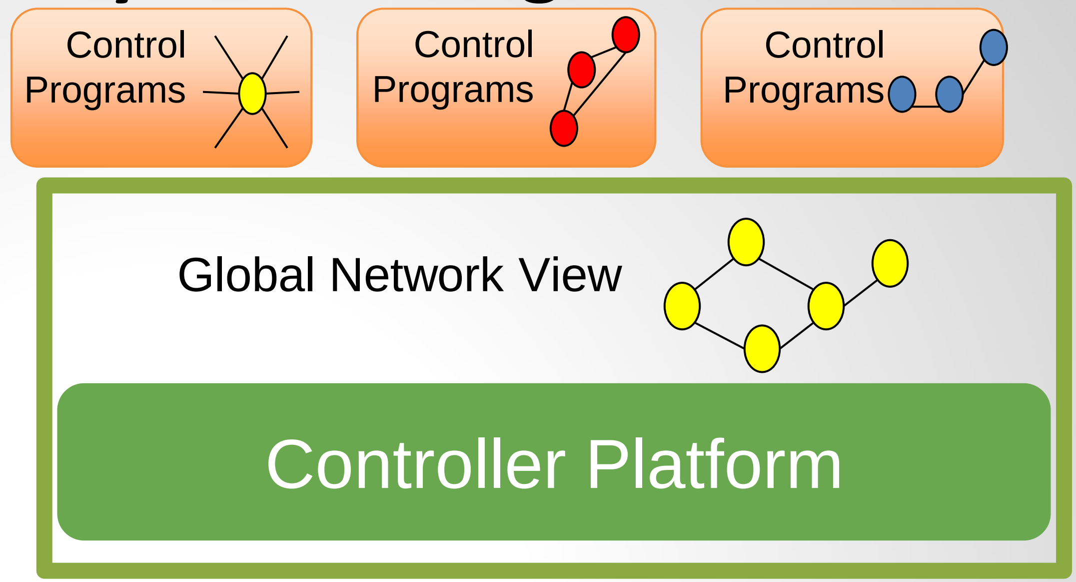
# Algorithms for Software-Defined Distributed Systems

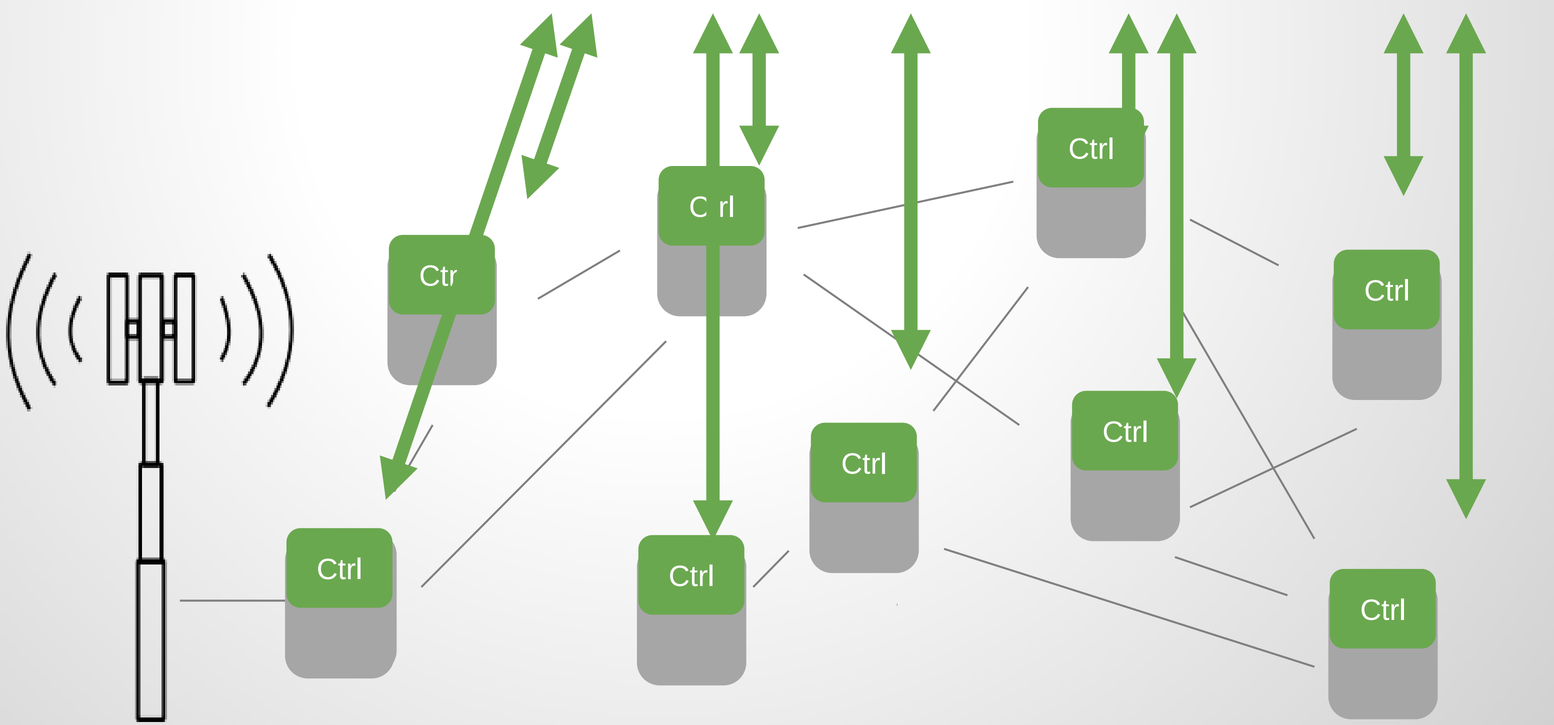
**Stefan Schmid**

TU Berlin & Telekom Innovation Labs (T-Labs)

# Flexible Distributed Systems: Programmable...

SDN **outsources** and **consolidates** control over multiple devices to (logically) centralized **software** controller



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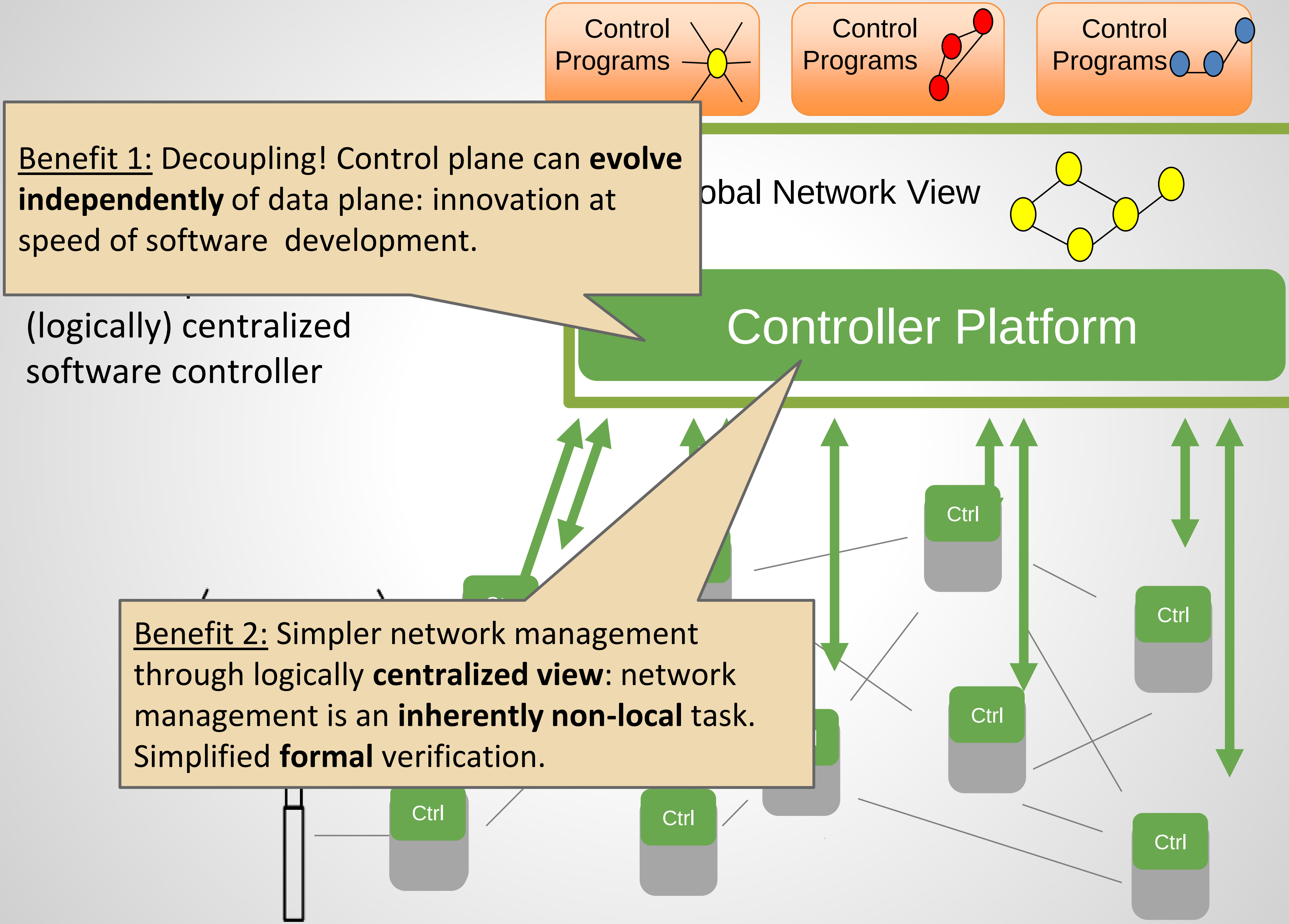

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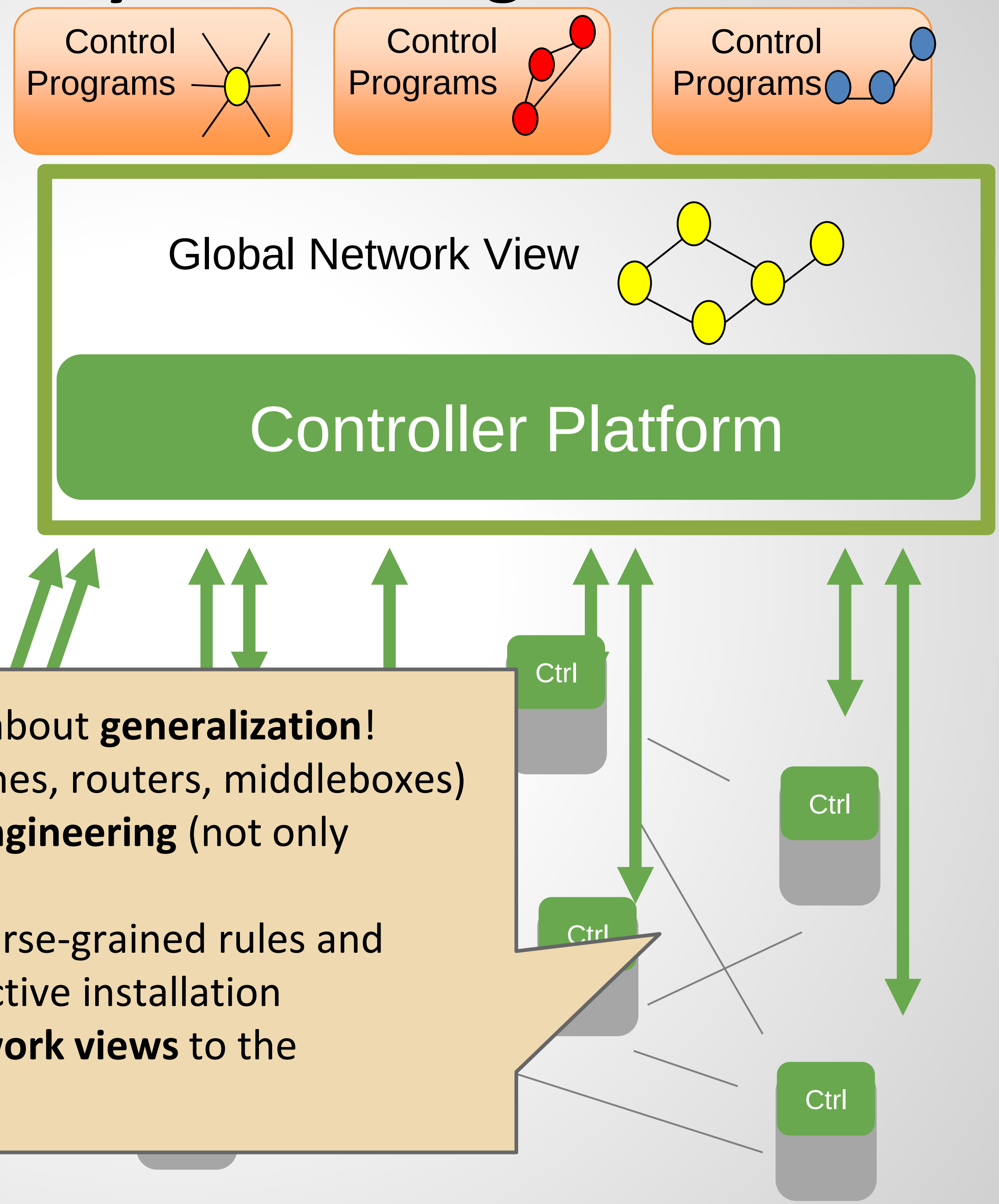



SDN outsources and consolidates control over multiple devices to (logically) centralized software controller

Benefit 3: Standard API OpenFlow is about **generalization**!

- Generalize **devices** (L2-L4: switches, routers, middleboxes)
- Generalize **routing and traffic engineering** (not only destination-based)
- Generalize **flow-installation**: coarse-grained rules and wildcards okay, proactive vs reactive installation
- Provide general and logical **network views** to the application / tenant

# Flexible Distributed Systems: ... and Virtualized

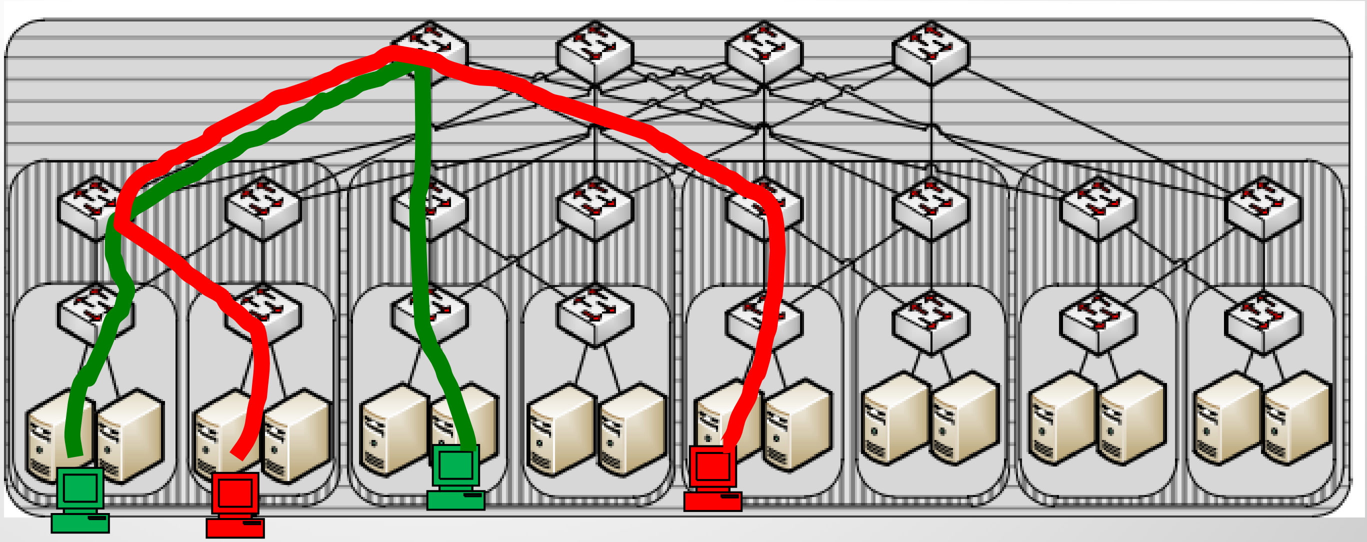
- Virtualization allows to **abstract**:
  - Hardware: compute, memory, storage, network resources
  - Or even entire distributed systems (including OS)
- **Decouples** the application from the substrate
- Introduces **flexibilities** for resource allocation
  - Improved **resource sharing** (esp. in commercial clouds)
  - Seamless migration

# Challenges

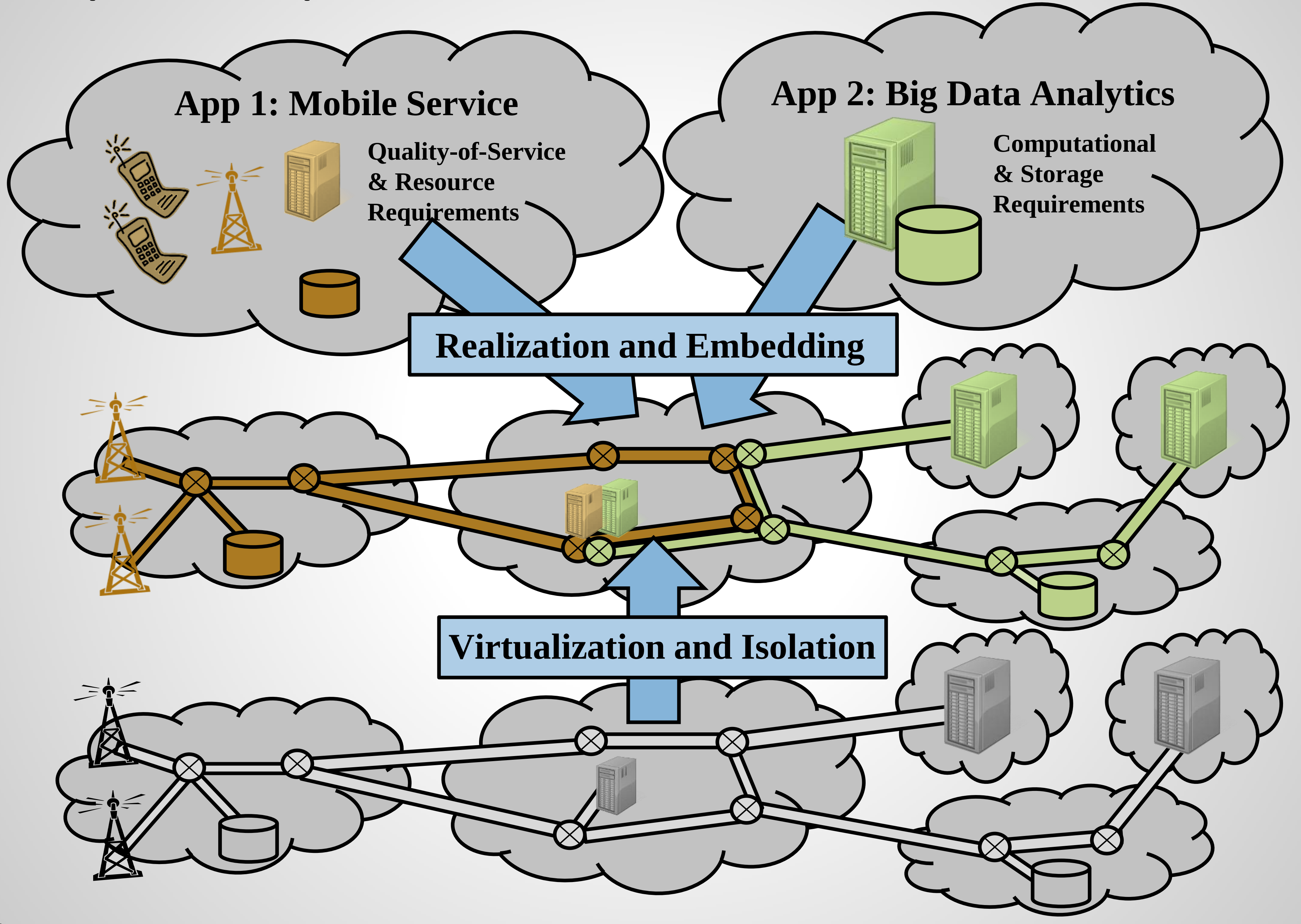
- Great…, but: SDN and virtualization are enablers, ***not solutions***! What to do with them *and how*?

- Example: Virtualization for better **resource sharing**
  - Many **flexibilities** to embed **virtual machines**
  - But: often **not enough** to provide the expected performance!

Need to virtualize the **entire system**: otherwise risk of **interference** on other resources (network, CPU, memory, I/O) : **unredictable performance**



# For predictable performance: full virtualization!



# Many Algorithmic Challenges

- How to maximize the resource **utilization/sharing**?
  - E.g., how to embed a maximal number of virtual Hadoop clusters?
- And still ensure a **predictable** application performance?
  - How to **meet the job deadline** in MapReduce application?
  - How to guarantee **low lookup latencies** in data store?
  - It’s not only about resource **contention**! **Skew** due to high demand also occurs in well-provisioned systems
- How to exploit allocation flexibilities to even mask and **compensate for** unpredictable events (e.g., failures)?
  - A key benefit of virtulization!

# It’s a Great Time to Be a Scientist

**”We are at an interesting inflection point!”**


**Keynote by George Varghese at SIGCOMM 2014**

# Challenges of More Flexible Distributed Systems

1. Kraken: Predictable cloud application performance through adaptive virtual clusters

2. C3: Low tail latency in cloud data stores through replica selection

3. Panopticon: How to introduce these innovative technologies in the first place? Case study: SDN

4. STN, Offroad, Peacock: How to render distributed systems more adaptive without shooting in your foot?

# Challenges of More Flexible Distributed Systems

1. <u>Kraken:</u> Predictable cloud application performance through adaptive virtual clusters

   CCR 2015, SIGMETRICS 2015

2. <u>C3:</u> Low tail latency in cloud data stores through replica selection

   USENIX NSDI 2015

3. <u>Panopticon:</u> How to introduce these innovative technologies in the first place? Case study: SDN

   USENIX ATC 2014

4. <u>STN, Offroad, Peacock:</u> How to [illegible]er distributed systems more adaptive without shooting in your foot?

   2x HotNets 2014
   INFOCOM 2015
   PODC 2015

# Challenges of More Flexible Distributed Systems

1. **Kraken: Predictable cloud application performance through adaptive virtual clusters**

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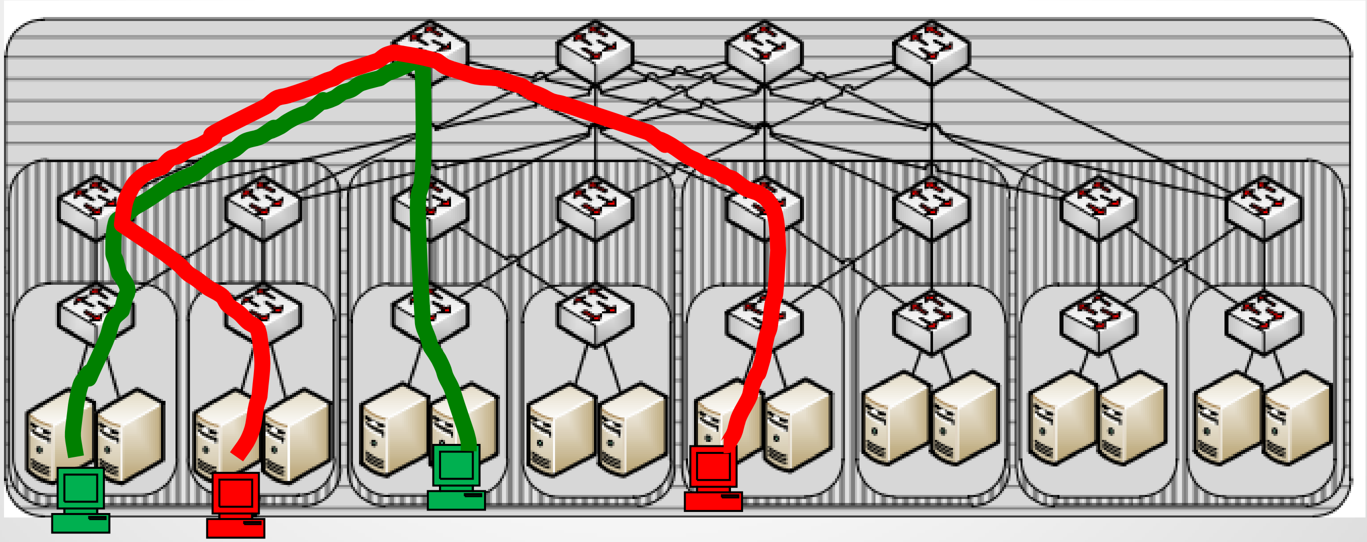
# Cloud Computing + Networking?!
# *Network matters!*

- Example: Batch Processing Applications such as Hadoop
  - **Communication intensive**: e.g., shuffle phase
  - Example Facebook: 33% of **execution time** due to communication
- For predictable preformance in shared cloud: need explicit bandwidth reservations!



- How to max utilization? A network **embeddig problem**!

# Let’s Exploit Allocation Flexibilities to Maximize Utilization

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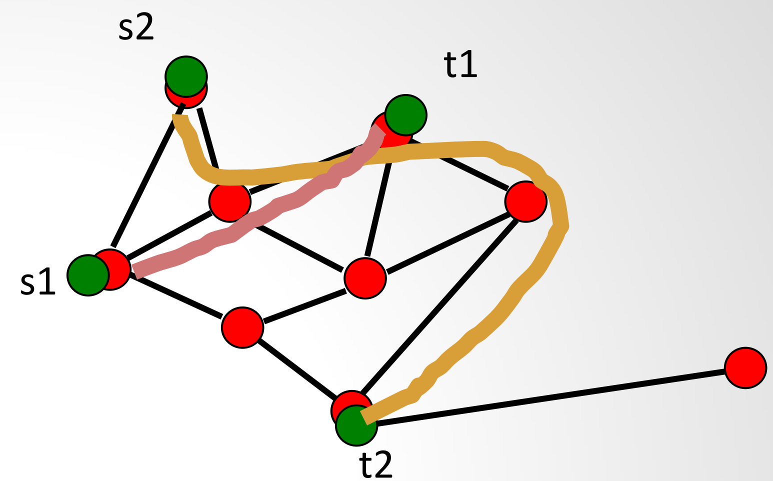
Start simple: exploit flexible routing between given VMs



# Let's Exploit Allocation Flexibilities to Maximize Utilization

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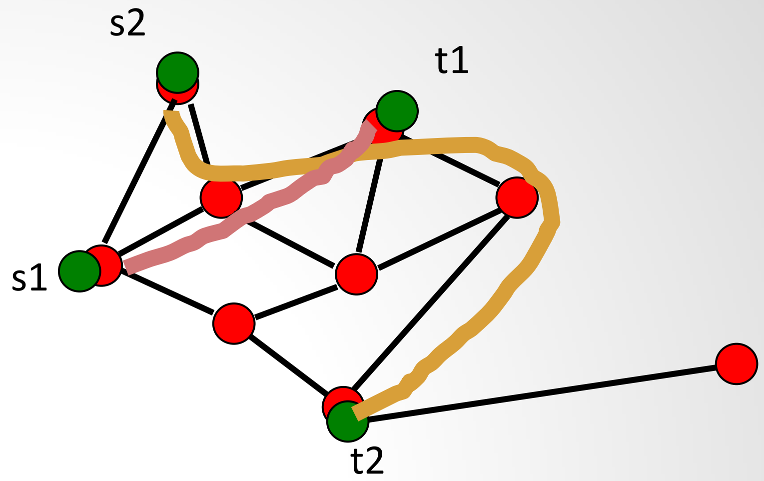

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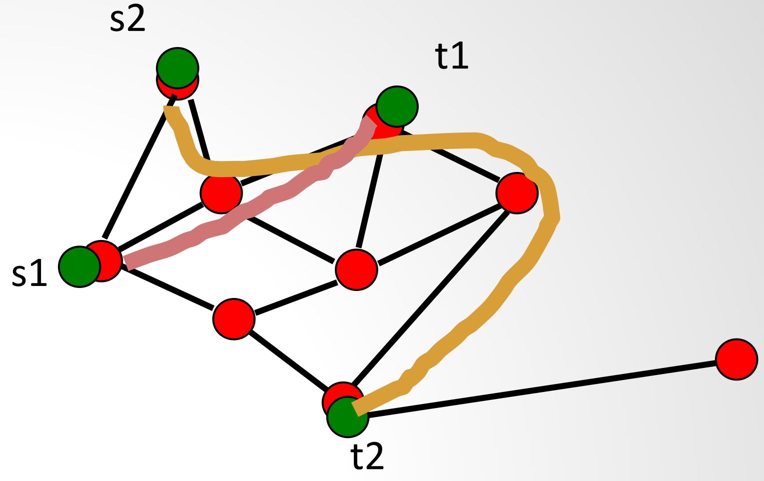

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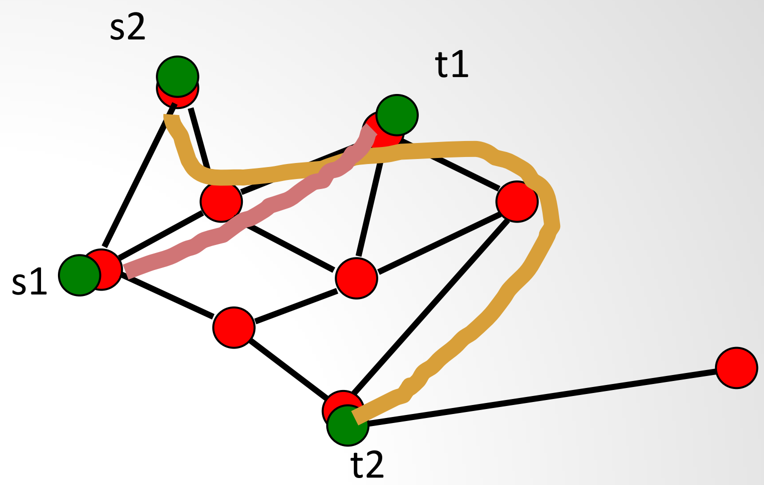


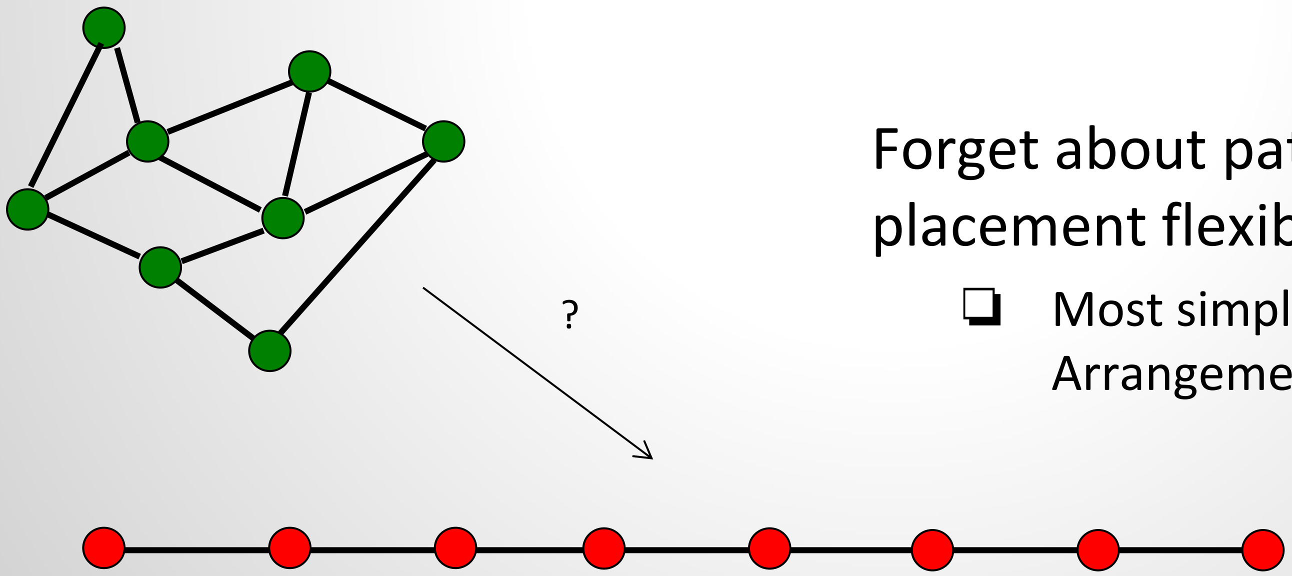


Forget about paths: exploit VM placement flexibilities!

- Most simple: Minimum Linear Arrangement without capacities

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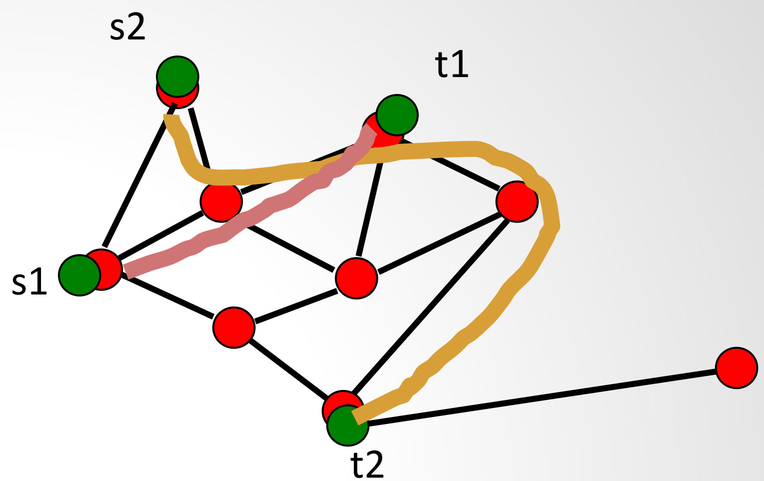


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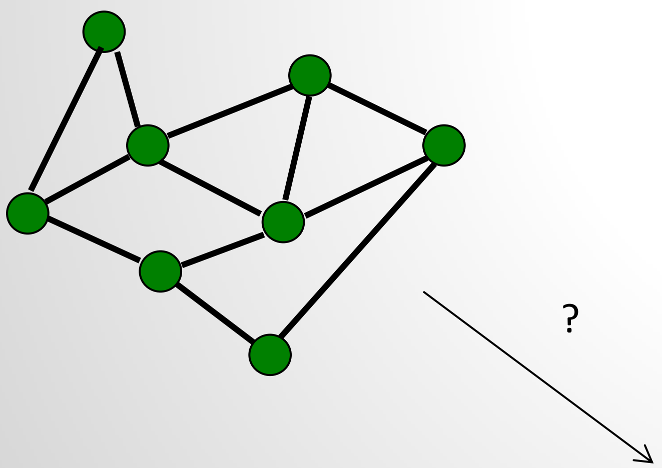
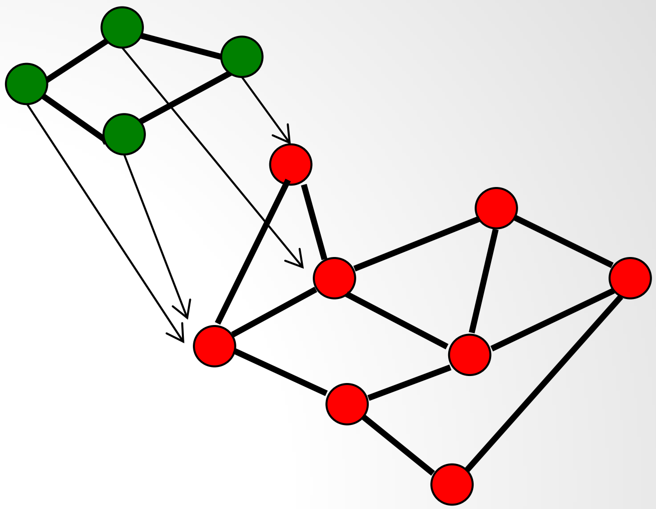



Forget about paths: exploit VM placement flexibilities!

