimal**, local solutions exist.
- **Take-home message 2:** Some tasks like **spanning tree computations** are inherently global but they can be locally verified efficiently with minimal additional communication!
- **Take-home message 3:** If network changes happen at different time scales, some pre-processing can speed up other tasks as well. A new non-purely local model.
- More in paper... 😊
- And there are other distributed computing techniques that may be useful for SDN! See e.g., the upcoming talk on “**Software Transactional Networking**”

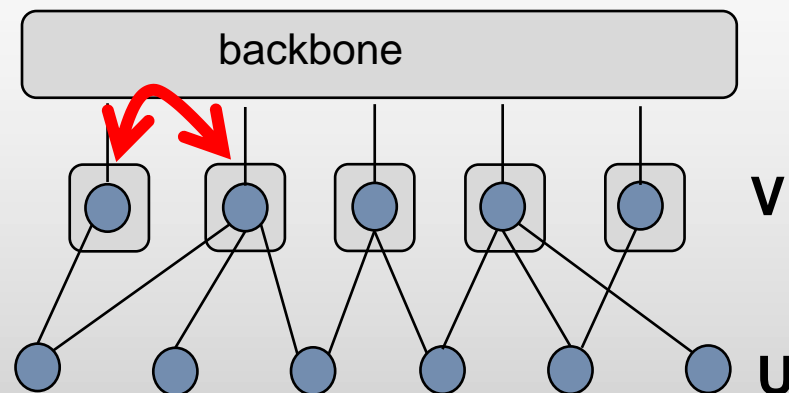
# Backup: Locality Preserving Simulation

Controllers simulate execution on graph:



## Algorithmic view:

distributed computation of the best matching



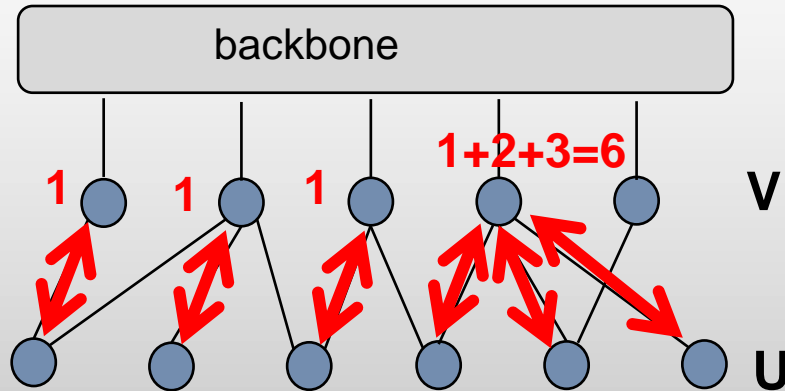
## Reality:

controllers V simulate execution; each node v in V simulates its incident nodes in U

Locality: Controllers only need to communicate with controllers within 2-hop distance in matching graph.

# Backup: From Local Algorithms to SDN: Link Assignment

A semi-matching problem:



## Semi-matching

Connect *all* customers U: *exactly one* incident edge. If a customer  $u$  connects to a POP with  $c$  clients connected to it, the customer  $u$  costs  $c$  (not one: quadratic!).

Minimize the average cost of customers!

**The bad news:** Generally the problem is inherently global (e.g., a long path that would allow a perfect matching).

**The good news:** Near-optimal solutions can be found efficiently and locally! E.g., Czygrinow (DISC 2012): runtime independent of graph size and local communication only.