Scalable Constraint-based Virtual Data Center Allocation

Sam Bayless
Nodir Kodirov
Ivan Beschastnikh
Holger H. Hoos
Alan J. Hu

Computer Science
University of British Columbia

Data centers, data centers, for all

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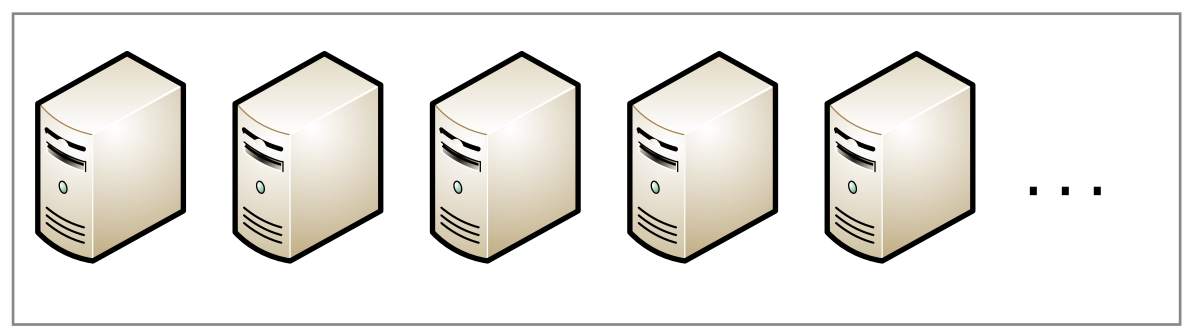
Flexible abstraction:



Provider

Data centers, data centers, for all

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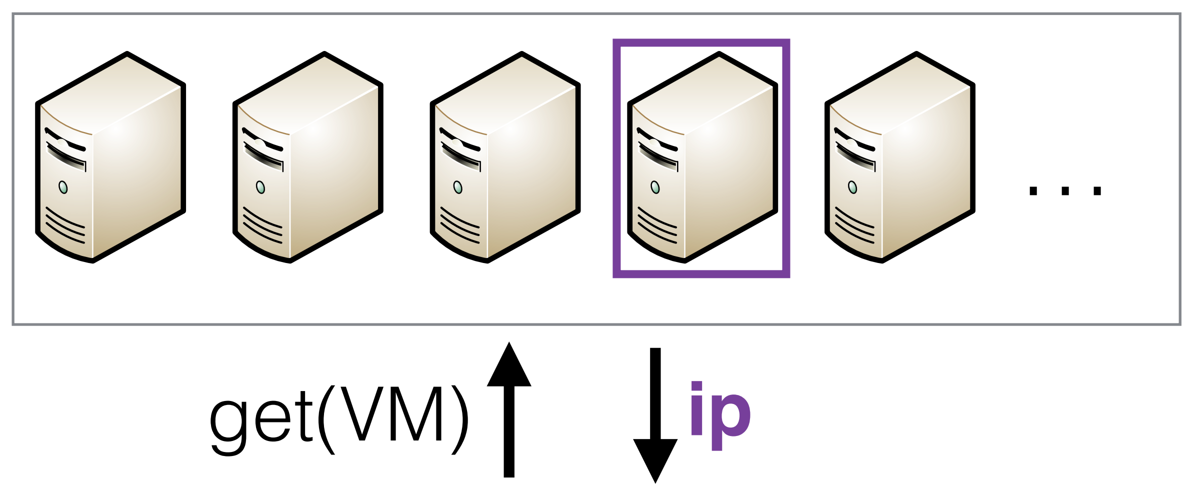


Provider

get(VM)

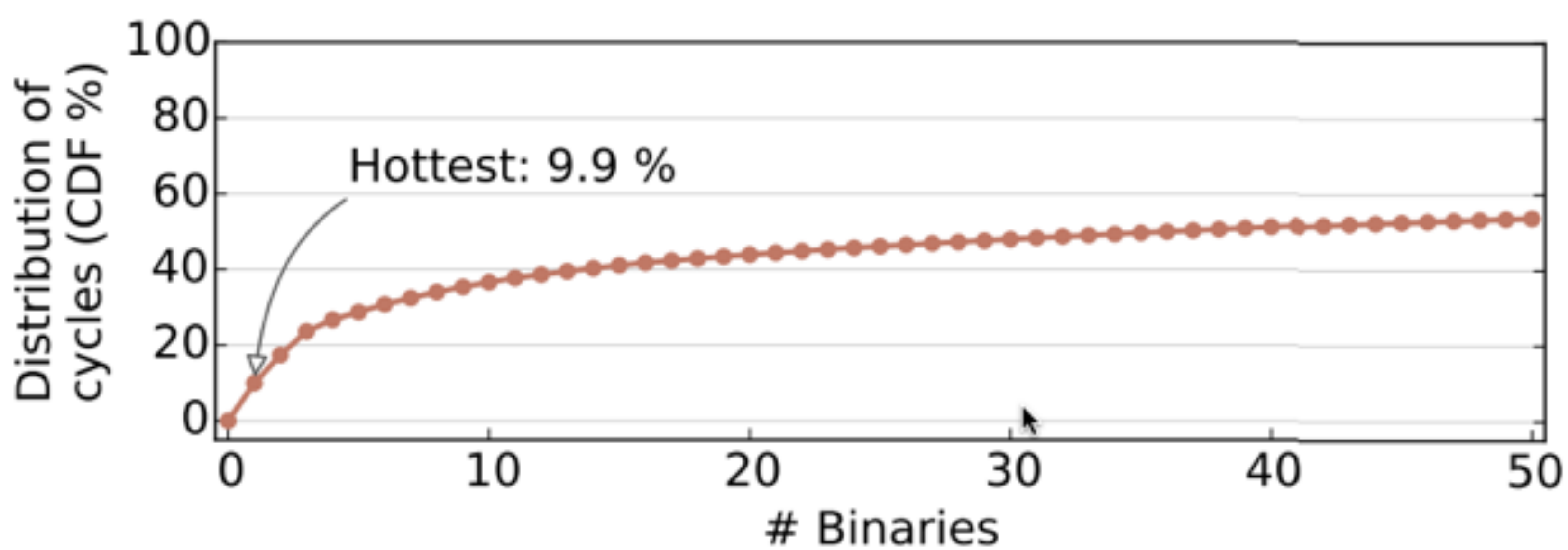
ip

Customer

Data centers, data centers, for all

- Cisco: traffic flowing through data centers will **triple** between 2014 and 2019 (reaching 10.4 ZB/year)

- Wide variety of applications being hosted [Benson et al. IMC'10, Kanev et al. ISCA'15]



More capacity + capabilities lead to more complex workloads

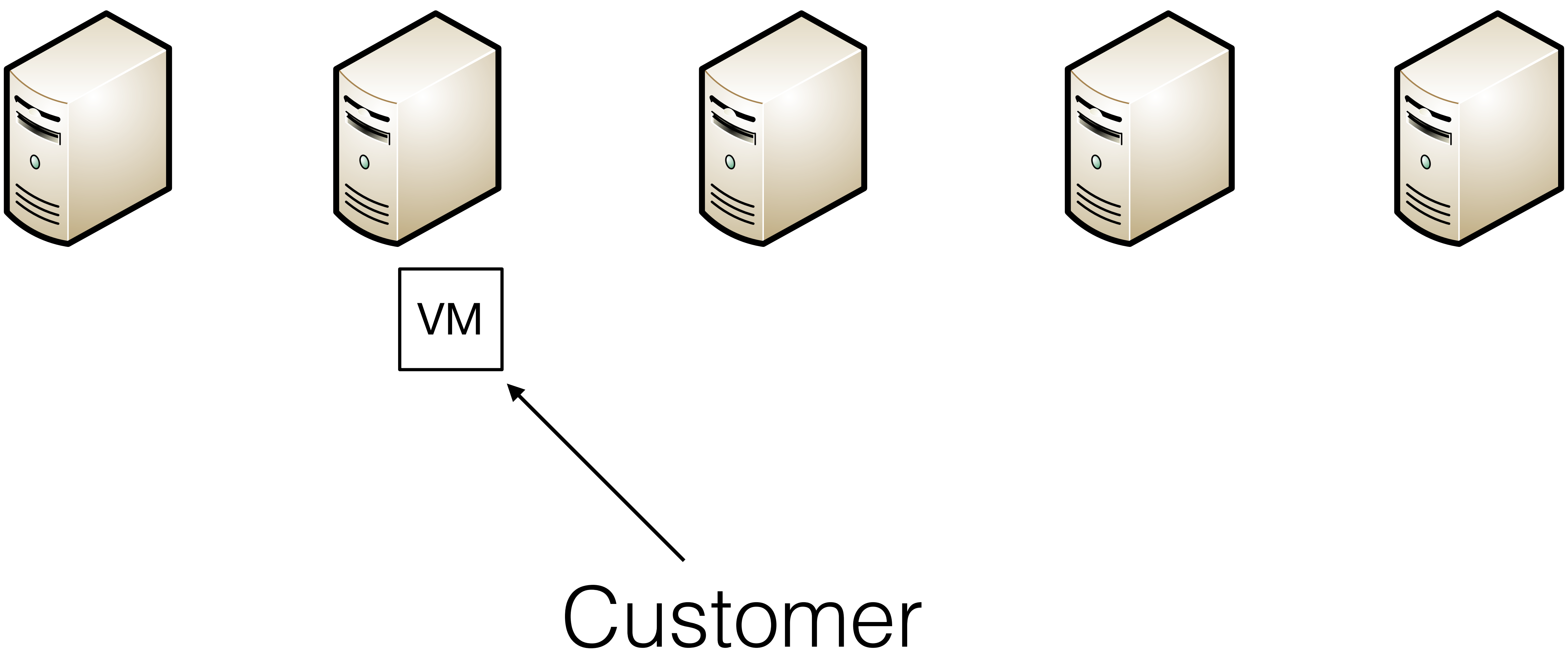
- Complex workload examples

    ➡ *Allocate a web-server, cache, database in a particular topology and with enough bandwidth to satisfy a certain QoS*

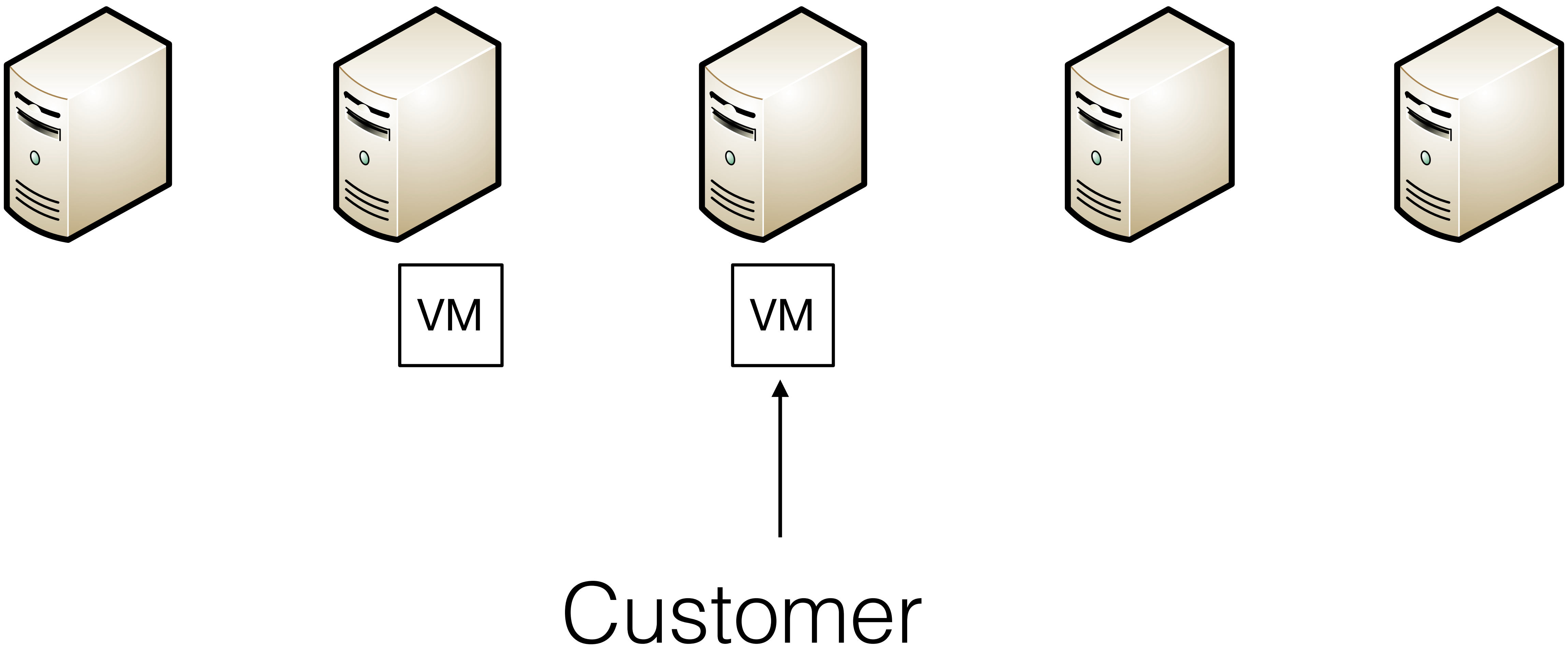
    ➡ *Deploy a distributed compute task in which some nodes communicate a lot, and others rarely*