- Most simple: Minimum Linear Arrangement without capacities
- NP-hard ☹

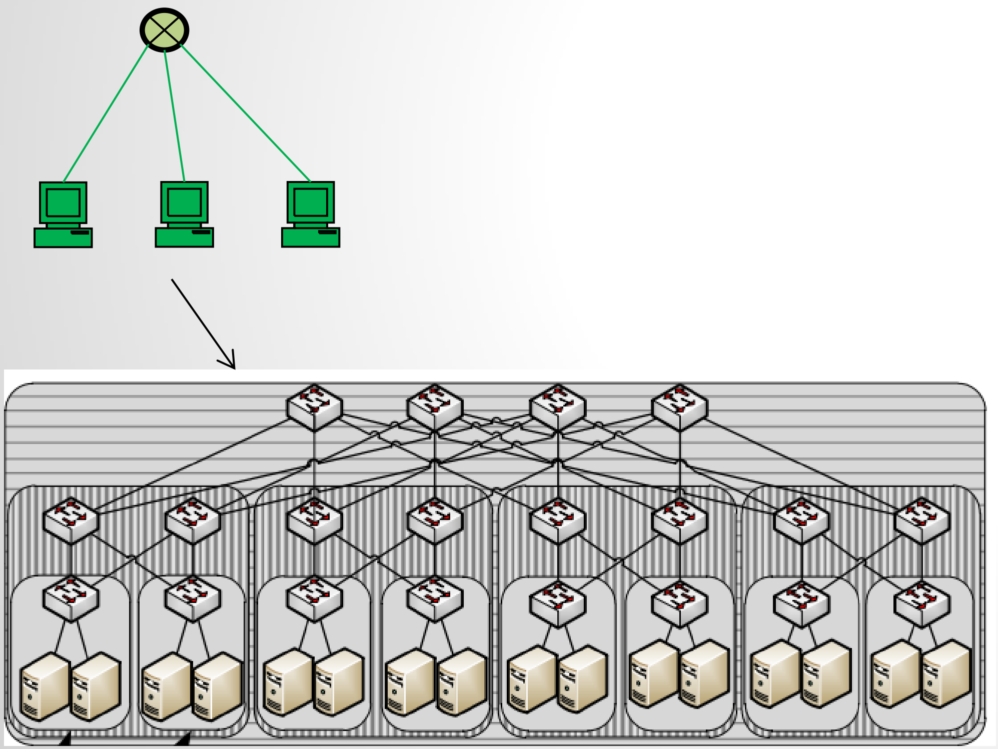
That's all Folks!

# Theory vs Practice



**Goal in theory:**

Embed as general as possible ***guest graph*** to as general as possible ***host graph***



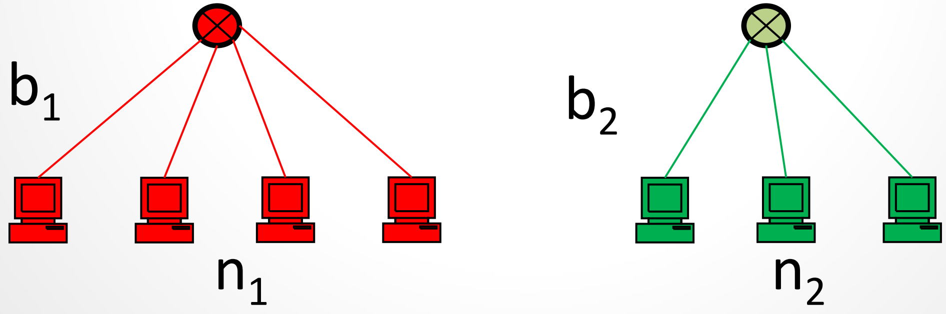
**Reality:**

Datacenters, WANs, etc. exhibit much **structure** that can be exploited! But also guest networks come with **simple specifications**

# Virtual Clusters

Rost, Fuerst, Schmid
CCR 2015

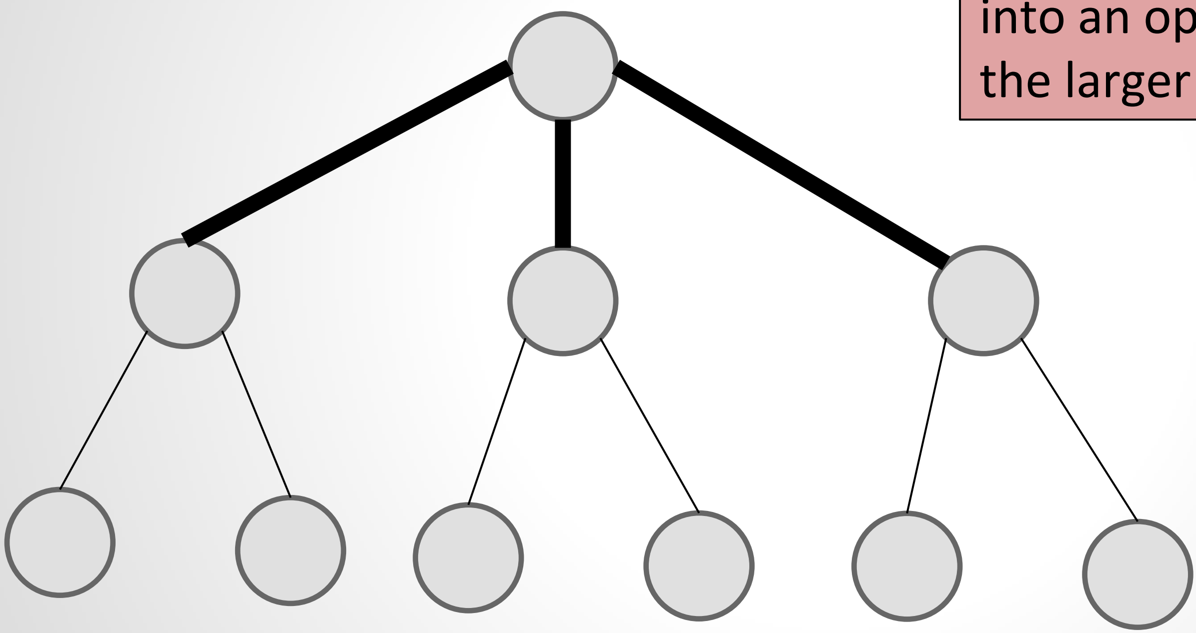
- A prominent abstraction for batch-processing applications: Virtual Cluster *VC(n,b)*
  - Connects *n* virtual machines to a «logical» switch with bandwidth guarantees *b*
  - A simple abstraction



# How to embed a Virtual Cluster in a Fat-Tree?

- Example: dynamic programming

Dynamic Program = optimal solutions for subproblems can efficiently be combined into an optimal solution for the larger problem!



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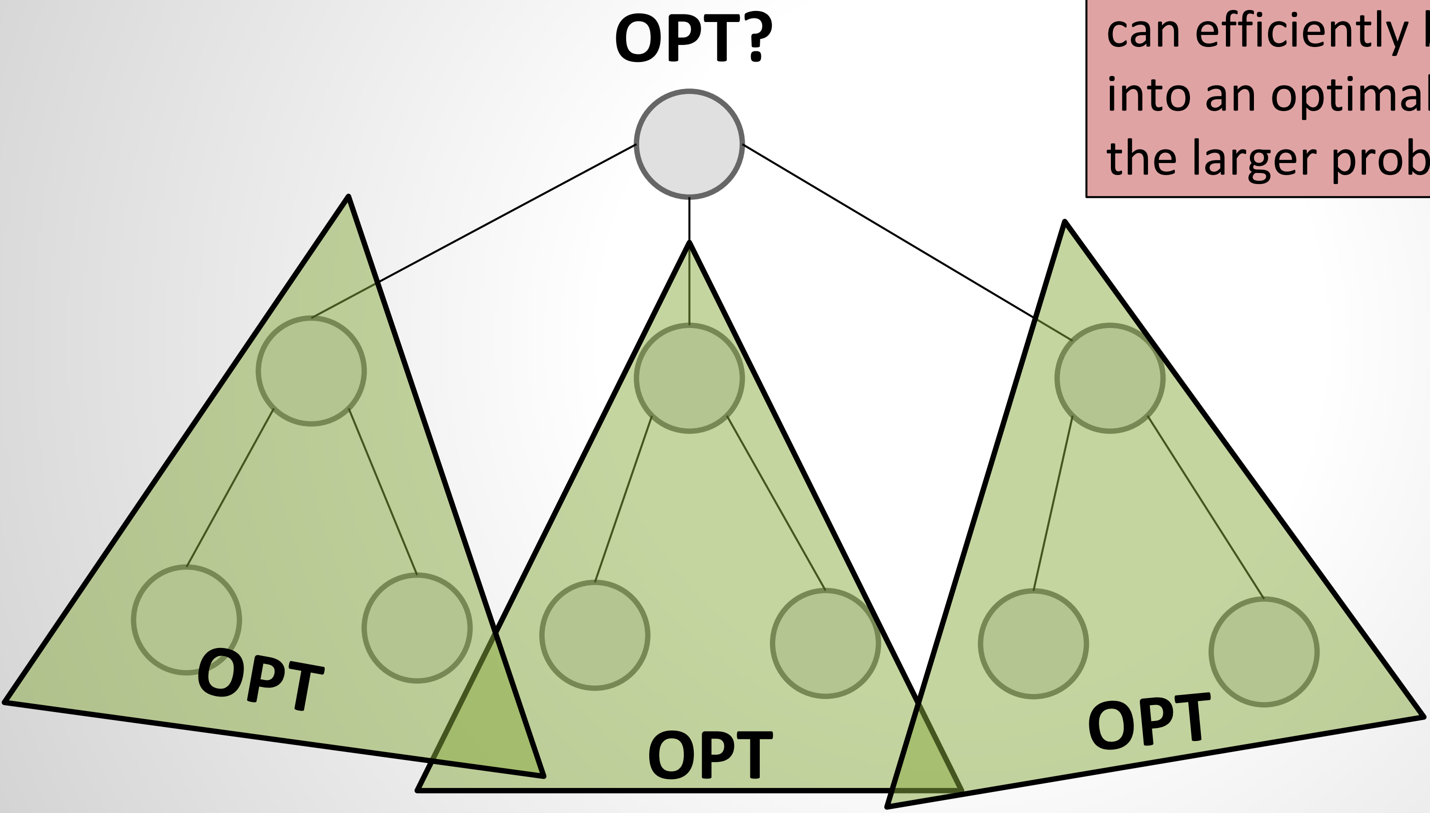

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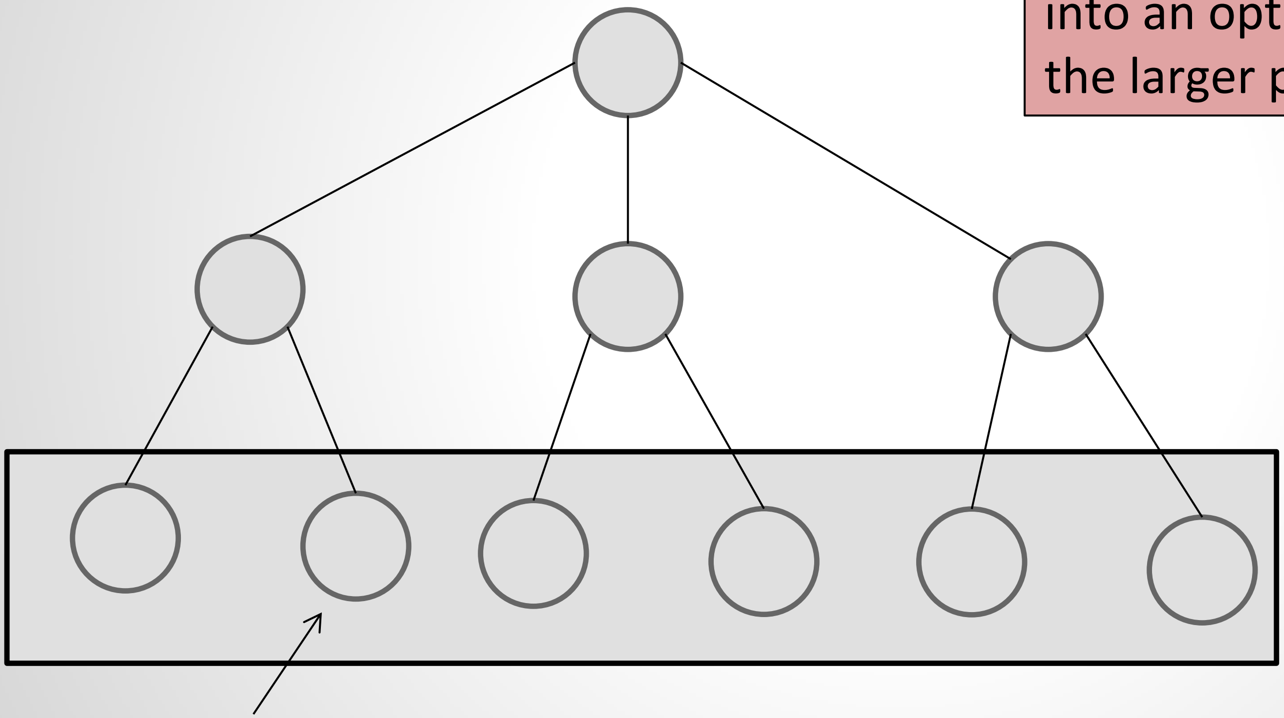

**t = 0: solve leaves!**

How to optimally embed x VMs here, $x \in \{0, ..., n\}$?

Cost = 0 or $\infty$!

# How to embed a Virtual Cluster in a Fat-Tree?

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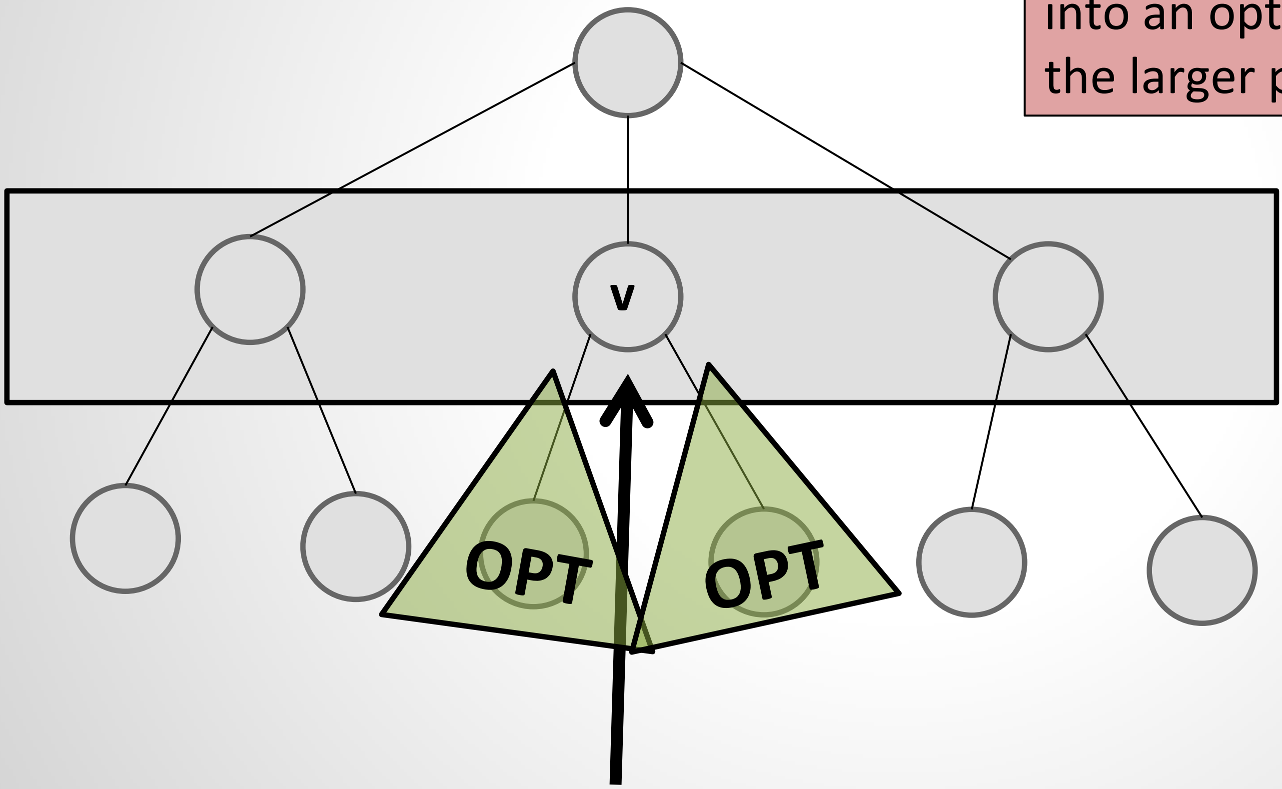


**t = 1: solve height 1!**

Cost[x] = $\min_y$ Cost[y] + Cost[x-y]

+ cross-traffic + connections to v

# How to embed a Virtual Cluster in a Fat-Tree?

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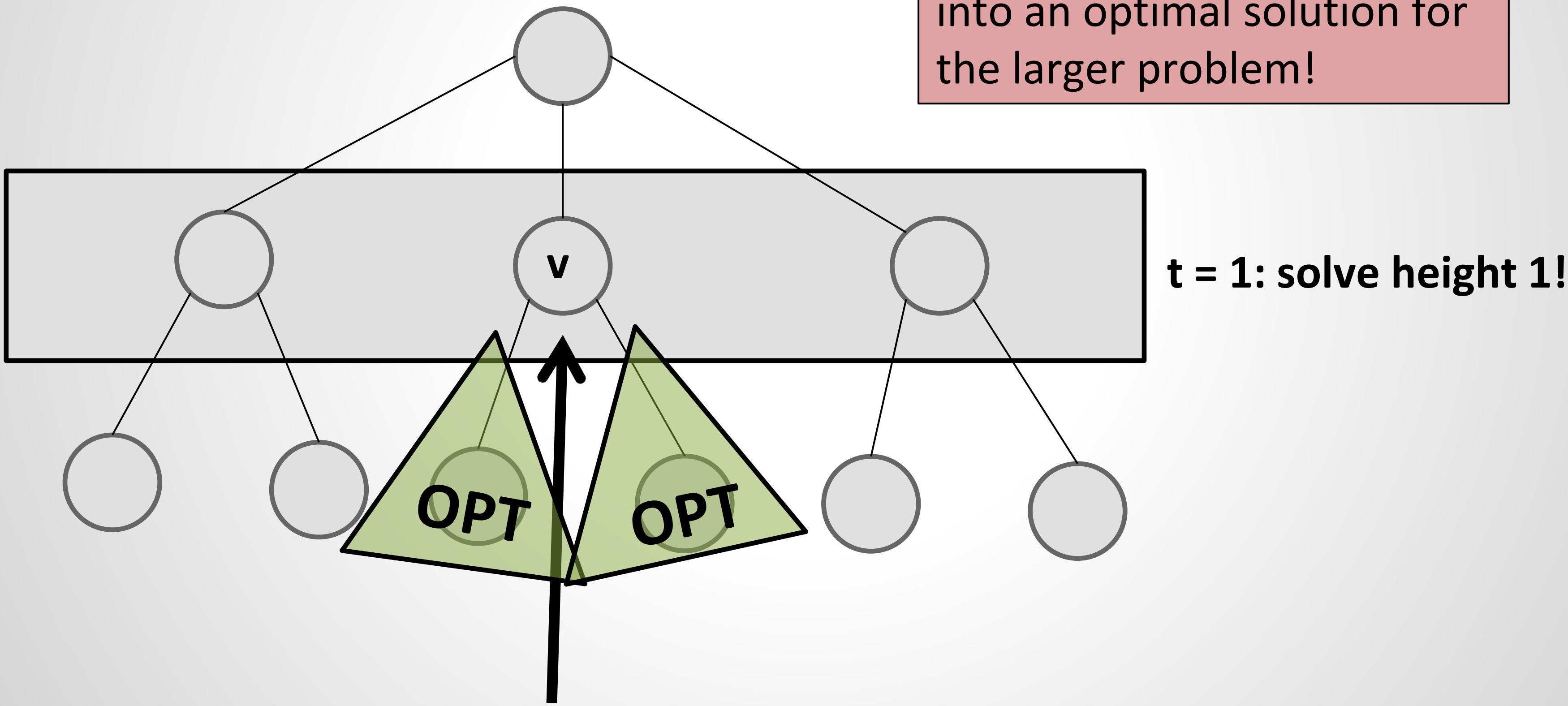
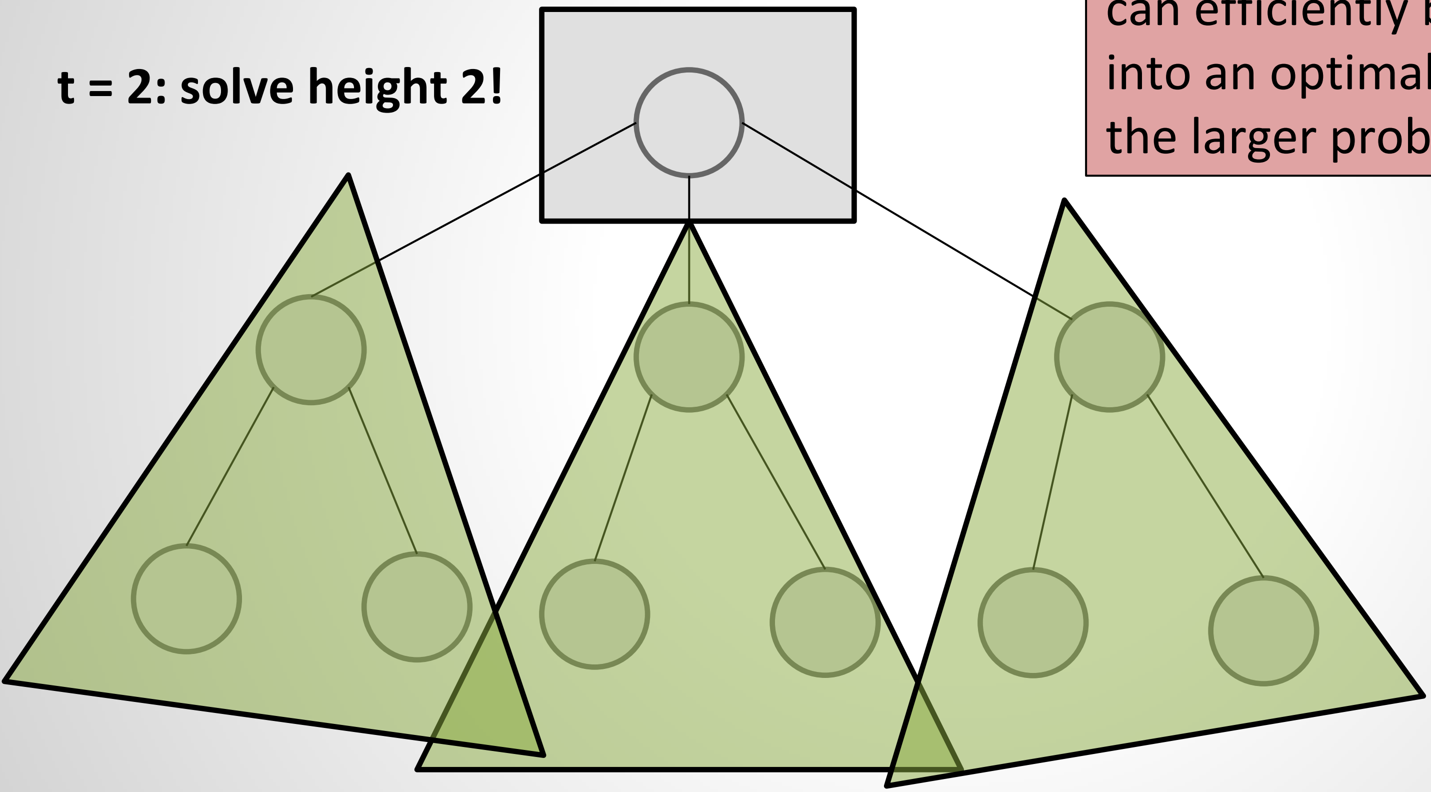



Cost[x] = $\min_y$ Cost[y] + Cost[x-y]

+ cross-traffic + connections to v } **Or just account on upward link (number of leaving links!)**

# How to embed a Virtual Cluster in a Fat-Tree?

**t = 2: solve height 2!**



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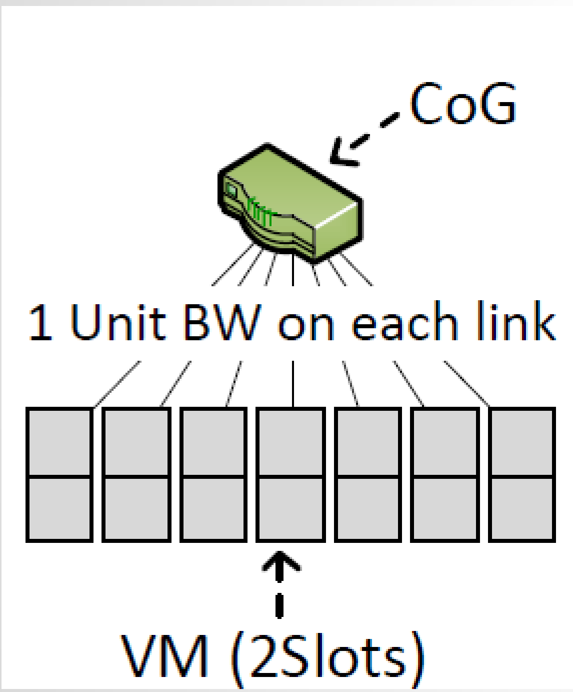
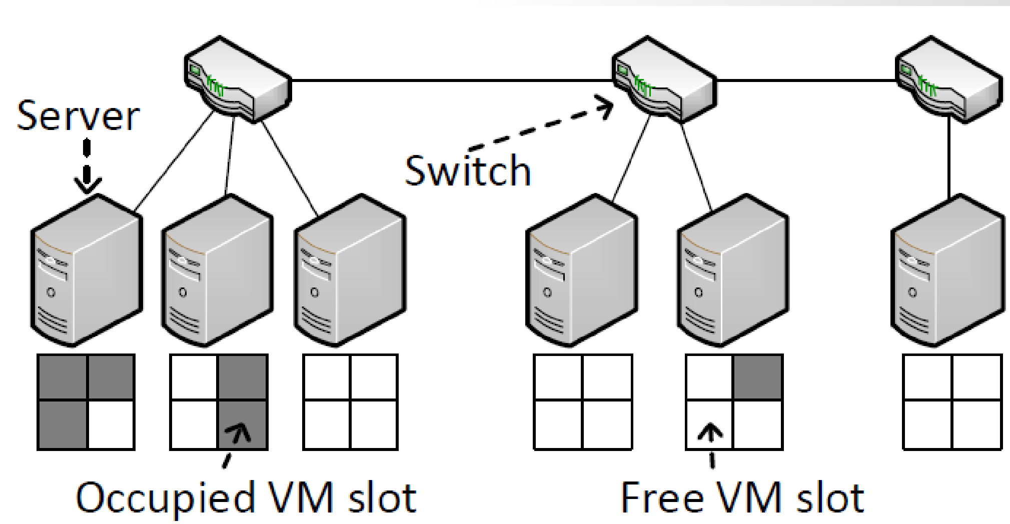
# How to embed a Virtual Cluster in a General Graph?

How to embed?



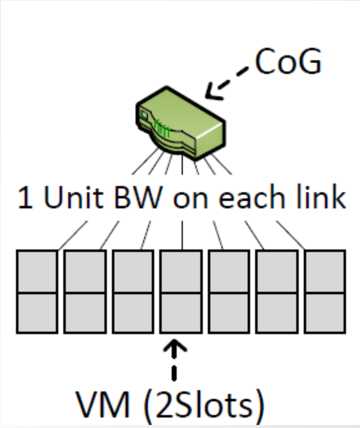

Host Graph

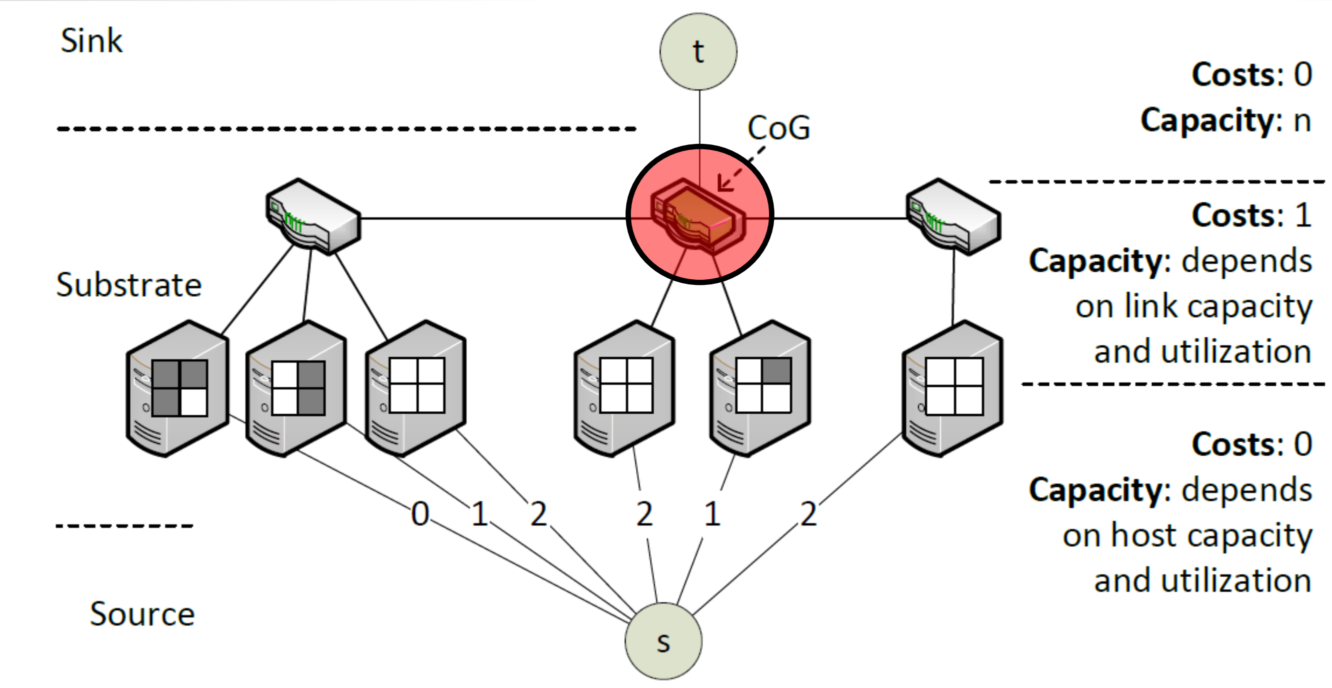
Guest Graph

# How to embed a Virtual Cluster in a General Graph?

Algorithm:

- Try all possible locations for virtual switch
- Extend network with artificial source s and sink t
- Add capacities
- Compute min-cost max-flow from s to t
  (or simply: min-cost flow of volume n)



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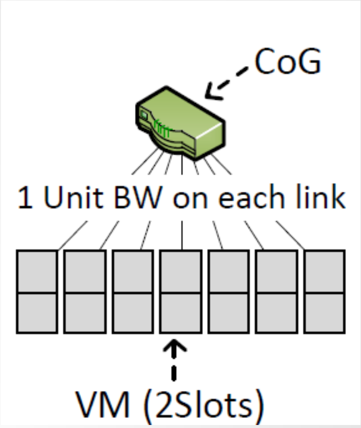


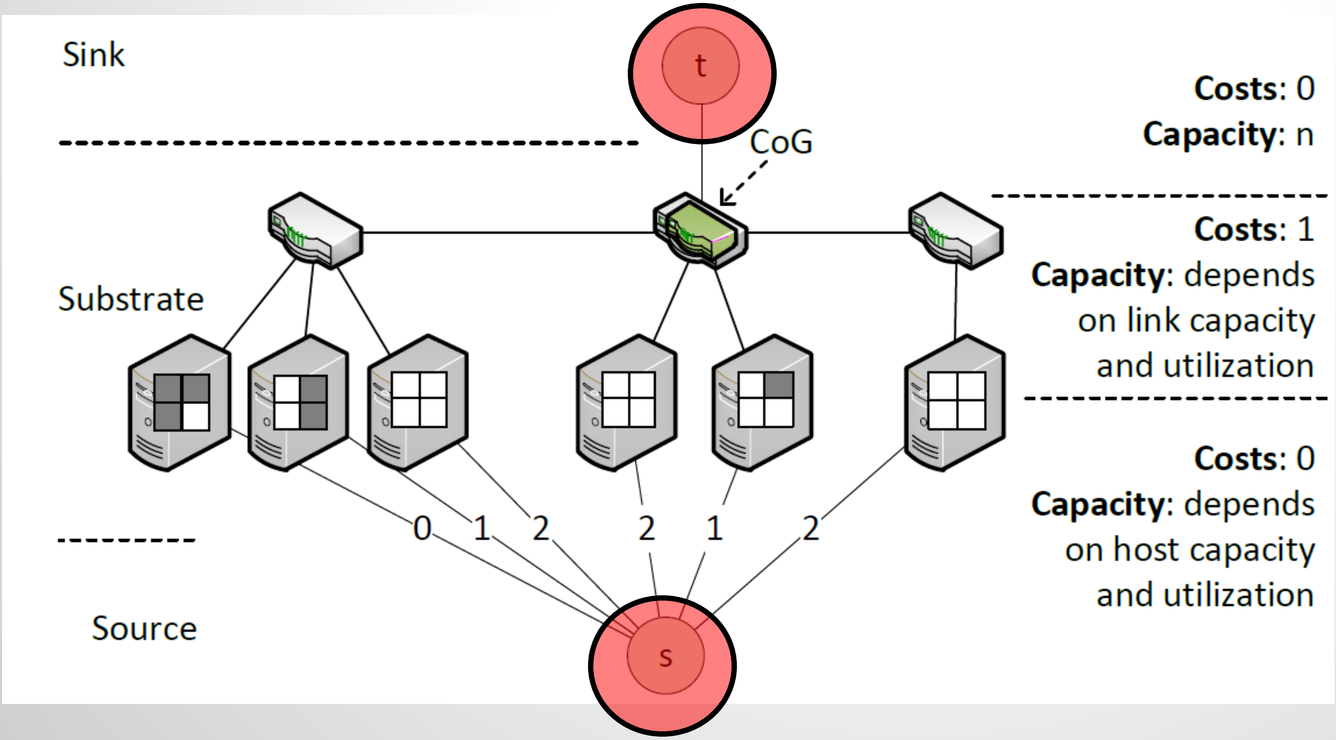

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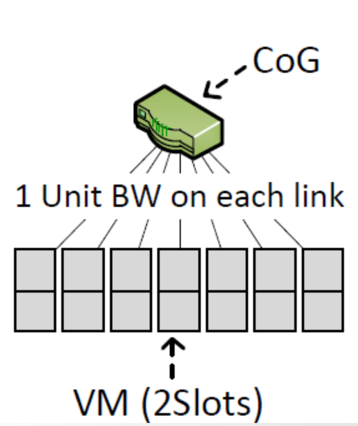


