Nomad: Mitigating Arbitrary Cloud Side Channels via Provider-Assisted Migration

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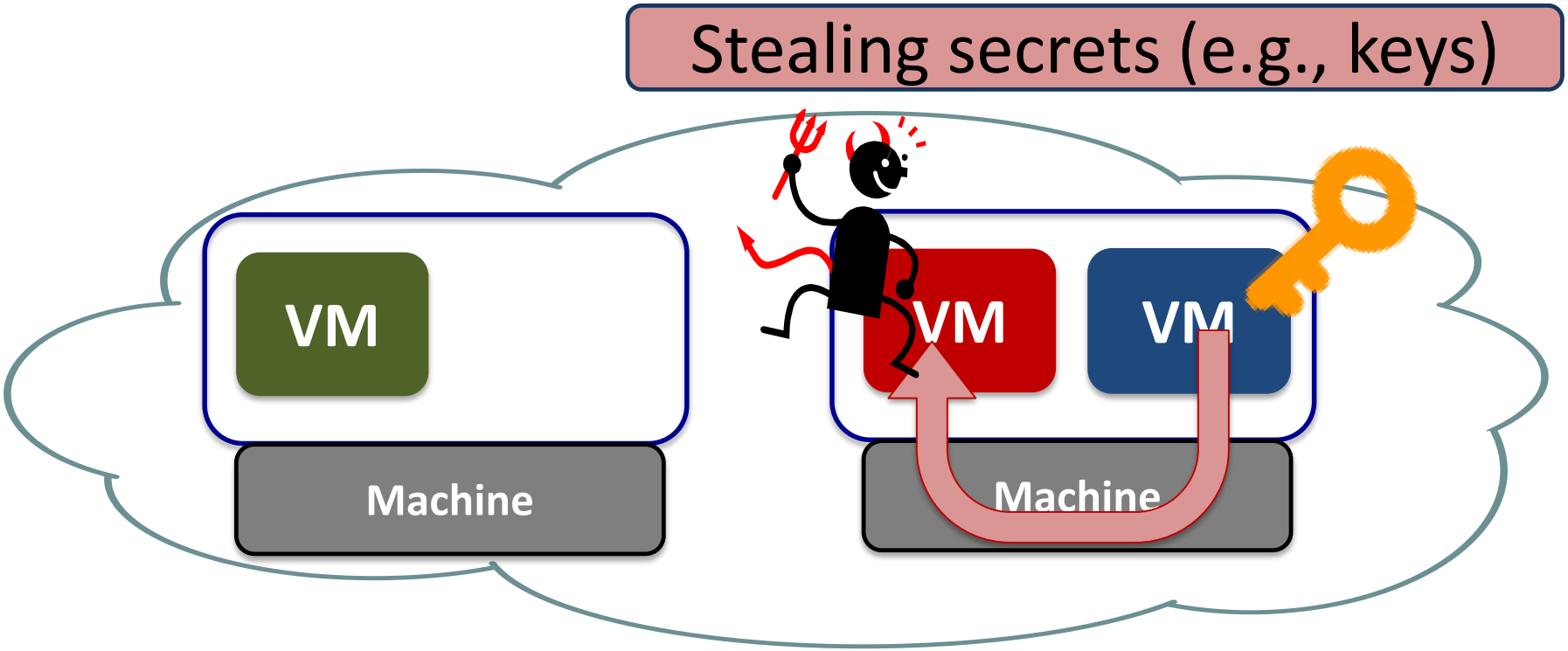
THE UNIVERSITY of NORTH CAROLINA at CHAPEL HILL

Co-residency side-channel attacks in clouds



- Many different vectors
  (e.g., L2/L3 cache, storage, main memory)

Demonstrated side-channel attacks are not limited to:
Y. Zhang et al., CCS2012; T. Ristenpart et al., CCS2009; F. Liu et al., Oakland 2015

Limitations of Current Defenses

1. Requires significant/detailed upgrades

2. Attack-specific

Proposed defense includes but not limited to: Y. Zhang et al., CCS2013; T. Kim et al., USENIXSec 2012; F. Liu and R. Lee, Micro 2014

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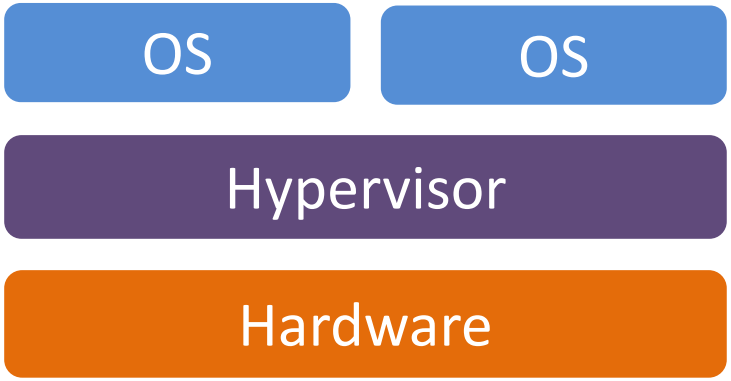

e.g., Noise injection

e.g., Deterministic execution

e.g., New cache design

2. Attack-specific

What about future side-channel attacks?

Proposed defense includes but not limited to: Y. Zhang et al., CCS2013; T. Kim et al., USENIXSec 2012; F. Liu and R. Lee, Micro 2014

Ideal Properties

1) General

2) Immediately deployable

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Single-tenancy?

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Nomad Ideas

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Tackle root-cause

→ Minimize co-residency

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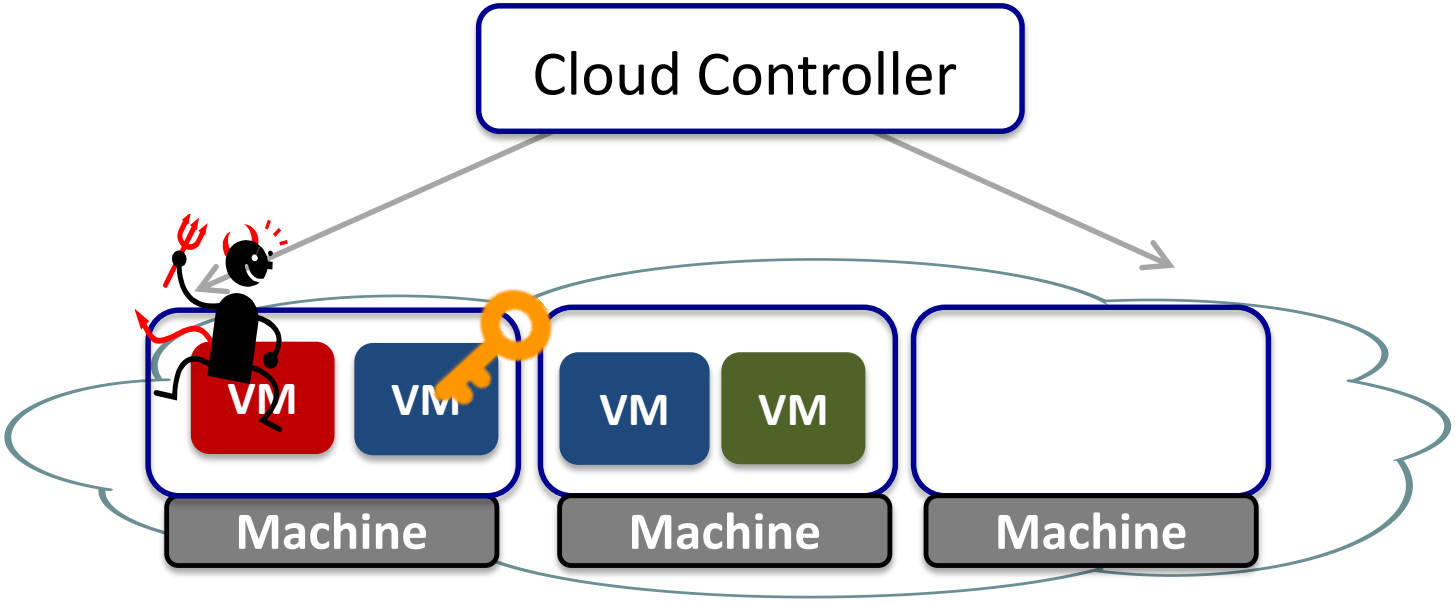
Migration