    ➡ *Allocate a chain of NFV elements some of which require special hardware (GPUs)*

VM allocation



VM allocation



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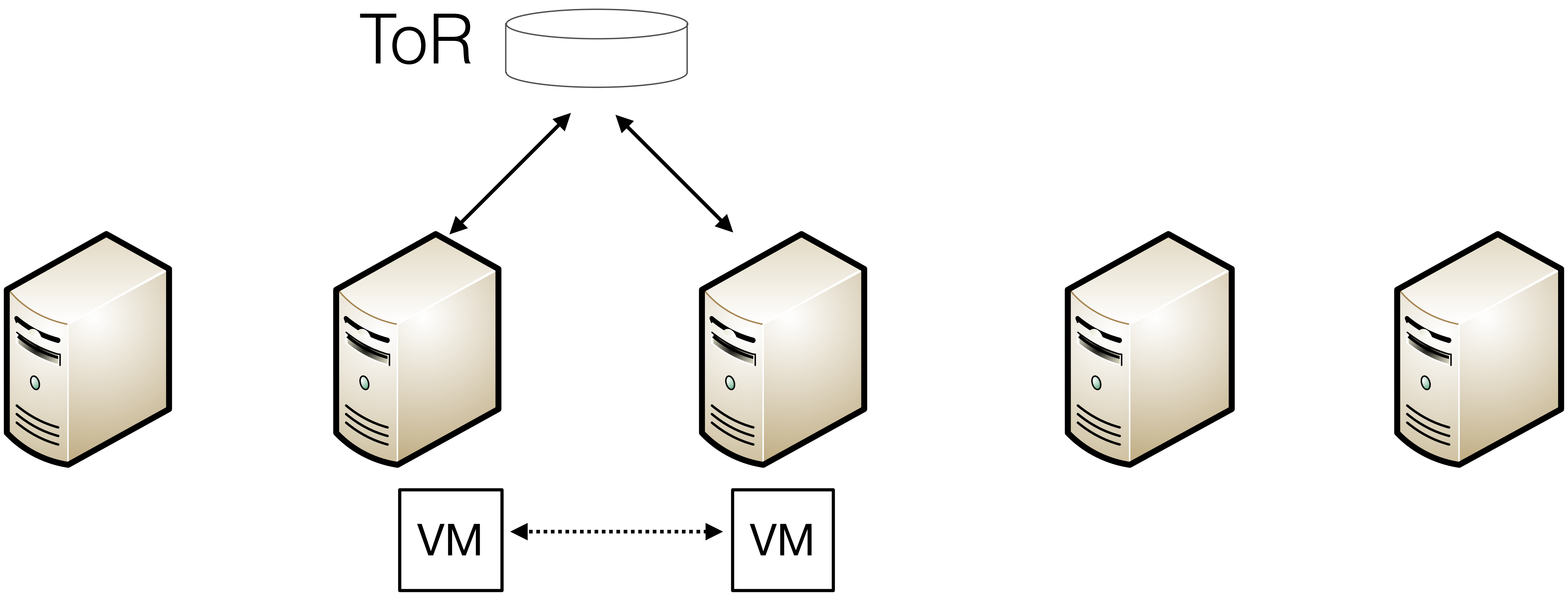
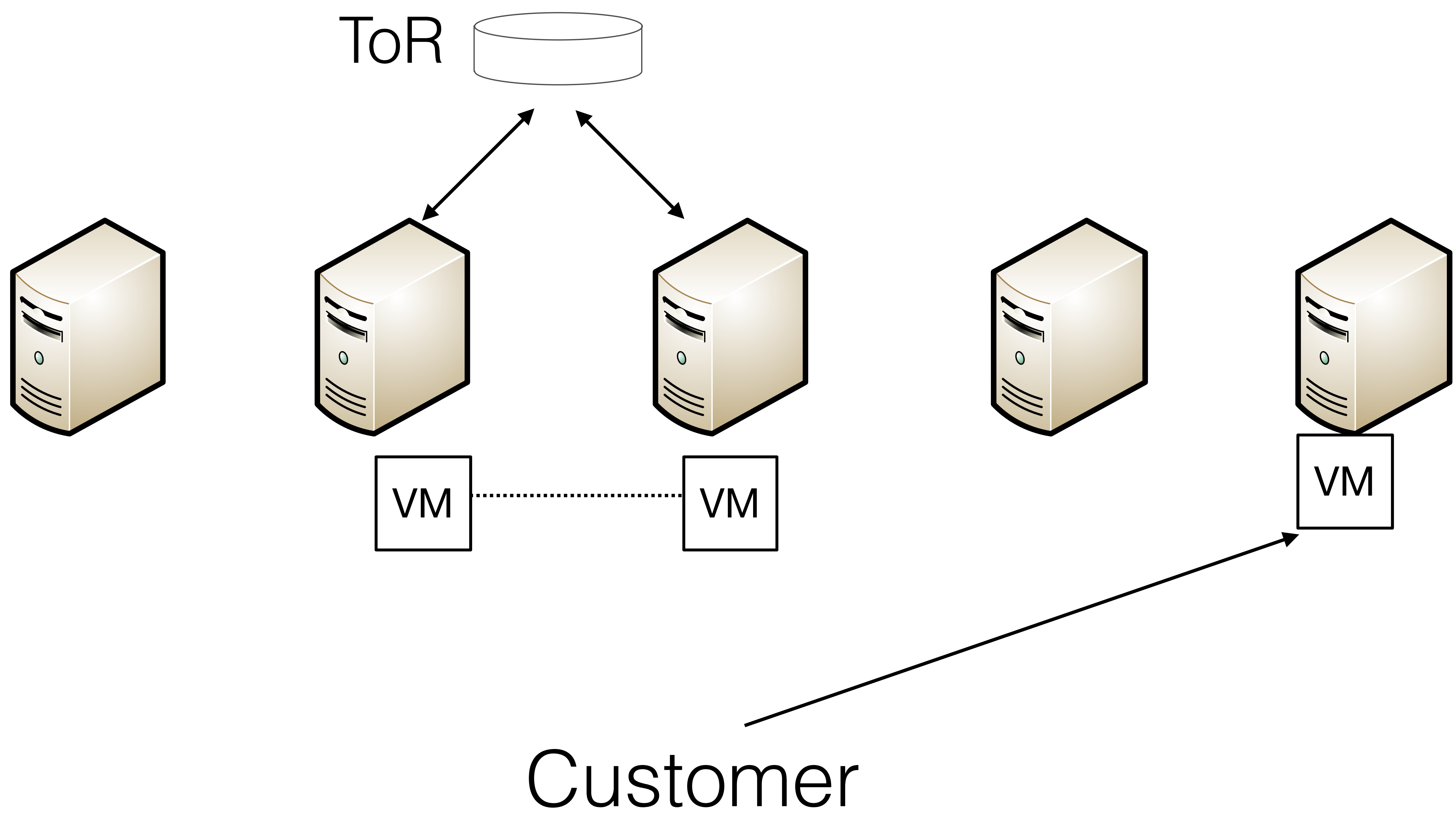