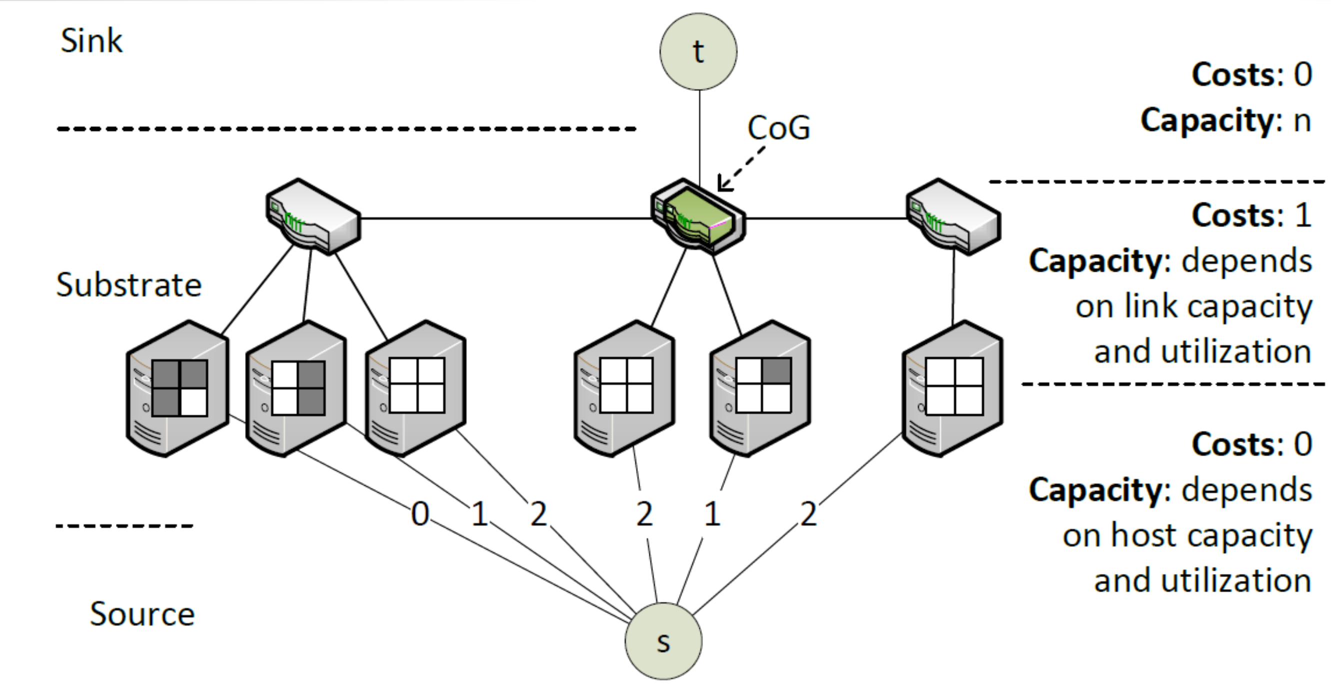


**enough to embed n VMs**

**capacity = floor(available resources / unit demand)**

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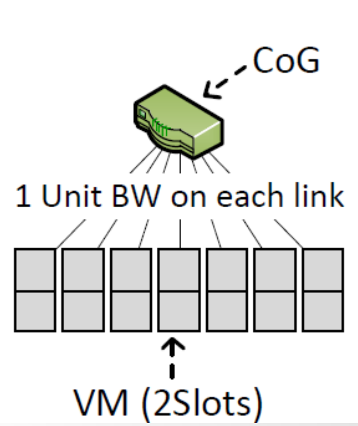
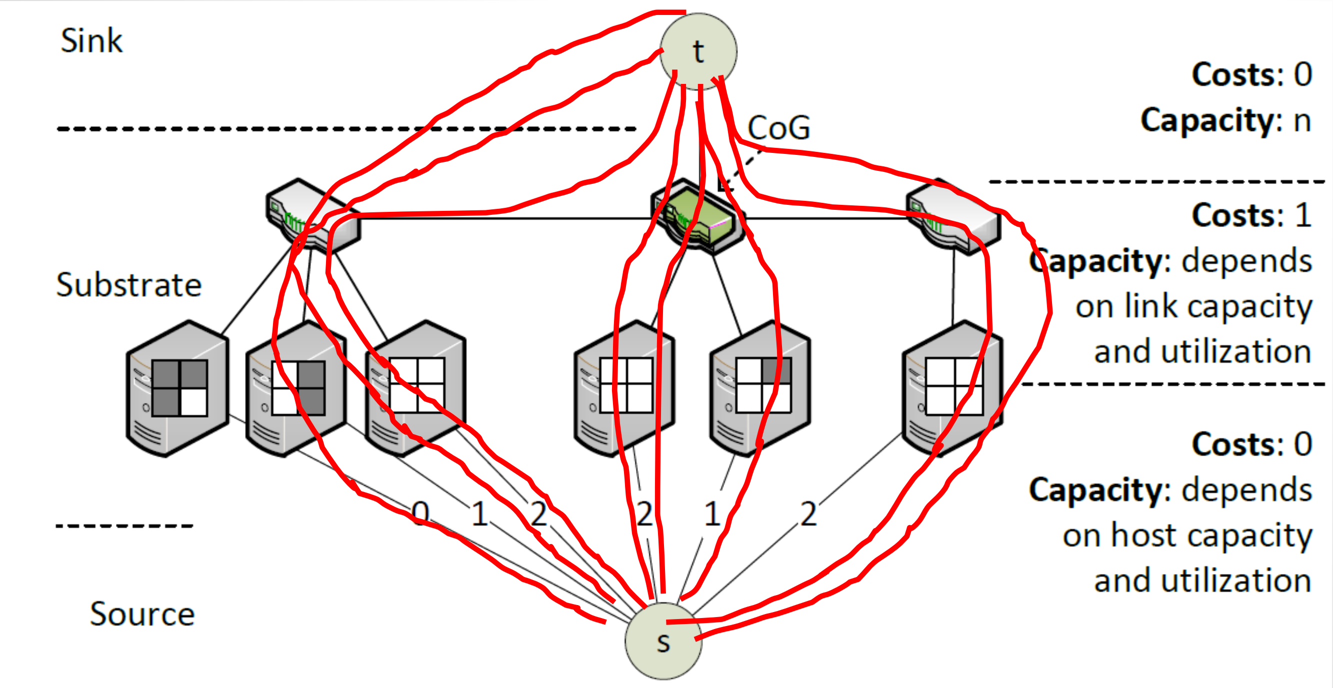


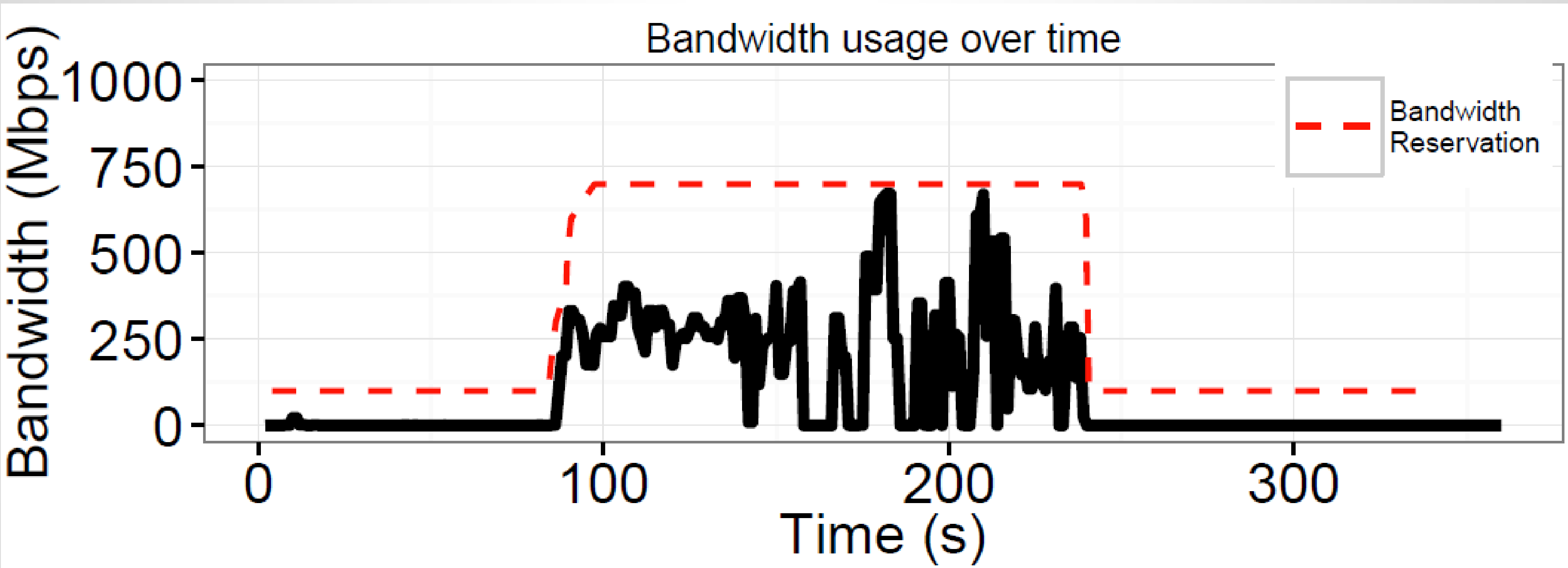

**Guaranteed integer if links are integer! (E.g., successive shortest paths)**

# Predictable Performance with Kraken

- This algorithm is used in **our system Kraken**
- Gives compute and network guarantees… but reality is more complicated:
  - **Static resource** reservations are **inefficient**: want to **change reservations / virtual clusters**!
  - It is also hard to predict resource requirements, stragglers, failures, job executions: want to be **online**
- Kraken allows to ***upgrade and downgrade*** resources in an ***online*** fashion, while providing minimal isolation guarantees

# The need for adjustments

Constant reservations would be wasteful:



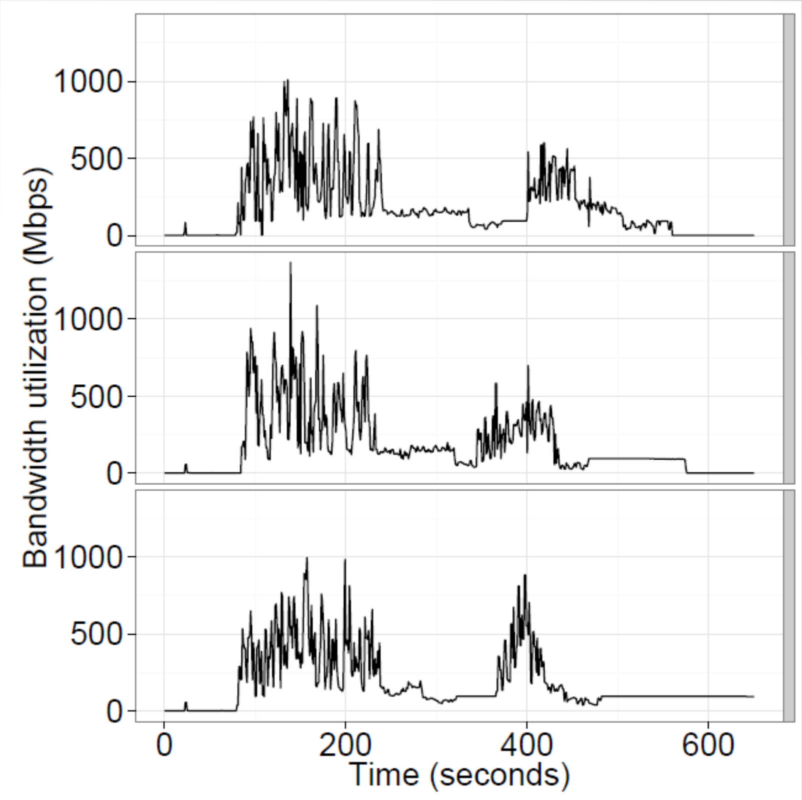

Bandwidth utilization of a TeraSort job over time.

In red: **Kraken**'s bandwidth reservation.

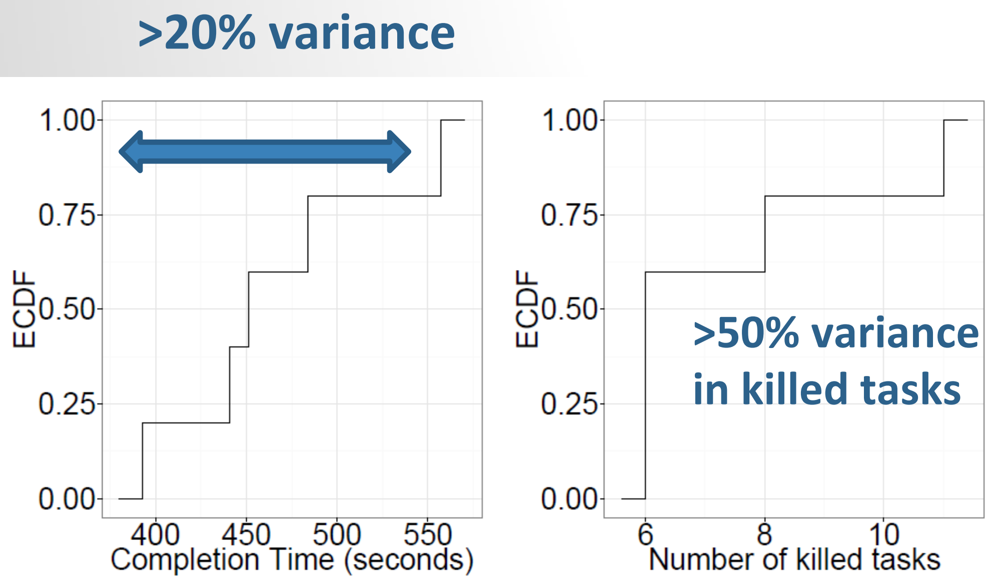
(Tasks inform Hadoop controller prior to shuffle phase; reservation with Linux *tc*.)

# The need for online adjustments

- ❑ ***Temporal*** resource patterns are hard to predict
- ❑ Resource allocations must be changed ***online***




Bandwidth utilization of 3 different runs of the same **TeraSort workload** (**without interference**)



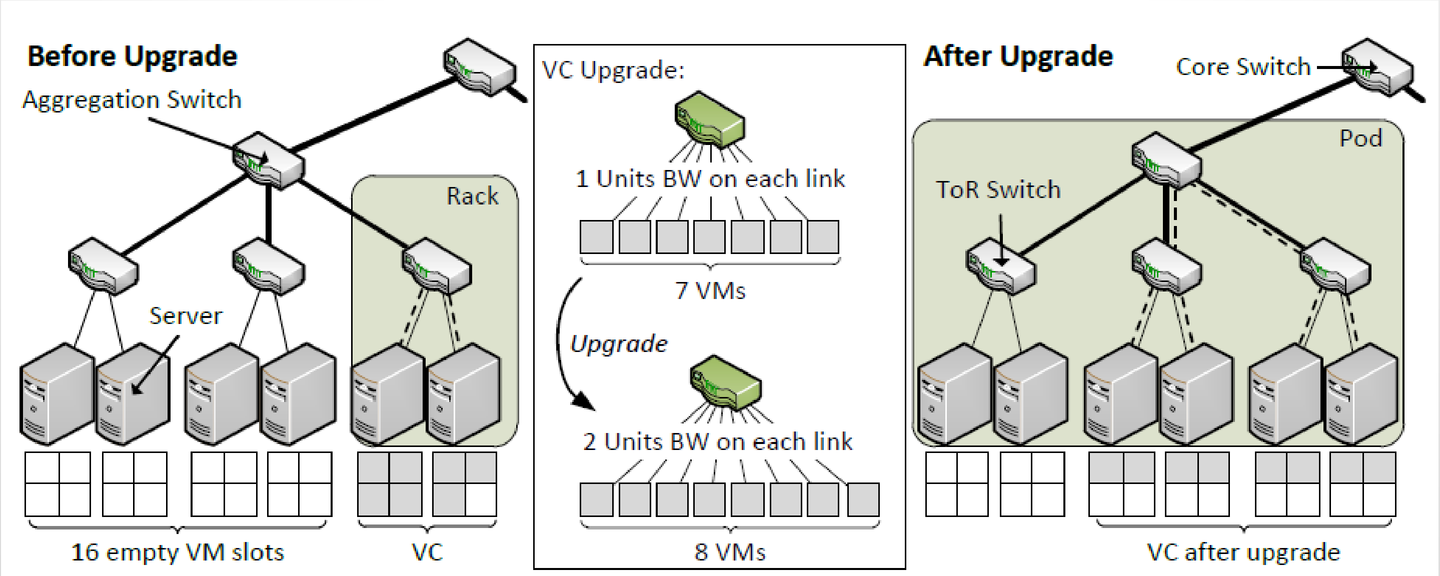

Completion times of jobs in the presence of **speculative execution** (*left*) and the number of speculated tasks (*right*)

# Kraken: Online Reconfigurations

Fuerst, Schmid, Suresh, Costa SIGMETRICS 2015

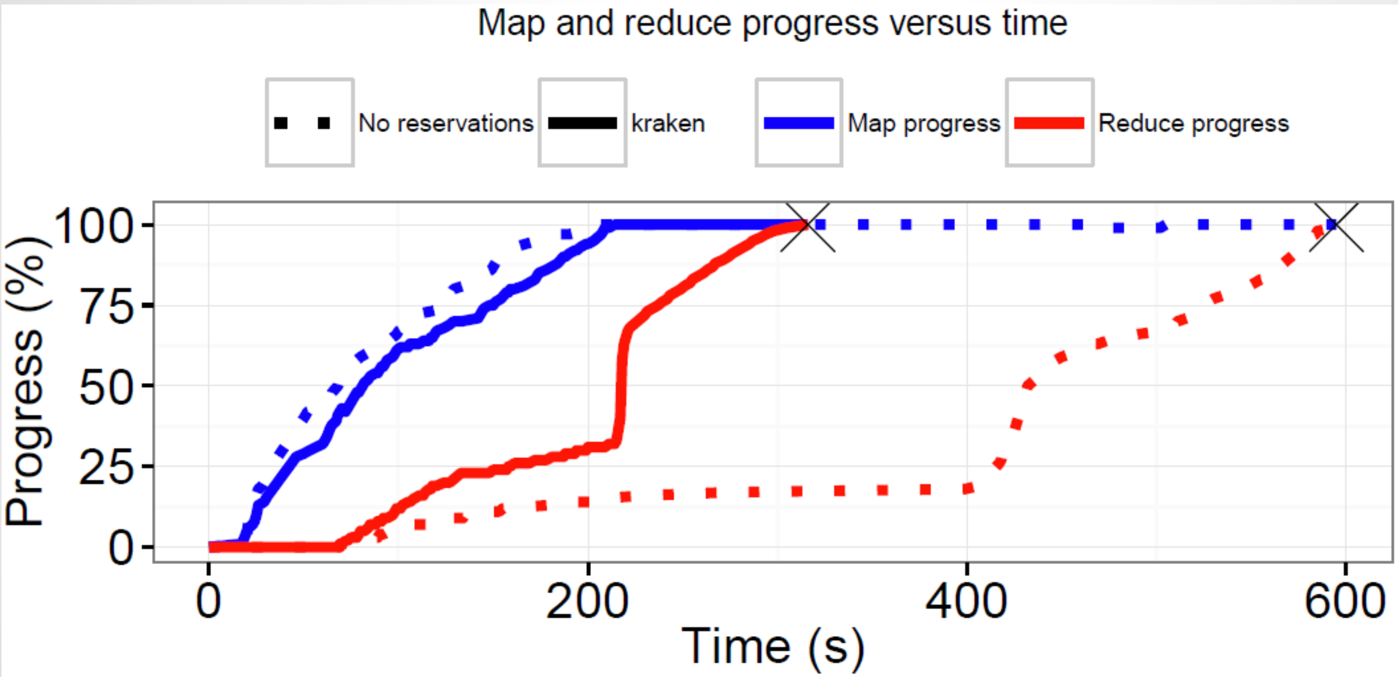
- Kraken provides:
  - Predictable performance through **bandwidth reservations**
  - **Resource-minimal** embeddings
  - Support for **online** resource adjustments
  - Support for **migration**

- Upgrades may require migrations:



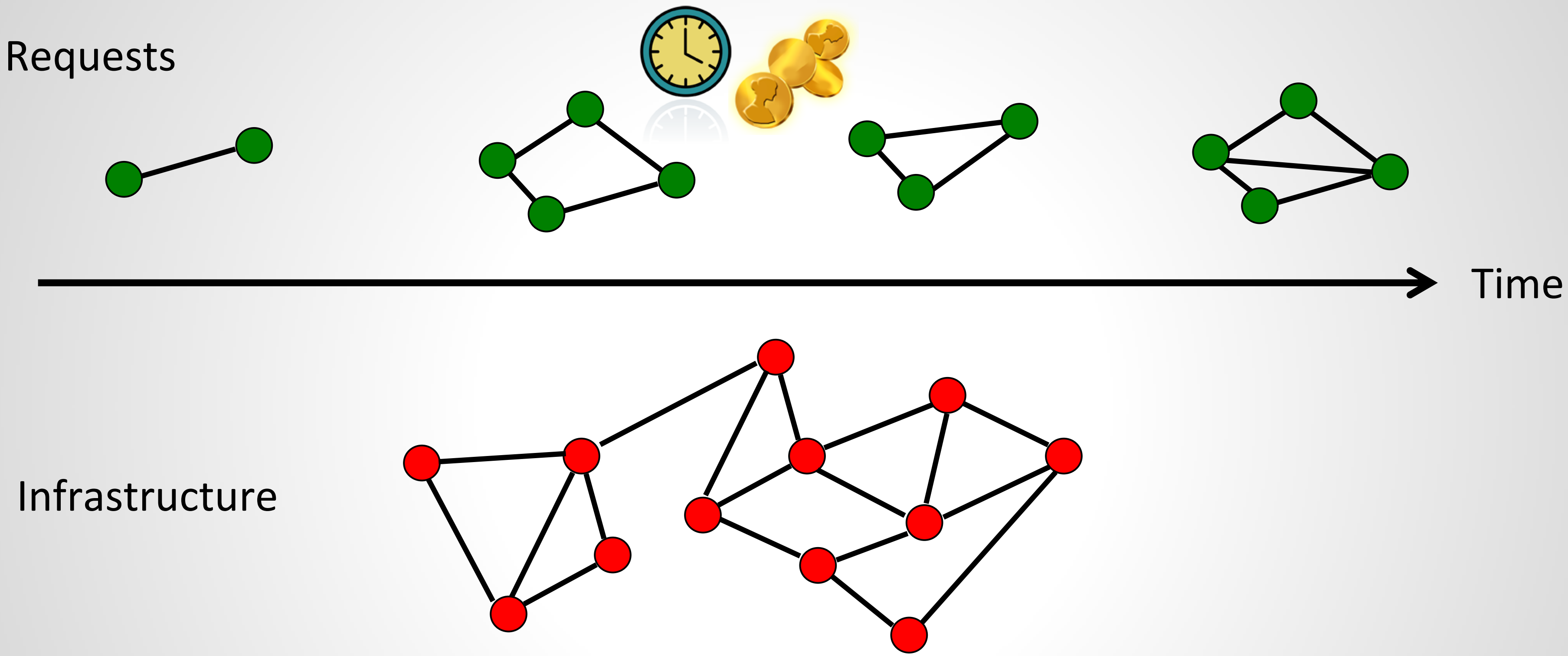
# Kraken: Predictable Performance

- Kraken is immune to interference (from *iperf*) :




*Kraken (in Hadoop-YARN) with iperf cross-traffic*

# *There is no infinite lunch*: QoS also Requires Admission Control




- ❑ Which ones to accept?
- ❑ Online primal-dual approach

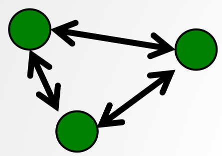
Even, Medina, Schaffrath, Schmid TCS 2013

# Online Admission Control: General Model

- Traffic models

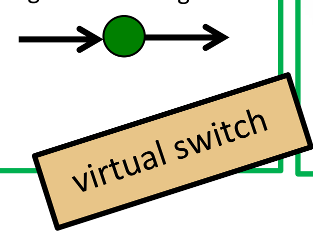
**Customer Pipe**

Traffic matrix: Bandwidth per VM pair (u,v)



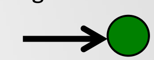
**Hose Model**

Per VM bandwidth: polytope of traffic matrices.




**Aggregate Ingress**

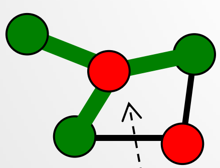
Only ingress specified: e.g., support multicast etc.




- Routing models

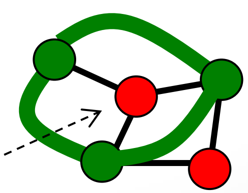
**Tree**

Steiner tree embedding



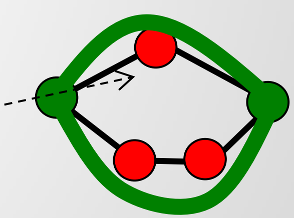
**Single Path**

Unsplittable paths



**Multi-Path**

Splittable paths (more capacity)



Relay costs: e.g., depending on packet rate

Primal and Dual

# Online Admission Control: Primal-Dual

| (I) | (II) |
|---|---|
| $\min Z_j^T \cdot \mathbf{1} + X^T \cdot C \;\; s.t.$ <br> $Z_j^T \cdot D_j + X^T \cdot A_j \geq B_j^T$ <br> $X, Z_j \geq \mathbf{0}$ | $\max B_j^T \cdot Y_j \;\; s.t.$ <br> $A_j \cdot Y_j \leq C$ <br> $D_j \cdot Y_j \leq \mathbf{1}$ <br> $Y_j \geq \mathbf{0}$ |

Fig. 1: (I) The primal covering LP. (II) The dual packing LP.

**Competitive Analysis**

Does not know t'>t.
Competitive ratio:
r = Cost(ON)/Cost(OFF)

**Algorithm**

**Algorithm 1** The General Integral (all-or-nothing) Packing Online Algorithm (GIPO).

Upon the $j$th round:

1. $f_{j,\ell} \leftarrow \operatorname{argmin}\{\gamma(j,\ell) : f_{j,\ell} \in \Delta_j\}$ (oracle procedure)
2. If $\gamma(j,\ell) < b_j$ then, (accept)
   (a) $y_{j,\ell} \leftarrow 1$.
   (b) For each row $e$ : If $A_{e,(j,\ell)} \neq 0$ do

$$x_e \leftarrow x_e \cdot 2^{A_{e,(j,\ell)}/c_e} + \frac{1}{w(j,\ell)} \cdot (2^{A_{e,(j,\ell)}/c_e} - 1).$$

   (c) $z_j \leftarrow b_j - \gamma(j,\ell)$.
3. Else, (reject)
   (a) $z_j \leftarrow 0$.

Primal and Dual

# Online Admission Control: Primal-Dual

| (I) | (II) |
|---|---|
| $\min Z_j^T \cdot \mathbf{1} + X^T \cdot C \;\; s.t.$ | $\max B_j^T \cdot Y_j \;\; s.t.$ |
| $Z_j^T \cdot D_j + X^T \cdot A_j \geq B_j^T$ | $A_j \cdot Y_j \leq C$ |
| $X, Z_j \geq \mathbf{0}$ | $D_j \cdot Y_j \leq \mathbf{1}$ |
| | $Y_j \geq \mathbf{0}$ |

Fig. 1: (I) The primal covering LP. (II) The dual packing LP.

Formulate the packing (dual) LP: Maximize profit

(Note: dynamic LP!)

**Competitive Analysis**

Does not know t'>t.
Competitive ratio:
r = Cost(ON)/Cost(OFF)

**Algorithm**

**Algorithm 1** The General Integral (all-or-nothing) Packing Online Algorithm (GIPO).

Upon the $j$th round:

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$$x_e \leftarrow x_e \cdot 2^{A_{e,(j,\ell)}/c_e} + \frac{1}{w(j,\ell)} \cdot \left(2^{A_{e,(j,\ell)}/c_e} - 1\right).$$

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Primal and Dual

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s.t. constraints

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primal-dual framework

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Embedding cost vs profit?

Primal and Dual

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If cheap: accept and update primal variables (always feasible solution)

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1. $f_{j,\ell} \leftarrow \text{argmin}\{\gamma(j,\ell) : f_{j,\ell} \in \Delta_j\}$ (oracle procedure) ← Computationally hard!
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Computationally hard!

Use your favorite approximation algorithm! If competitive ratio ρ and approximation r, overall competitive ratio ρ*r.

# Challenges of More Flexible Distributed Systems

1. Kraken: Predictable cloud application performance through adaptive virtual clusters

2. **C3: Low tail latency in cloud data stores through replica selection**

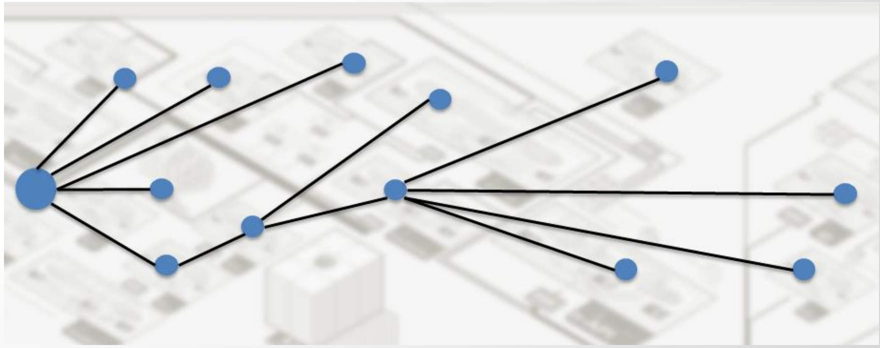
3. Panopticon: How to introduce these innovative technologies in the first place? Case study: SDN

4. STN, Offroad, Peacock: How to render distributed systems more adaptive without shooting in your foot?

# Latency-Critical Applications

- Another critical requirement besides bandwidth, especially in cloud data stores is ***latency***
  - Today's interactive **web** applications require **fluid** response time
  - Degraded user experience directly impacts **revenue**

- **Tail** matters...
  - Web applications = multi-tier, **large** distributed systems
  - 1 request involves **10(0)s** data accesses / servers!
  - A **single late** read may delay entire request



# How to cut tail latency?

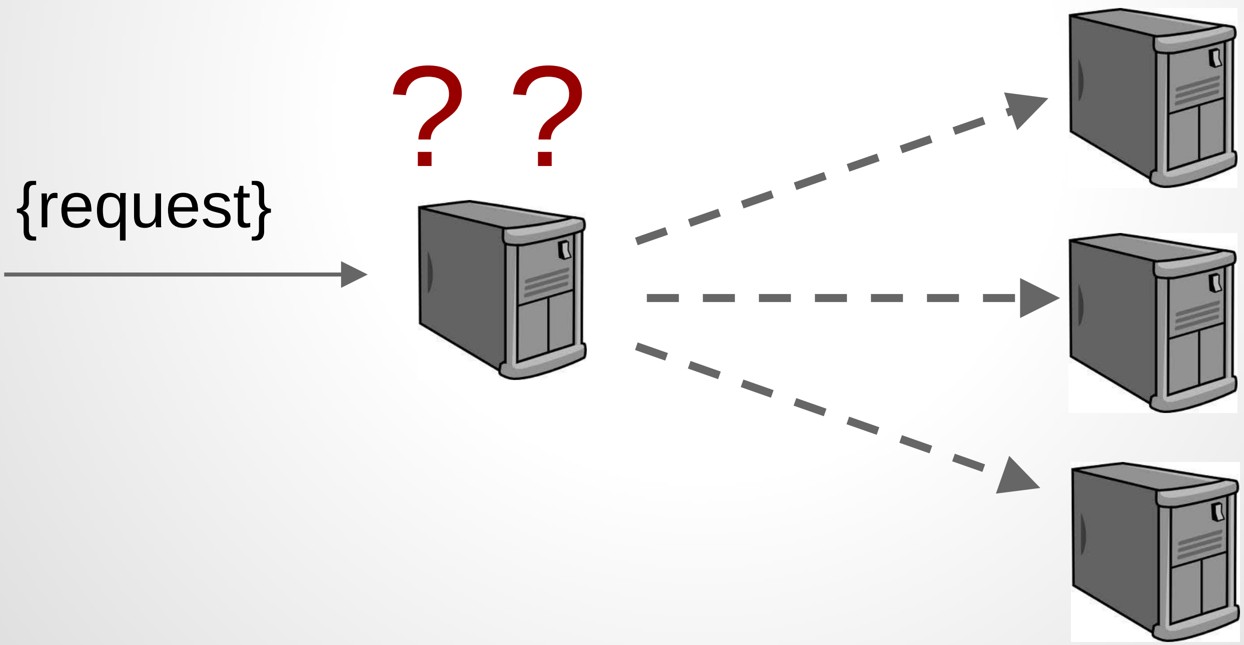
- How to guarantee low tail in shared cloud? A non-trivial challenge even in **well-provisioned** systems
  - **Skews** in demand, time-varying service times, stragglers, ...
  - No time to make make **rigorous optimizations or reservations**

- Idea C3: Exploit **replica selection**!
  - Many distributed DBs resp. **key-value stores** have redundancy
  - **Opportunity** often overlooked so far

- Our focus: **Cassandra** (1-hop DHT, server = client)
  - Powers, e.g., Ebay, Netflix, Spotify
  - More sophisticated than MongoDB or Riak

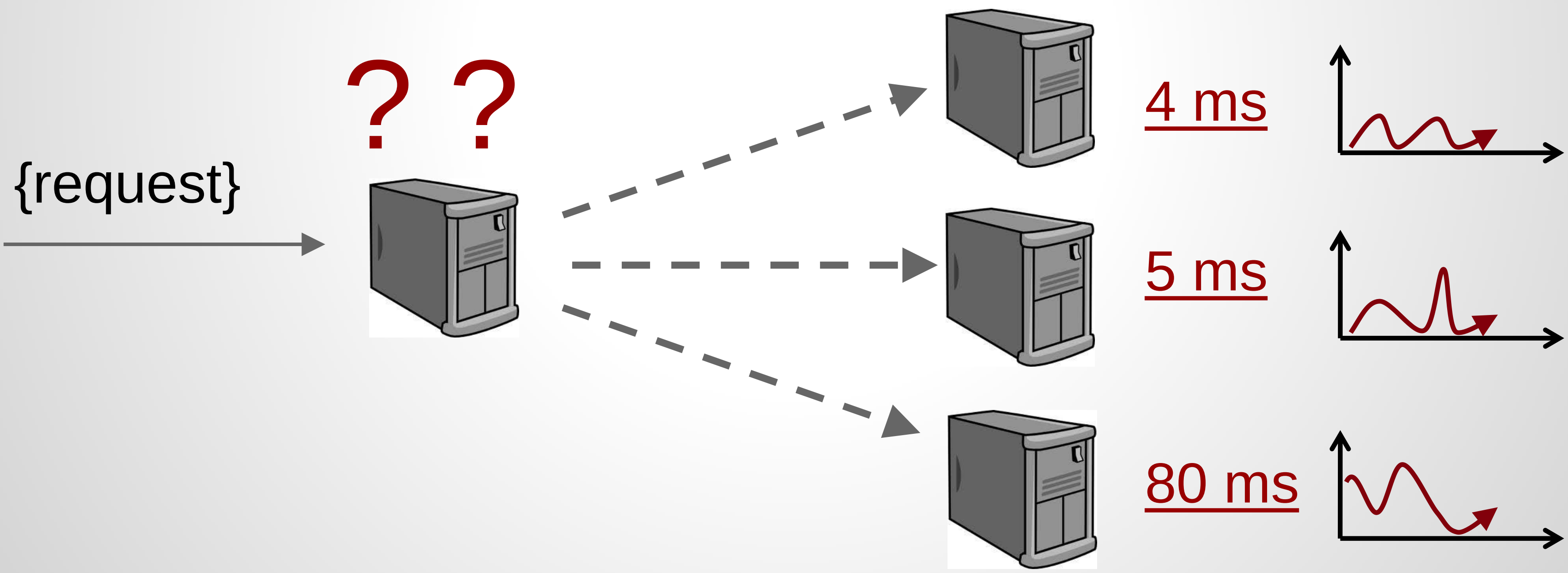
# C3: Exploit Replica Selection

- Great idea! But how? Just go for «the best»?