Nomad Vision: Migration-as-a-Service

- Provider-assisted



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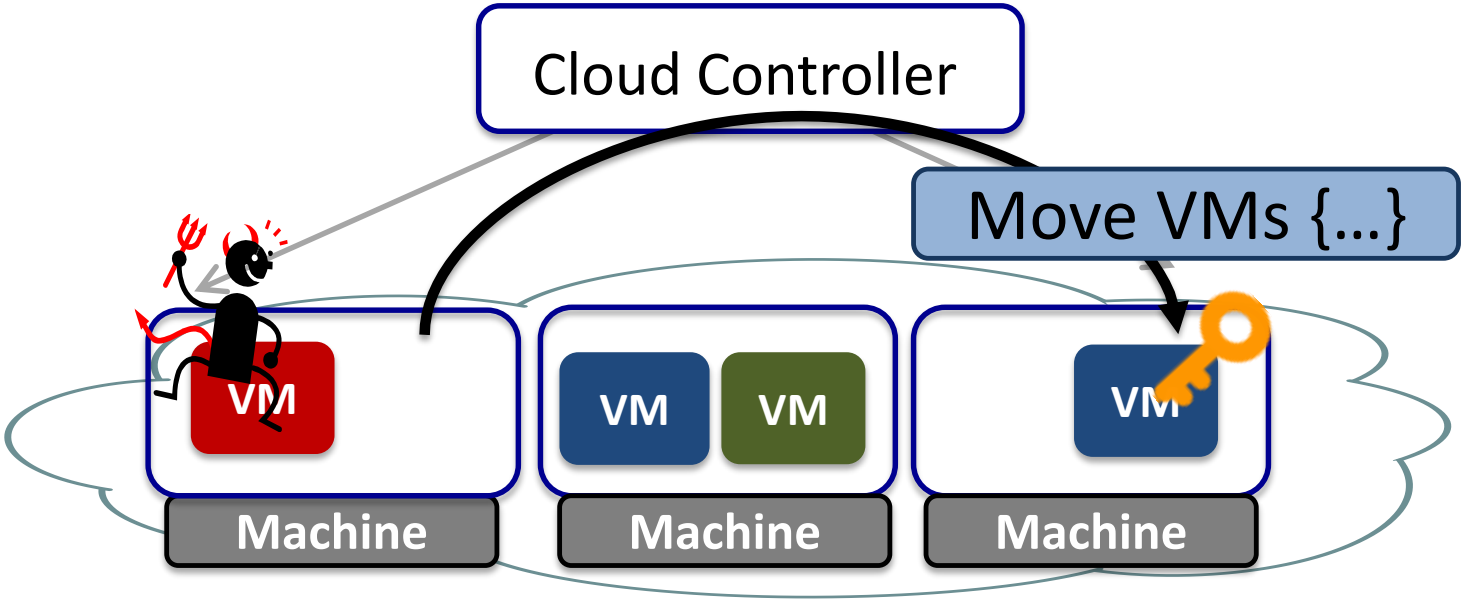
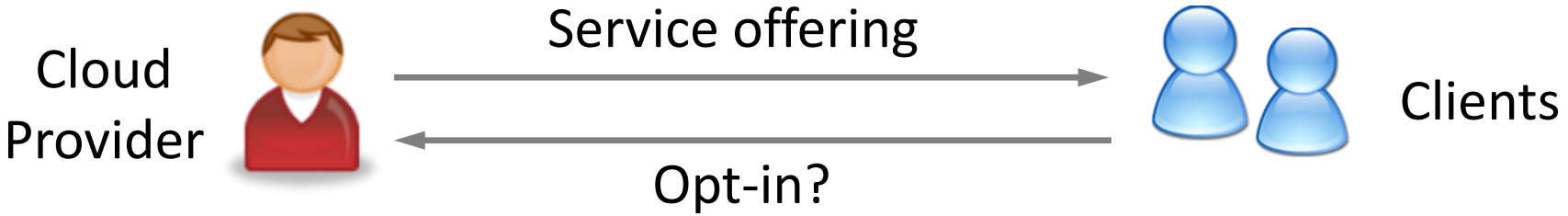


Nomad Vision: Migration-as-a-Service

- Opt-in Service



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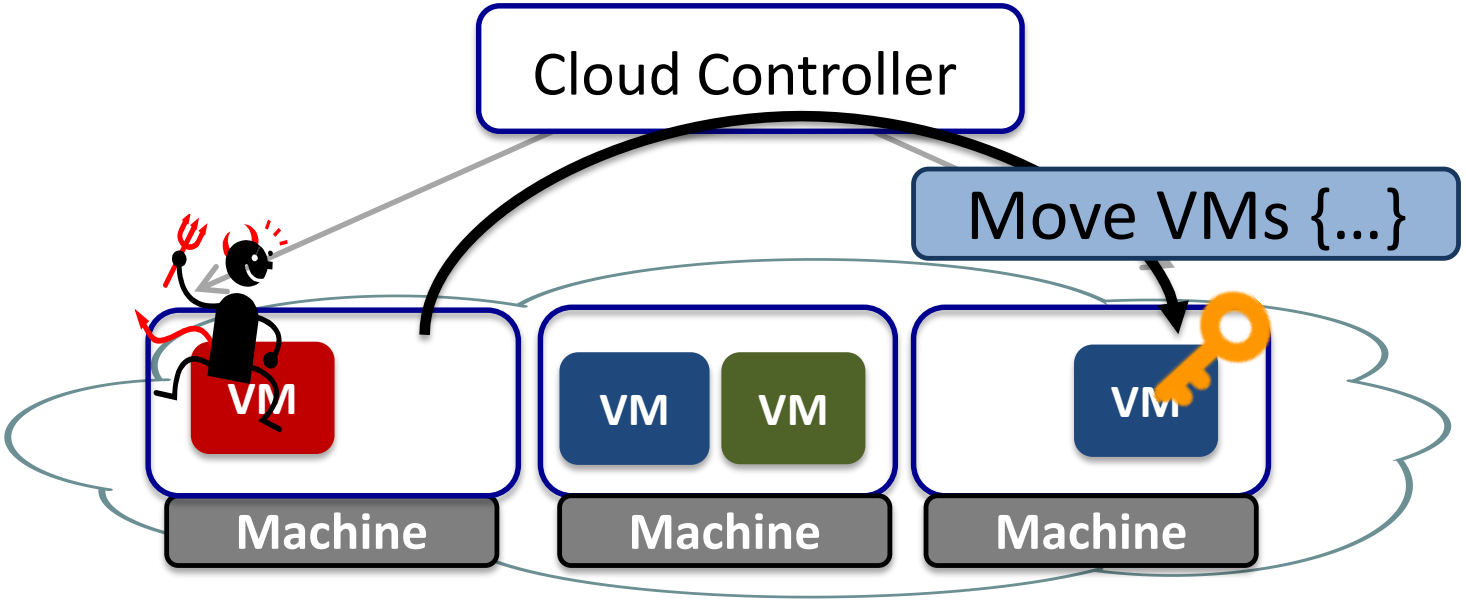
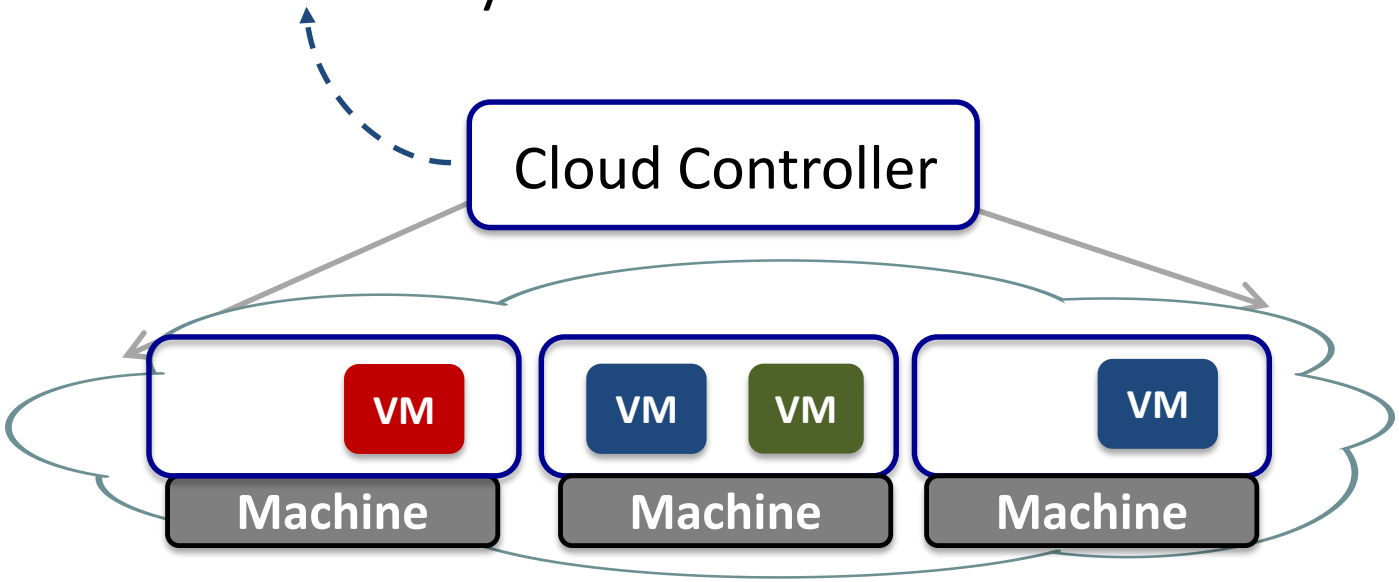