Customer

VM allocation



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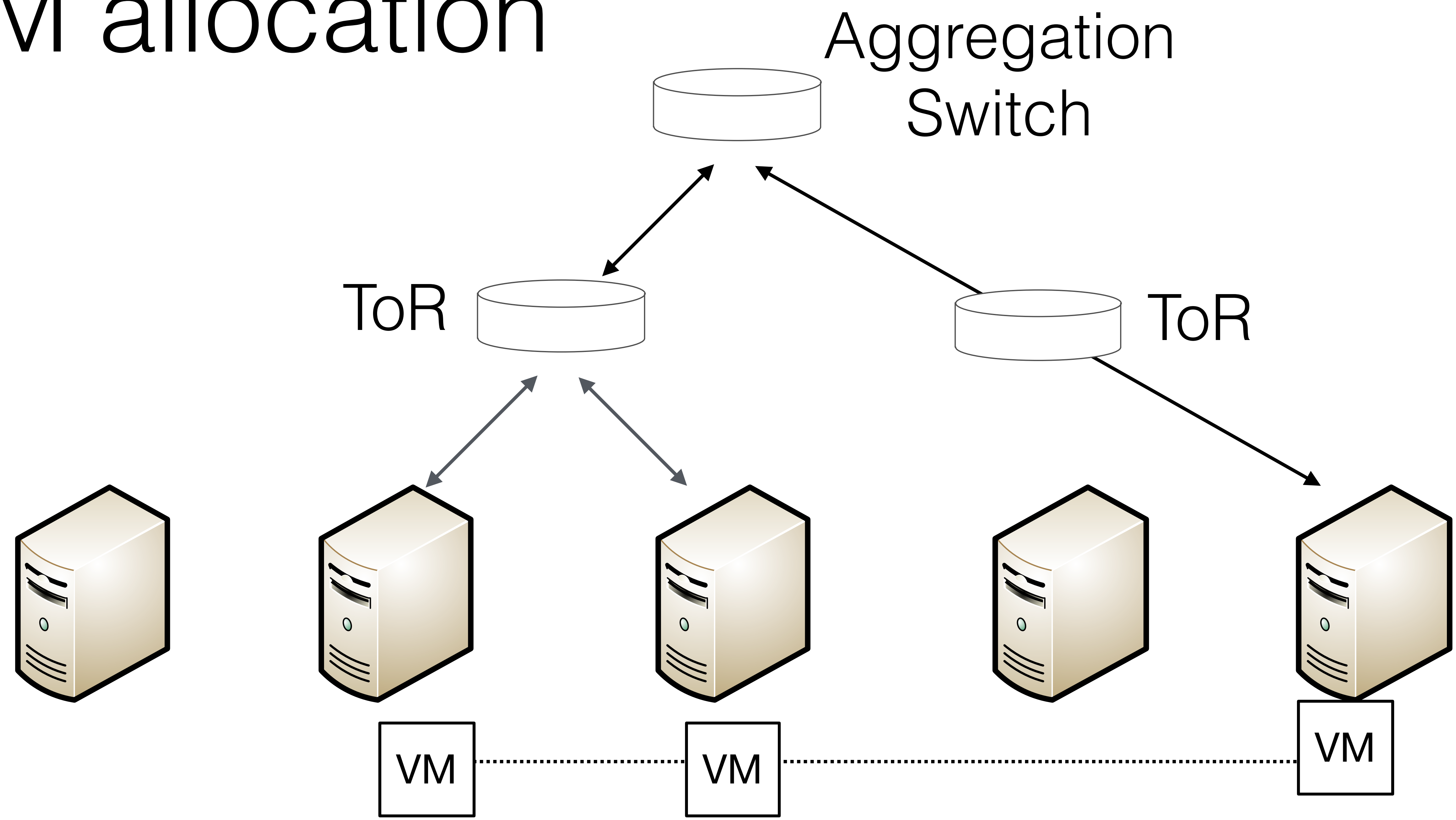
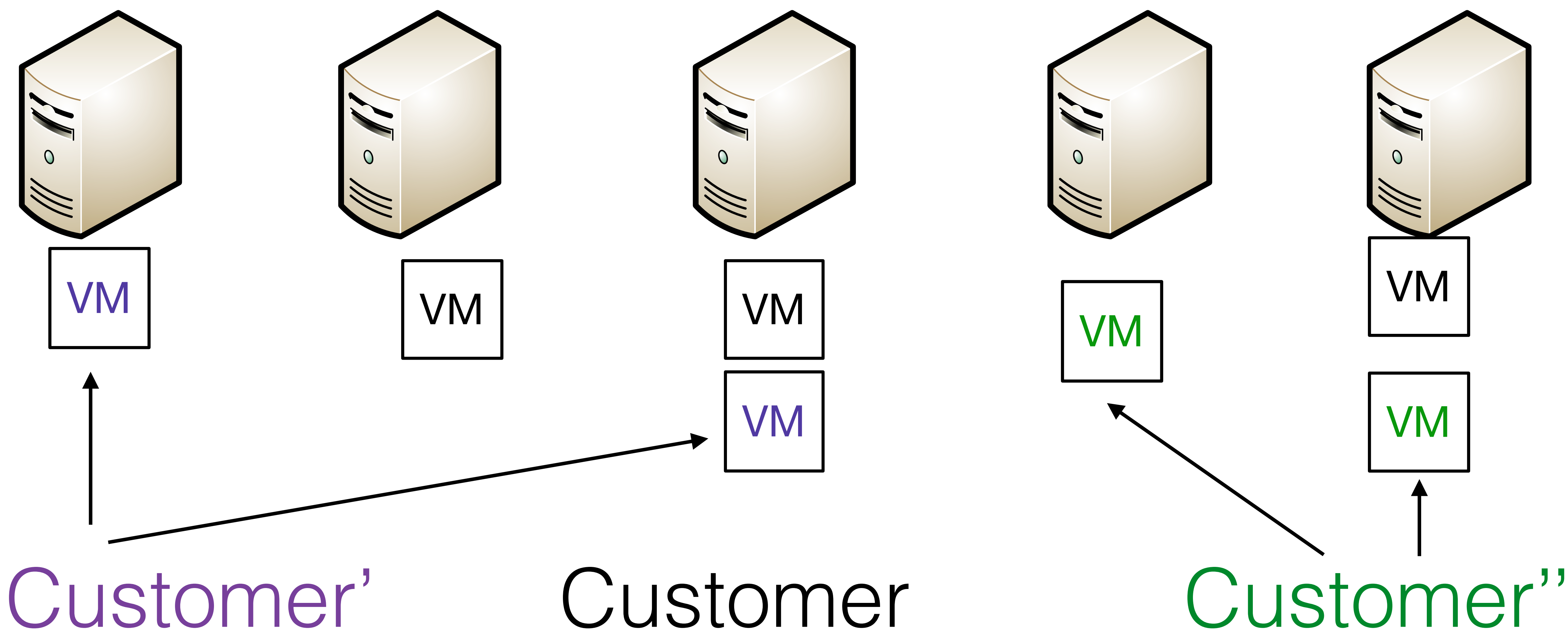
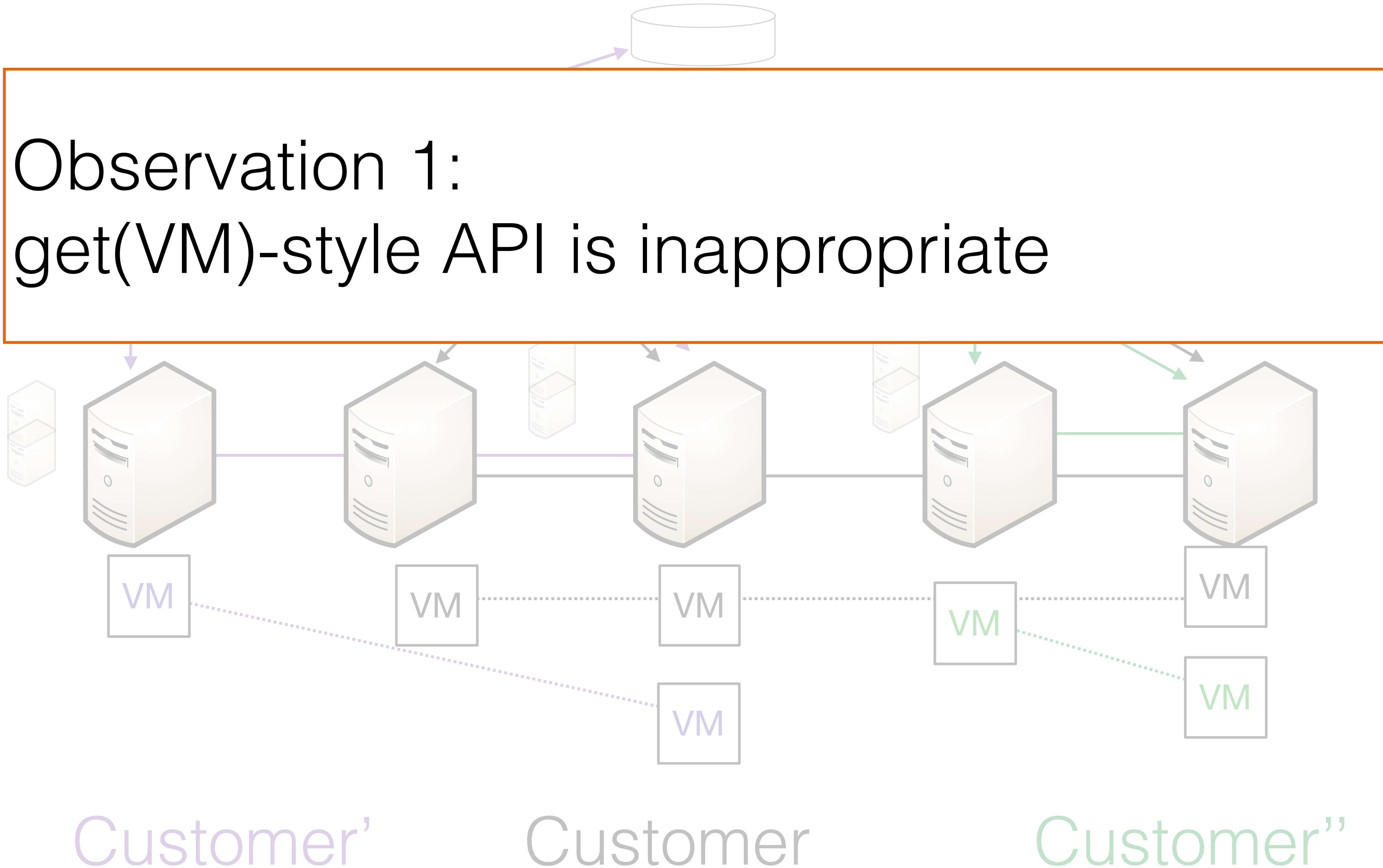


Customer

VM allocation: multi-tenancy



VM allocation



Observation 1:
get(VM)-style API is inappropriate

VM allocation

Observation 1:
get(VM)-style API is inappropriate

Observation 2:
It is more effective to allocate virtual data centers (VDCs), than virtual machines (VMs)

Customer’ Customer Customer’’

As DCs evolve, so must the programming models and allocation mechanisms

- Allocation one VM at a time: get(VM)
  - Sub-optimal for the provider <u>and</u> the customer
  - More info about an allocation: helps the provider plan and to effectively pack the data center
  - Customers benefit since they get the properties that they ultimately need

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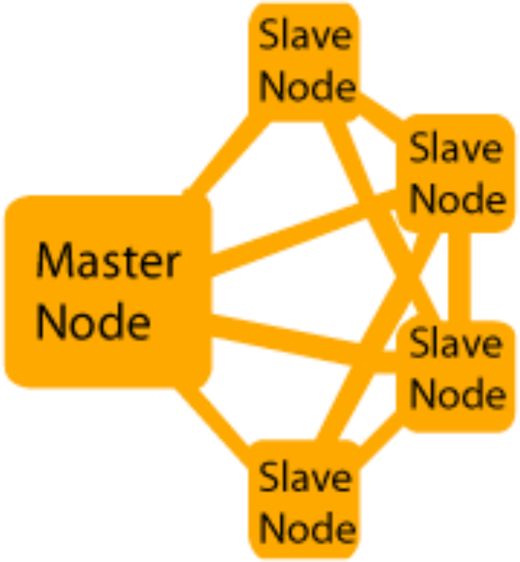
AWS Lambda



Amazon EMR (Hadoop)

In this talk

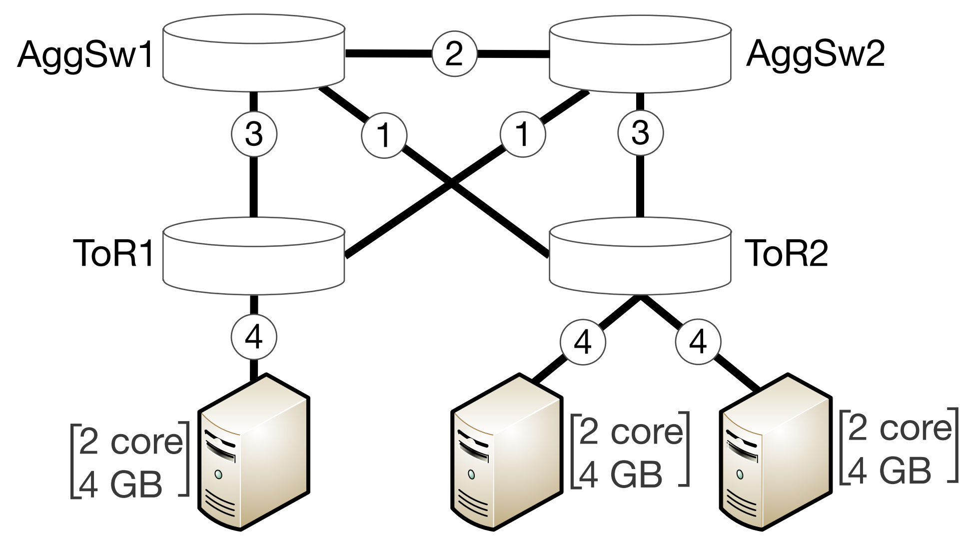
- Introduce virtual data center (VDC) allocation
- Discuss prior work (there is lots of it, mostly in the networking community)
- Describe NetSolver: our approach to solve VDC allocation (based on MonoSAT SMT-solver)
- Show how NetSolver compares to other approaches

What's the problem?

- Multi-path VDC allocation
  - Input 1: a (directed/undirected) physical DC topology (**DC**) with edge capacities/latencies and per-host constraints (disk/memory/CPU/GPU/etc)
  - Input 2: a virtual data center (**VDC**) that describe connectivity graph between VMs, and connectivity/VM requirements
  - Output: **assignment** of VMs to hosts, and virtual edges to physical paths (possibly multi-path) s.t. all constraints (end-to-end bandw, and VM) are satisfied and respect DC

What’s the problem?