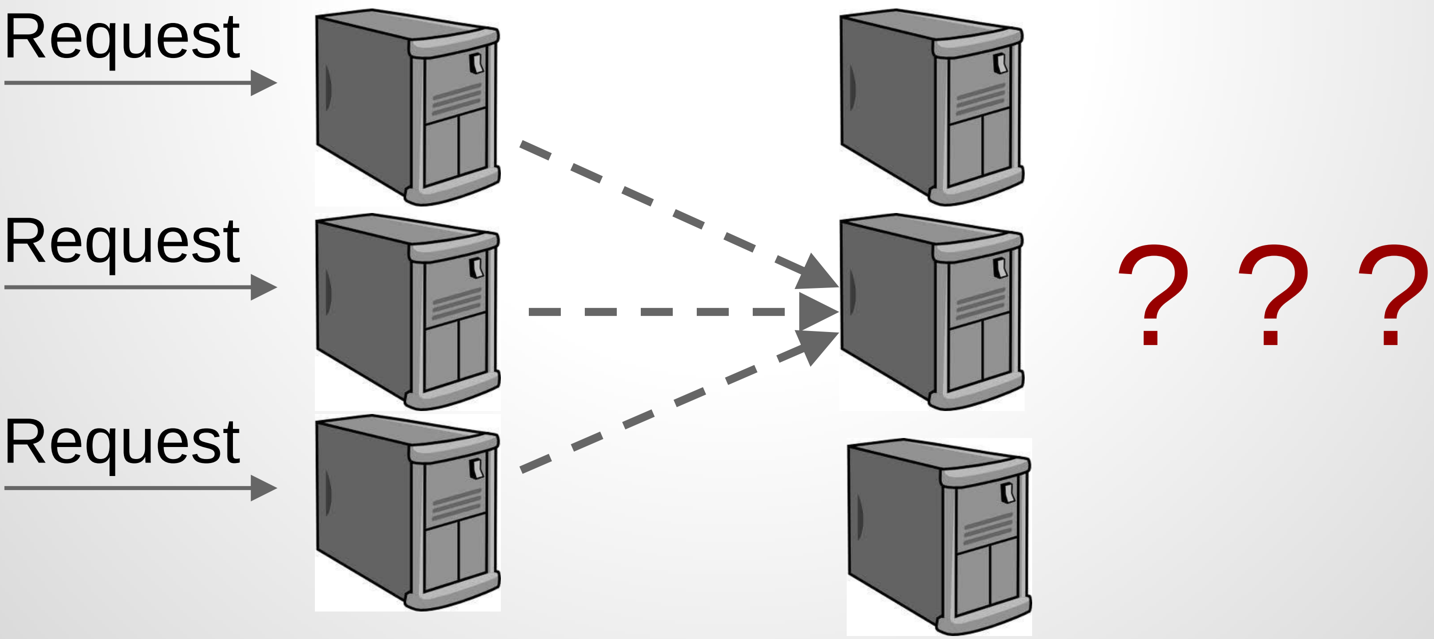
# Careful: «The best» can change

- Not so simple!
  - Need to deal with **heterogenous** and **time-varying** service times
  - Background garbage collection, log compaction, TCP, deamons



# Careful: Herd Behavior

- Potentially high **fan-in** and **herd behavior**!
- Observed in Cassandra Dynamic Snitching (DS)
  - Coarse **time intervals** and **I/O gossiping**
  - **Synchronization** and stale information

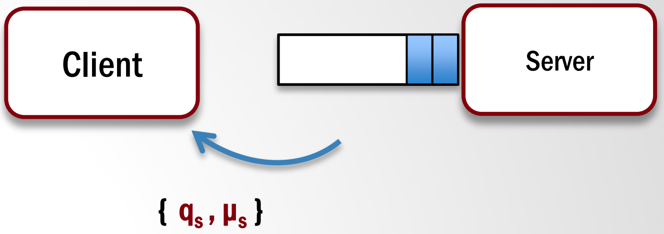



**A coordination / control theory problem!**

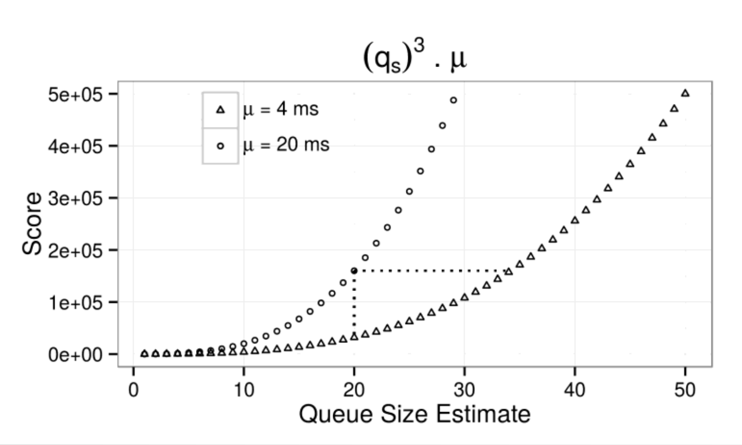
# C3 in a Nutshell

- 4 Principles:
  - Stay informed: **piggy-back** queue state and service times
  - Stay reactive and don't commit: use **backpressure queue**
  - Leverage heterogeity: **compensate** for service times
  - Avoid redundancy

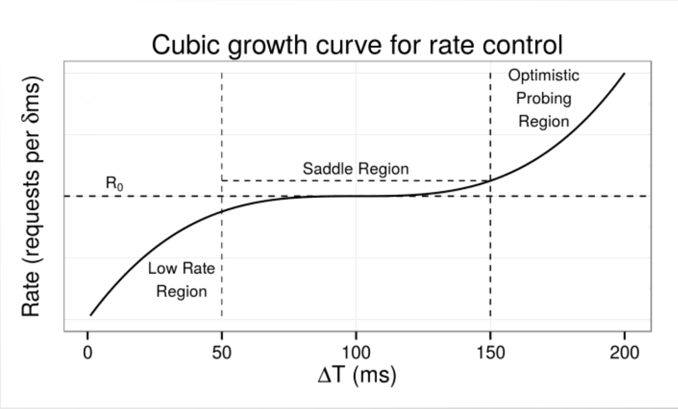
Suresh, Canini, Schmid, Feldmann
NSDI 2015




- Mechanism 1: replica ranking
  - Penalize larger queues

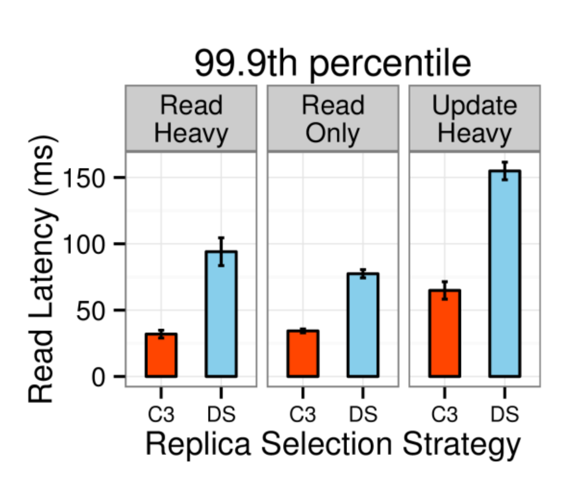



- Mechanism 2: rate control
  - Goal: match service rate and keep pipeline full
  - Cubic, with saddle region

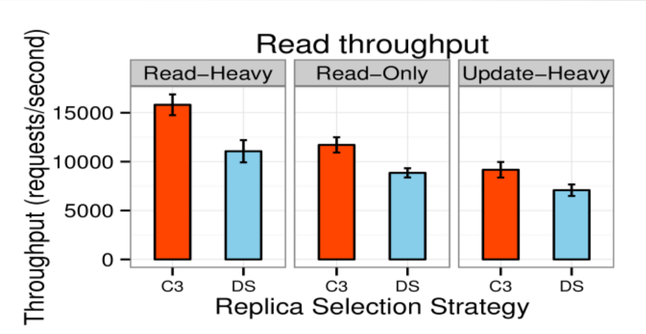


# Performance Evaluation

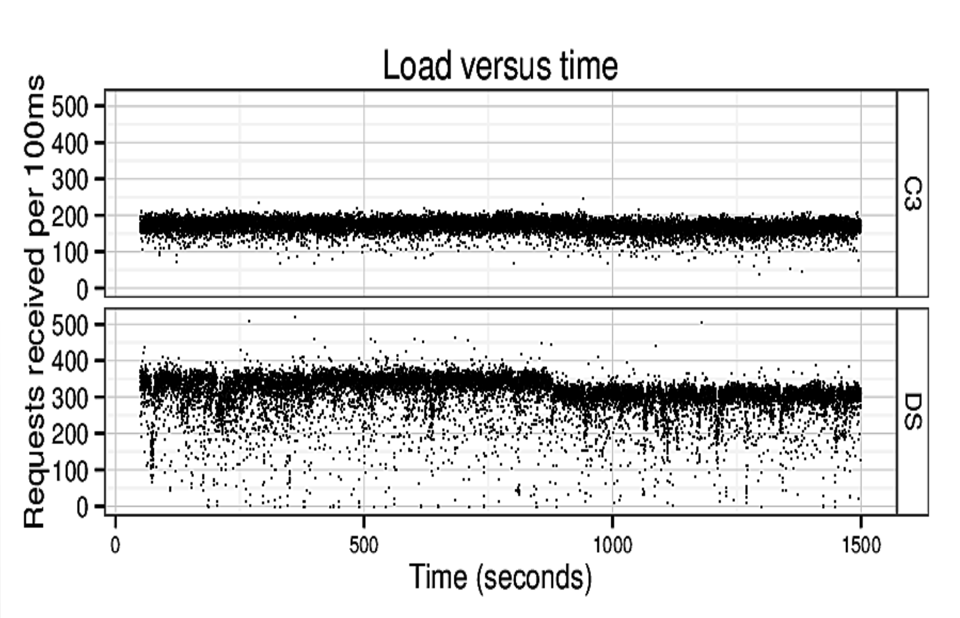
- Methodology:
  - **Amazon EC2**
    - disk vs SSD
  - BigFoot testbed
  - Simulations
- Lower tail latency
  - 2-3x for 99.9%




- Higher read throughput...




- ... and lower load (and variance)!



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# SDN Use Cases Today

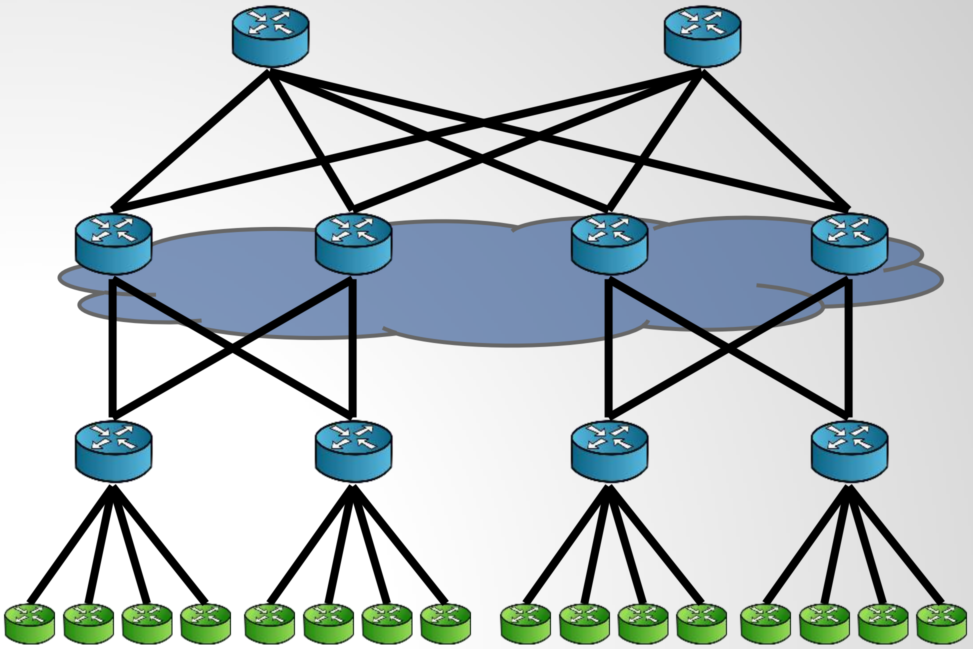
Many use cases discussed today, e.g. in:

- Enterprise networks
- Datacenters
- WANs
- IXPs
- ISPs

} Existing deployments! (Enterprise networks, Datacenters, WANs, IXPs)

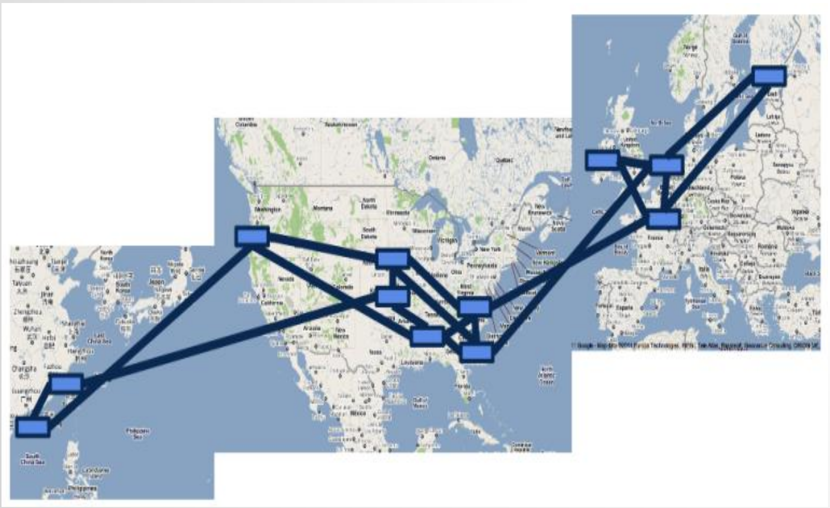
**How to deploy SDN cost effectively?**

# SDN Deployment



Datacenter: Easy

- SDN can be deployed at **software edge** (terminate links at Open vSwitch)
- 2 Control Planes: **ECMP Fabric**



WAN: «Easy»

- Google B4: **small network**
- Can be deployed at end of long-haul fiber (replace IP core router)

# SDN Deployment

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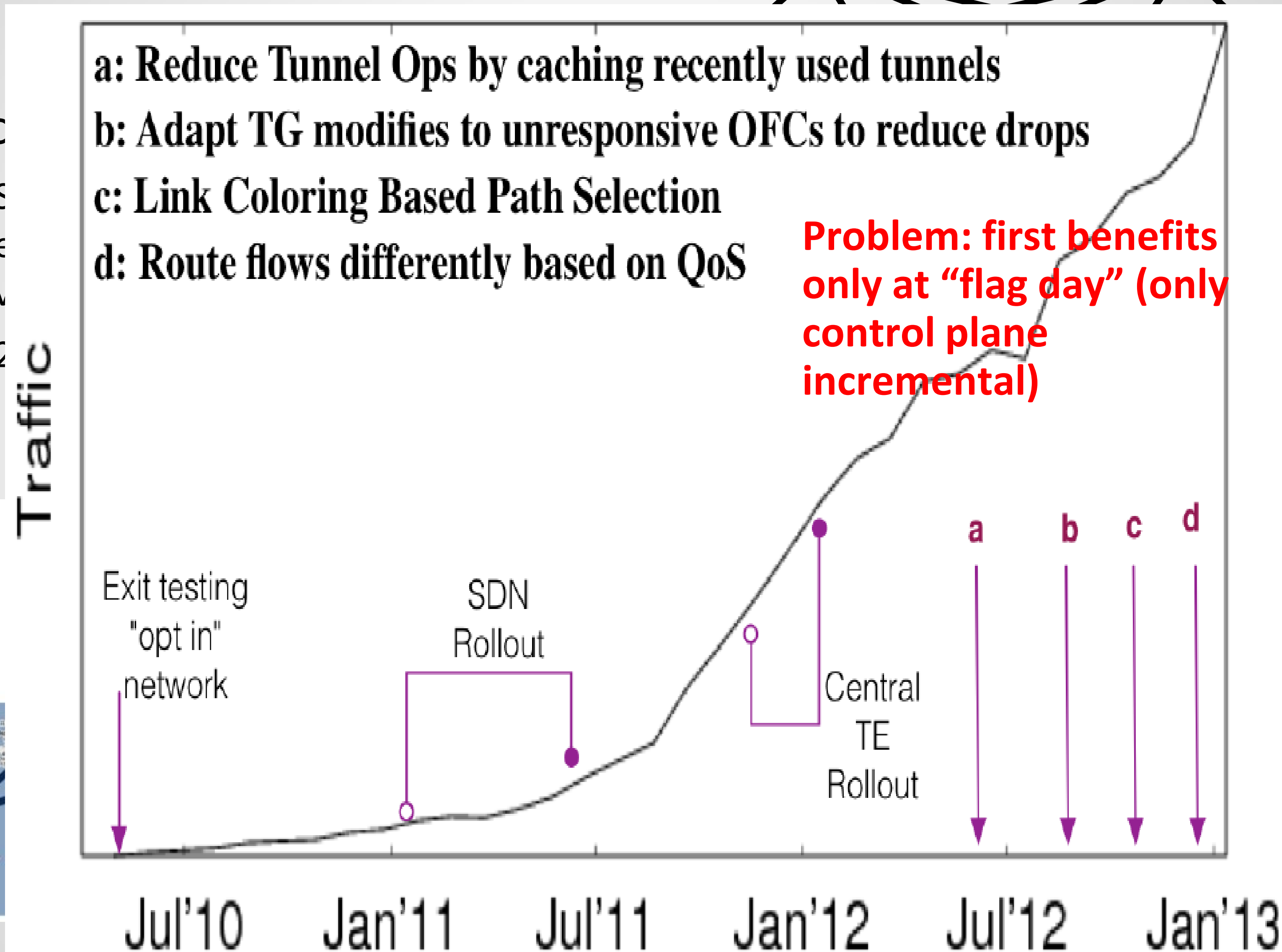
- 2

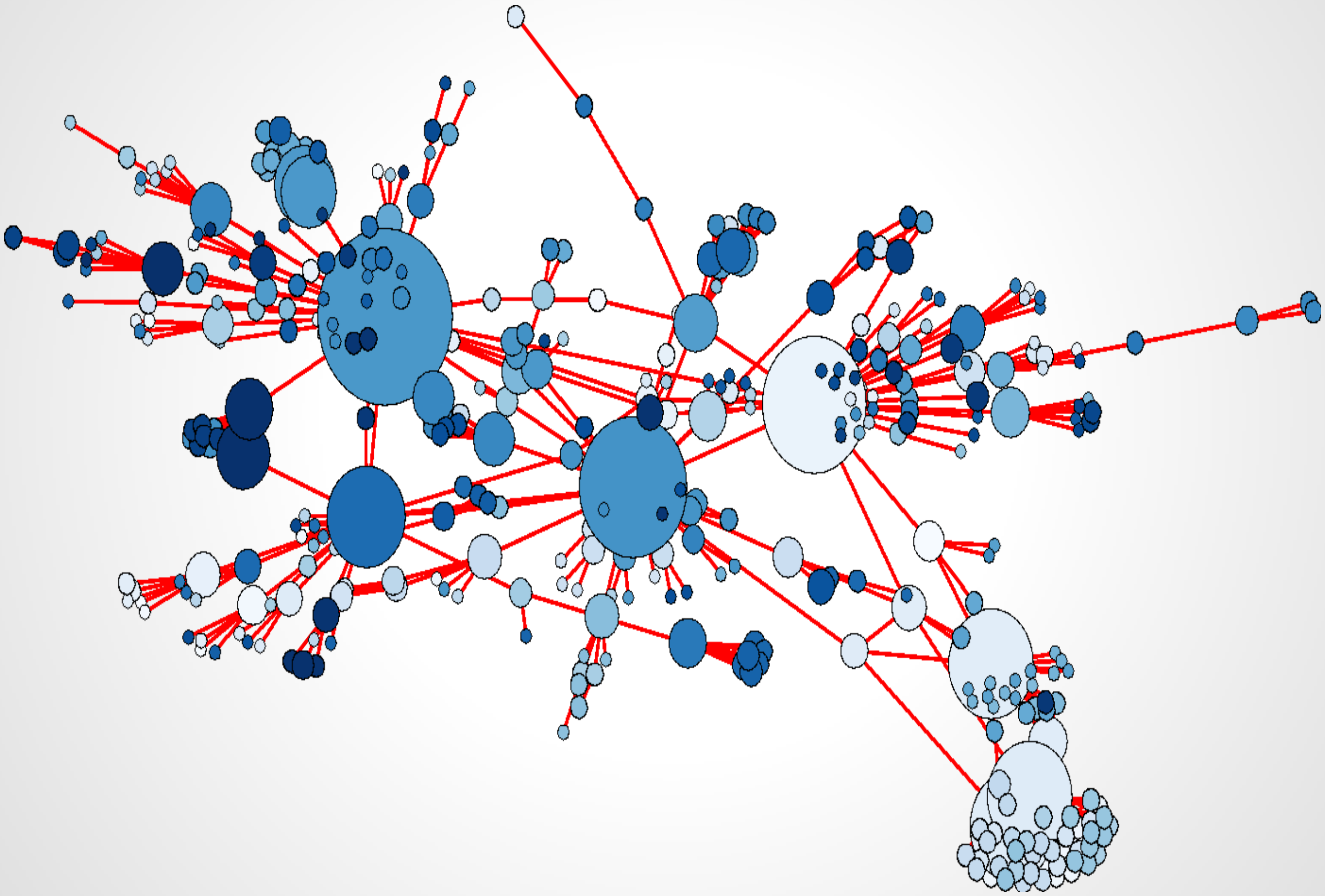



)

# But how to deploy SDN in enterprise?

- Large and complex networks, **budgets limited**
- Idea: Can we **incrementally deploy SDN** into enterprise campus networks?
- And what **SDN benefits** can be realized in a hybrid deployment?

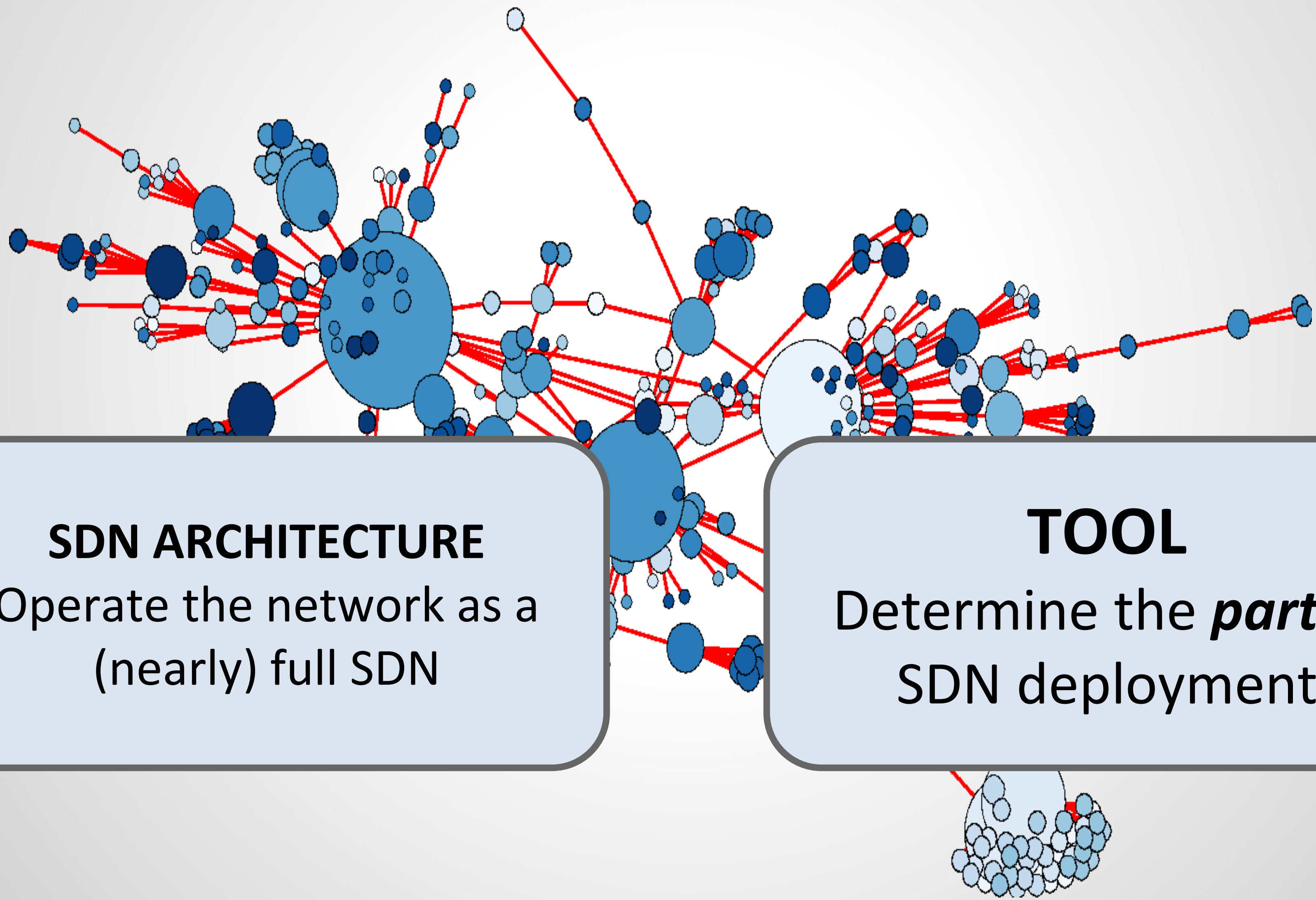
# Can we deploy SDN at enterprise edge?



**The edge is large, and not in software!**

# Panopticon

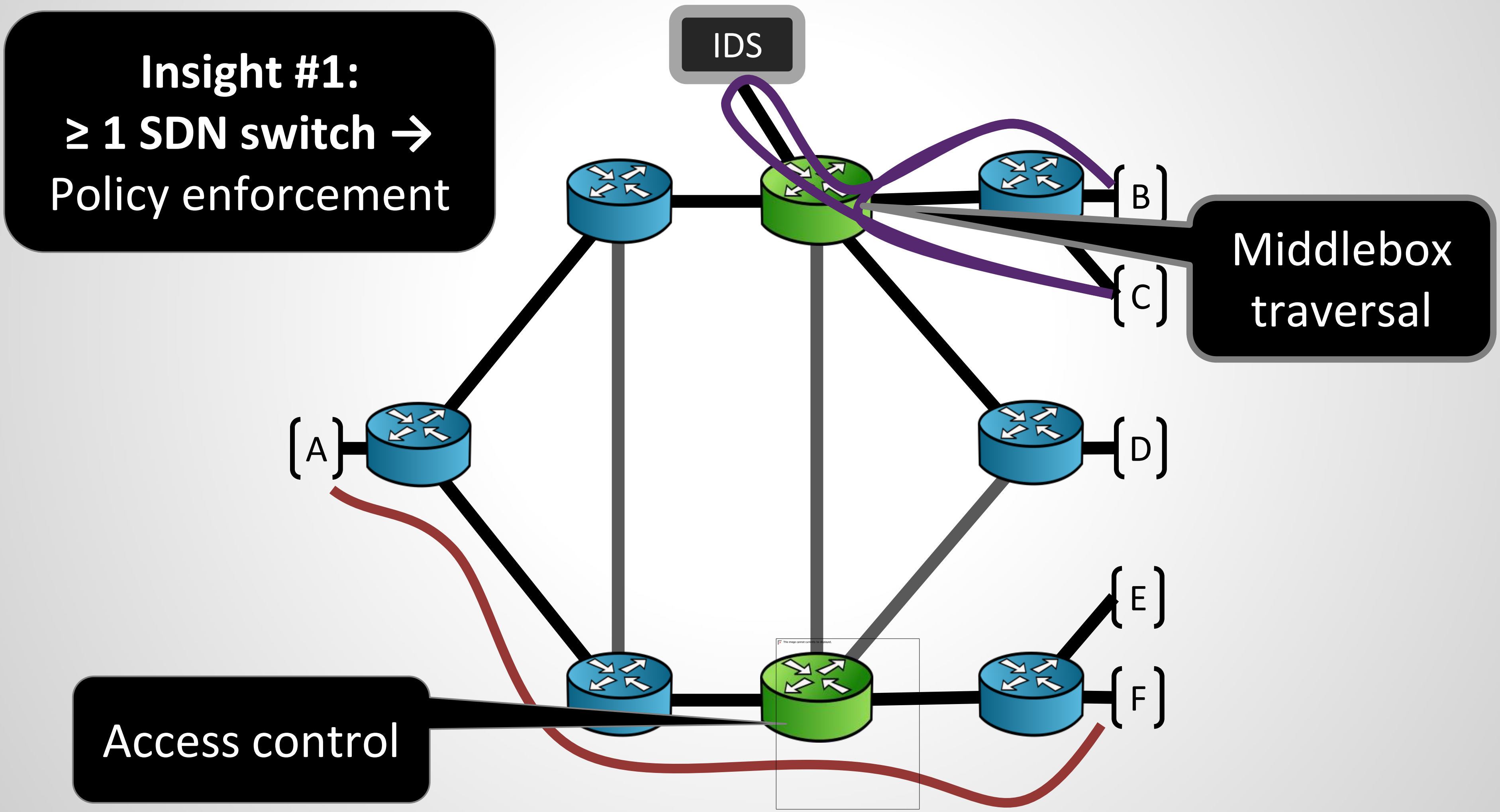
Levin, Canini, Schmid,
Schaffert, Feldmann
ATC 2014



**SDN ARCHITECTURE**
Operate the network as a (nearly) full SDN

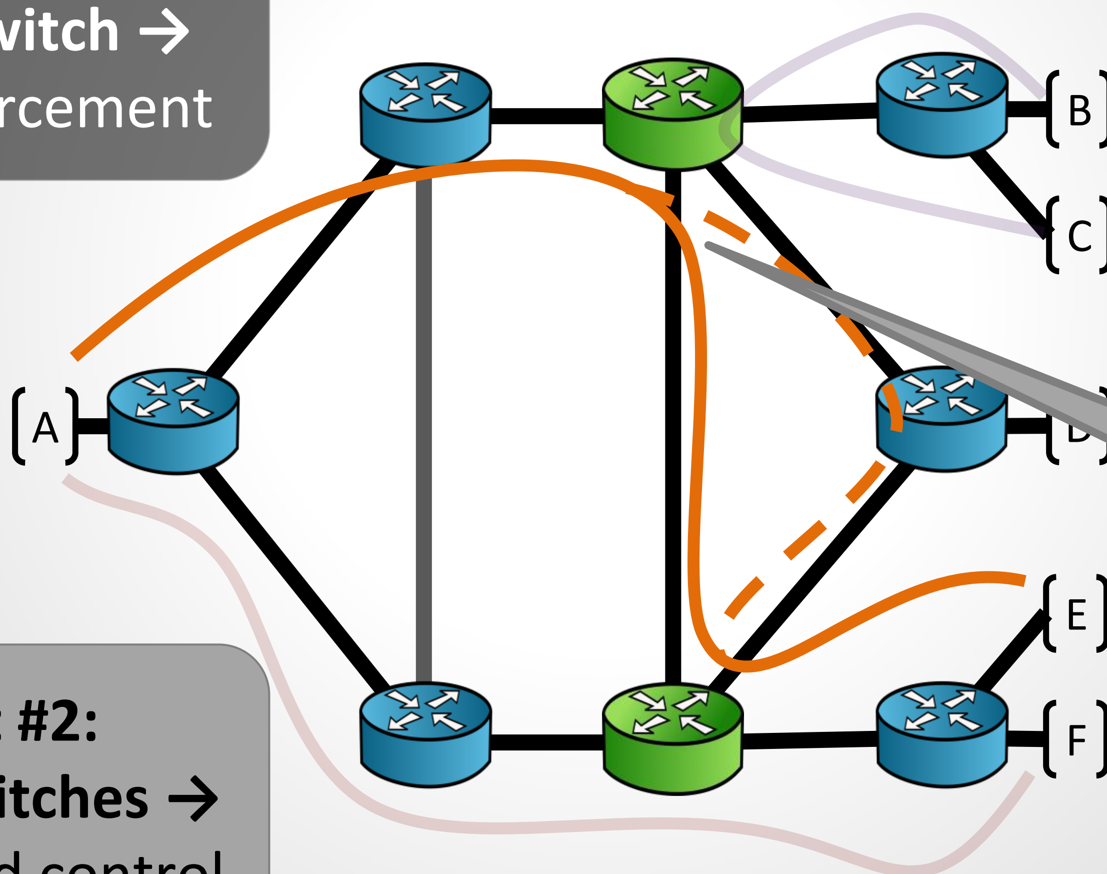
**TOOL**
Determine the ***partial*** SDN deployment