Nomad Practical Challenges

Logic

Characterize information leakage due to co-residency



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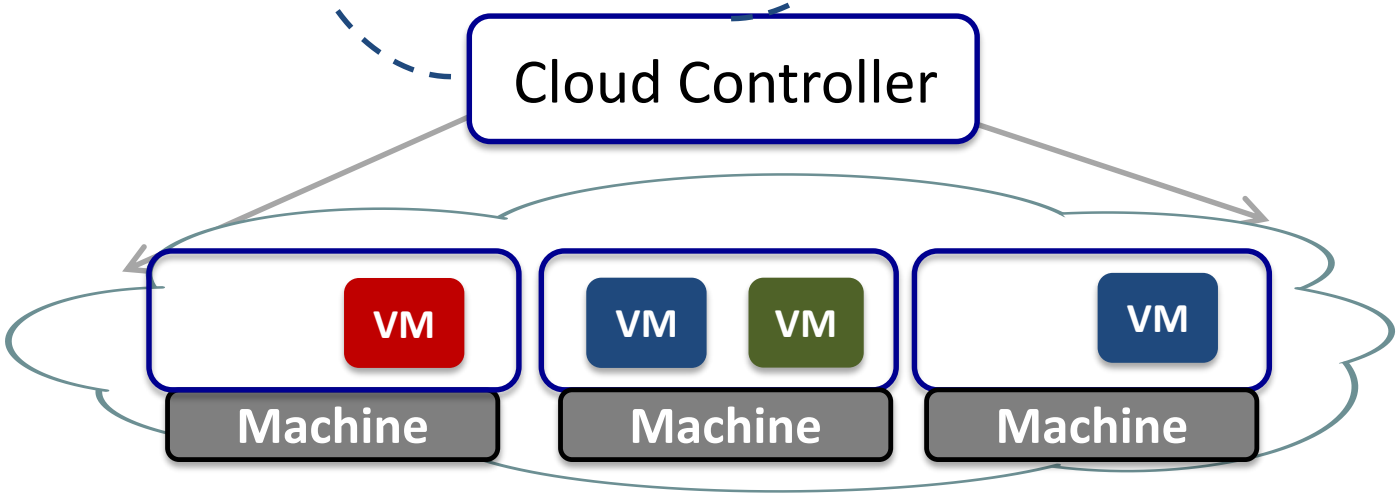

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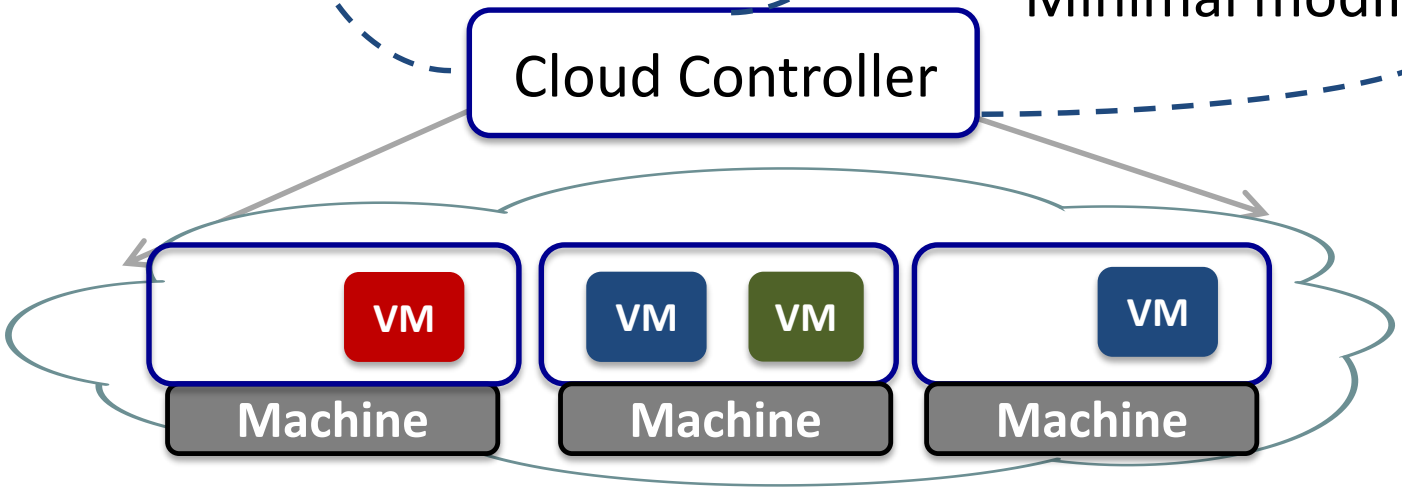
Minimal modifications?



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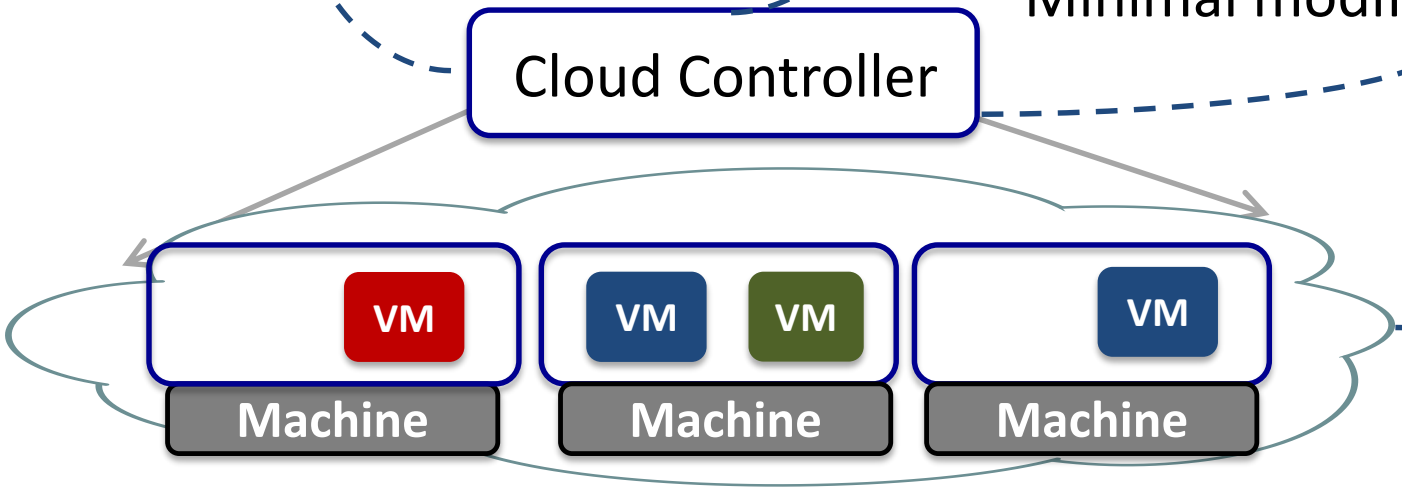

Practical Impact (applications)

1) Advancement of VM migration techniques
2) Many cloud workloads with in-built resilience to migration