Physical DC topology:



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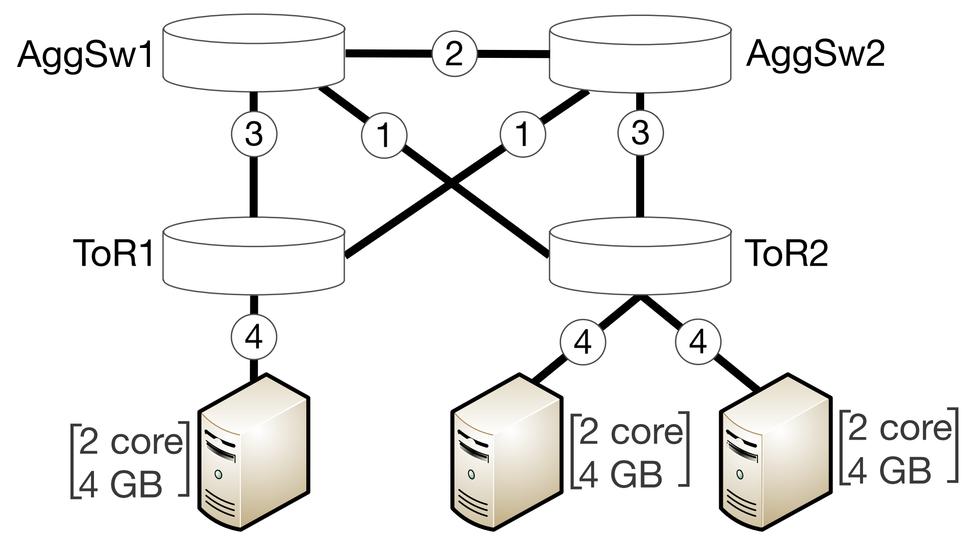
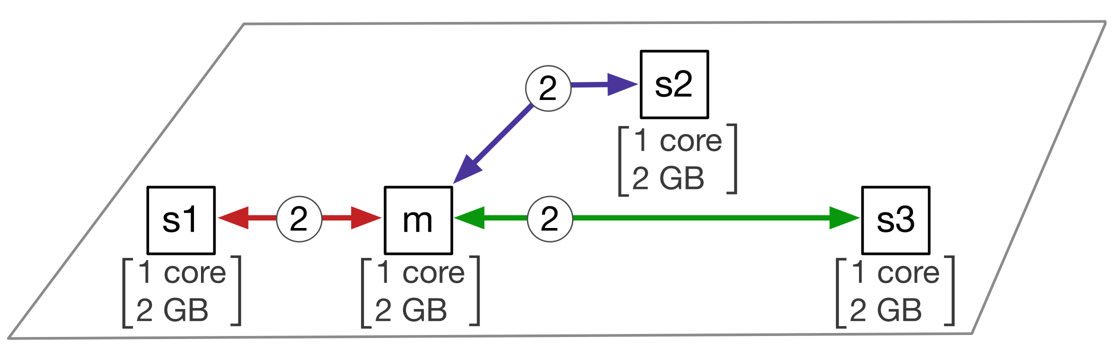
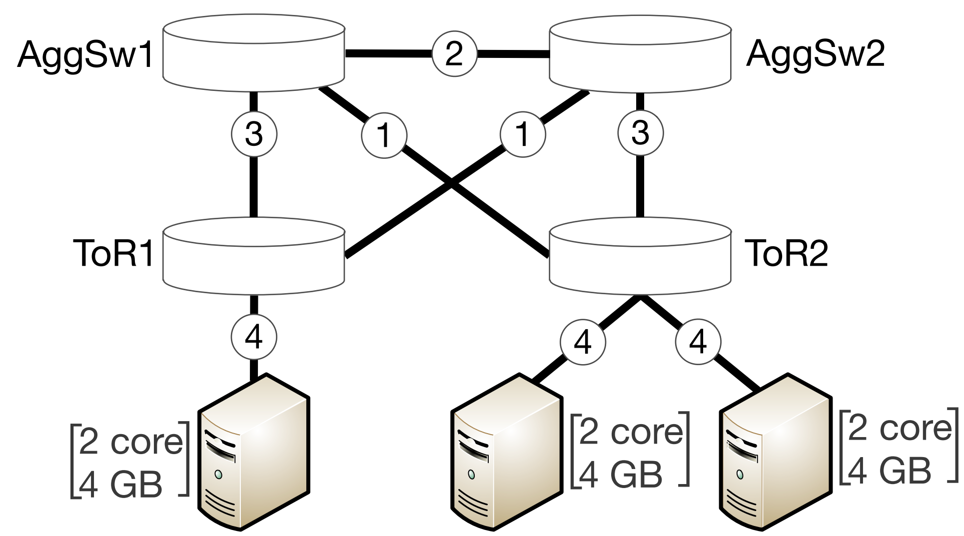


Virtual data center (VDC):



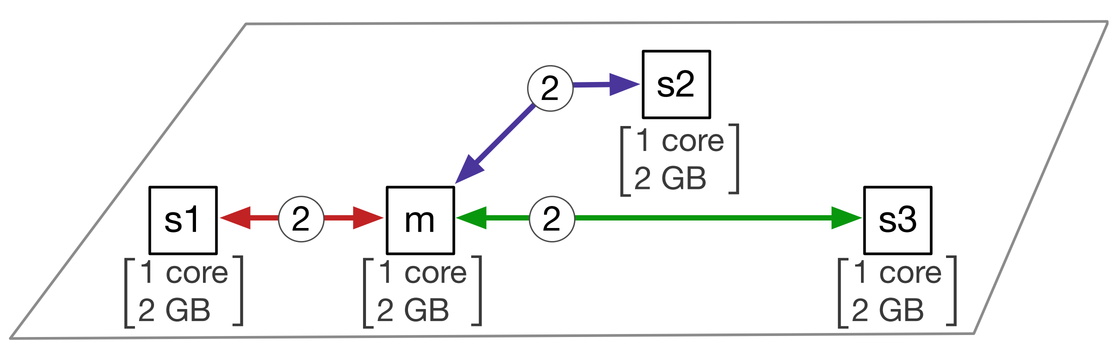
What's the problem?

Physical DC topology:



Output: **Mapping**

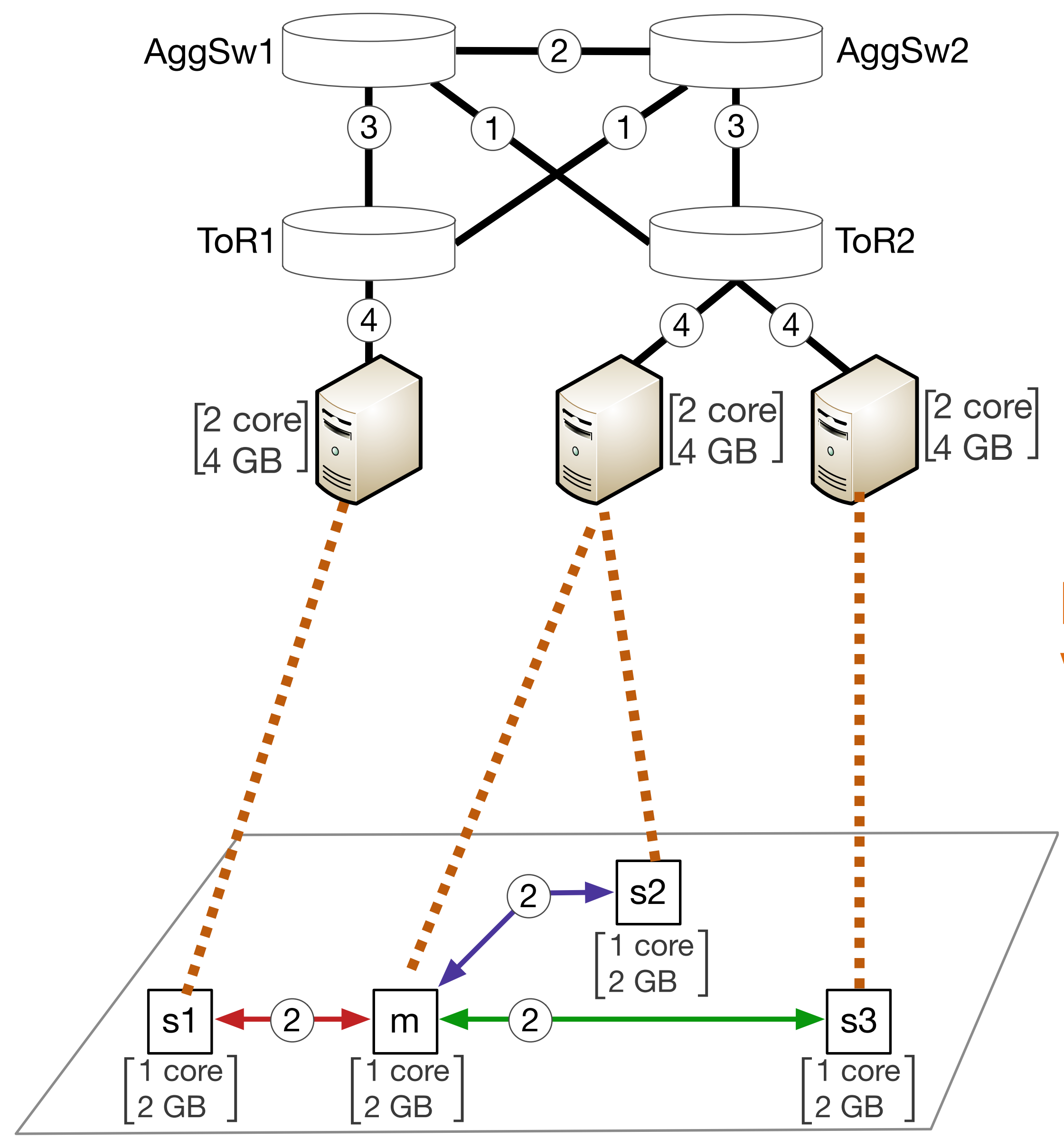
Virtual data center (VDC):



Example NetSolver solution

Physical DC topology:

Virtual data center (VDC):