# Get Functionality with Waypoint Enforcement



# Larger Deployment = More Flexibility

**Insight #1:**
**≥ 1 SDN switch →**
Policy enforcement

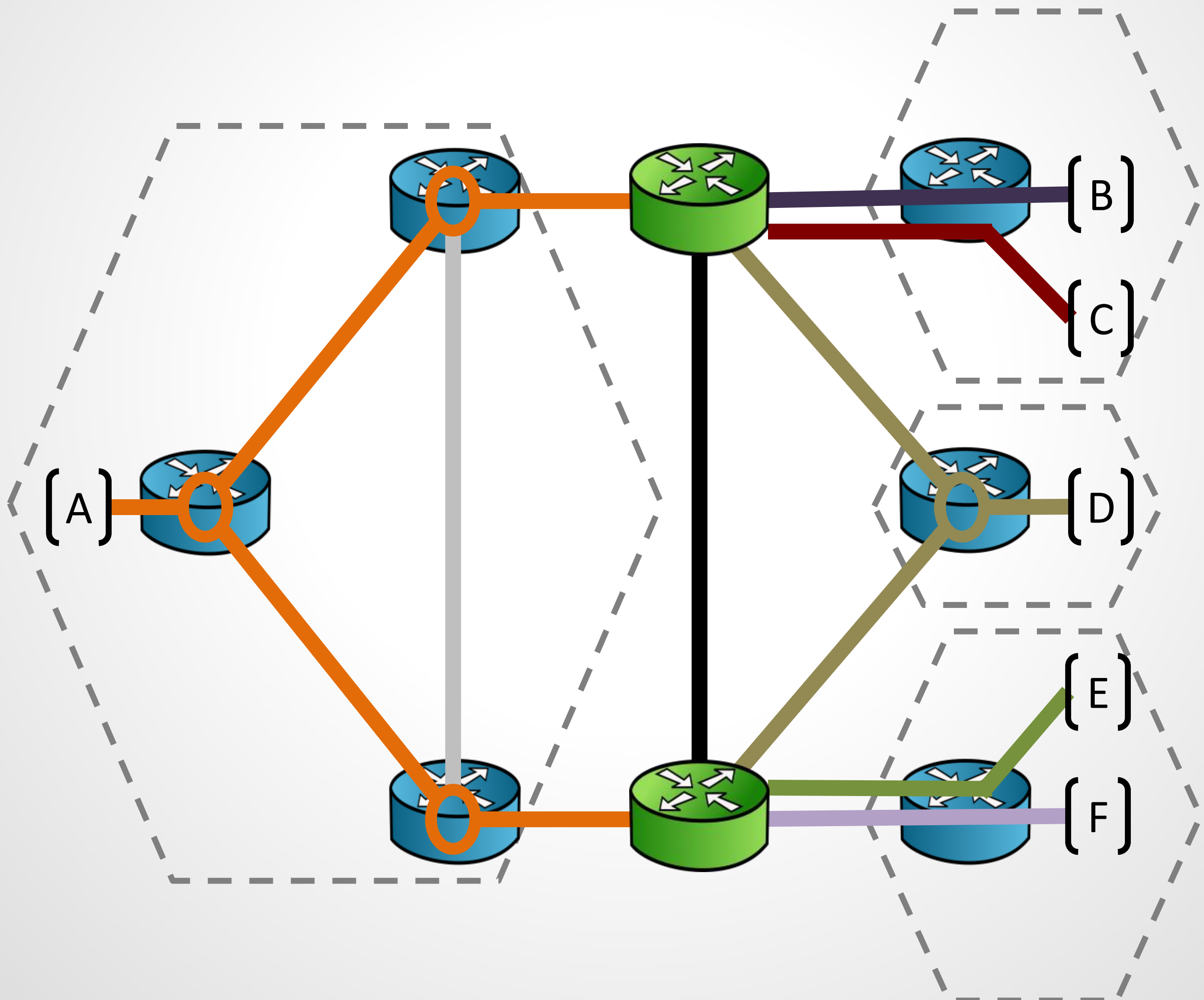



Traffic load-balancing

**Insight #2:**
**≥ 2 SDN switches →**
Fine-grained control

# Panopticon: Building the Logical SDN Abstraction

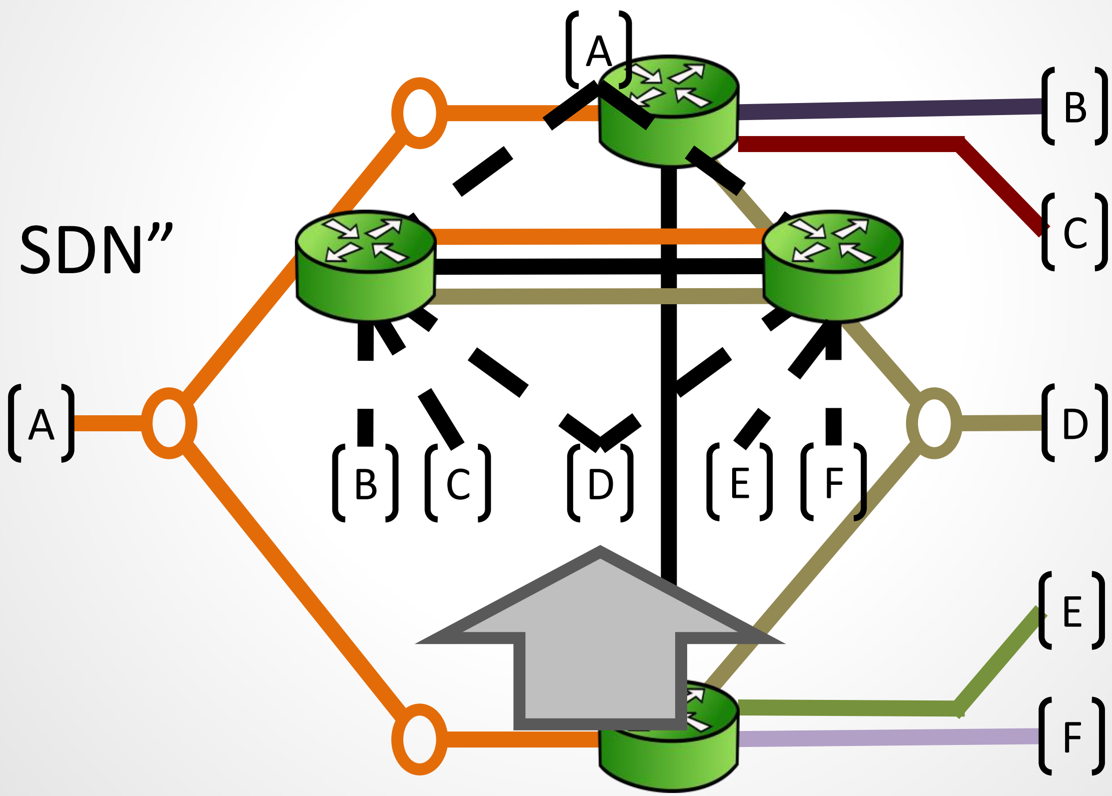
1. Restrict traffic by using VLANs

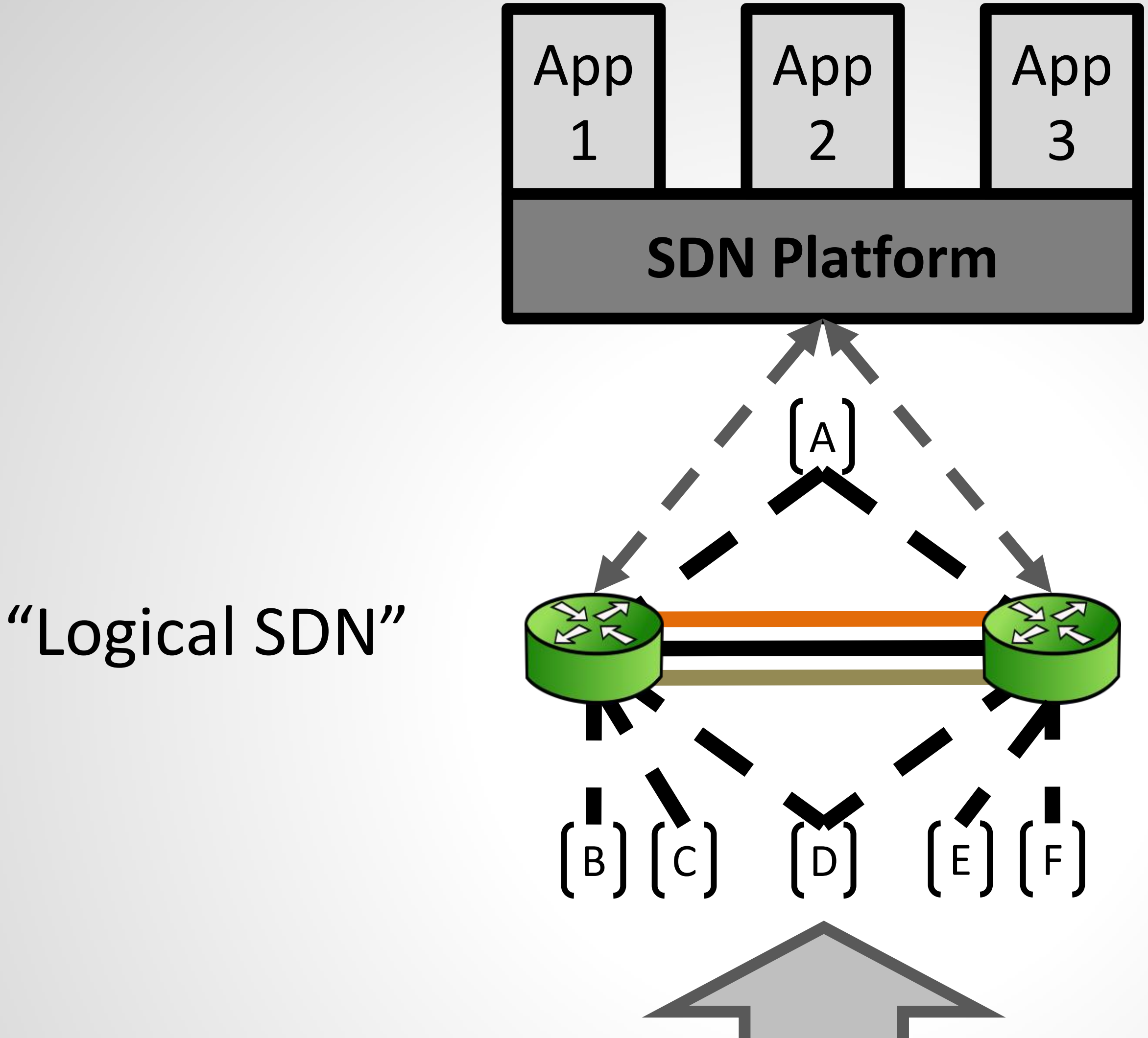


# Panopticon: Building the Logical SDN Abstraction

2. Build logical SDN

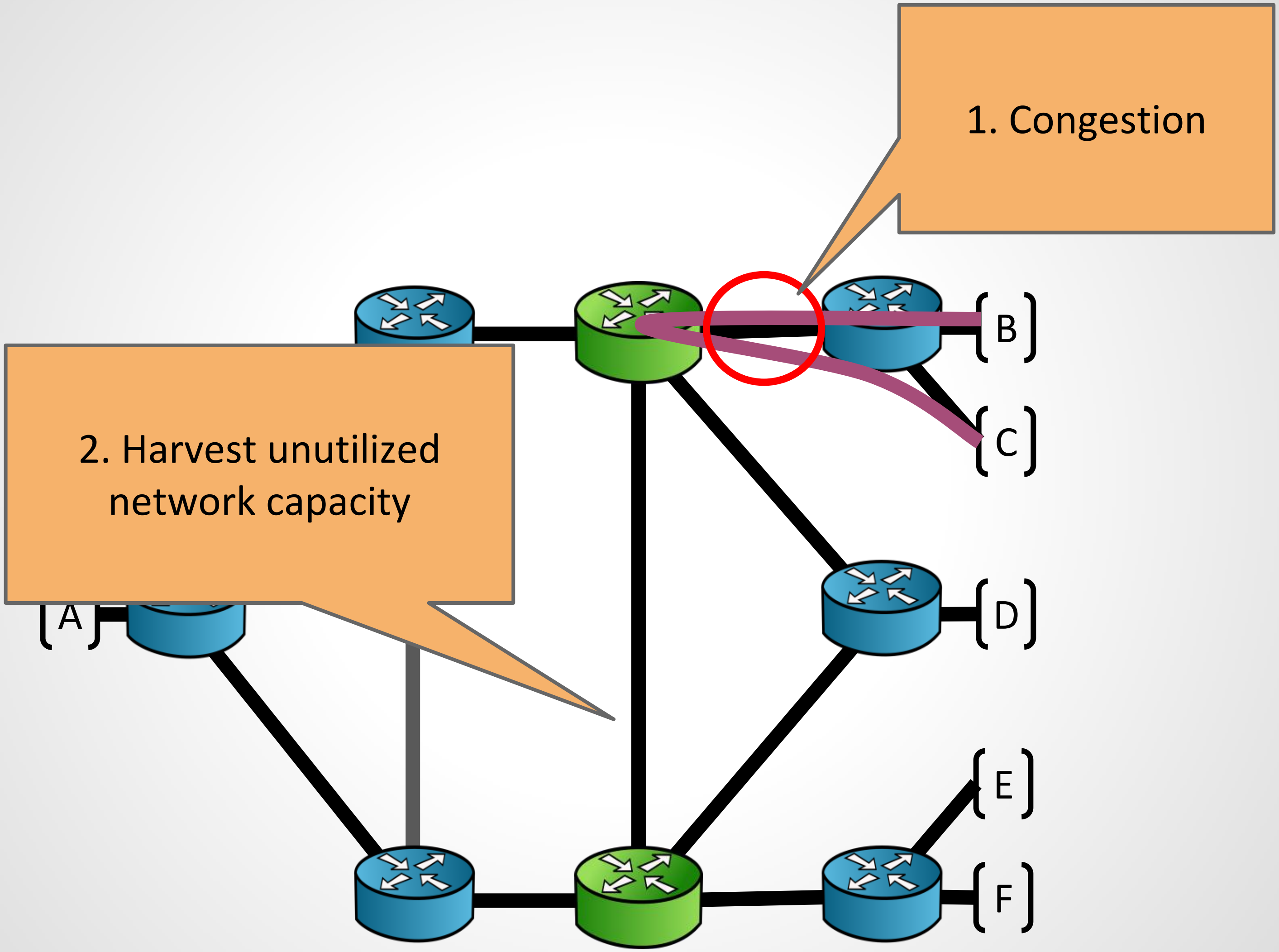
"Logical SDN"






**PANOPTICON provides the abstraction of a (nearly) fully-deployed SDN in a partially upgraded network**

# Good or Bad Impact on Traffic?



# Challenges of More Flexible Distributed Systems

1. Kraken: Predictable cloud application performance through adaptive virtual clusters

2. C3: Low tail latency in cloud data stores through replica selection

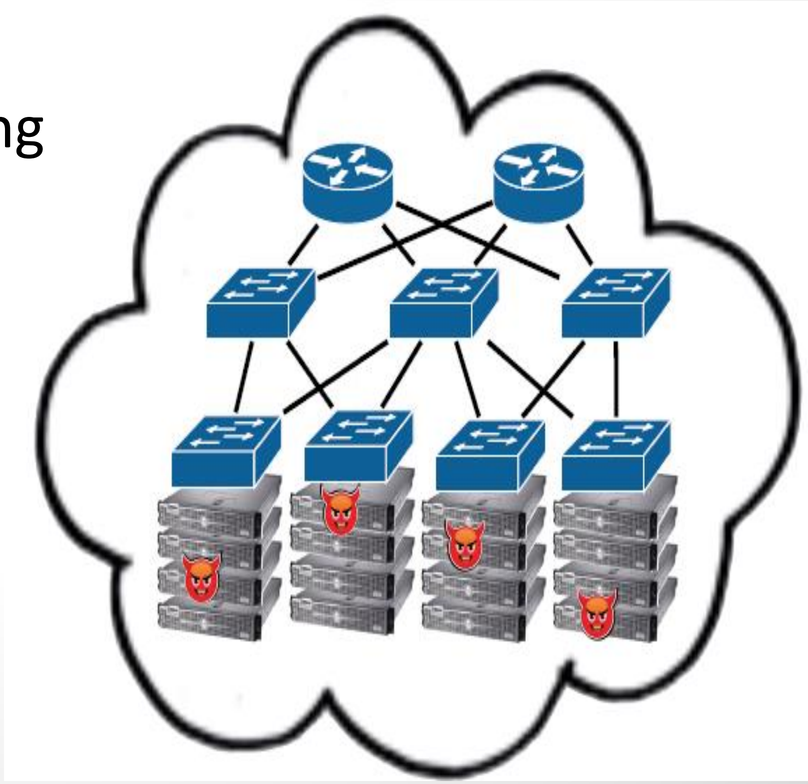
3. Panopticon: How to introduce these innovative technologies in the first place? Case study: SDN

4. **STN, Offroad, Peacock: How to render distributed systems more adaptive without shooting in your foot?**

# Correct Operation is Important!

Example: trend to move the infrastructure to the cloud (e.g., the CIA).

What if your traffic was *not* isolated from other tenants during periods of routine maintenance?



# Example: Outages



Even technically sophisticated companies are struggling to build networks that provide reliable performance.

github SOCIAL CODING

*We discovered a misconfiguration on this pair of switches that caused what's called a "bridge loop" in the network.*

*A network change was […] executed incorrectly […] more "stuck" volumes and added more requests to the re-mirroring storm*

amazon web services

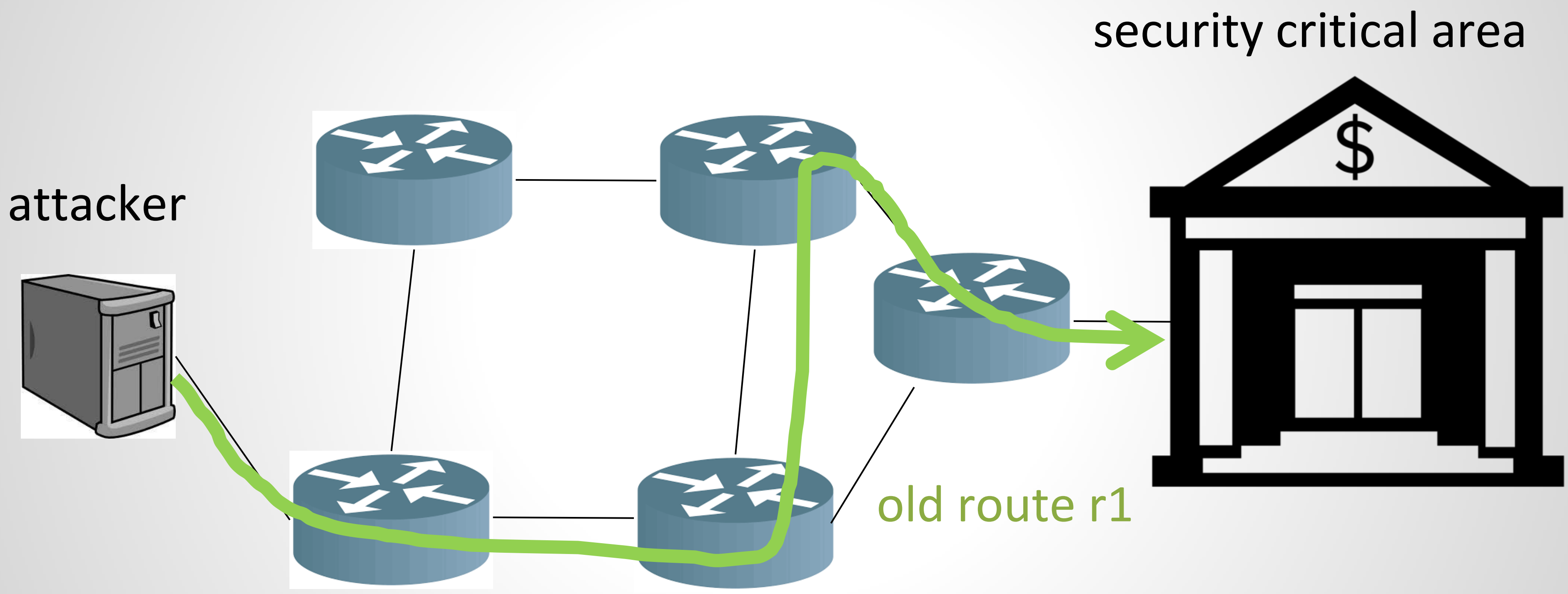
Go Daddy.com

*Service outage was due to a series of internal network events that corrupted router data tables*

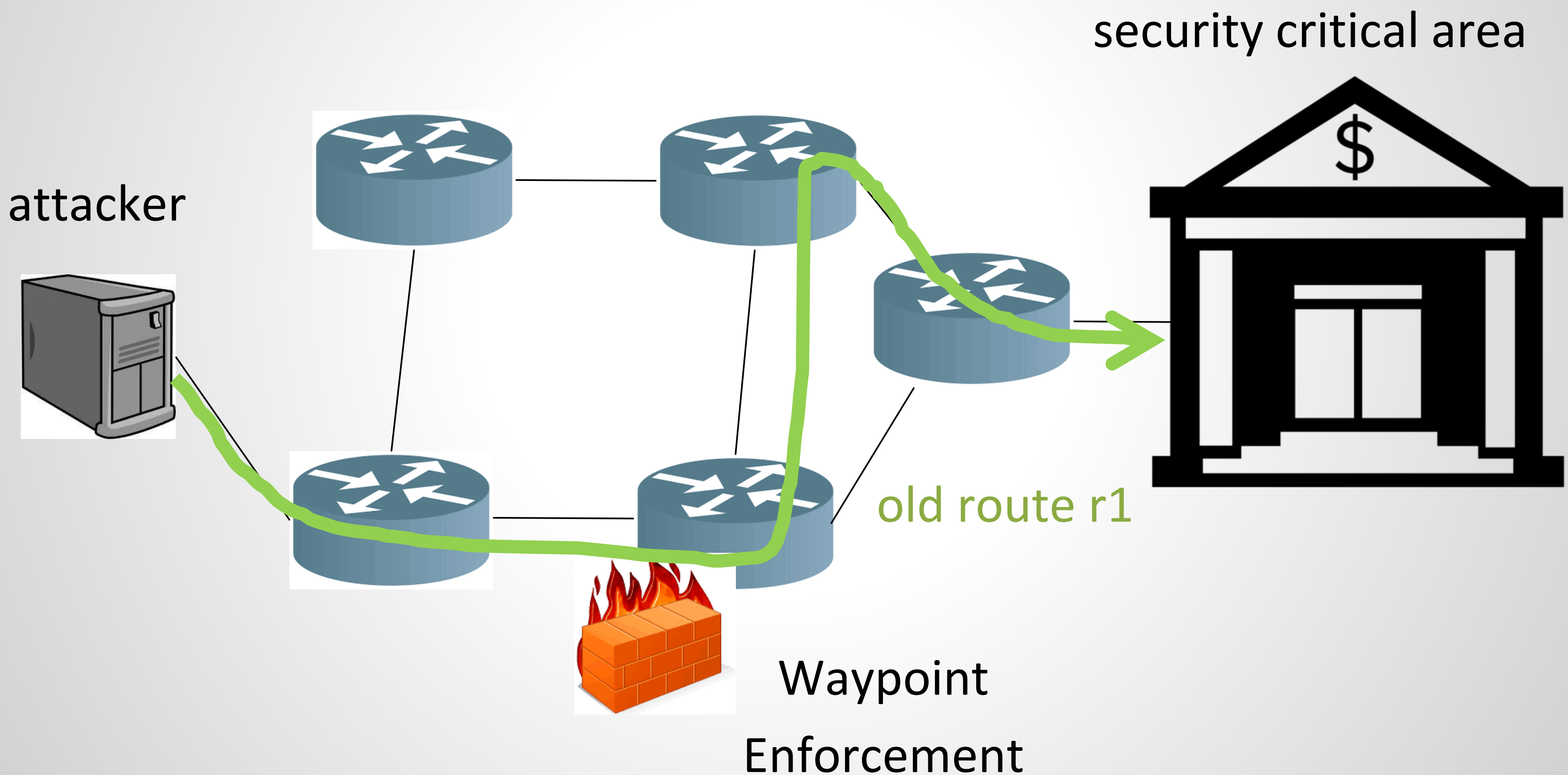
*Experienced a network connectivity issue […] interrupted the airline's flight departures, airport processing and reservations systems*

United Airlines

# Example: Security-Critical Updates



# Example: Security-Critical Updates



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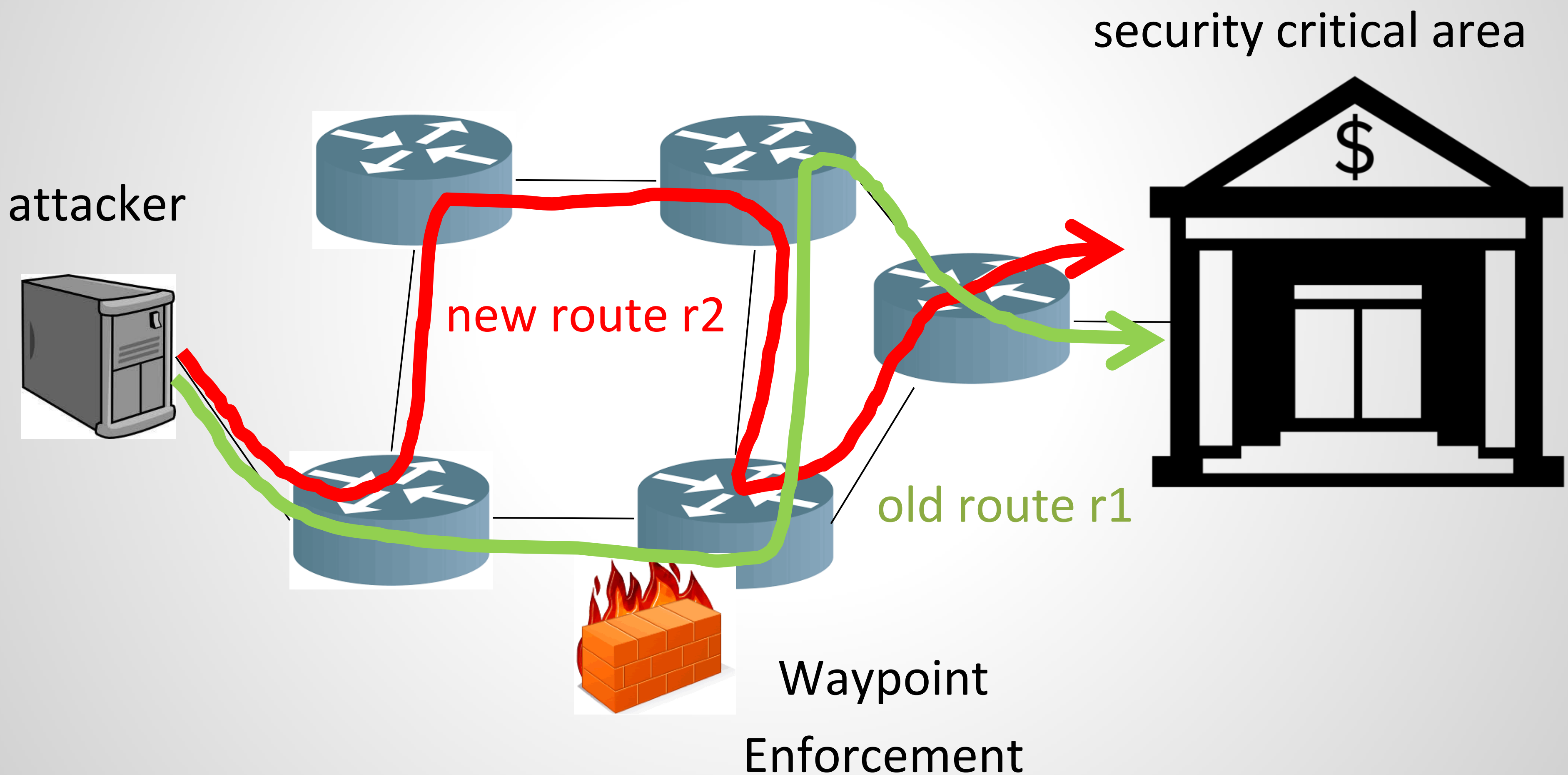
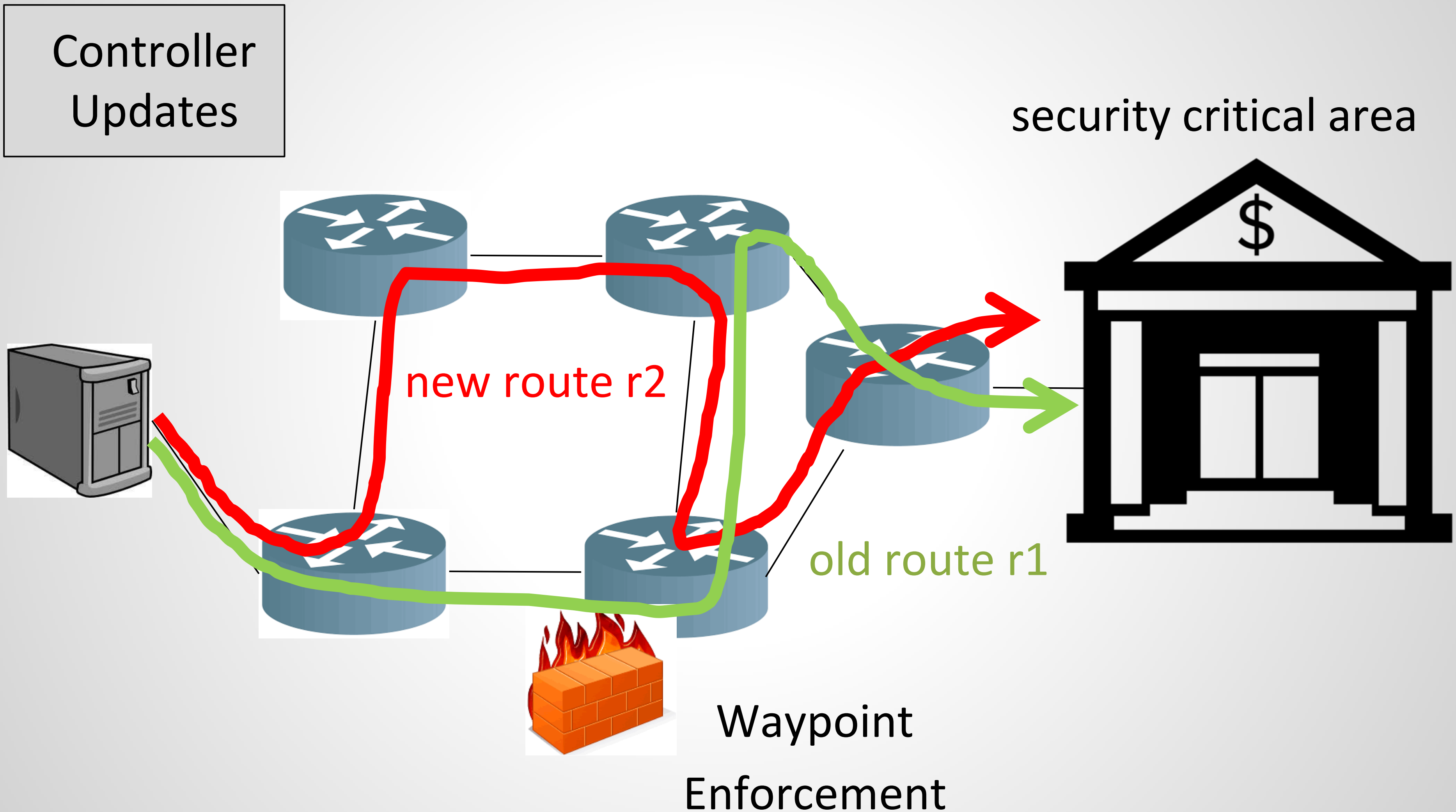


# Example: Security-Critical Updates

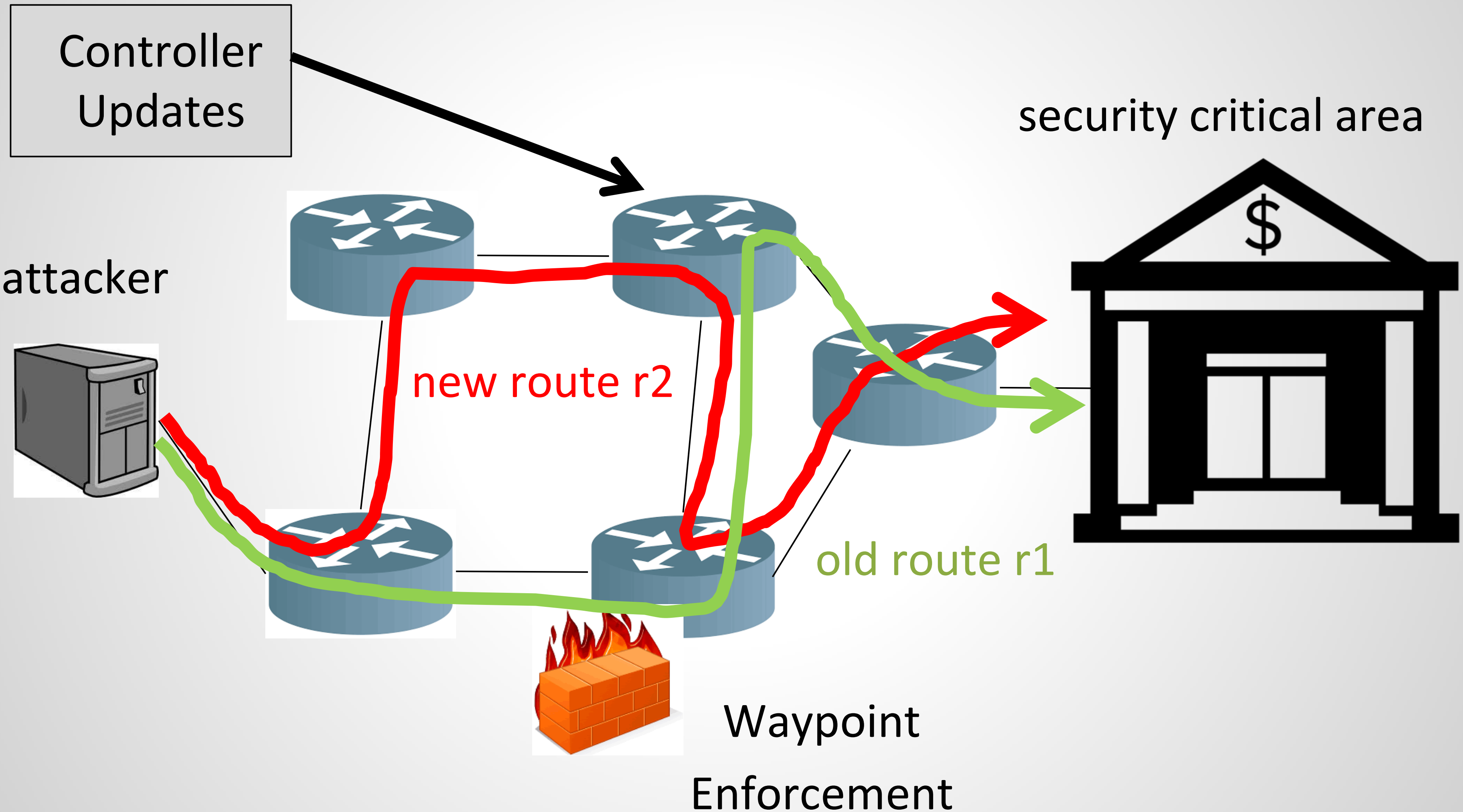


# How to update networks consistently?

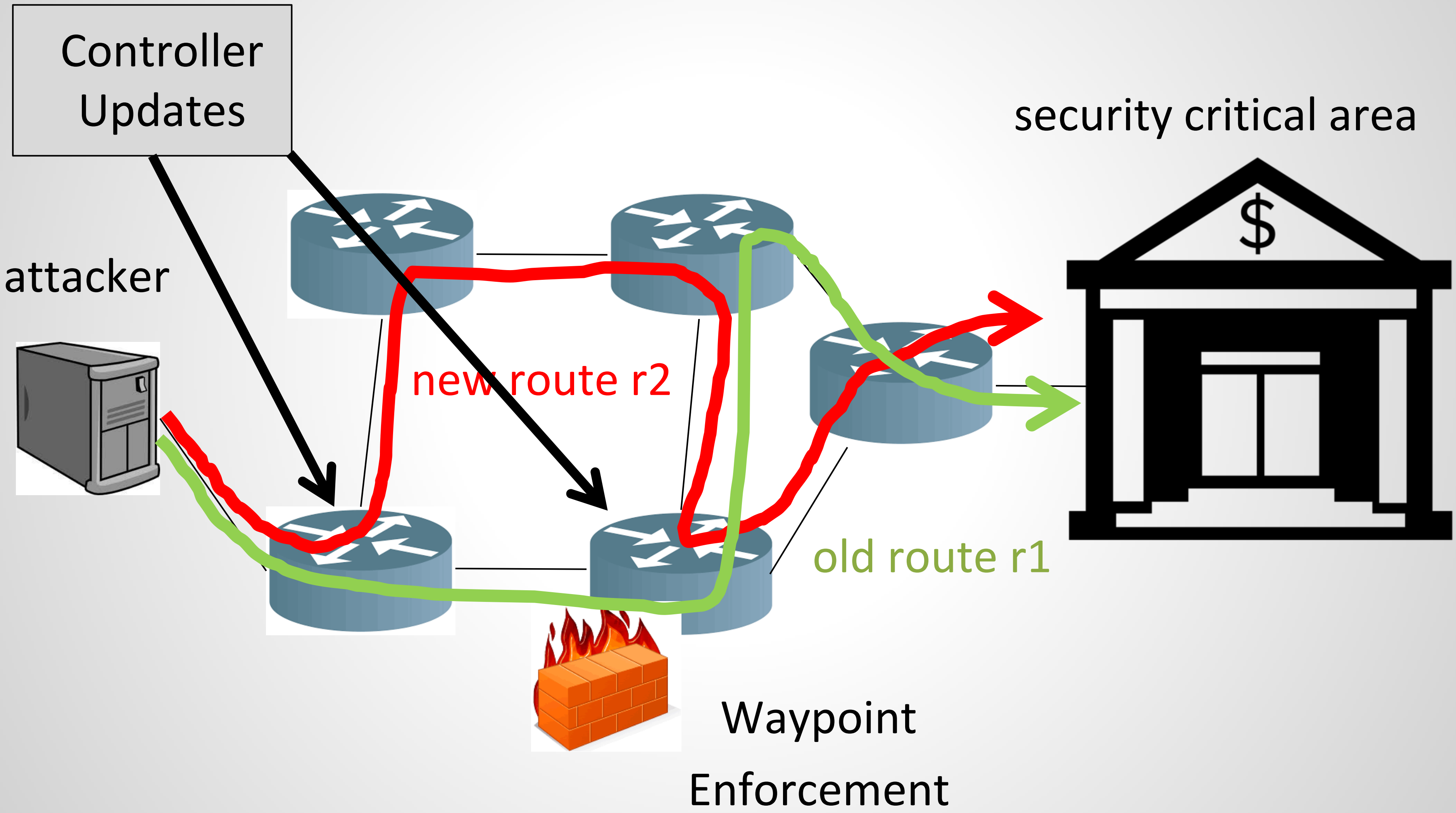
- Idea: Use tagging and **2-phase commit**
  - Problematic: header space, TCAM space, middleboxes
- Better solution: Update network in ***rounds***! [7]
  - Round = subset of nodes are updated
  - Restrict concurrency s.t. consistency maintained
  - How many rounds are needed?