Our Work

1. Idea

General side-channel defense via migration

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2. Logic

Characterize information leakage due to co-residency

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3. Scalable Design

Scalable VM migration strategy that can handle large cloud deployments

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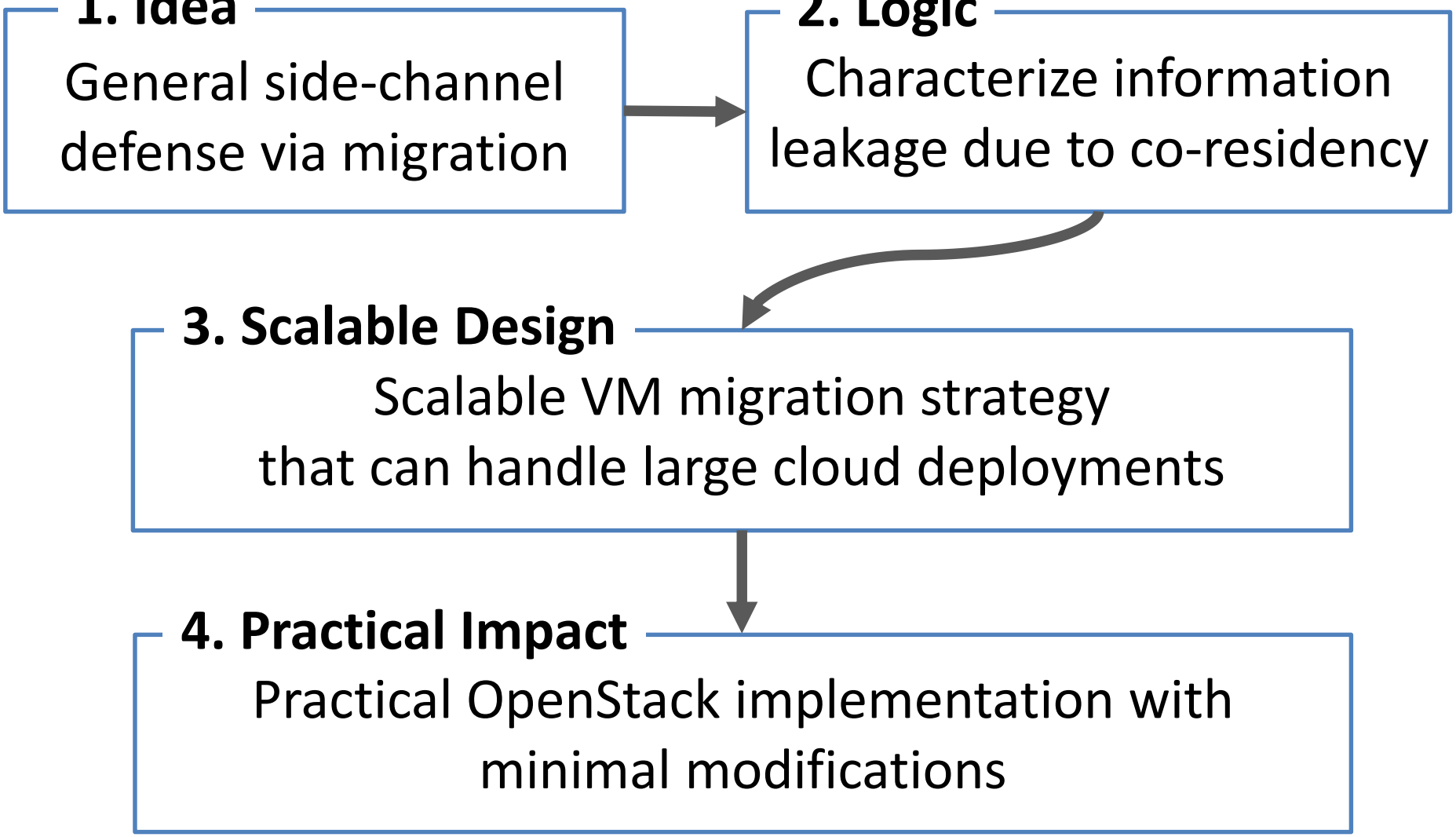
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Threat Model

Objective: Extract secrets via co-residency

- Can use any kind of resource
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- No info. sharing across distinct clients

Provider

- Don’t know which other clients are malicious

Information Leakage (InfoLeak) Model

Clients

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VM-level view

Replicated? (R or NR)

R

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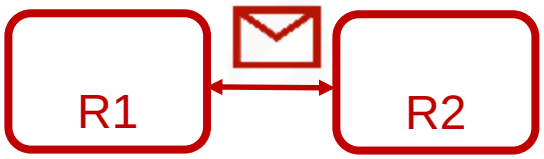

NR

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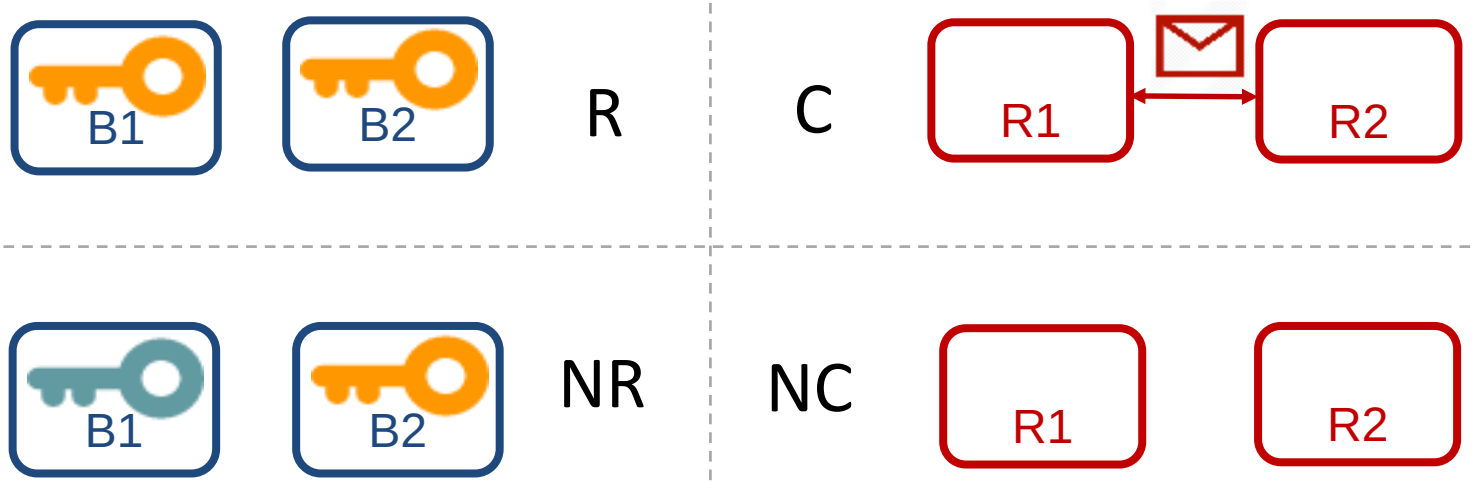
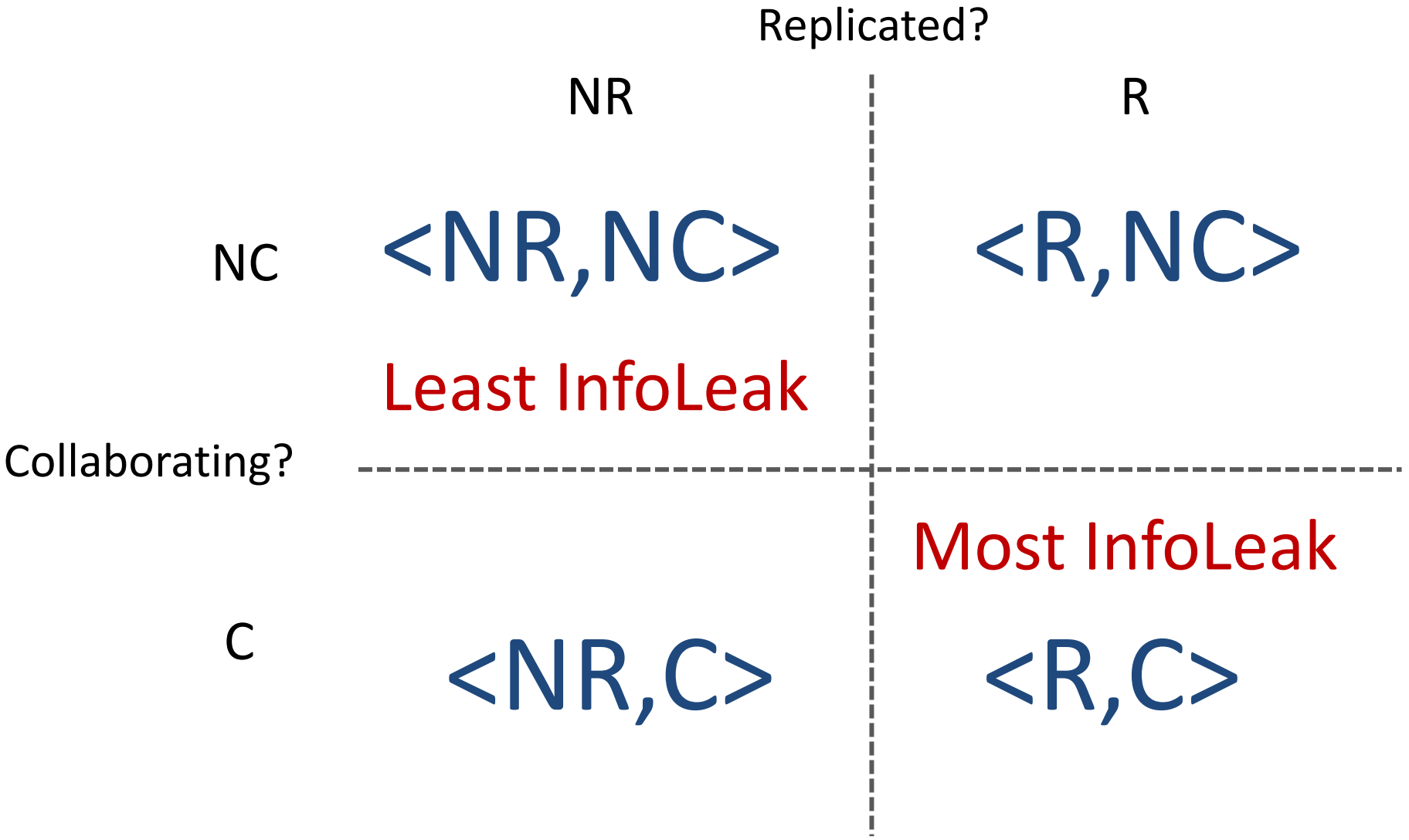