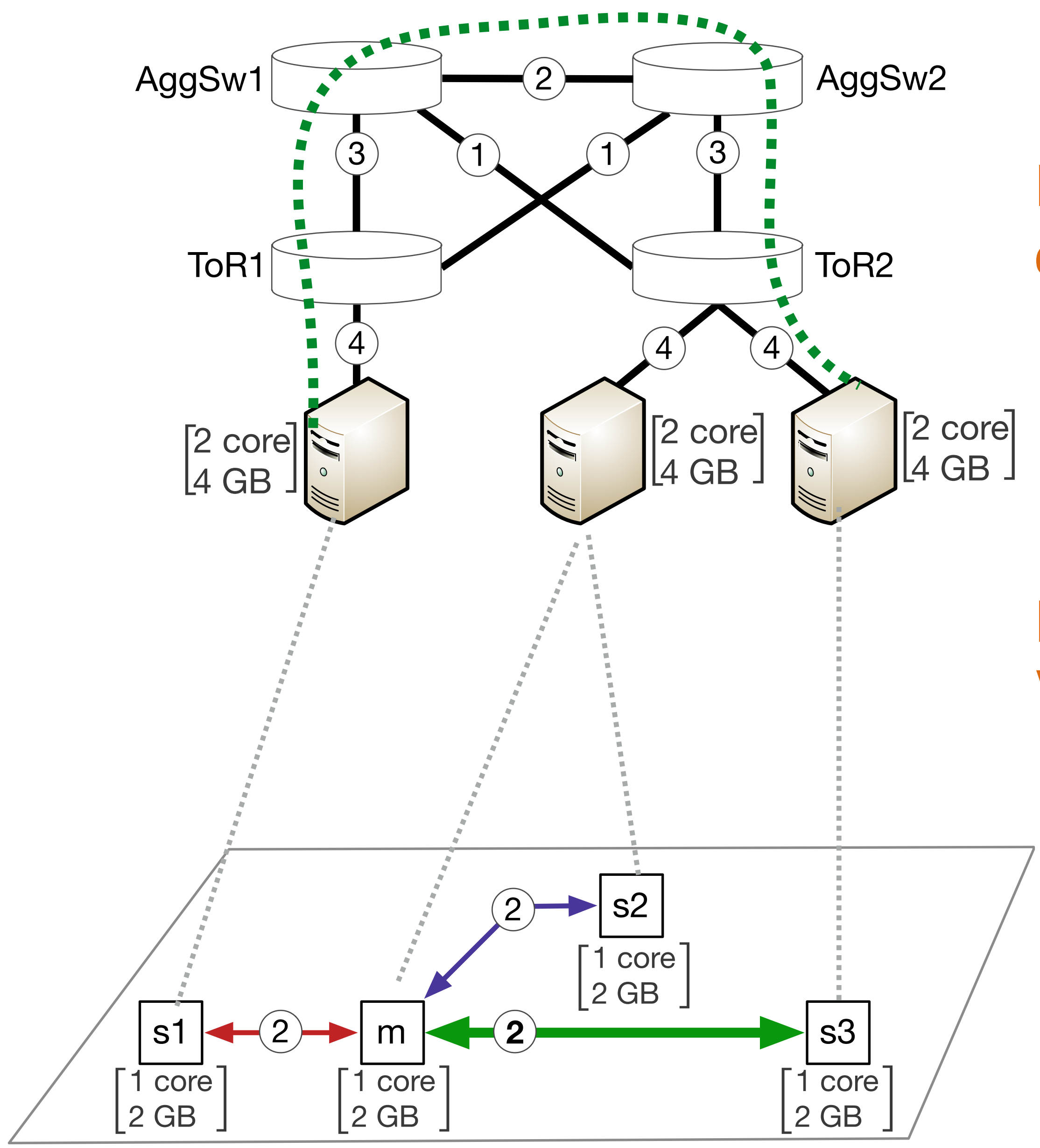


Mapping 1:
VM -> host

Example NetSolver solution

Physical DC topology:

Virtual data center (VDC):



Mapping 2: VM-VM edges -> paths

Mapping 1: VM -> host

Example NetSolver solution

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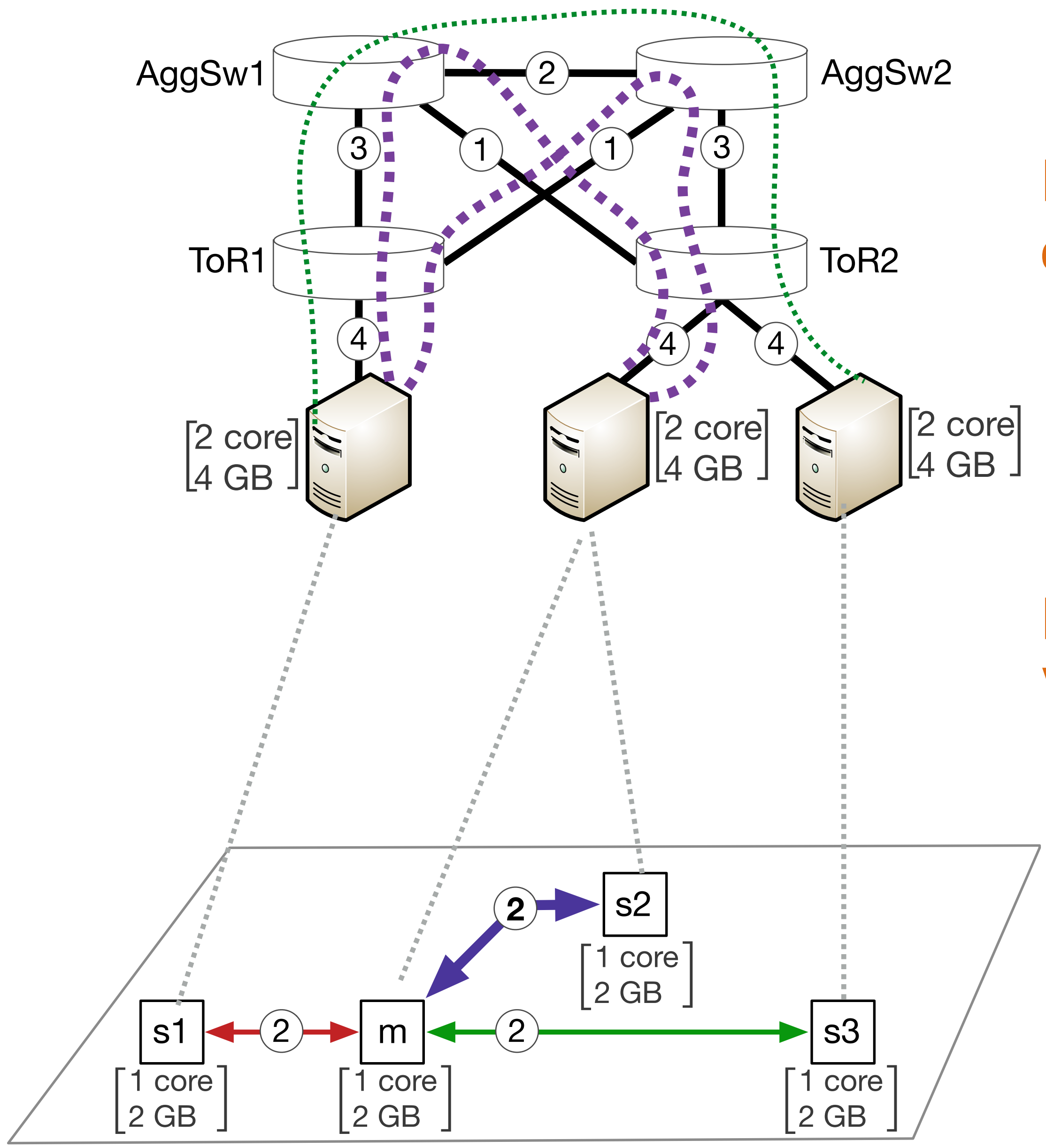

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Virtual data center (VDC):

Example NetSolver solution

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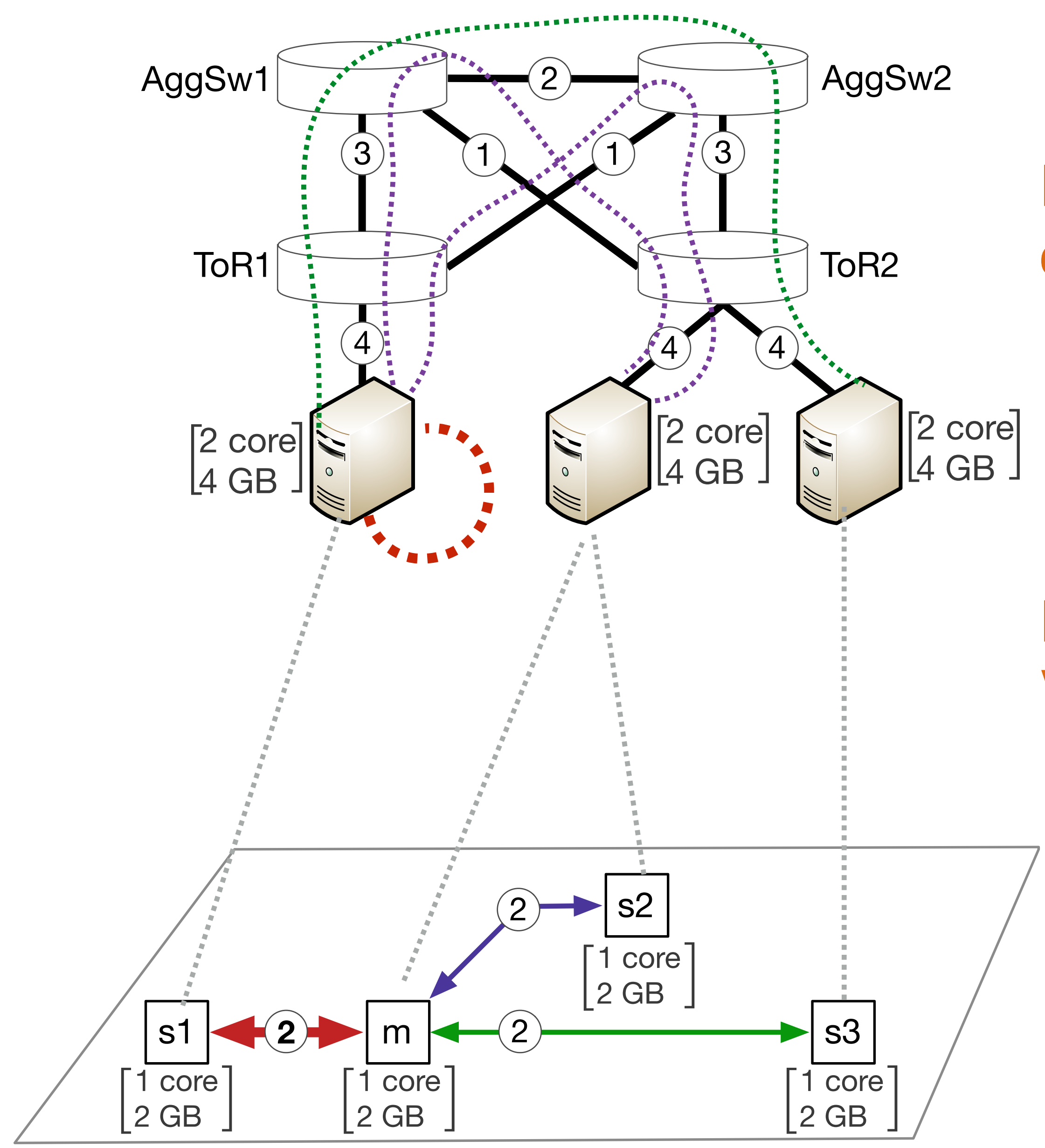

Mapping 2: VM-VM edges -> paths

Mapping 1: VM -> host

Virtual data center (VDC):

Related work dimensions

- Sound: respect end-to-end bandw. guarantees
- VDC topology: Star/Hose/All
- DC topology: Tree/All
- Complete: finds a solution if a solution exists
- Multi-VM: can map more than one VM to a host
- Multi-path: supports multi-path allocations

Related work break-down

Algorithm	Sound	VDC Topology	Data Center Topology	Complete	Multi-VM	Multi-path
SecondNet [29]						
Importance Sampling [48]						
Oktopus [8]						
VDCPlanner [54]						
HVC-ACE [43]						
GAR-SP/PS [50]						
RW-MM-SP/PS [15]						
D-ViNE [16]						
ASID [36]						
VirtualRack [31]						
Z3-AR [51]						
NETSOLVER (this paper)						

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HVC-ACE [43]	✓	Hose	All		✓	✓
GAR-SP/PS [50]	✓	All	$<$ 200 nodes		✓	✓
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MonoSAT background

- Switch to other slide-deck

The MonoSAT constraint solver

MonoSAT is an SMT solver for monotonic theories.
MonoSAT supports:

- Graph constraints (shortest paths, maximum flows...)
- Finite state machines & string acceptance
- Temporal logic (CTL) synthesis
- 2D polygonal geometry constraints
- Bounded integer & cardinality constraints
- Propositional logic (Boolean satisfiability)
- Has C++, Python, and Java bindings

Finite Monotonic Predicates

A predicate p is positive monotonic iff:

- : $p(\ldots, x, \ldots), x \leq y \implies p(\ldots, y, \ldots)$

A predicate p is negative monotonic iff:

- : $\neg p(\ldots, x, \ldots), x \leq y \implies \neg p(\ldots, y, \ldots)$

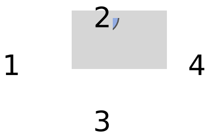
Monotonic theories

Many useful predicates are monotonic:

- Graph Predicates:
  - Reachability
  - Shortest paths
  - Maximum $s - t$ flow
  - Minimum Spanning Tree
  - Acyclicity

Monotonic predicates

'Reachability' is monotonic with respect to edges:



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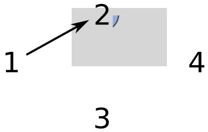

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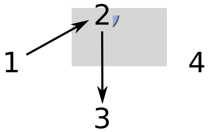

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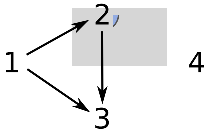
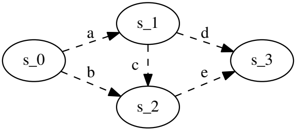


Graph constraints in MonoSAT

MonoSAT supports constraints over one or more finite graphs:

- Combines arbitrary Boolean constraints with high performance graph constraints.
- Supported graph constraints
  - Reachability
  - Shortest paths
  - Maximum *s*-*t* flow
  - Minimum spanning tree
  - Acyclicity
- Graphs can be directed
- Edges can have bit vector weights/capacities
- Scales to 100,000s of nodes and edges

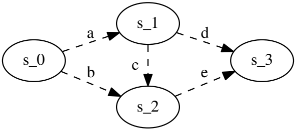
Graph constraints in MonoSAT



$$(\neg a \vee \neg b) \wedge (\neg d \vee \neg e) \wedge reaches(s_0, s_3) \wedge \neg reaches(s_1, s_3)$$

Figure : A directed graph with edge inclusion controlled by Booleans $\{a, b, c, d, e\}$, and a formula constraining the graph.

Graph constraints in MonoSAT



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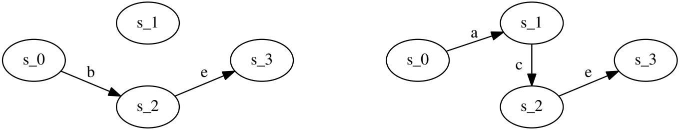
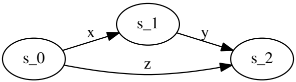


Figure : Satisfying (left) and unsatisfying (right) solutions.

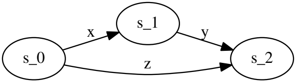
Weighted graph constraints in MONOSAT



$$(x > 1) \wedge (x < y) \wedge (y < 4) \wedge (z = y) \wedge (shortestPath(s_0, s_2) \leq 3)$$

Figure : A directed graph with variable edge weights, and a formula constraining those weights.

Weighted graph constraints in MonoSAT



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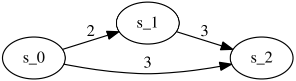

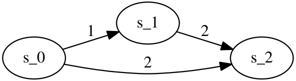

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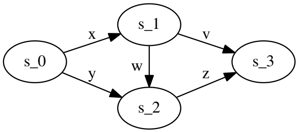
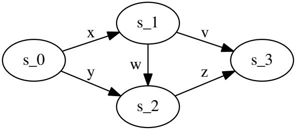
Maximum-flow graph constraints in MONOSAT



$$(x \leq z \leq 2) \wedge (x > y) \wedge (z > v) \wedge (2 \leq \mathit{maximumFlow}(s_0, s_2) \leq 3)$$

Figure : A directed graph with variable edge weights, and a formula constraining those weights.

Maximum-flow graph constraints in MONOSAT



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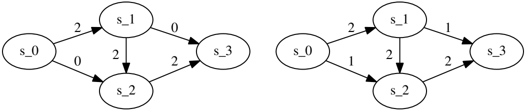
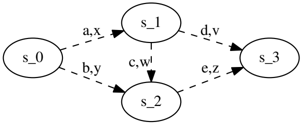


Figure : Two satisfying solutions.

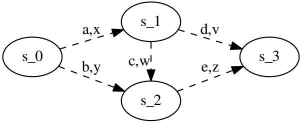
Combined graph constraints in MONOSAT



$$\neg reaches(s_0, s_2) \land shortestPath(s_2, s_3) = maximumFlow(s_0, s_3)$$

Figure : A graph with edge inclusion controlled by Booleans $\{a, b, c, d, e\}$, and edge weights $\{v, w, x, y, z\}$.

Combined graph constraints in MonoSAT



$$\neg reaches(s_0, s_2) \wedge shortestPath(s_2, s_3) = maximumFlow(s_0, s_3)$$

Figure : A graph with edge inclusion controlled by Booleans $\{a, b, c, d, e\}$, and edge weights $\{v, w, x, y, z\}$.

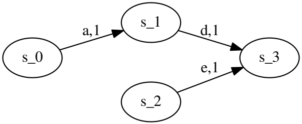


Figure : A satisfying solution.

NetSolver design

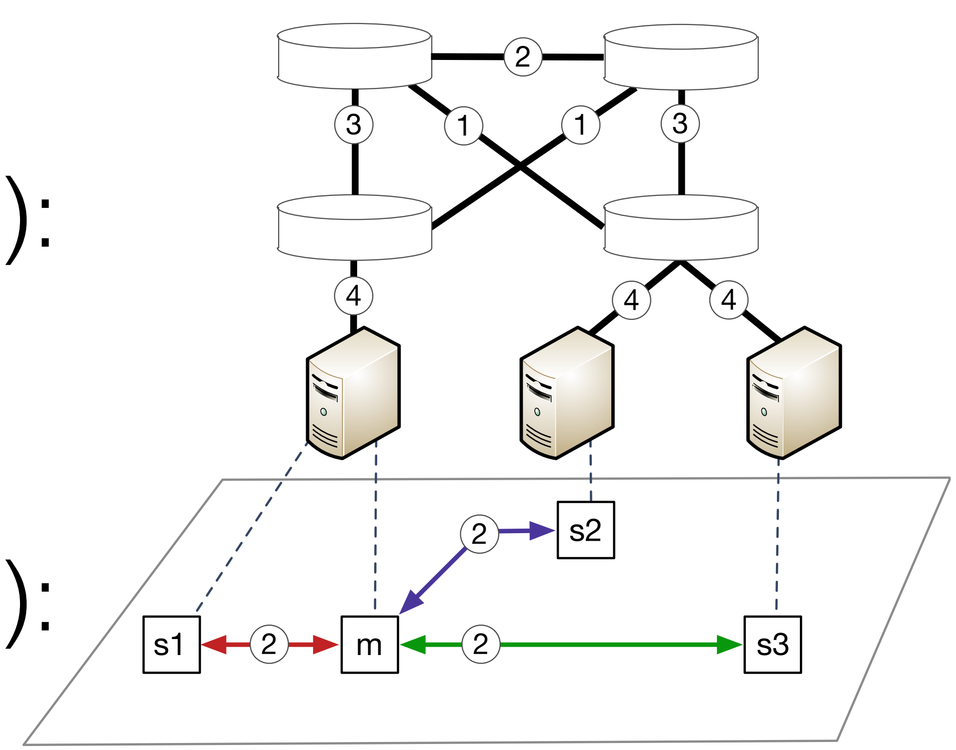
- Basic idea: encode VDC allocation as a MonoSAT query. Either outputs a solution or one does not exist
    - Global constraints: connectivity and bandwidth
    - Local constraints: VMs respect host resources
- <u>Challenge</u>: efficiency (e.g., each VM-VM path can be modeled as a max-flow constraint, these are expensive)

Global constraints

- **Assume**: that we know the VM-host assignments
- Given:
    - Directed graph $G = (V, E)$ and integer constraints $c(u, v)$ on each edge $(u, v) \in E$
    - K commodity demands, $i \in K, i = (s_i, t_i, d_i)$ representing demand d_i between $s_i \in V$ and $t_i \in V$

Graph (DC):

Demands (VDC):



Global constraints

- **Assume**: that we know the VM to host assignment
- Given:
    - Directed graph $G = (V, E)$ and integer constraints $c(u, v)$ on each edge $(u, v) \in E$
    - K commodity demands, $i \in K, i = (s_i, t_i, d_i)$ representing demand d_i between $s_i \in V$ and $t_i \in V$
- Integral multi-commodity flow problem:
    - Find feasible flow such that each d_i satisfied
    - For each edge (u, v) total flow of all capacities is $\leq c(u, v)$

Commodity flow encoding

- Create graphs $G_{1...|K|}$: one per demand with same topology as G
- For each edge $(u,v)_i \in G_i$ create a new **symbolic** capacity $c(u,v)_i \leq c(u,v)$
- **Assert:** that $\sum_i c(u,v)_i \leq c(u,v)$
- **Assert:** for each demand $i = (s_i, t_i, d_i), \text{max-flow}(s_i, t_i) \geq d$
- Solver's task: find partitioning of capacities across K graphs while satisfying lower-bounds across all demands

Modeling local constraints

- Construct a graph G that is the VDC and one node for each VM
- For each VM v and each server $s \in G$, create directed symbolic edge e_{vs} with unlimited capacity; e_{vs} controls allocation of v to servers
- **Assert**: for each VM v, exactly on e_{vs} enabled
- **Assert**: for each server s, set of VMs assigned to s obey server's local resources
- **Assert**: G satisfies flow (s_i, t_i, d_i) for each commodity constraint

Further technical innovations

- Naive encoding slow: $|V|^2$ max-flow constraints in worst case. Optimize by merging demands from same source

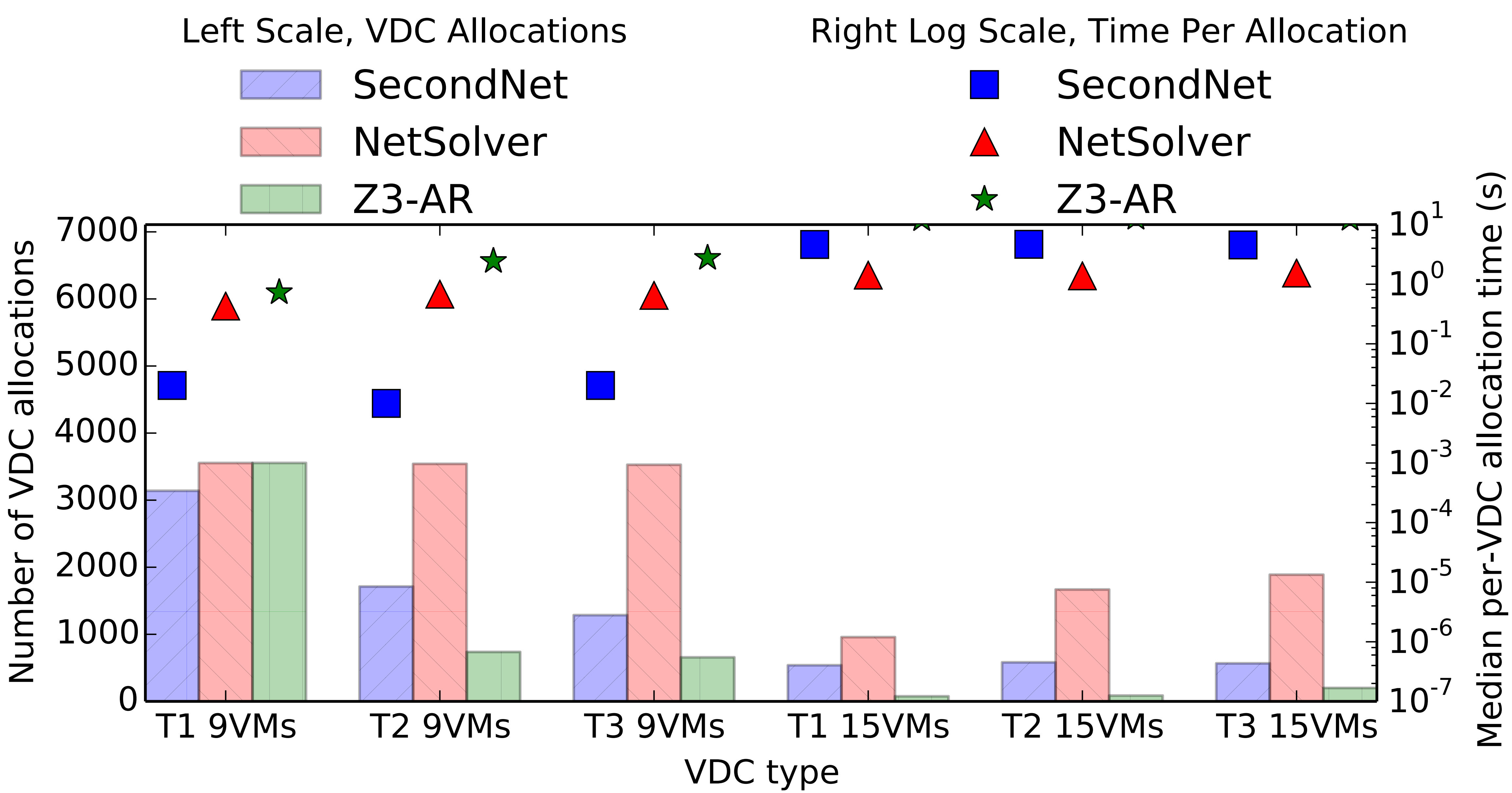
- So far assumed that VDC topology constant: only works for allocating sequence of identical VDCs