[7] Good Network Updates for Bad Packets: Waypoint Enforcement Beyond Destination-Based Routing Policies. Arne Ludwig, Matthias Rost, Damien Foucard, and Stefan Schmid. 13th ACM Workshop on Hot Topics in Networks (HotNets), Los Angeles, California, USA, October 2014.

# Solution: Round 1

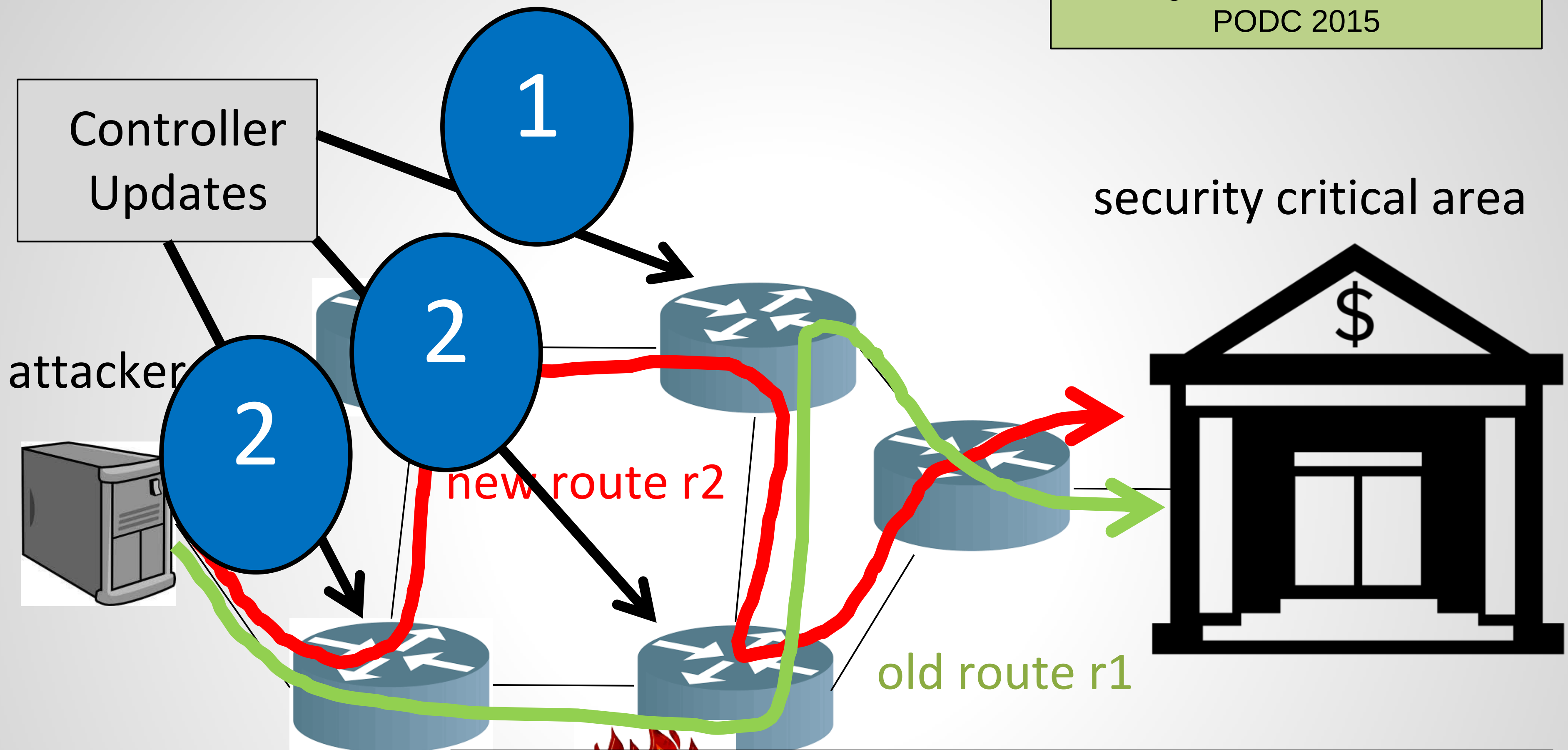


# Solution: Round 2



# Solution

Ludwig, Rost, Fourcard, Schmid
HotNets 2014
Ludwig, Marcinkowski, Schmid
PODC 2015




- ❑ How many rounds are needed?
- ❑ How to also avoid loops? Related to **Feedback Arc Set Problems**
- ❑ What properties conflict?
- ❑ **NP-hard** but efficient algorithms exist!

# Distributed Control: for redundancy, multi-user, …

Canini, Kuznetsov, Levin Schmid
INFOCOM 2015

Control should be distributed!

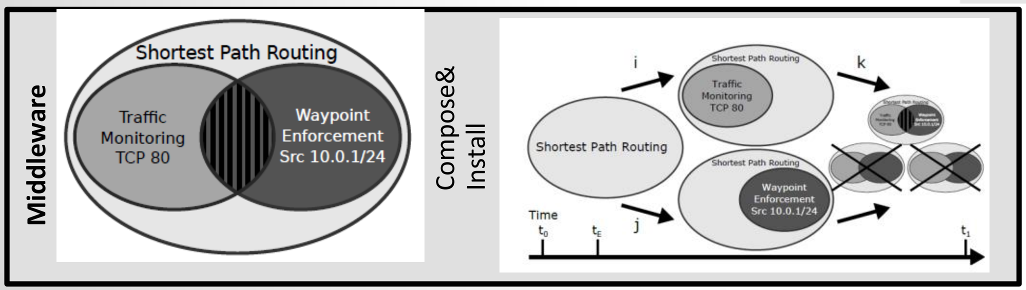
***STN:*** A transactional interface

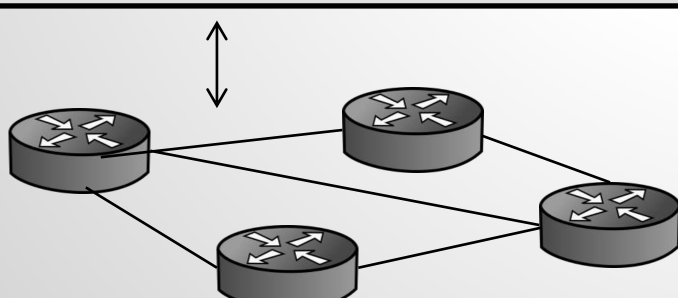
Install

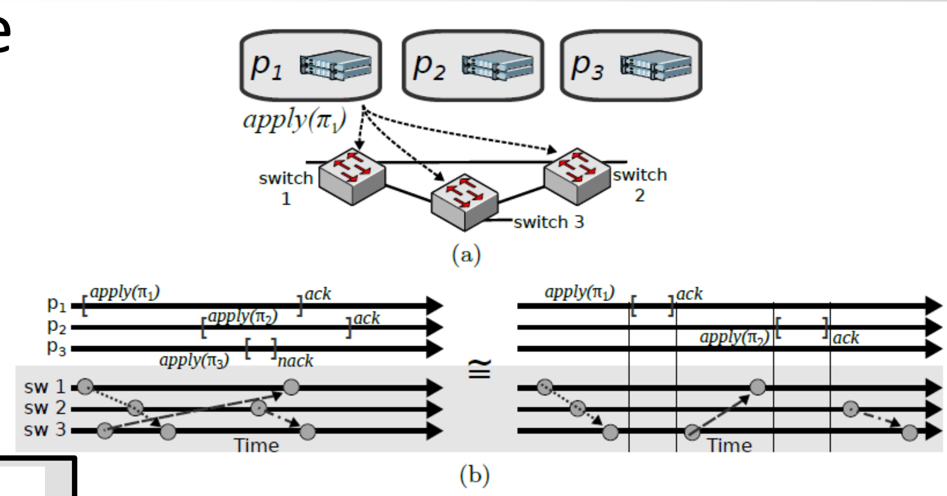
ACK/NAK

Install

ACK/NAK






**Problem:** Conflict free, per-packet consistent policy composition and installation

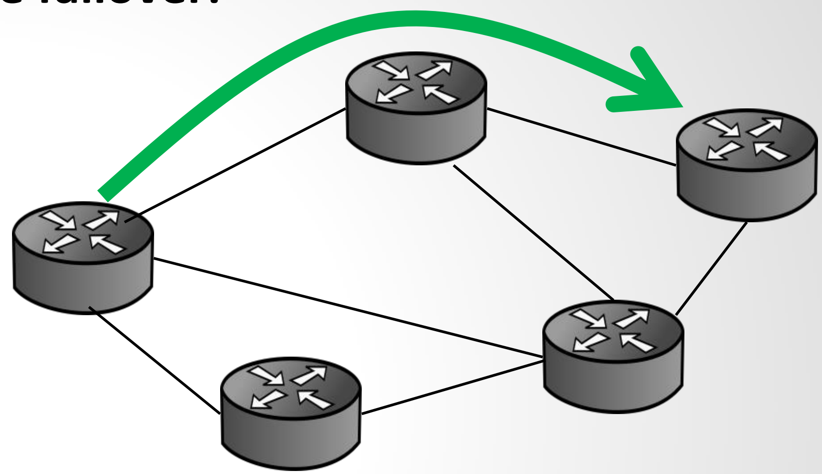
**Holy Grails:** Linearizability (Safety), Wait-freedom (Liveness)

# Challenge: Fast Robust Routing Mechanisms

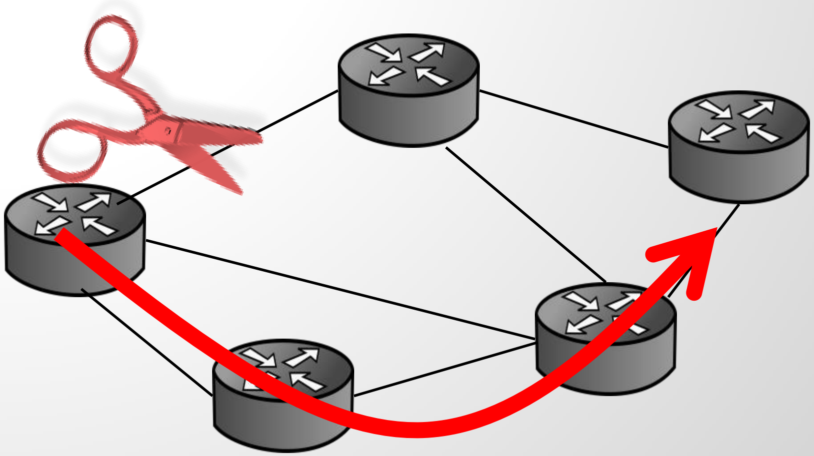
- **Link failures** today are not uncommon [1]

- Modern networks provide **robust routing mechanisms**
  - i.e., routing which reacts to failures
  - example: MPLS local and global path protection

**Before failover:**

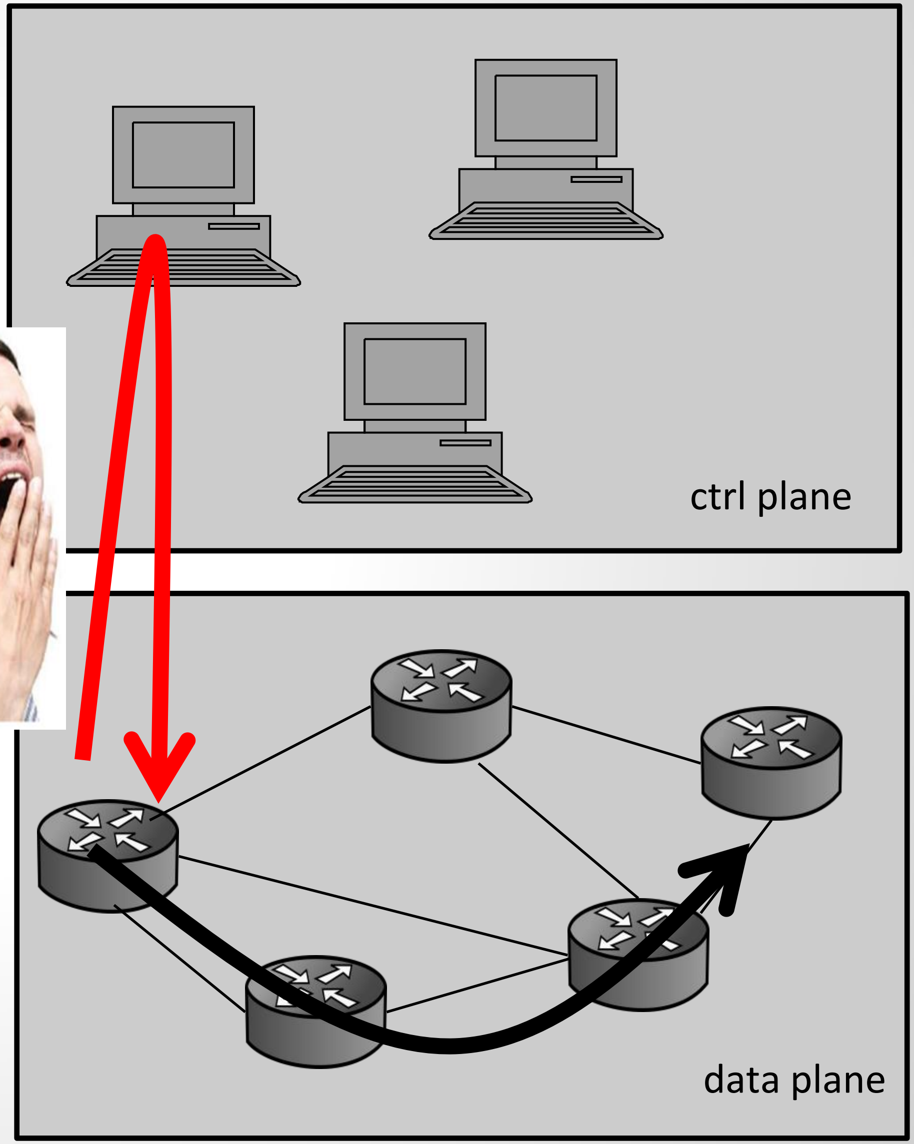


**After failover:**



# Fast In-band Failover

- Important that failover happens **fast = in-band**
  - Reaction time in control plane can be orders of magnitude slower
- For this reason: **OpenFlow Local Fast Failover Mechanism**
  - Supports conditional forwarding rules (depend on the local state of the link: live or not?)
- Gives fast but local and perhaps "**suboptimal**" forwarding sets
  - Controller improves globally later…



- Important that failove
  **fast = in-band**
  - Reaction time in contr
    orders of magnitude s

However, not much is known about how to ***use*** the OpenFlow fast failover mechanism.
E.g.: **How many failures** can be tolerated without losing connectivity?

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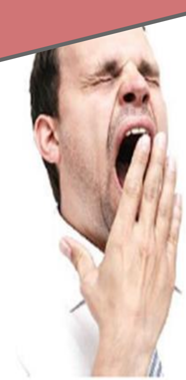

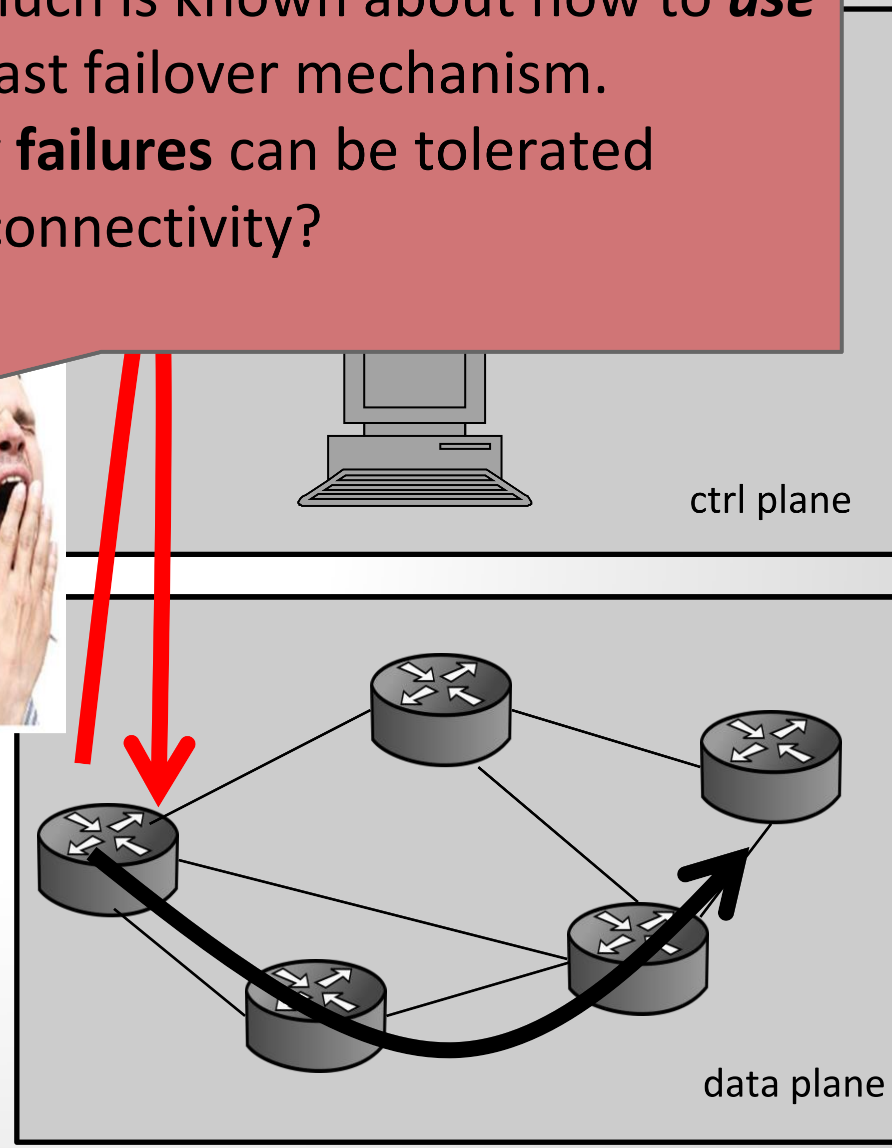


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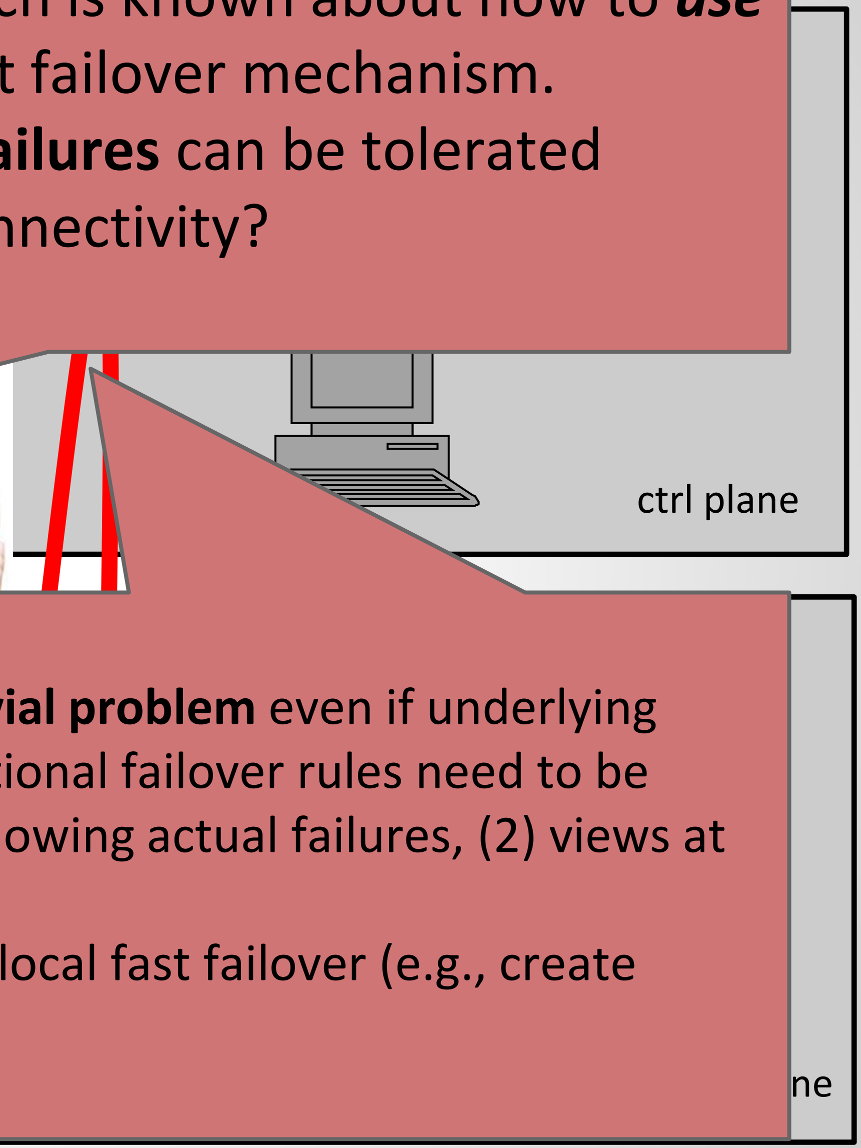


However, not much is known about how to ***use*** the OpenFlow fast failover mechanism.
E.g.: **How many failures** can be tolerated without losing connectivity?

How to use mechanism is a **non-trivial problem** even if underlying network stays connected: (1) conditional failover rules need to be allocated **ahead of time**, without knowing actual failures, (2) views at runtime are **inherently local**.
How not to **shoot in your foot** with local fast failover (e.g., create forwarding loops)?

# Offroad and SmartSouth

Schiff, Borokhovich, Schmid
HotSDN 2014, HotNets 2014

- **Offroad**: already with today's Openflow, provable connectivity can be implemented in-band
  - Even without per-switch state
- **SmartSouth**: already with today's Openflow, many additional functionality could in principle be implemented in-band
  - E.g., anycast, sampling, snapshots, blackhole detection, ...
- Trend for «Openflow 2.0»: improve functionality of Openflow switches further
  - Registers, bitmasking, no longer field-specific, ...

# Conclusion

- Programmable and virtualized systems: ***opportunities*** for improved resource allocation and utilization

- But also ***challenges*** in terms of resource interference and predictable application performance

- Making the network a ***first class citizen*** can help to improve performance

- ***High potential*** but also ***risks*** of a more dynamic control

**Thank you!**

*And thanks to my co-authors, mainly: Marco Canini, Paolo Costa, Carlo Fürst, Petr Kuznetsov, Dan Levin, Arne Ludwig, Matthias Rost, Jukka Suomela, Lalith Suresh*

# References


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[2] Beyond the Stars: Revisiting Virtual Cluster Embeddings. Matthias Rost, Carlo Fuerst, and Stefan Schmid. ACM SIGCOMM Computer Communication Review (CCR), July 2015.

[3] A Distributed and Robust SDN Control Plane for Transactional Network Updates, Marco Canini, Petr Kuznetsov, Dan Levin, and Stefan Schmid. IEEE INFOCOM 2015.

[4] OpenSDWN: Programmatic Control over Home and Enterprise WiFi. Julius Schulz-Zander, Carlos Mayer, Bogdan Ciobotaru, Stefan Schmid, and Anja Feldmann. ACM Sigcomm Symposium on SDN Research (SOSR), Santa Clara, California, USA, June 2015.

[5] C3: Cutting Tail Latency in Cloud Data Stores via Adaptive Replica Selection. Lalith Suresh, Marco Canini, Stefan Schmid, and Anja Feldmann. 12th USENIX Symposium on Networked Systems Design and Implementation (NSDI), Oakland, California, USA, May 2015.

[5] Exploiting Locality in Distributed SDN Control. Stefan Schmid and Jukka Suomela. ACM SIGCOMM HotSDN, 2013.

[6] AeroFlux: A Near-Sighted Controller Architecture for Software-Defined Wireless Networks. Julius Schulz-Zander, Nadi Sarrar, and Stefan Schmid. Open Networking Summit (ONS), 2014.

[7] A Provable Data Plane Connectivity with Local Fast Failover: Introducing OpenFlow Graph Algorithms. Michael Borokhovich, Liron Schiff, and Stefan Schmid. ACM SIGCOMM HotSDN, 2014.

[8] Reclaiming the Brain: Useful OpenFlow Functions in the Data Plane. Liron Schiff, Michael Borokhovich, and Stefan Schmid. 13th ACM Workshop on Hot Topics in Networks (HotNets), 2014.

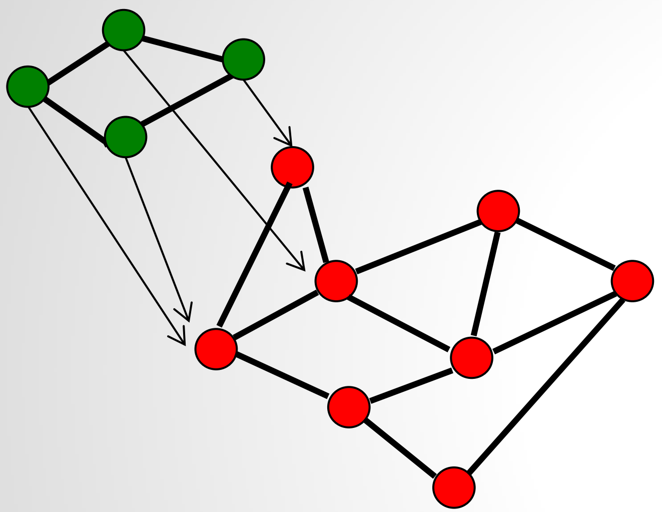
[7] Good Network Updates for Bad Packets: Waypoint Enforcement Beyond Destination-Based Routing Policies. Arne Ludwig, Matthias Rost, Damien Foucard, and Stefan Schmid. 13th ACM Workshop on Hot Topics in Networks (HotNets), Los Angeles, California, USA, October 2014.

[6] Panopticon: Reaping the Benefits of Incremental SDN Deployment in Enterprise Networks. Dan Levin, Marco Canini, Stefan Schmid, Fabian Schaffert, and Anja Feldmann. USENIX Annual Technical Conference (ATC), 2014.

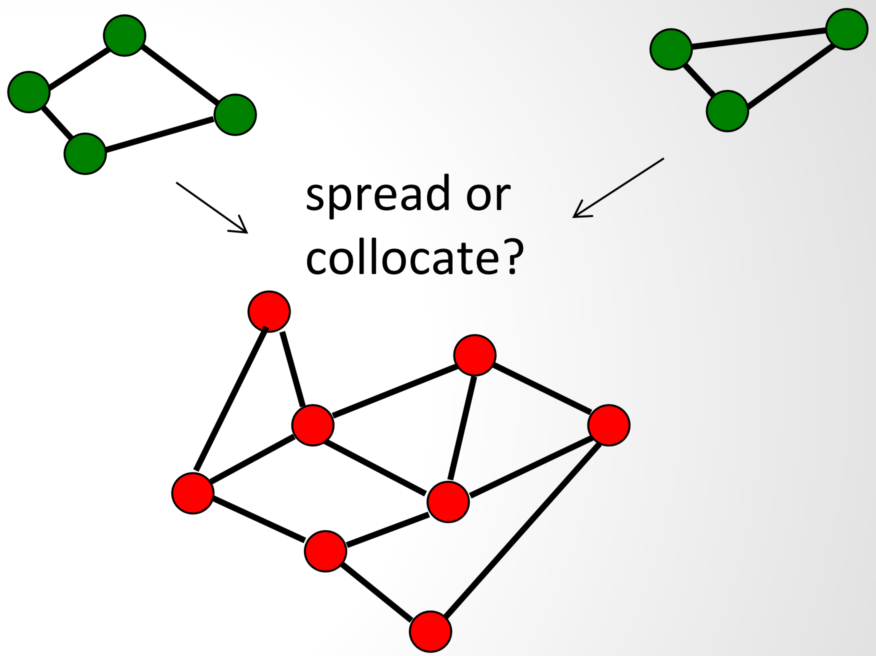
# Backup Slides

# Flavors of VNet Embedding Problems (VNEP)

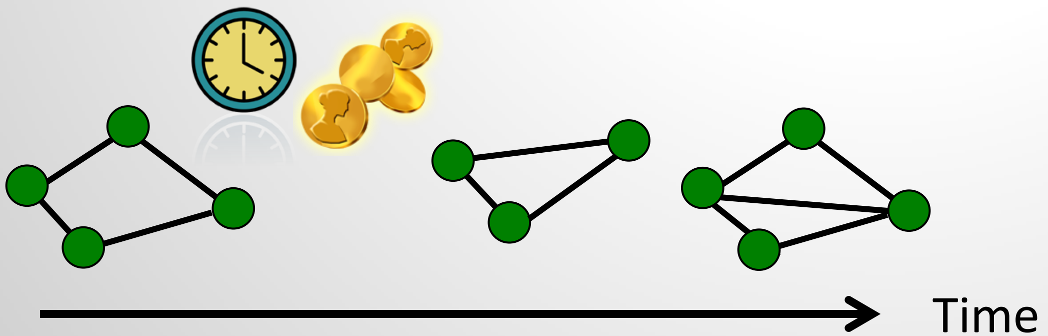
**Minimize embedding footprint of a single VNet :**



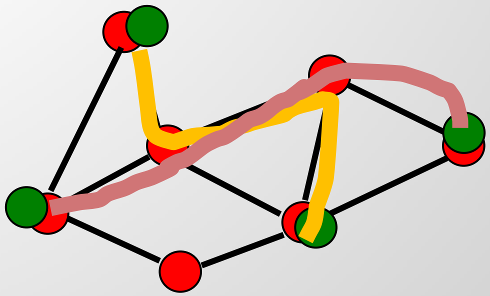
**Minimize max load of multiple VNets or collocate to save energy:**




**Maximize profit over time:**



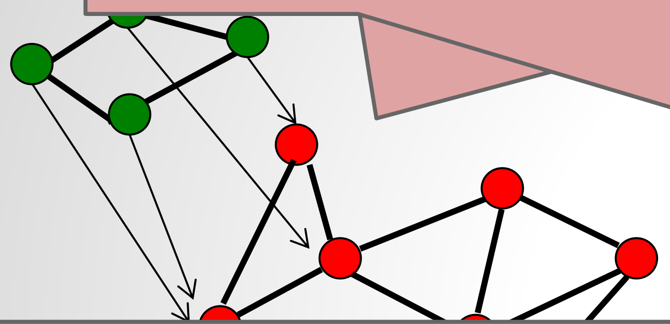

**Endpoints fixed:**

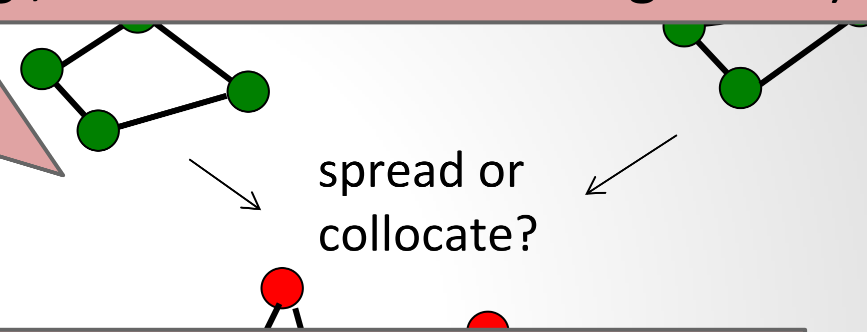


# Flavors of VNet Embedding Problems (VNEP)

**Great opportunities?:** Already for a line host graph, computing the footprint and load optimal embedding of a single VNet is NP-hard (e.g., minimum linear arrangement).

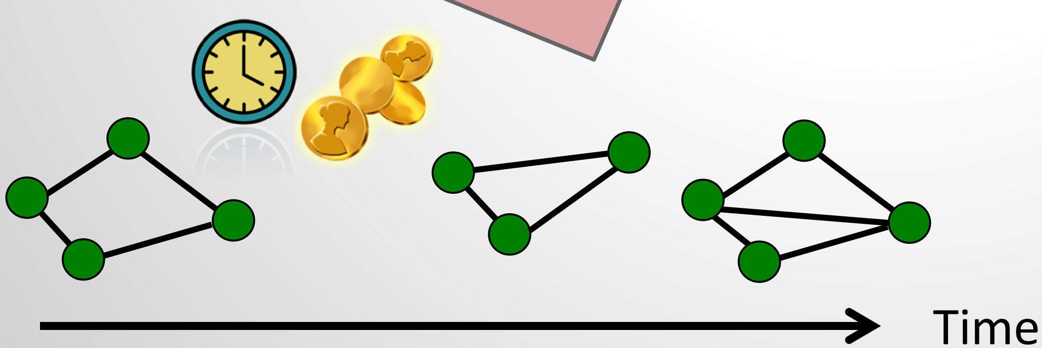
**Mini**
**singl**






**... and:** Generalization of Online Call Control for entire networks, plus embedding problem on top!

**Maximize profit**

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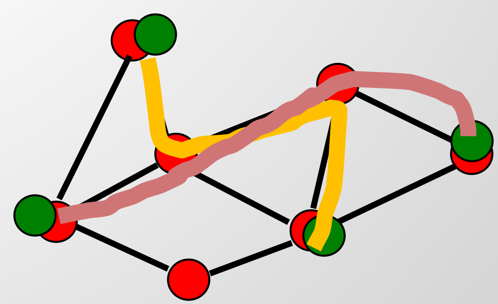
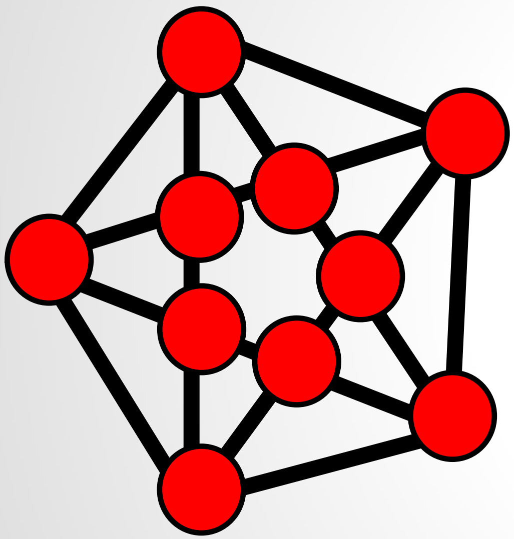
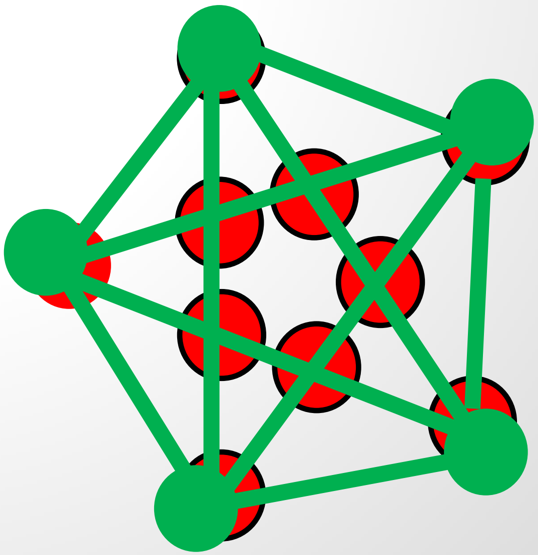


# Cannot directly apply minor theory!

It is possible to embed a guest graph G on a host graph H, even though G is not a minor of H:

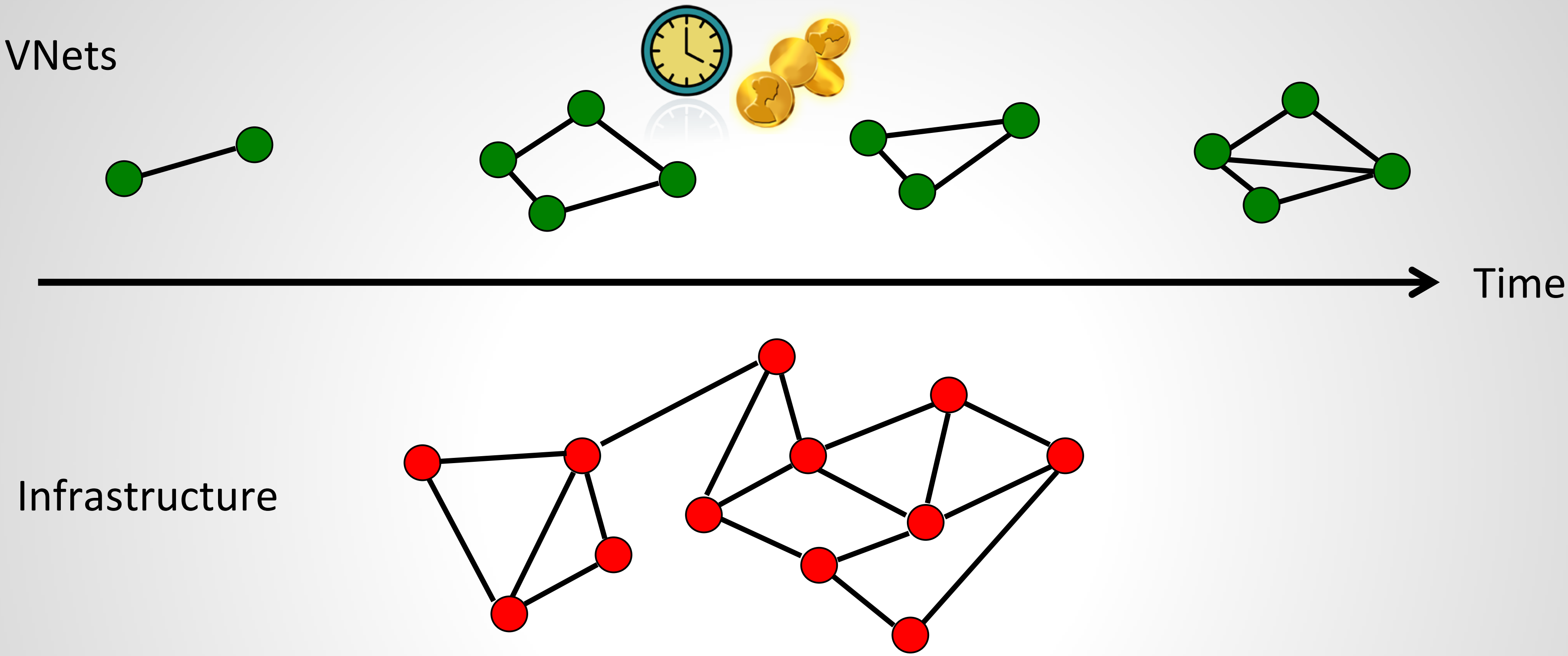


Planar Graph H: K5 and K3,3 minor-free…



… but possible to embed G=K5!