Information Leakage (*InfoLeak*) Model



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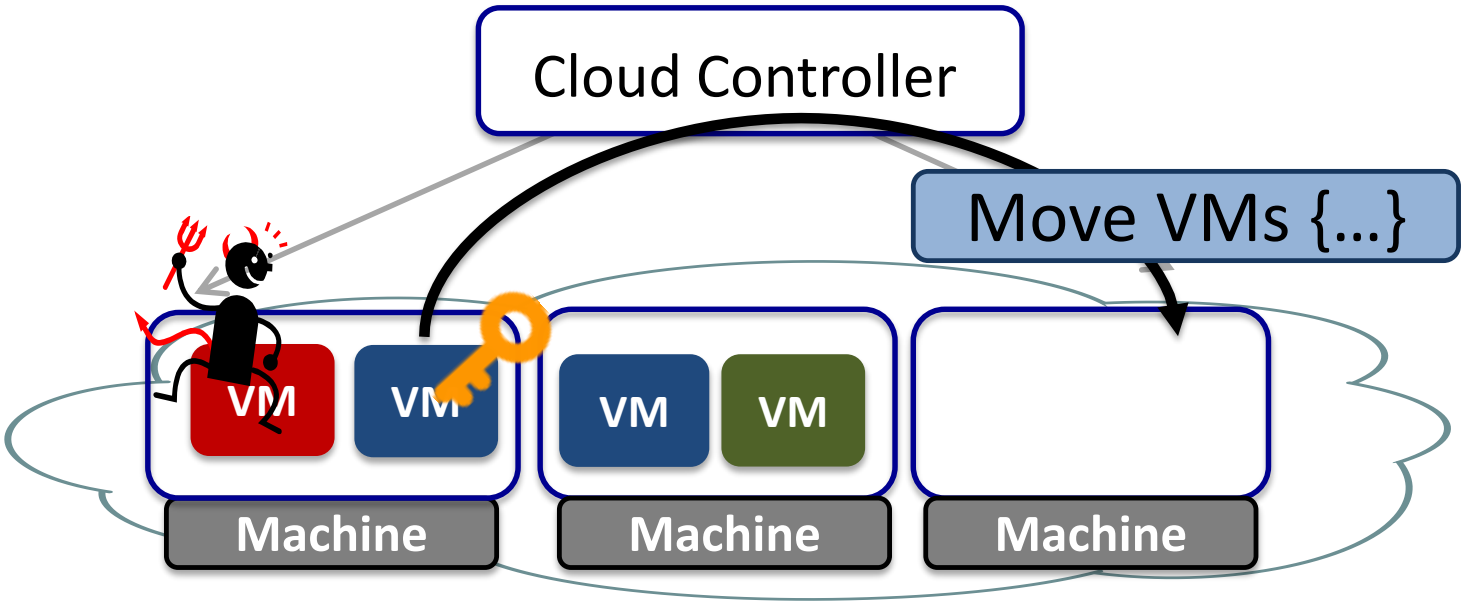
System Overview



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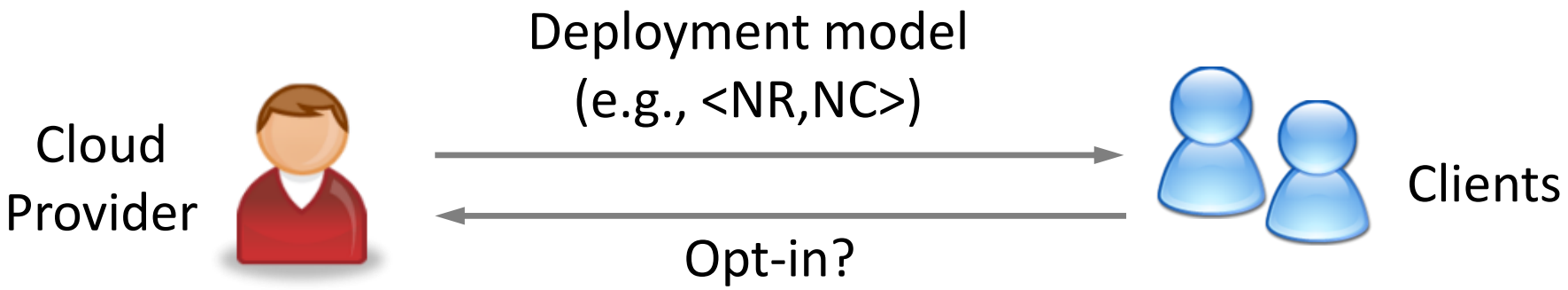
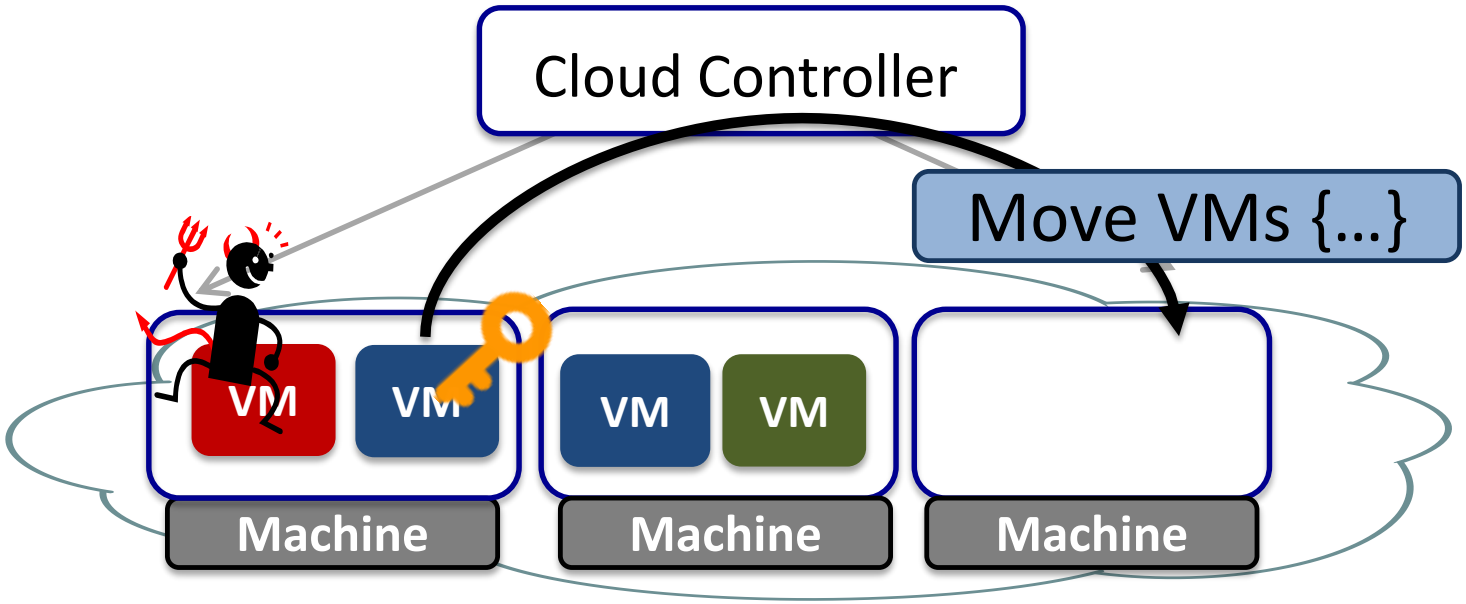
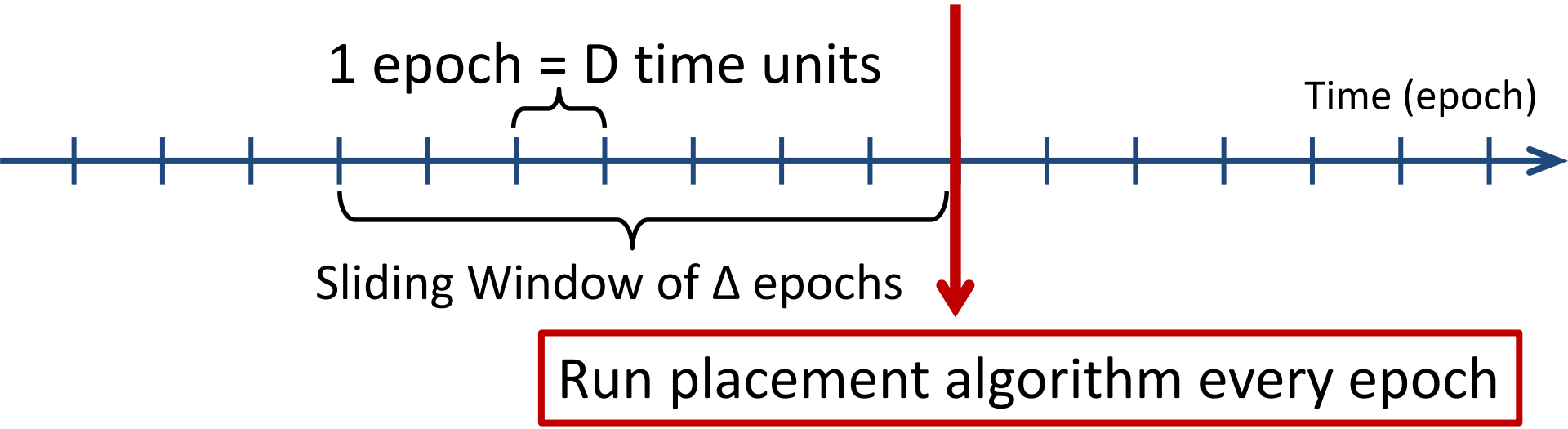