  - To allocate diverse VDCs, encode superset of VDCs and use MonoSAT's assumption mechanism to disable parts of this superset during allocation

NetSolver Evaluation

- Key questions:
  - Can a sound+complete scale to realistic topologies?
  - Are there any practical benefits to being complete?
  - How does NetSolver compare to related work?
    - SecondNet (CoNEXT’10)
    - Z3-based abstraction refinement technique (FMCAD’13)

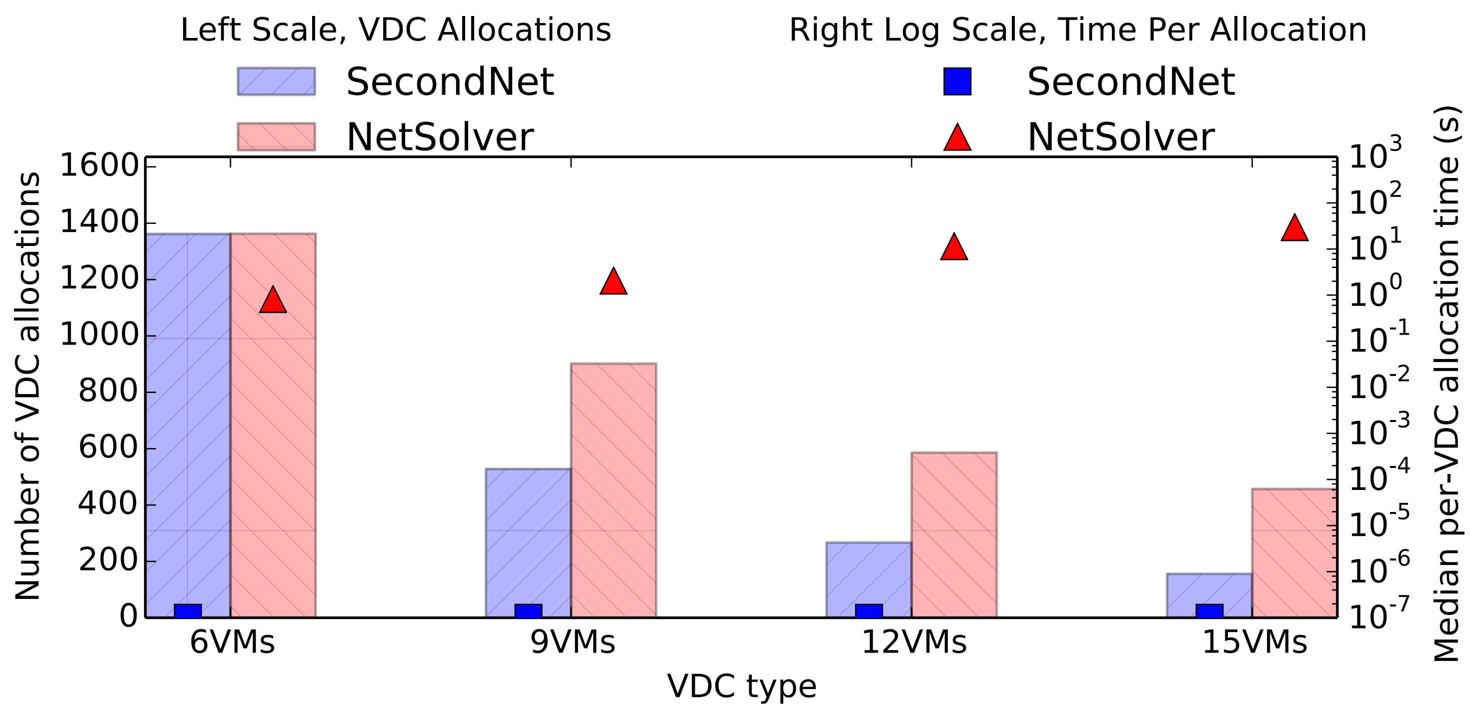
Identical VDC packing and median alloc runtime (Tree)



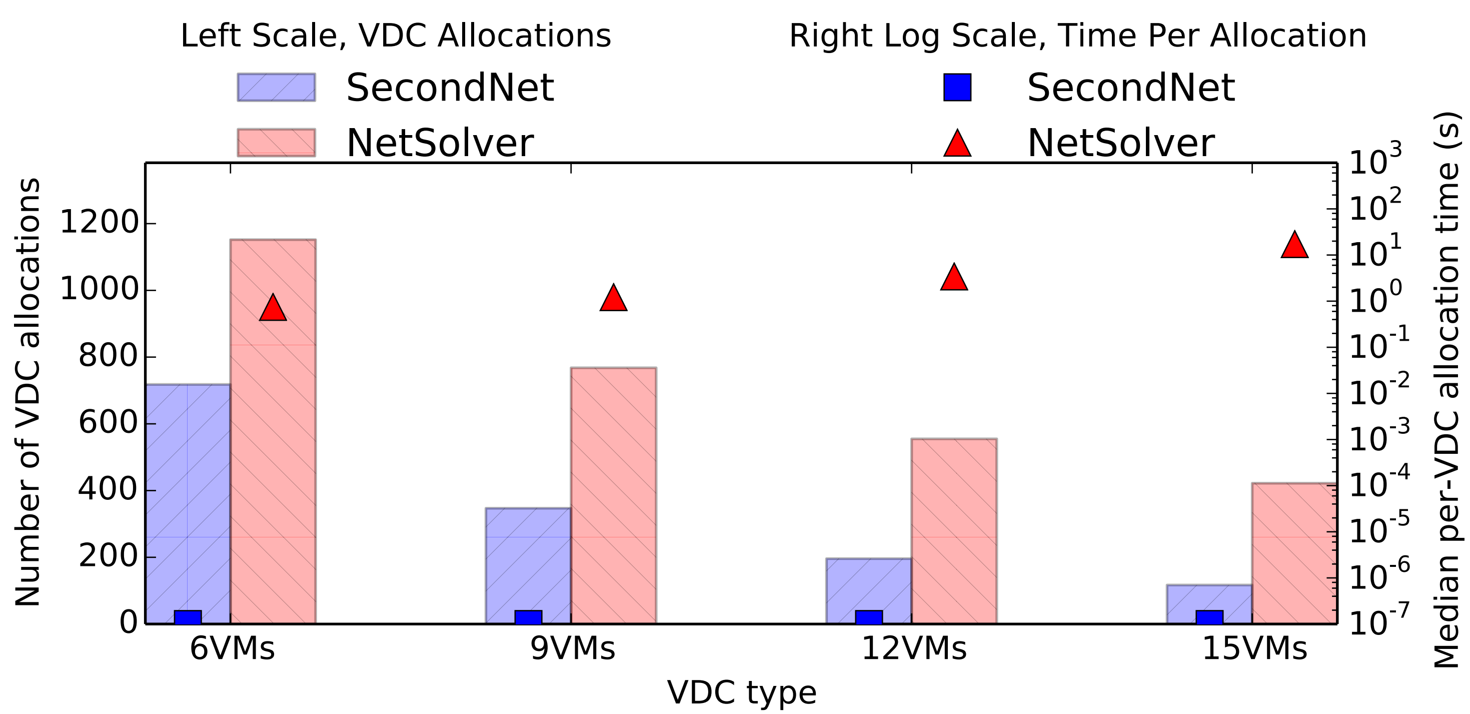
2000 servers, 16 cores; varying VDC sizes; Tree DC topologies

Identical VDC packing and median alloc runtime (BCube/FatTree)

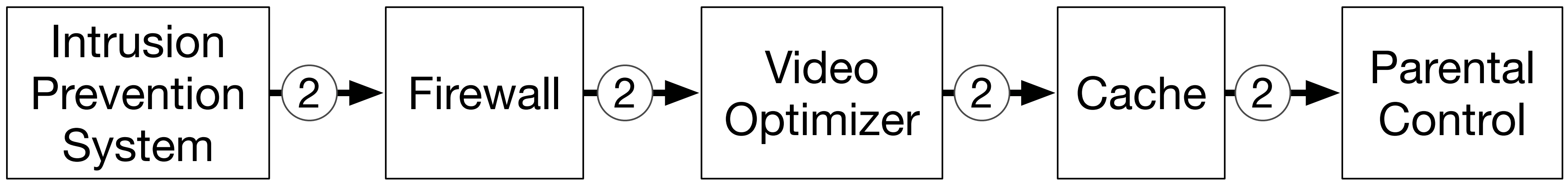
512 servers, 16 cores; varying VDC sizes; BCube DC topologies