# Online Access Control (1)

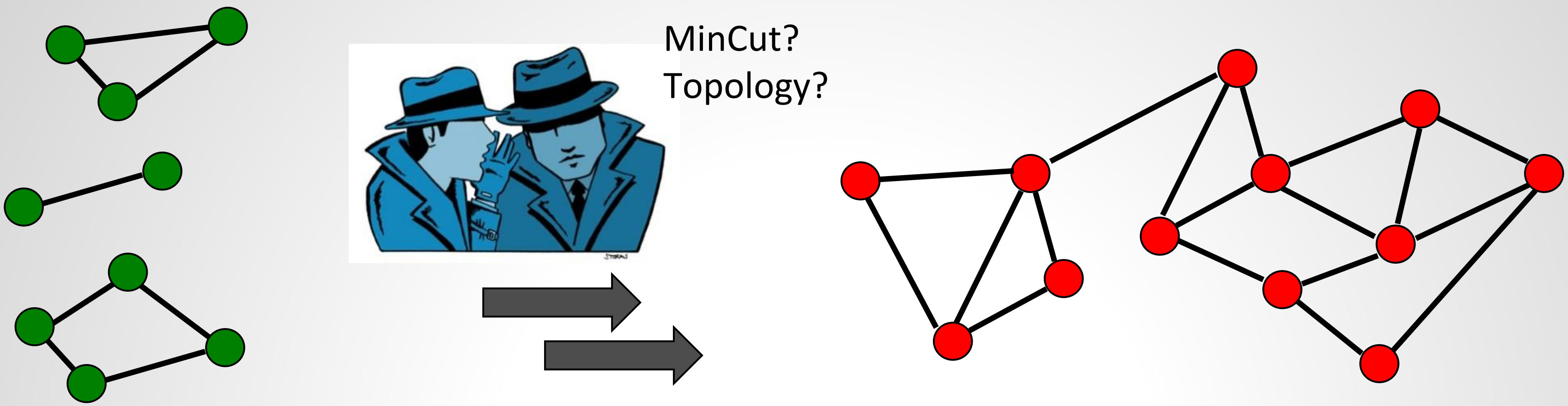



- Assume: end-point locations given
- Different routing and traffic models
- Price and duration
- Which ones to accept?
- Online Primal-Dual Framework (Buchbinder and Naor)

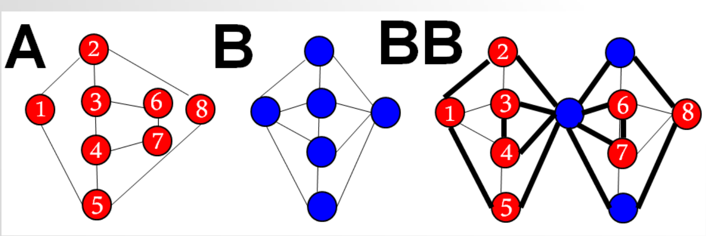
# Solving the VNEP

- Formulate a Mixed Integer Program!
- Leverage additional structure!
- Use online primal-dual approach
- **Discussion:**
  - **Virtual network embedding a potential threat?**
  - Adding migration support
  - Beyond graph structures

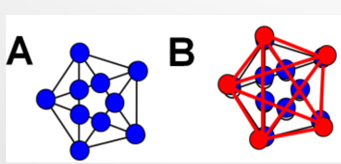
# Security Aspects



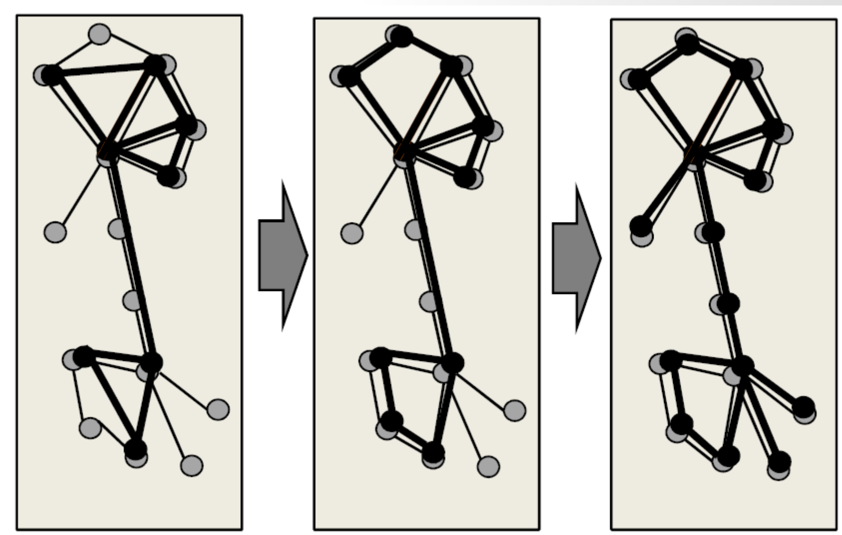

Find dense parts first! But careful:
A cannot be embedded in B.
B cannot be embedded in A.
But A can be embedded in BB.




Different from minor relation: Can embed cliques in planar graphs.



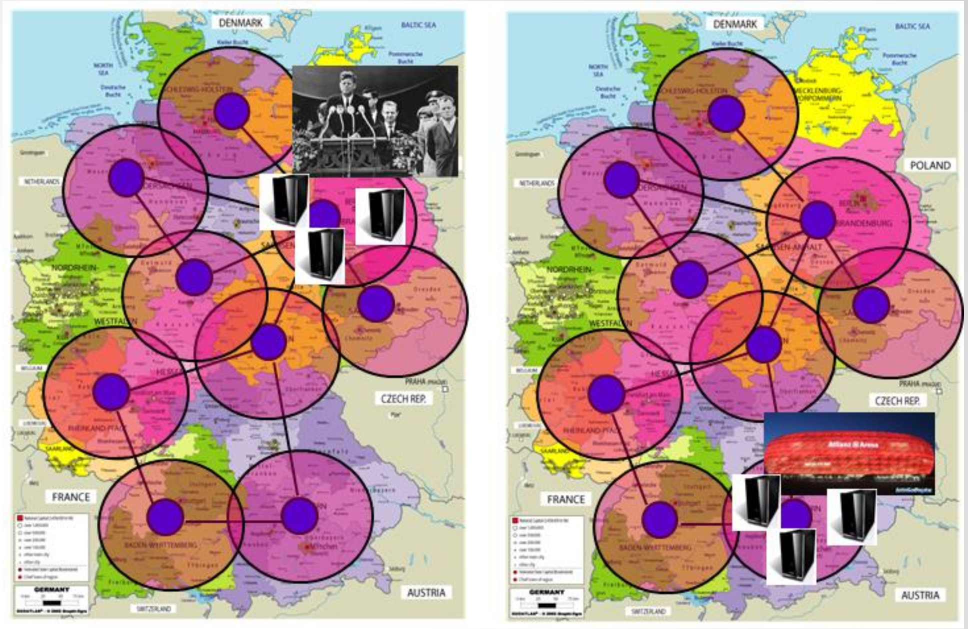

Algorithm



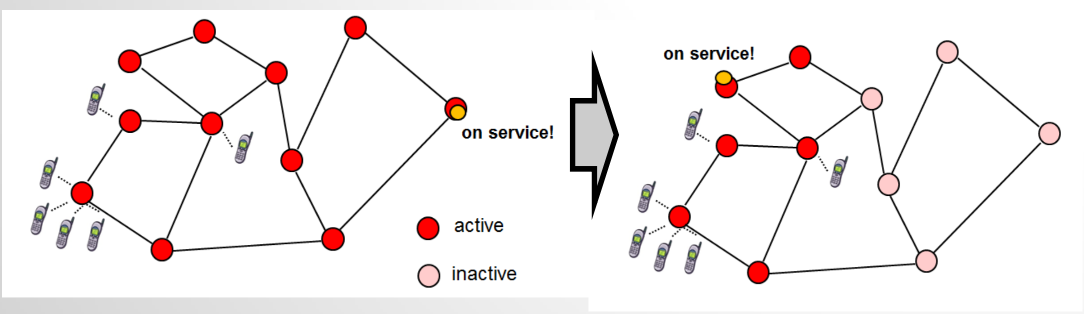
Knitting | Expand links | Repeat

# Migration

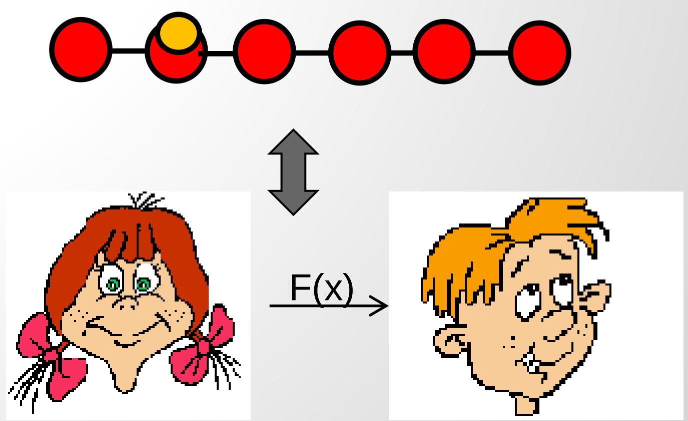
- Service or CloudNet migration
- Access cost: latency
- Migration cost: service interruption / bandwidth
- Variant of Uniform Metrical Task System (graph-based access)
- Allows for O(log n / loglog n) solutions (unlike MTS)




Amortized migration:



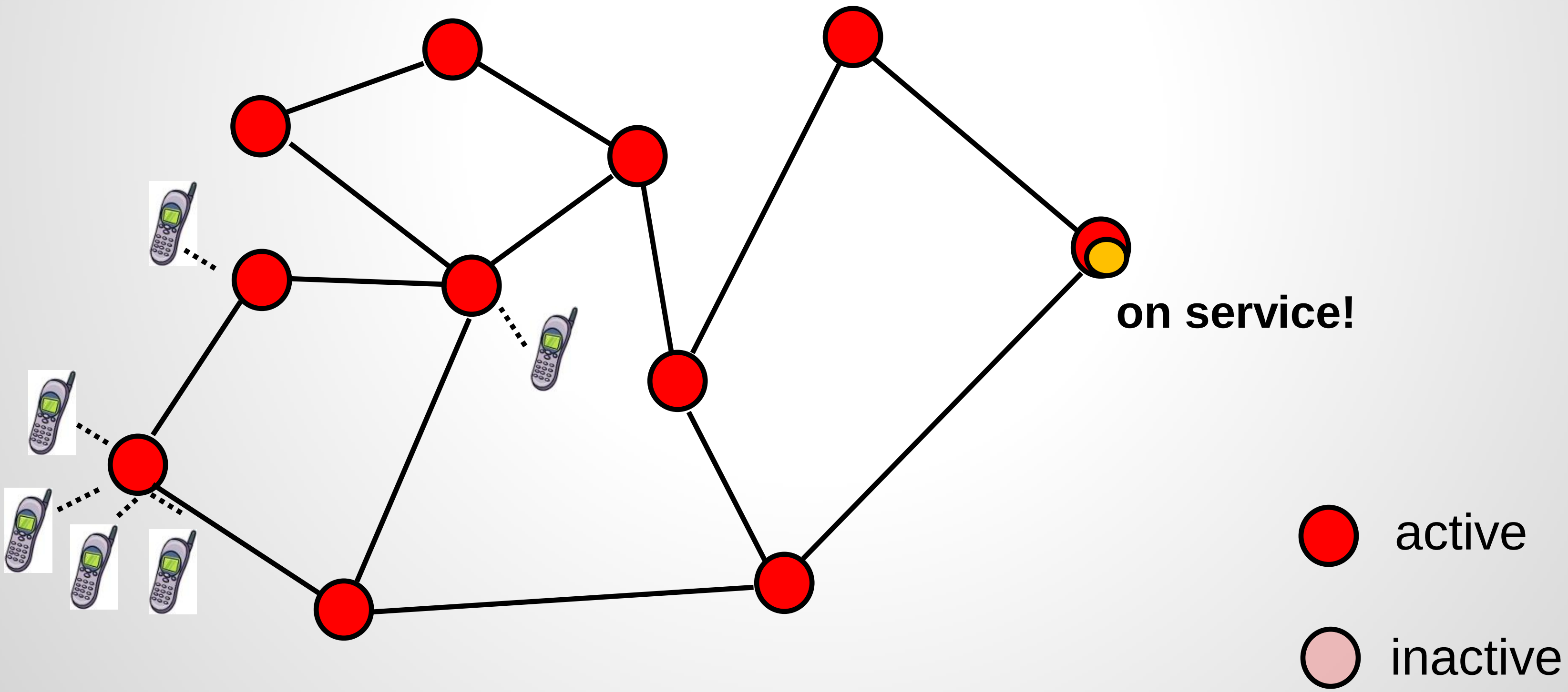

Lower bound: Online function tracking



# Migration: Example

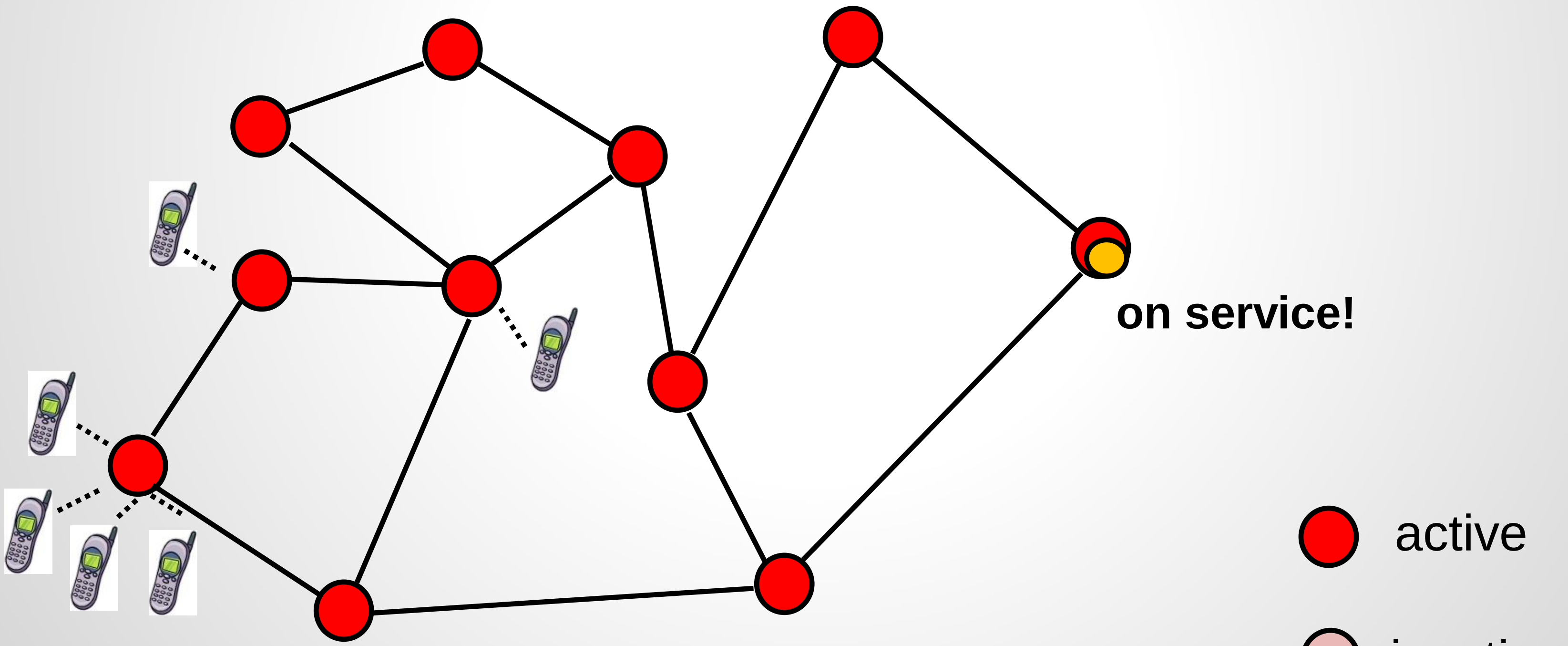
- Single service
- Migration Cost m
- Access Cost 1
- Goal: minimize sum of both?

**Realm of competitive analysis!**



# Migration: Example

- O(log n) competitive ratio only
- O(log n / loglog n) not elegant (yet)



# Migration: Example

- O(log n) competitive ratio only
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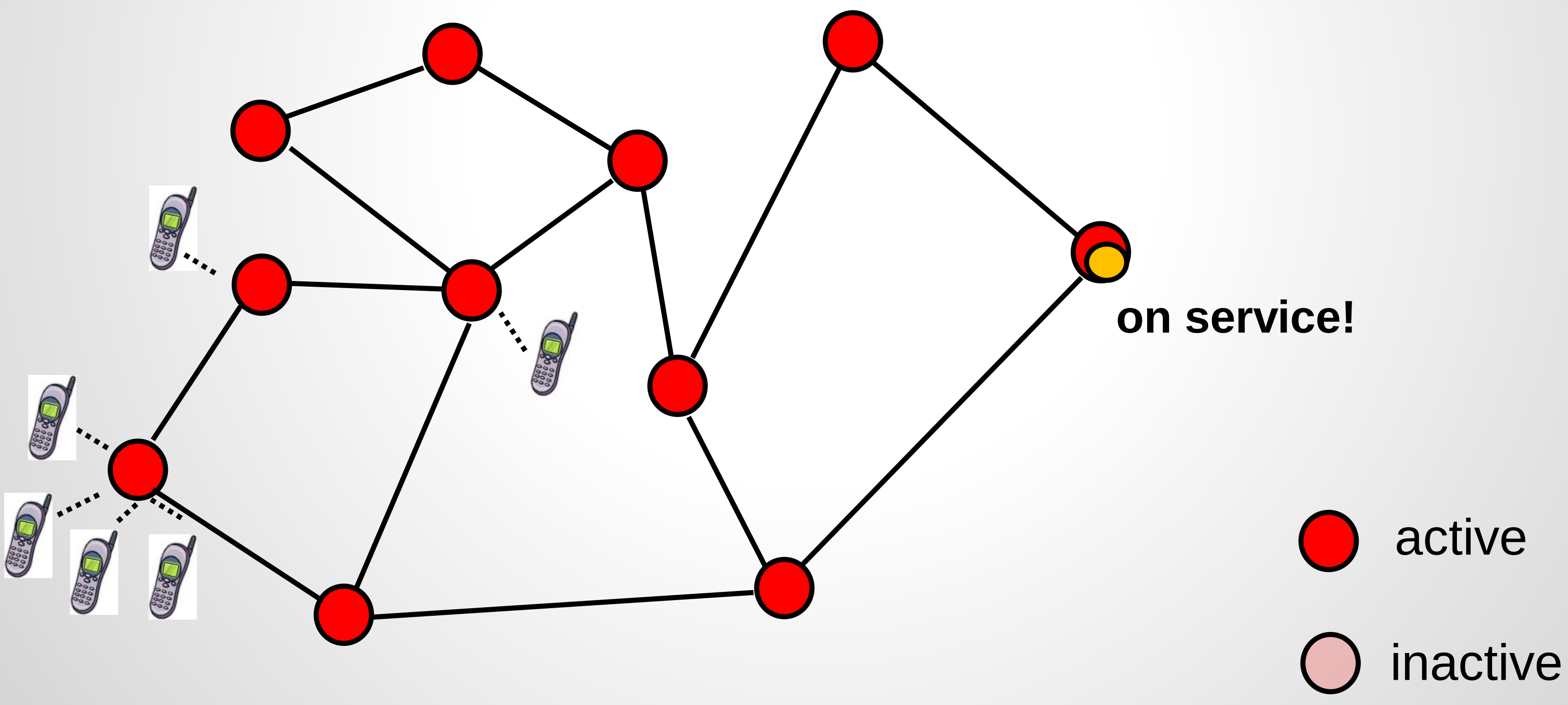
**Deterministic Algo: Amortize!**

1. Access cost counters at each node (if service there)
2. When counter exceeds *m*, deactivate nodes with counters > m/2, migrate to active node in center of active component: minimal sum of distances
3. When no node left, epoch ends. Reset and restart.



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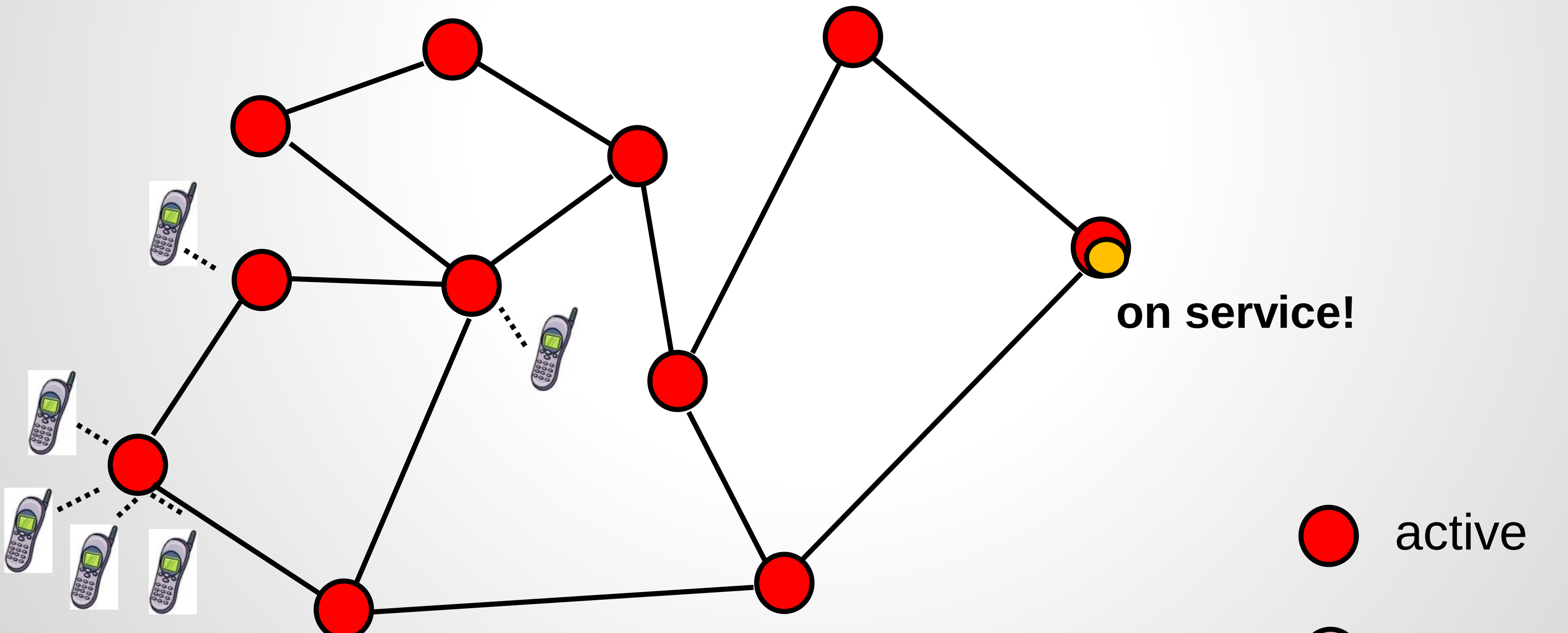
## @ t = 0:



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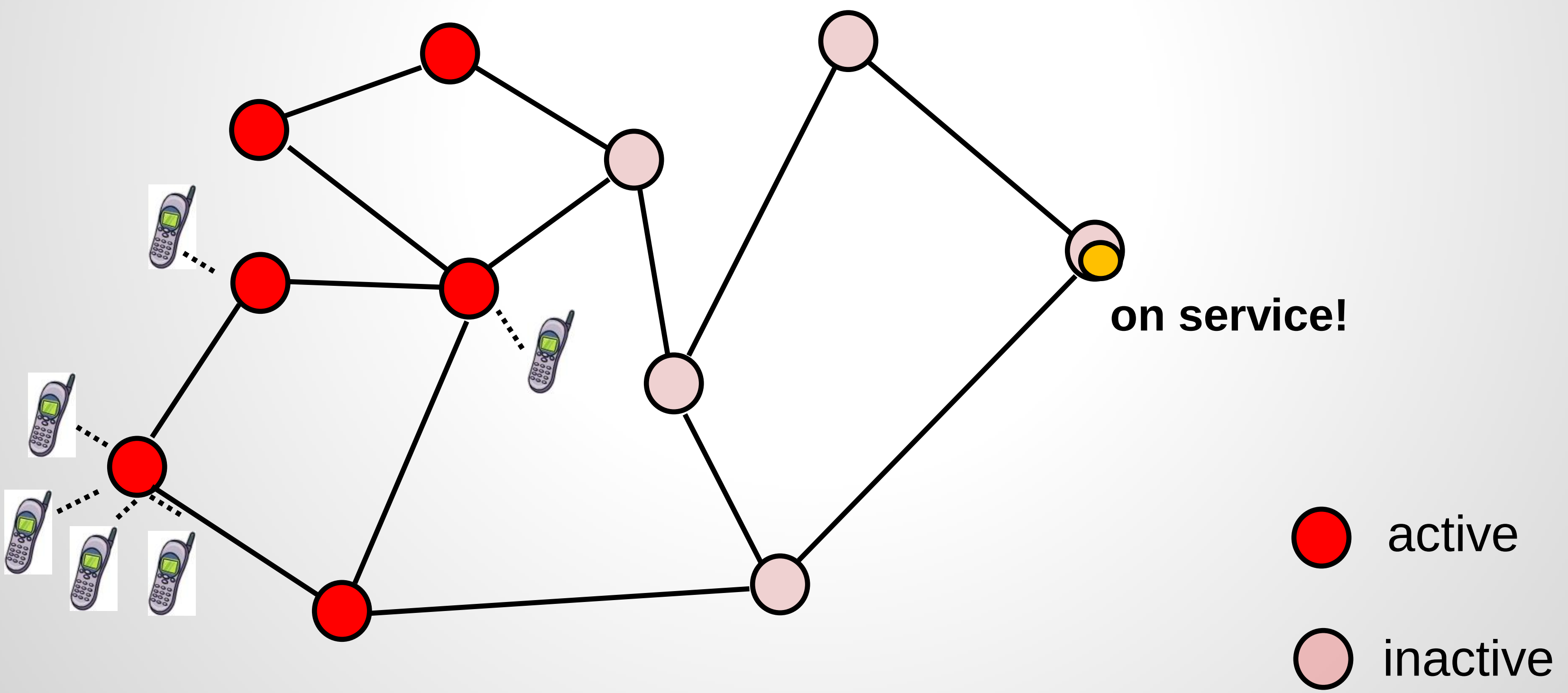

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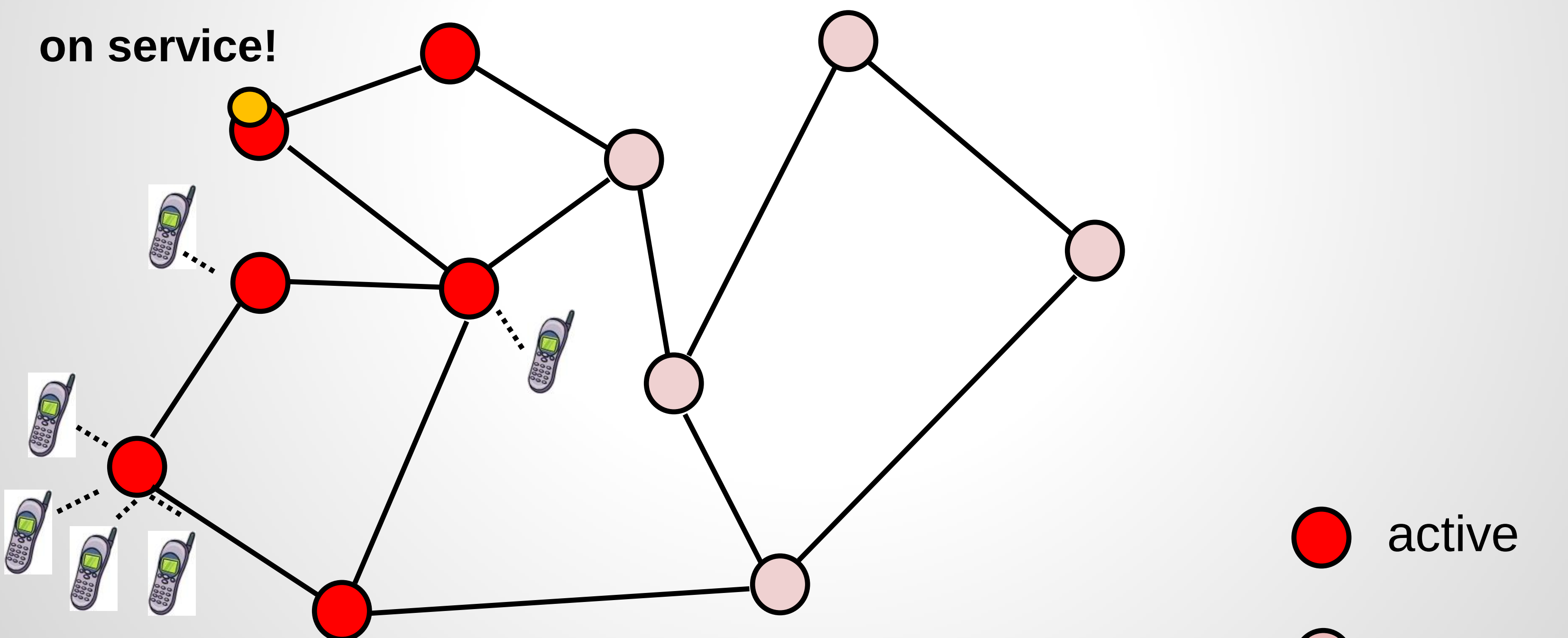
## @ t = 1:

**on service!**



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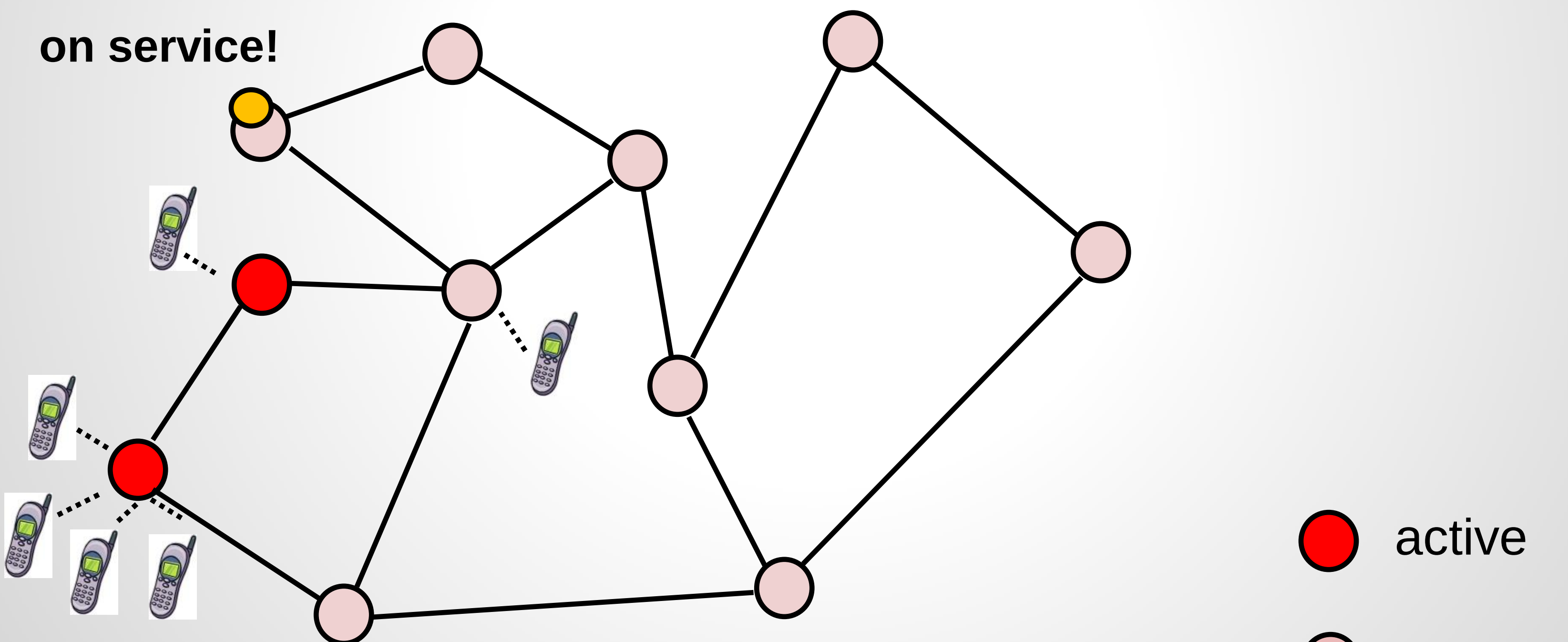
3. When no node left, epoch ends. Reset and restart.