Operational Timeline



Run placement algorithm every epoch

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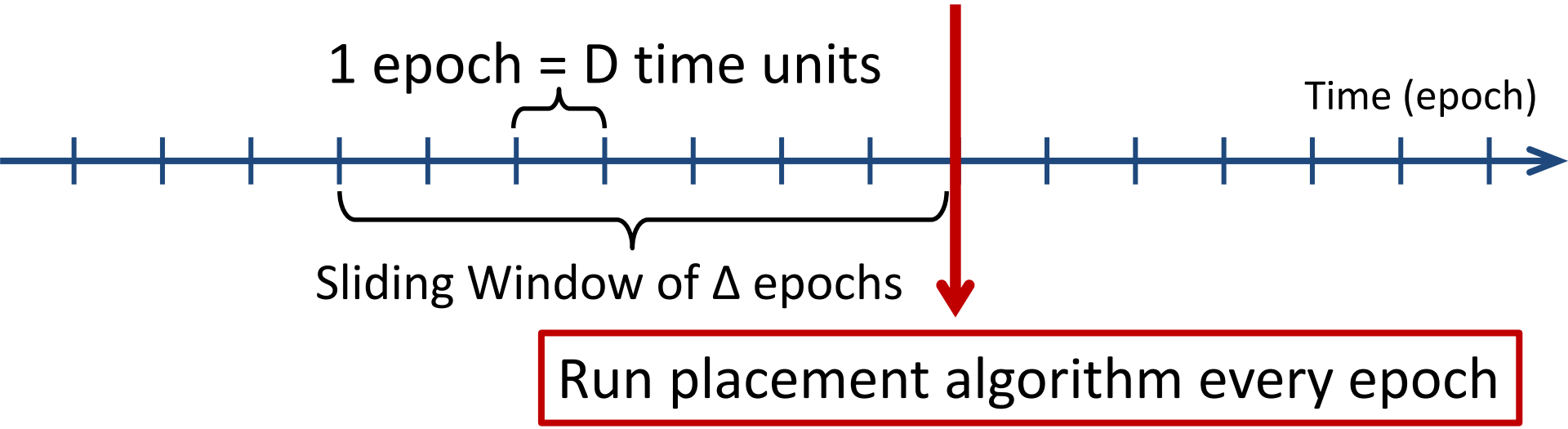

Side-channel Parameters:

- K: Information leakage rate (i.e., bits per time unit)
- P: secret length (i.e., bits)

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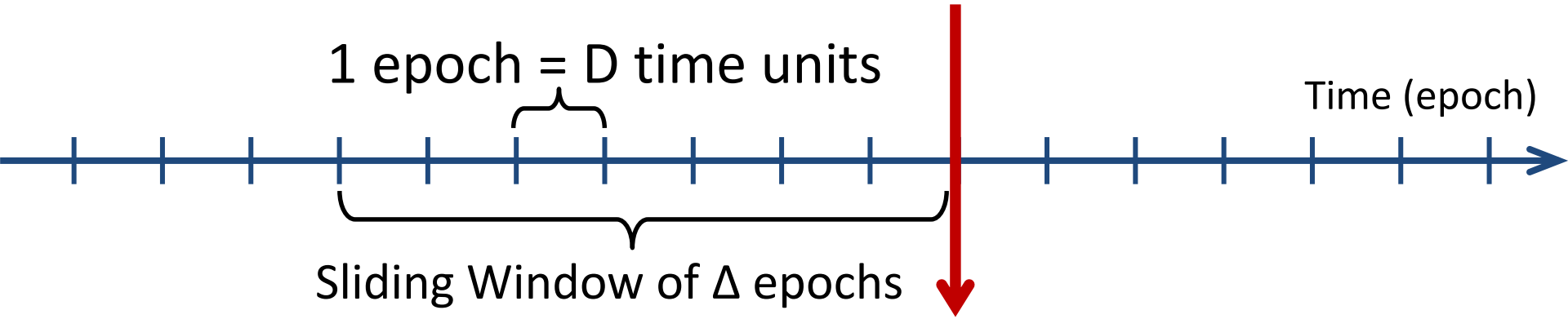


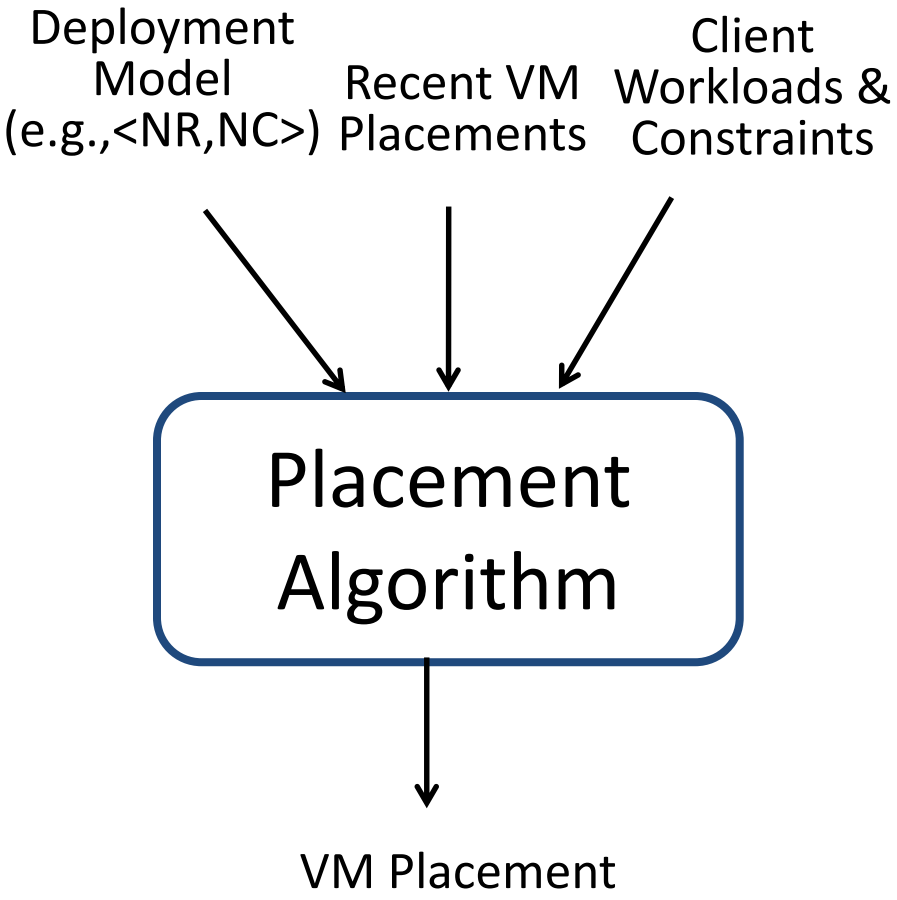
Run placement algorithm every epoch

Extracted secret (bits) if two VMs are co-resident for Δ epochs

Provider chooses D and Δ to AT LEAST satisfy:

$$D * \Delta * K < P$$

Placement Algorithm



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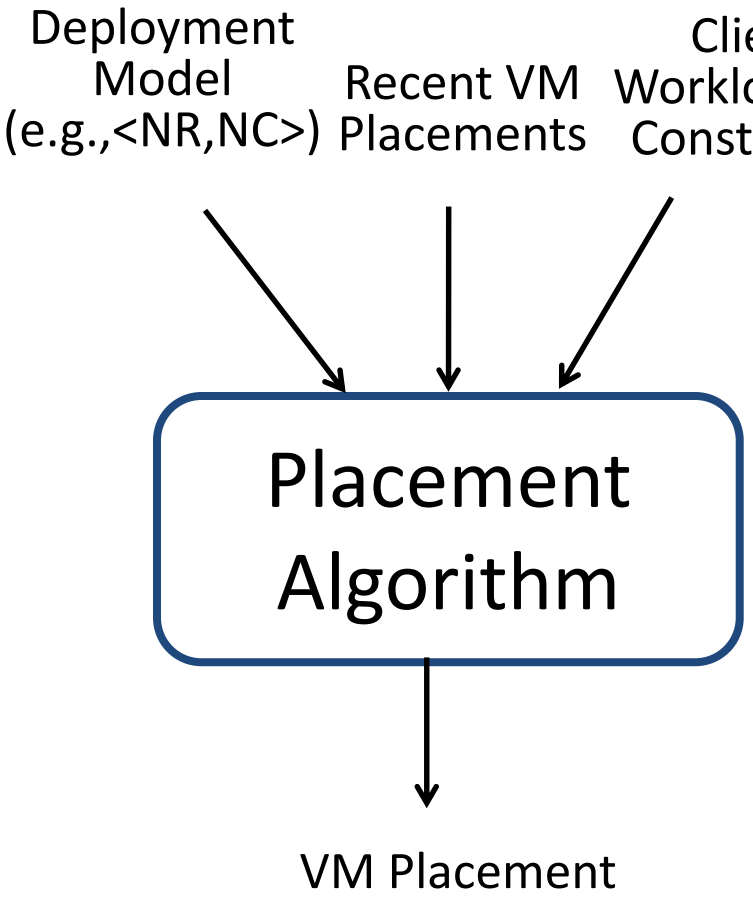


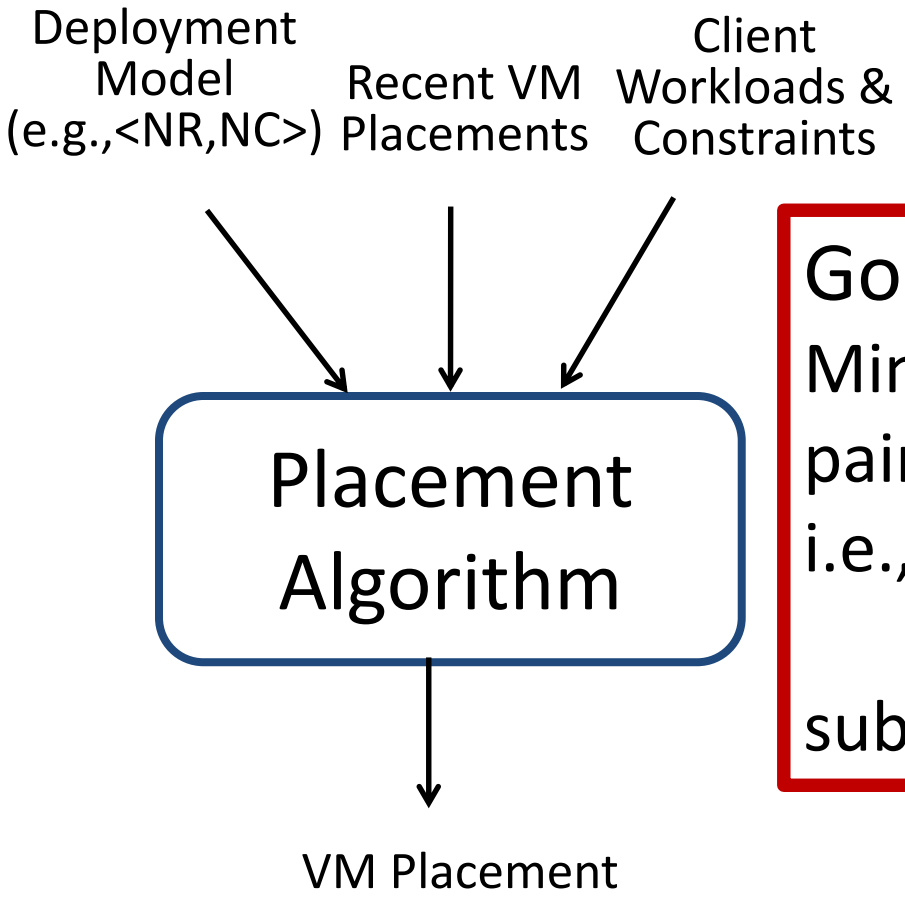
Goal (per epoch):

Minimize a *global* sum of a client-pair InfoLeak across past Δ epochs

i.e., $\sum_{c,c'} InfoLeak_{c \to c'}([t-\Delta, t])$

subject to a fixed migration budget

Placement Algorithm



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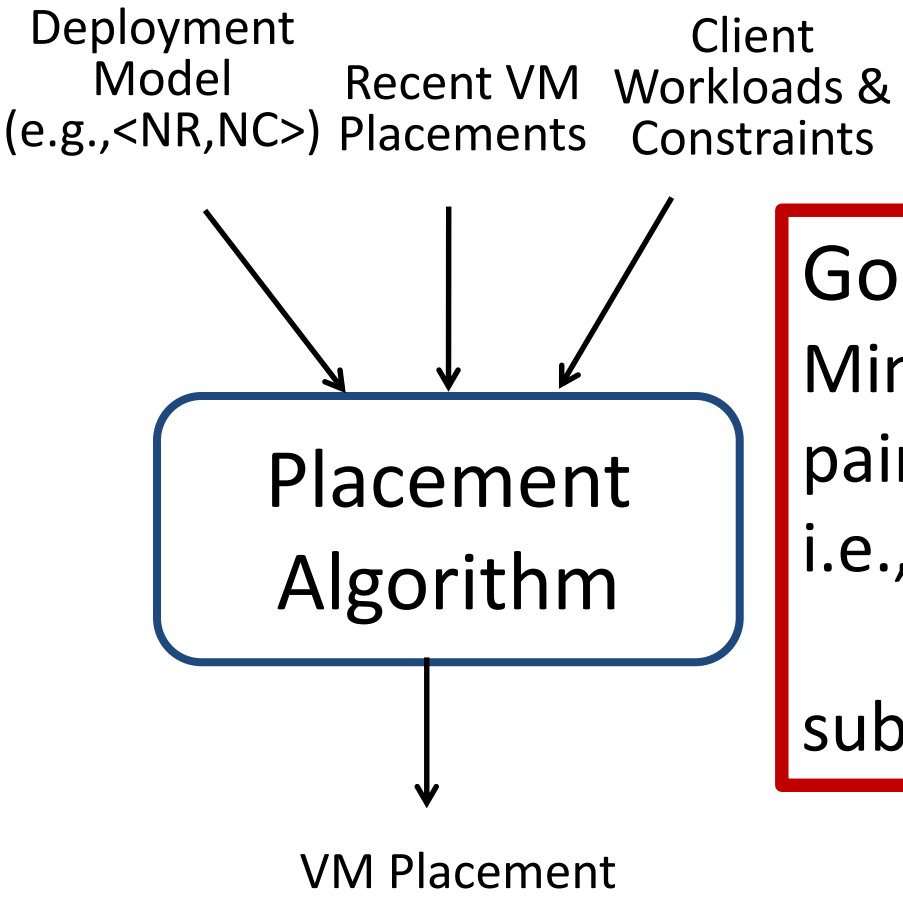