432 servers, 16 cores; varying VDC sizes; FatTree DC topologies

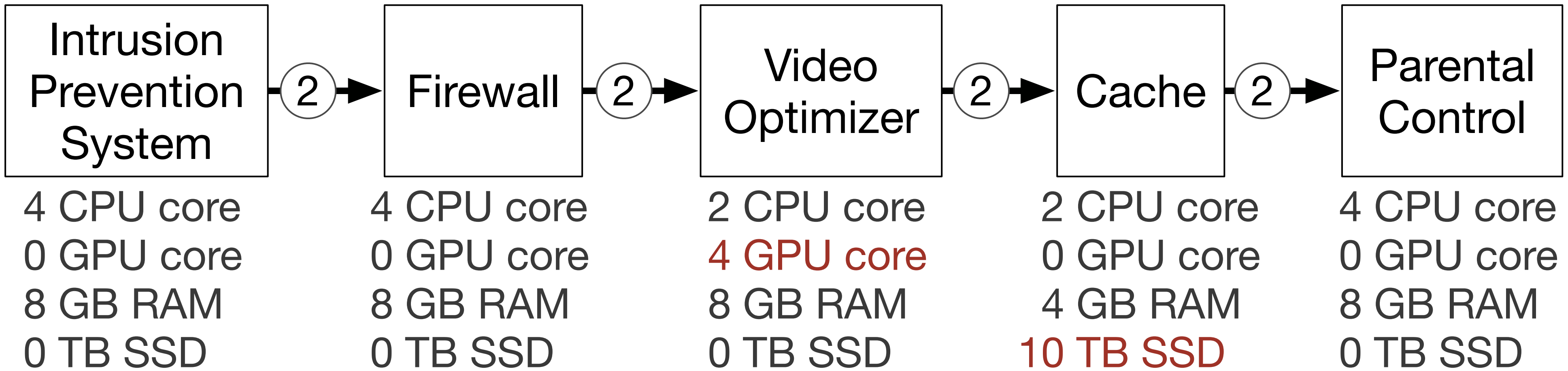


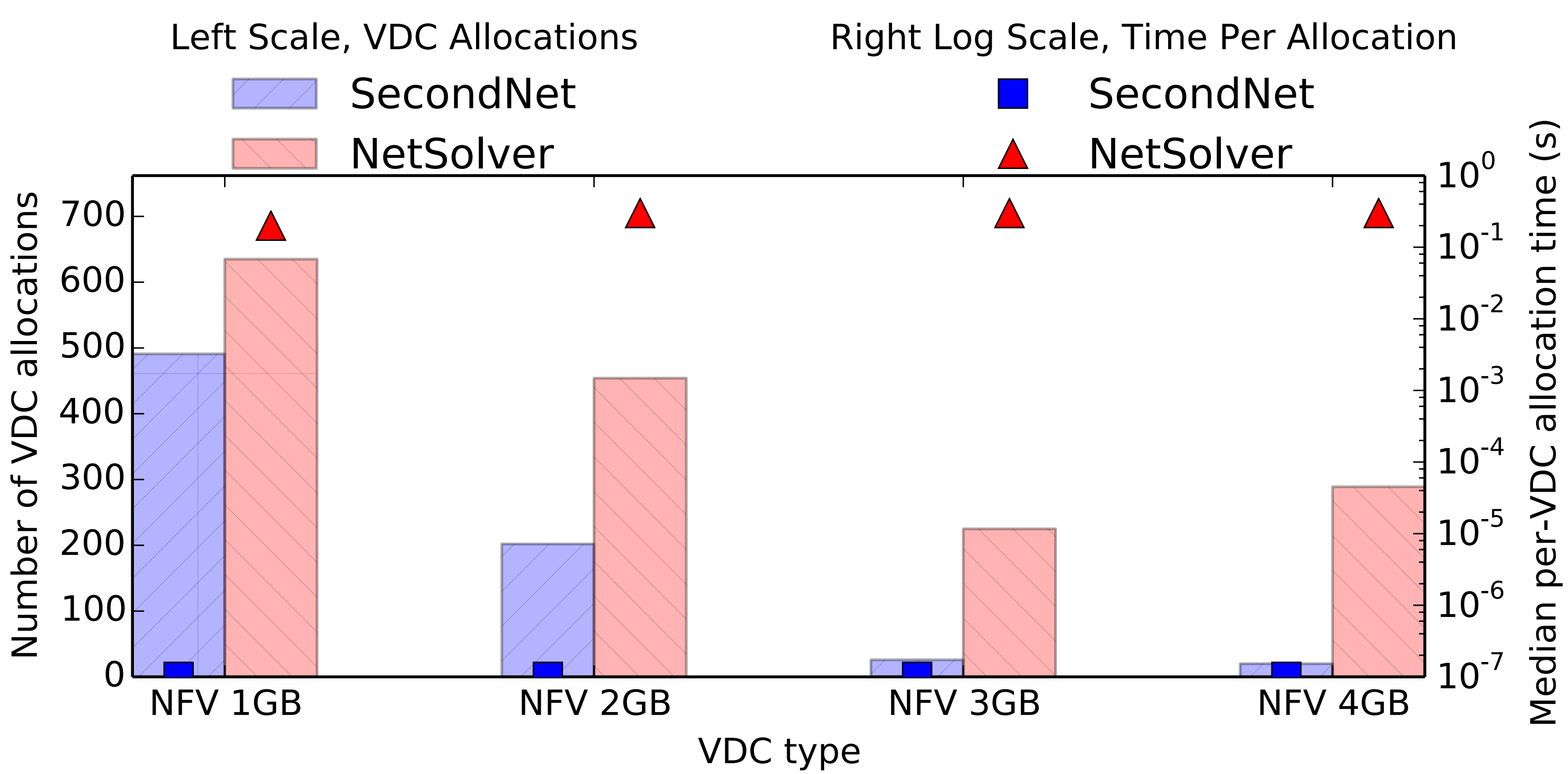
NFV chain allocation



Intrusion Prevention System	Firewall	Video Optimizer	Cache	Parental Control
4 CPU core	4 CPU core	2 CPU core	2 CPU core	4 CPU core
0 GPU core	0 GPU core	4 GPU core	0 GPU core	0 GPU core
8 GB RAM	8 GB RAM	8 GB RAM	4 GB RAM	8 GB RAM
0 TB SSD	0 TB SSD	0 TB SSD	10 TB SSD	0 TB SSD

NFV chain allocation

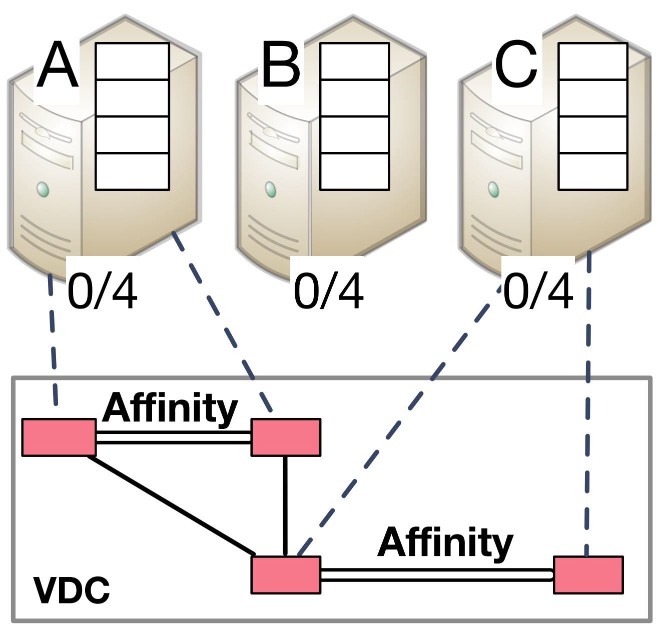




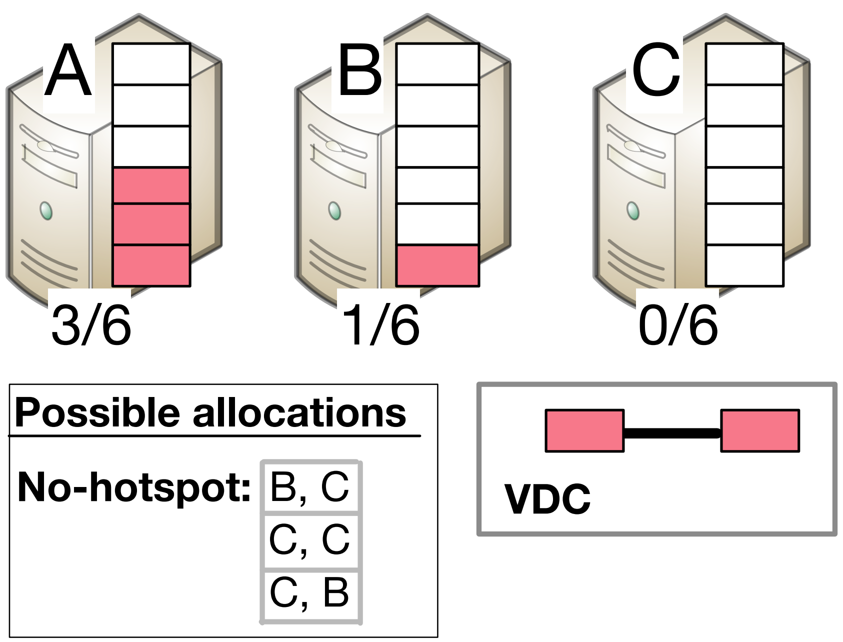
1200 servers; commercial DC topology; increasing chain bandwidth constraint

Extensibility

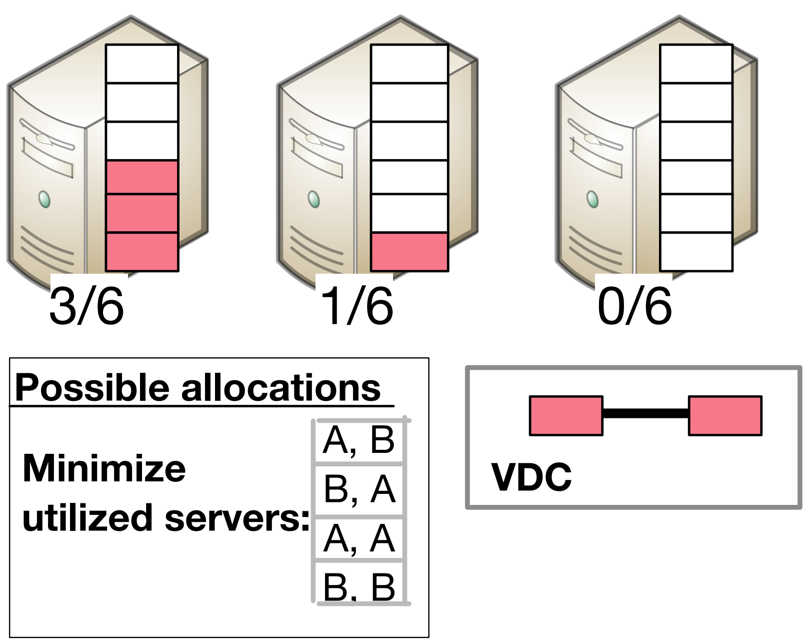
- NetSolver supports a variety of additional constraints



Affinity

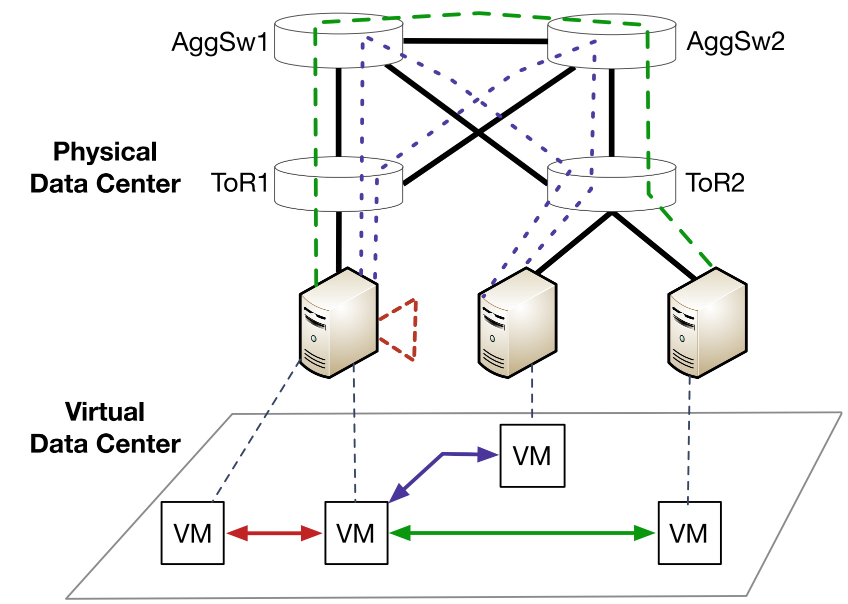


No hotspots



Minimize utilized severs

Contributions



- Developed NetSolver, a new VDC allocator
  - NetSolver encodes problem into MonoSAT. Can be reused for other problems: NFV placement, data migration, task distribution, etc
  - Improves DC capacity utilization by 300% over prior work (but slower than incomplete approaches)
  - Constraints-based approach flexibly extends to other kinds of constraints, such as (anti-)affinity