## @ t = 2:

**on service!**



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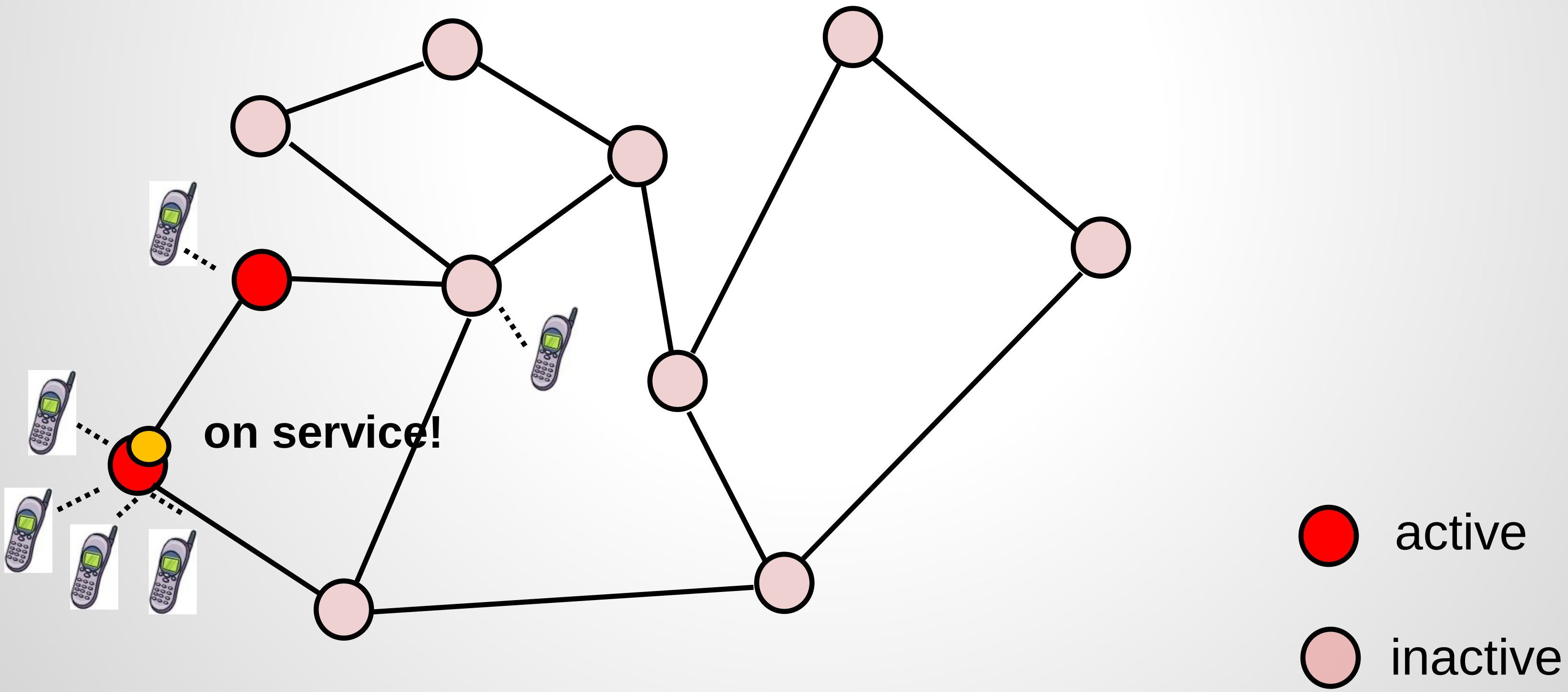
**@ t = 2:**



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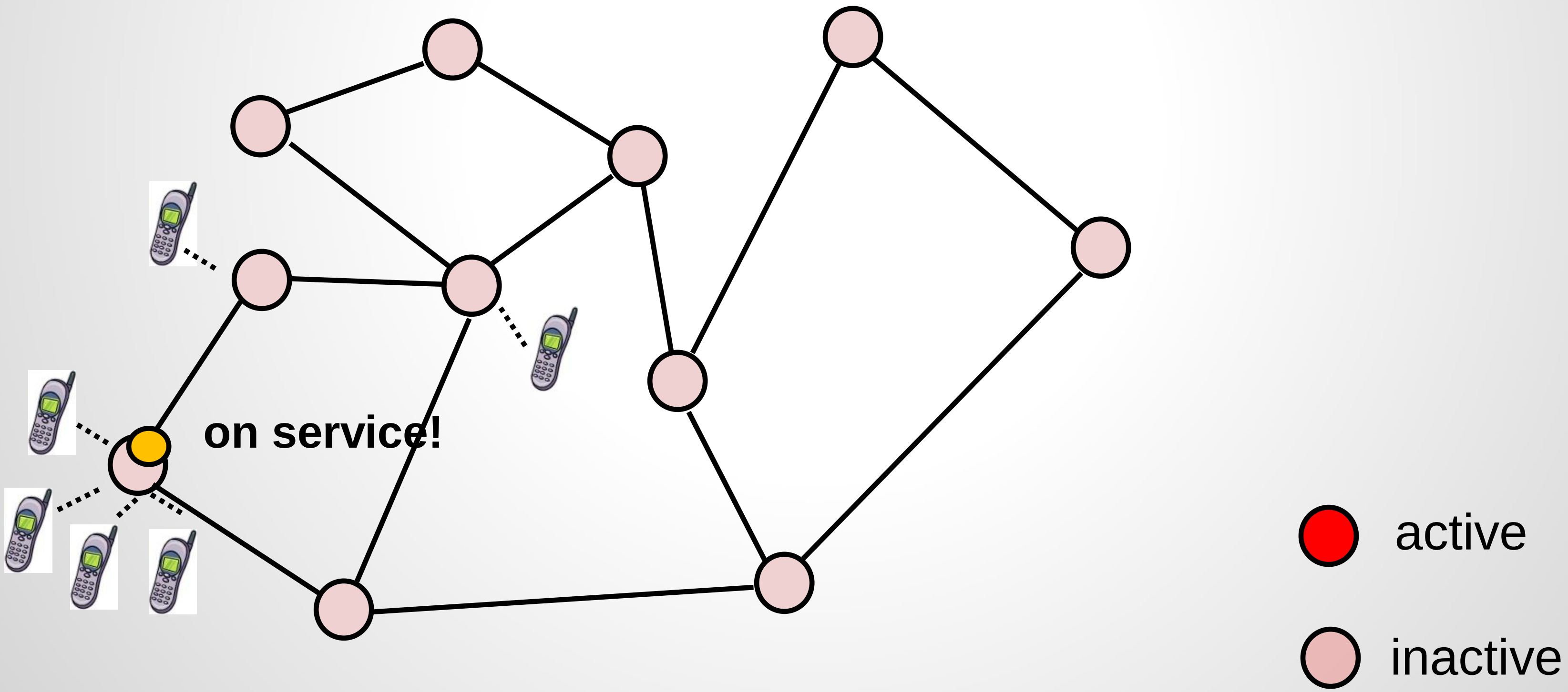
3. When no node left, epoch ends. Reset and restart.

## @ t = 3: epoch ends!



# Migration: Example

- O(log n) competitive ratio only
- O(log n / loglog n) not elegant (yet)

**Deterministic Algo: Amortize!**

1. Access cost counters at each node (if service there)
2. When counter exceeds *m*, deactivate nodes with counters > m/2, migrate to active node in center of active component: minimal sum of distances
3. When no node left, epoch ends. Reset and restart.

# Analysis

**Offline algorithm OFF has cost >m/2 per epoch:**

1. True if OFF migrates at least once.
2. If OFF does not migrate: any single location has access cost >m/2.

**Online algorithm ON has cost at most O(m log n) per epoch:**

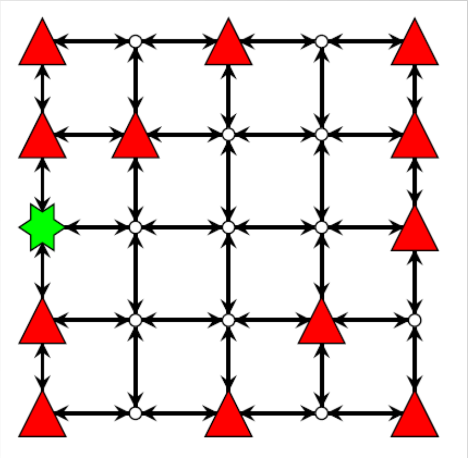
1. Access costs *per phase* at most m: counters
2. Migration cost per phase: m
3. How many phases? Due to center strategy, at least 1/8-th of active nodes become passive

# Solving the VNEP

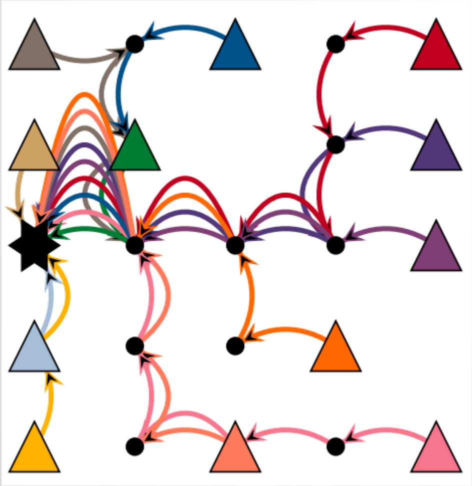
- Formulate a Mixed Integer Program!
- Leverage additional structure!
- Use online primal-dual approach
- **Discussion:**
  - Virtual network embedding a potential threat?
  - Adding migration support
  - **Beyond graph structures**

# Beyond Graph Specifications

Substrate:



- Example: Multicast with in-network processing
- The topology becomes subject to optimization as well
- Example: Cost efficient multicast or aggregation

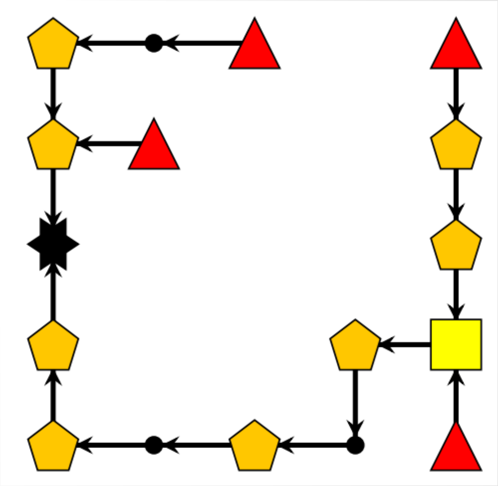


n unicasts

(43 edges, 0 nodes)

**Best of both worlds?**

**Joint optimization!**

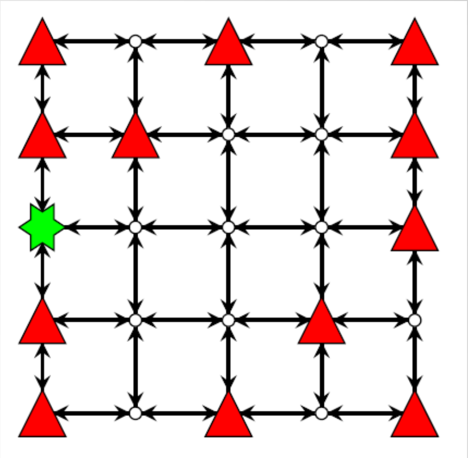


Multicast / Steiner tree

(16 edges, 9 nodes)

# Beyond Graph Specifications

Substrate:



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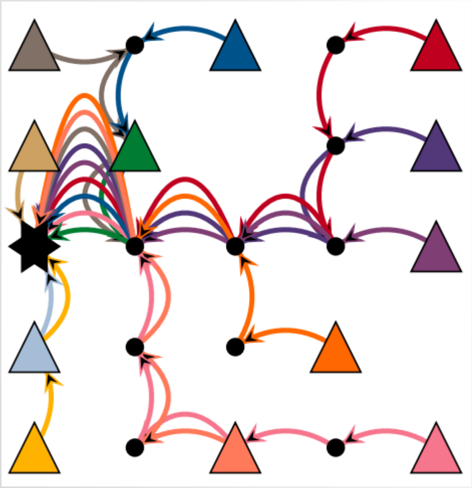

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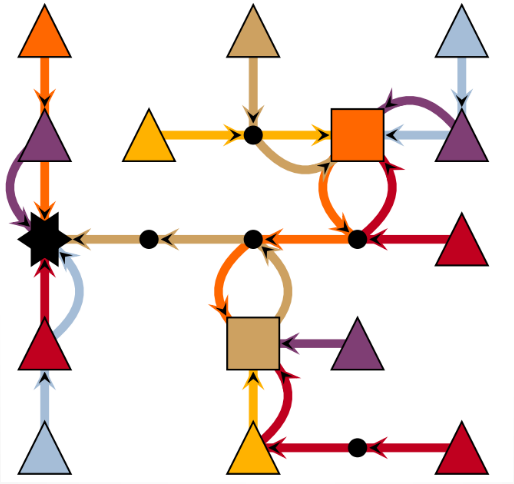
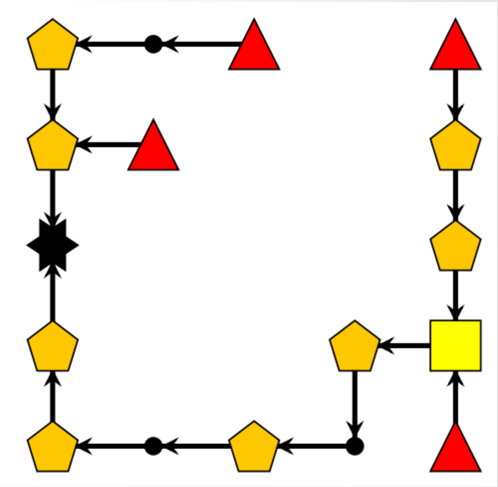


Joint optimization: Virtual Steiner Arborescence

(26 edges, 2 nodes)

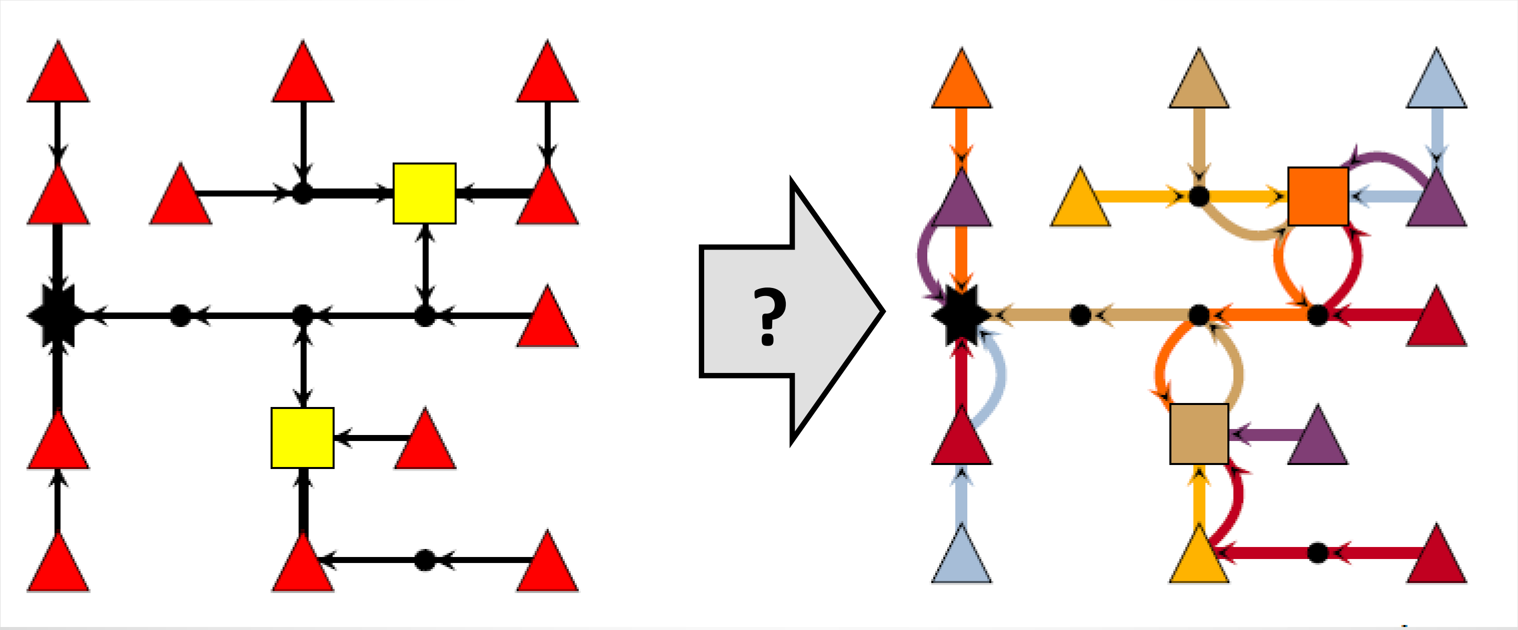


Multicast / Steiner tree

(16 edges, 9 nodes)

# Beyond Graph Specifications

- Approach: Single-commodity MIP and path decomposition
  - Multi-commodity: 1,200,000 integer variables
  - Single-commodity: 6,000 integer variables
  - But lose information



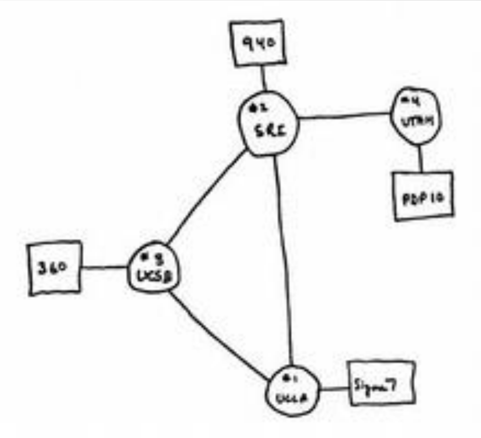
# "(Network) Virtualization: The Killer Application for SDN" (Nick McKeown)

The Internet has changed radically over the last decades

**Historic goal:** Connectivity between a small set of super-computers

**Applications:** File transfer and emails among scientists

**Situation now:** Non-negligible fraction of the world population is constantly online




## New requirements:

- More traffic, new demands on reliability and predictability
- Thus: use infrastructure more efficiently, use in-network caches: TE beyond destination-based routing, …
- Many different applications: Google docs vs datacenter synchronization vs on-demand video
- SDN allows us to schedule and route different applications according to their needs

# Rigorous Solutions for the Geneal Embedding Problem: MIP

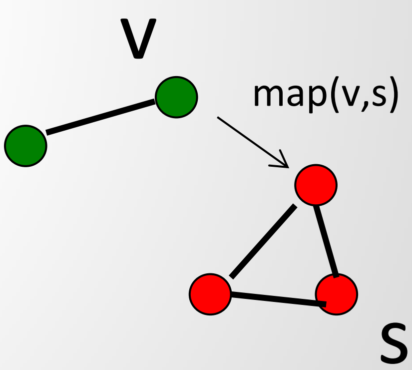
UCC 2012

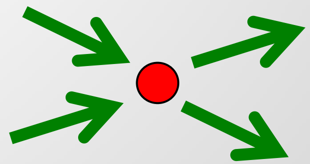
Recipe:

- A (linear) objective function (e.g., load or footprint)
- A set of (linear) constraints
- Feed it to your favorite solver (CPLEX, Gurobi, etc.)

Details:

- Introduce binary variables ***map(v,s)*** to map virtual nodes *v* on substrate node *s*
- Introduce flow variables for paths (splittable or not?)
- Ensure **flow conservation**: all flow entering a node must leave the node, unless it is the source or the destination



# Rigorous Solutions for the Geneal Embedding Problem: MIP

**Constants:**

Requests : $R$

Substrate Vertices : $V_s$

Substrate Edges : $E_s : V_s \times V_s$

Unique : $uni\_check_s : \forall (s_1, s_2) \in E_s : (s_2, s_1) \notin E_s$

SNode Capacity : $snc(s) \rightarrow \mathbb{R}^+, s \in V_s$

SLink Capacity : $slc(e_s) \rightarrow \mathbb{R}^+, e_s \in E_S$

Virtual Vertices : $V_v(r), r \in R$

Virtual Edges : $E_v(r) :\rightarrow V_v(r) \times V_v(r), r \in R$

Unique : $uni\_check_v : \forall r \in R, (v_1, v_2) \in E_v(r) : (v_2, v_1) \notin E_v(r)$

VNode Demand : $vnd(r, v) \rightarrow \mathbb{R}^+, r \in R, v \in V_v(r)$

VEdge Demand : $vld(r, e_v) \rightarrow \mathbb{R}^+, r \in R, e_v \in E_v(r)$

Edges-Reverse : $ER_s : \forall (s_1, s_2) \in E_s \exists (s_2, s_1) \in ER_s \wedge |E_s| = |ER_s|$

Edges-Bidirectional : $EB_s : E_s \cup ER_s$

Migration Cost : $mig\_cost(r, v, s) \rightarrow \mathbb{R}^{+\ |V_v(r)| \times |V_s|}, r \in R, v \in V_v(r), s \in V_s$

Possible Placements : $place(r, v, s) \rightarrow \{0, 1\}^{|V_v(r)| \times |V_s|}, r \in R, v \in V_v(r), s \in V_s$

**Variables:**

Node Mapping : $n\_map(r, v, s) \in \{0, 1\}, r \in R, v \in V_v(r), s \in V_s$

Flow Allocation : $f\_alloc(r, e, eb) \geq 0, r \in R, e \in E_v(r), eb \in EB_s$

**Constraints:**

Each Node Mapped : $\forall r \in R, v \in V_v(r) : \sum_{s \in V_s} n\_map(r, v, s) \cdot place(r, v, s) = 1$

Feasible : $\forall s \in V_s : \sum_{r \in R, v \in V_v(r)} n\_map(r, v, s) \cdot vnd(r, v) \leq snc(s)$

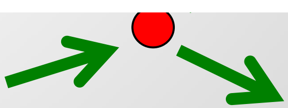
Guarantee Link Realization : $\forall r \in R, (v_1, v_2) \in E_v(r), s \in V_s \sum_{(s, s_2) \in V_s \times V_s \cap EB_s} f\_alloc(r, v_1, v_2, s, s_2) - \sum_{(s_1, s) \in V_s \times V_s \cap EB_s} f\_alloc(r, v_1, v_2, s_1, s) = vld(r, v_1, v_2) \cdot (n\_map(r, v_1, s) - n\_map(r, v_2, s))$

Realize Flows : $\forall (s_1, s_2) \in E_s \sum_{r \in R, (v_1, v_2)} f\_alloc(r, v_1, v_2, s_1, s_2) + f\_alloc(r, v_1, v_2, s_2, s_1) \leq slc(s_1, s_2)$

**Objective function:**

Minimize Embedding Cost : $min : \sum_{r \in R, (v_1, v_2) \in E_v(r), (s_1, s_2) \in E_s} f\_alloc(r, v_1, v_2, s_1, s_2) + f\_alloc(r, v_1, v_2, s_2, s_1)$

entering a node must leave the node,
unless it is the source or the destination

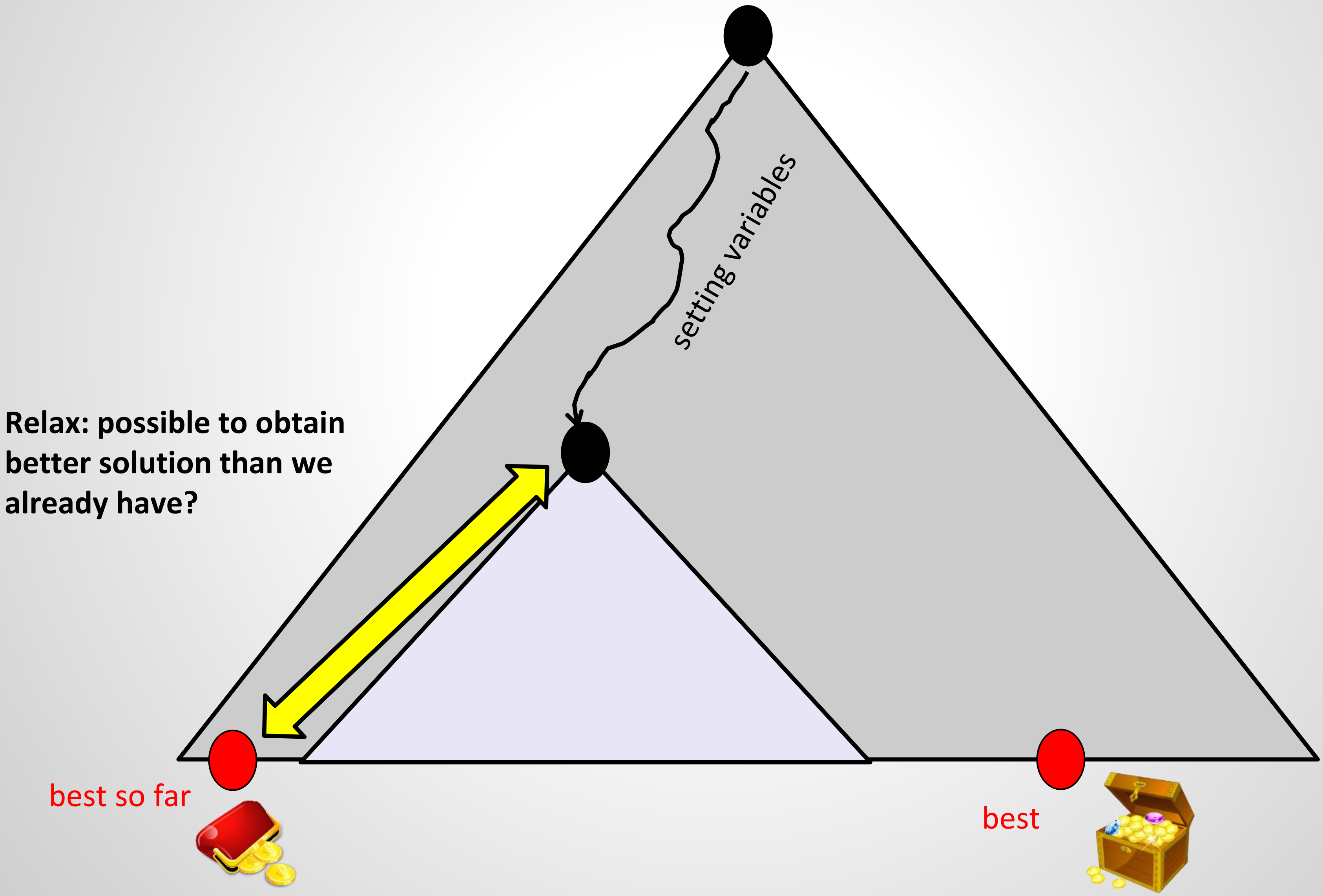


# Mixed Integer Programs (1)

- MIPs can be quite fast
  - For pure integer programs, SAT solvers likely faster
- However, that's not the end of the story: MIP $\neq$ MIP
  - The specific formulation matters!
- For example: many solvers use relaxations
  - Make integer variables continuous: resulting linear programs (LPs) can be solved in polynomial time!
  - How good can solution in this subtree (given fixed variables) be at most? (More flexibility: solution can only be better!)
  - If already this is worse than currently best solution, we can cut!
- Relaxations can also be used as a basis for heuristics
  - E.g., round fractional solutions to closest integer?

# Mixed Integer Programs (2)

Branch & bound tree:

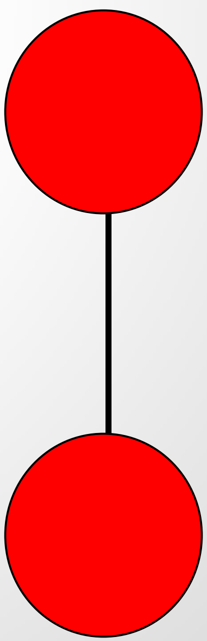


# Mixed Integer Programs (3)

- Recall: Relaxations useful if they give good bounds
- However it's hard to formulate a MIP for VNEP which yields useful relaxations!
- What happens here?

VNet:

Physical Network:



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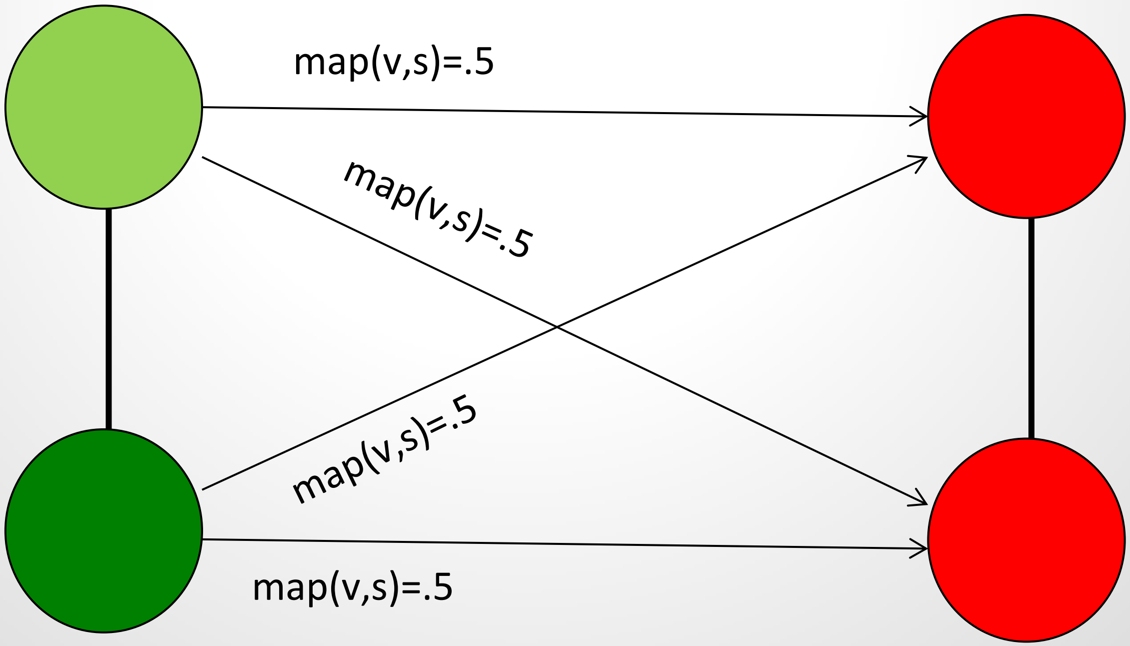

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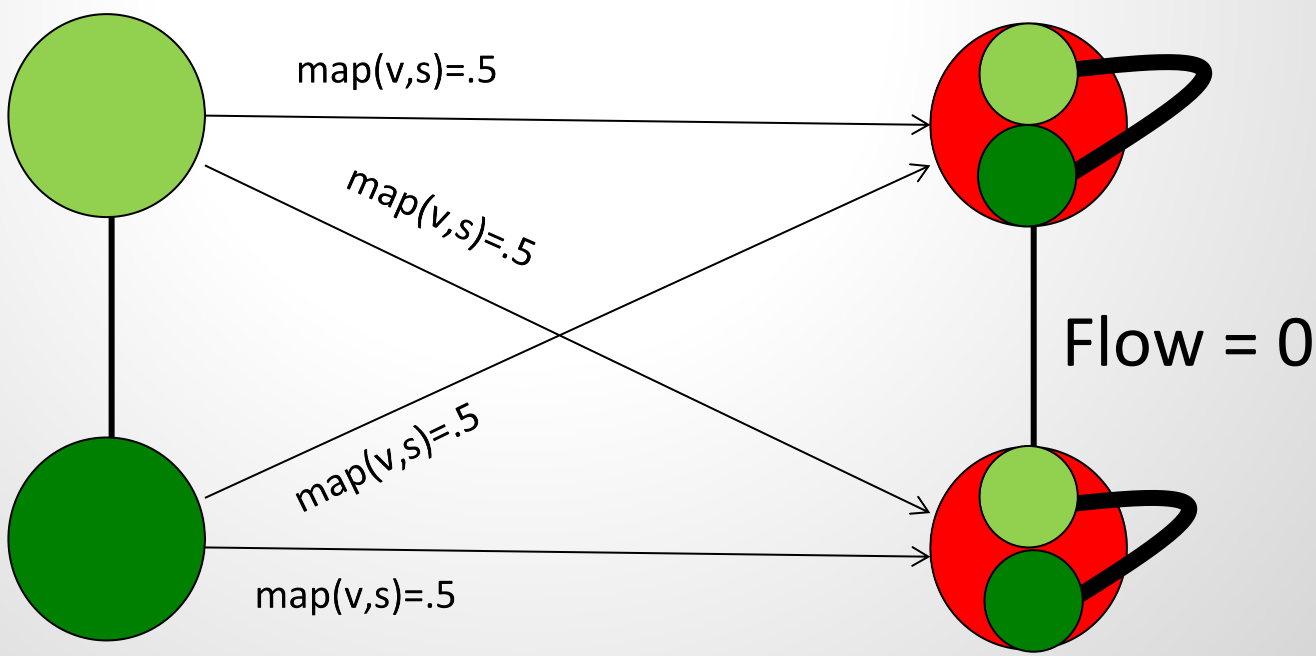

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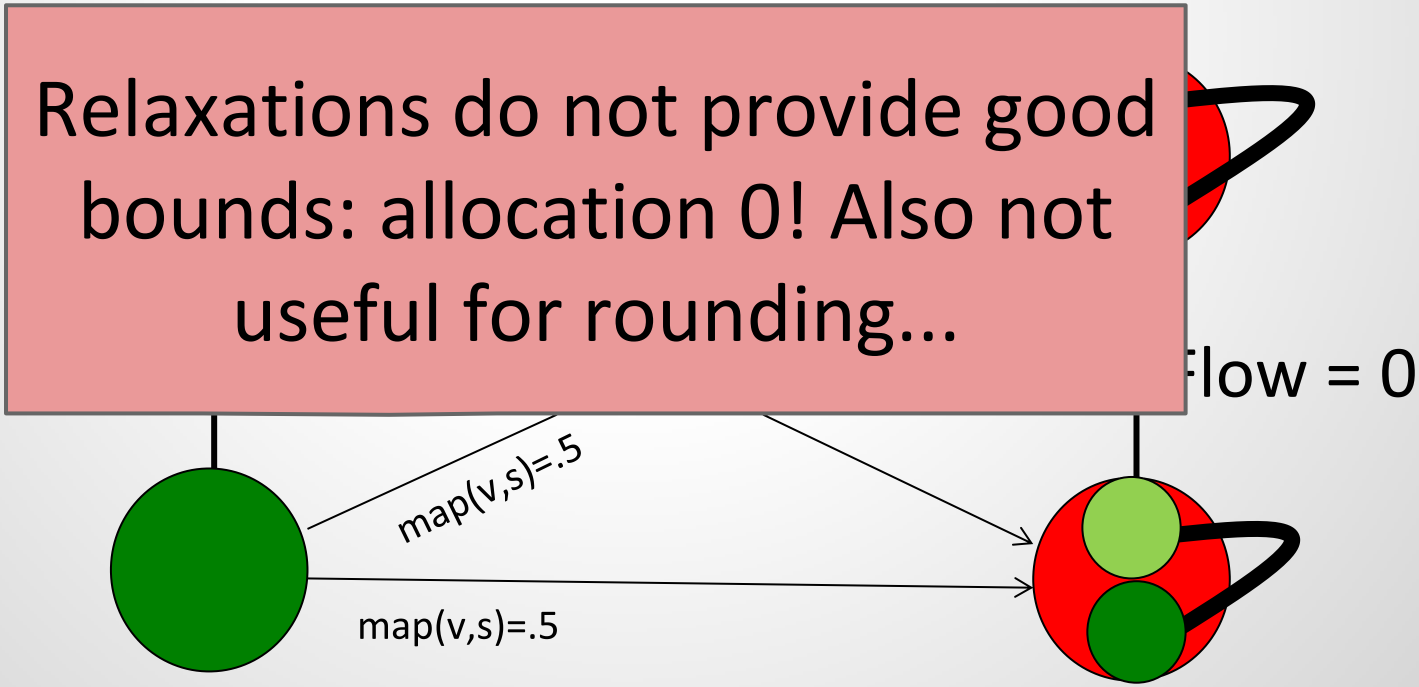
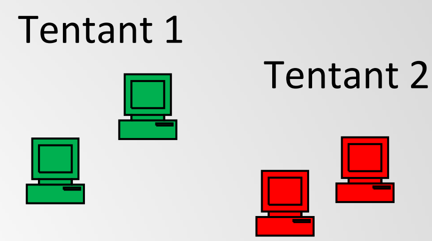


# Example 1: Embedding

## Where to allocate my virtual machines?




- For a predictable performance, try to avoid interference! Keep it local!
- Or make explicit bandwidth reservations! And keep it local to keep reservations small.
- .... but avoid static bandwidth reservations and make resource reservations in online fashion.