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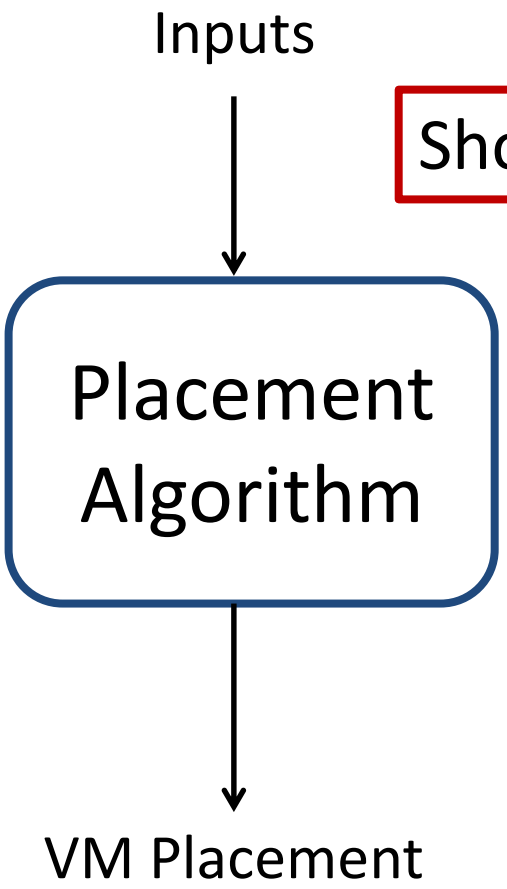
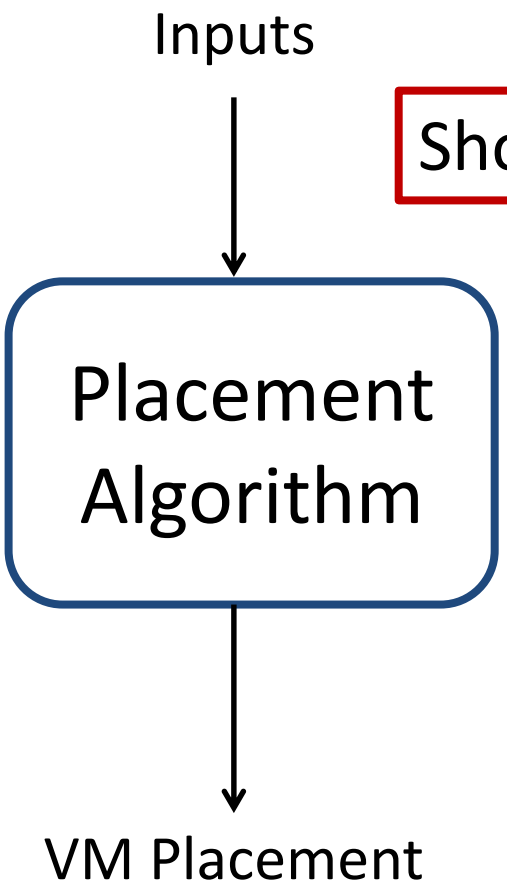
F(Network Capacity)

Challenge: Scalability



Should handle tens of thousands of servers

Challenge: Scalability



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- ILP (Integer Linear Programming)

For 40 machines, D > 1 day

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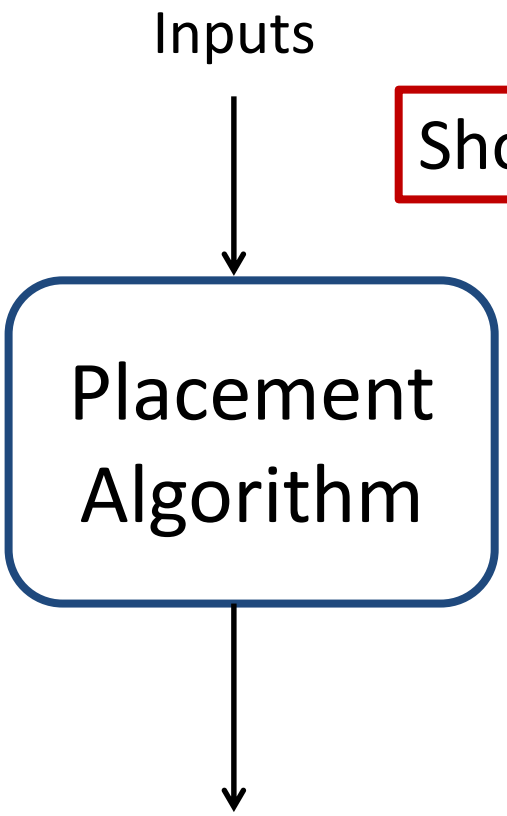

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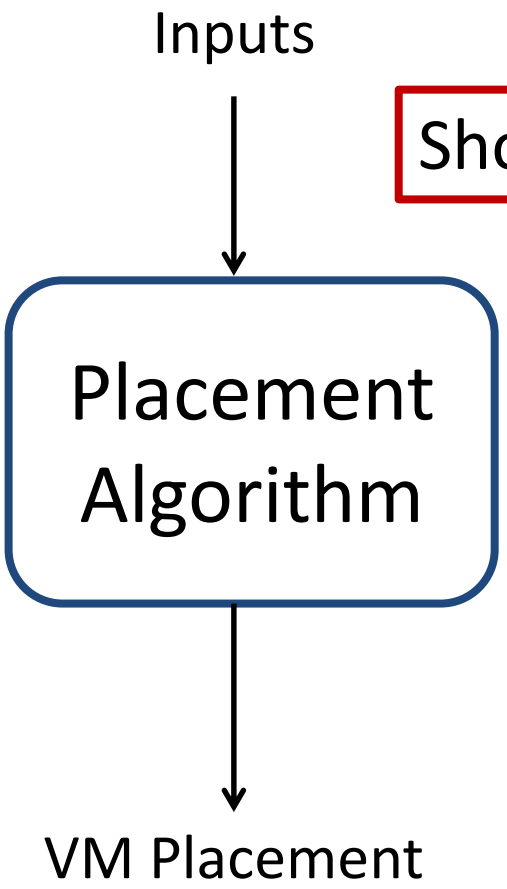

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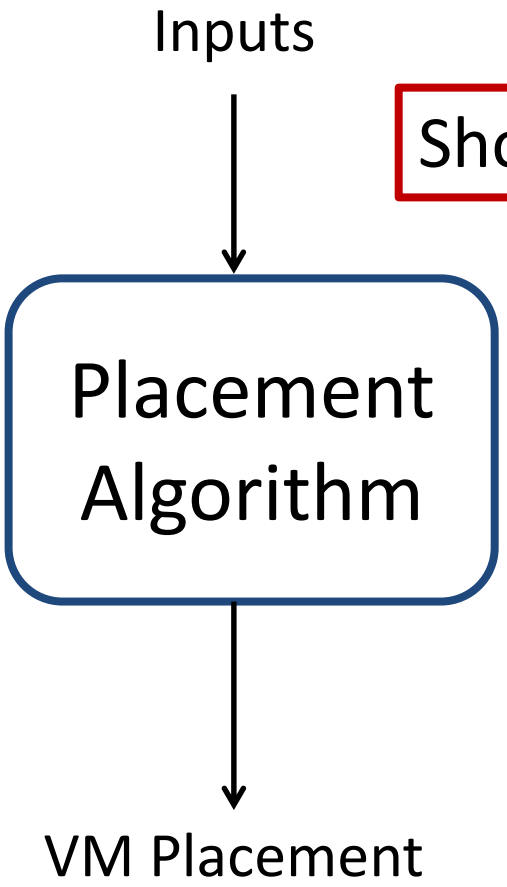

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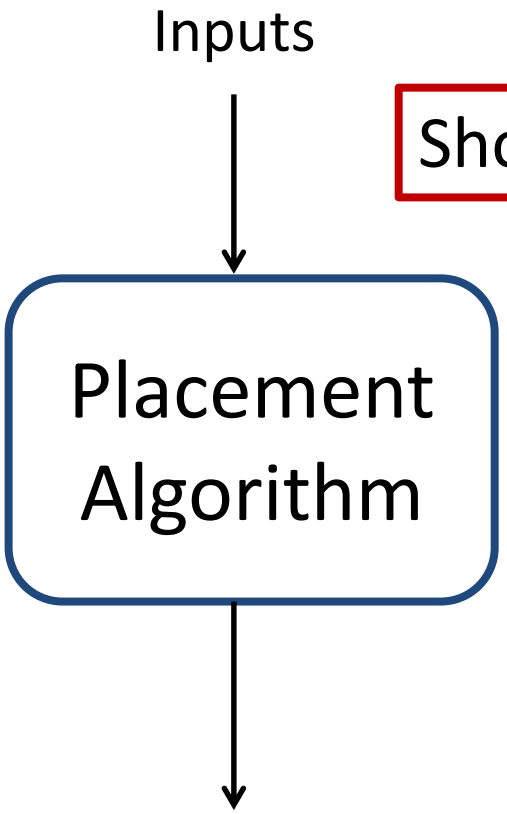

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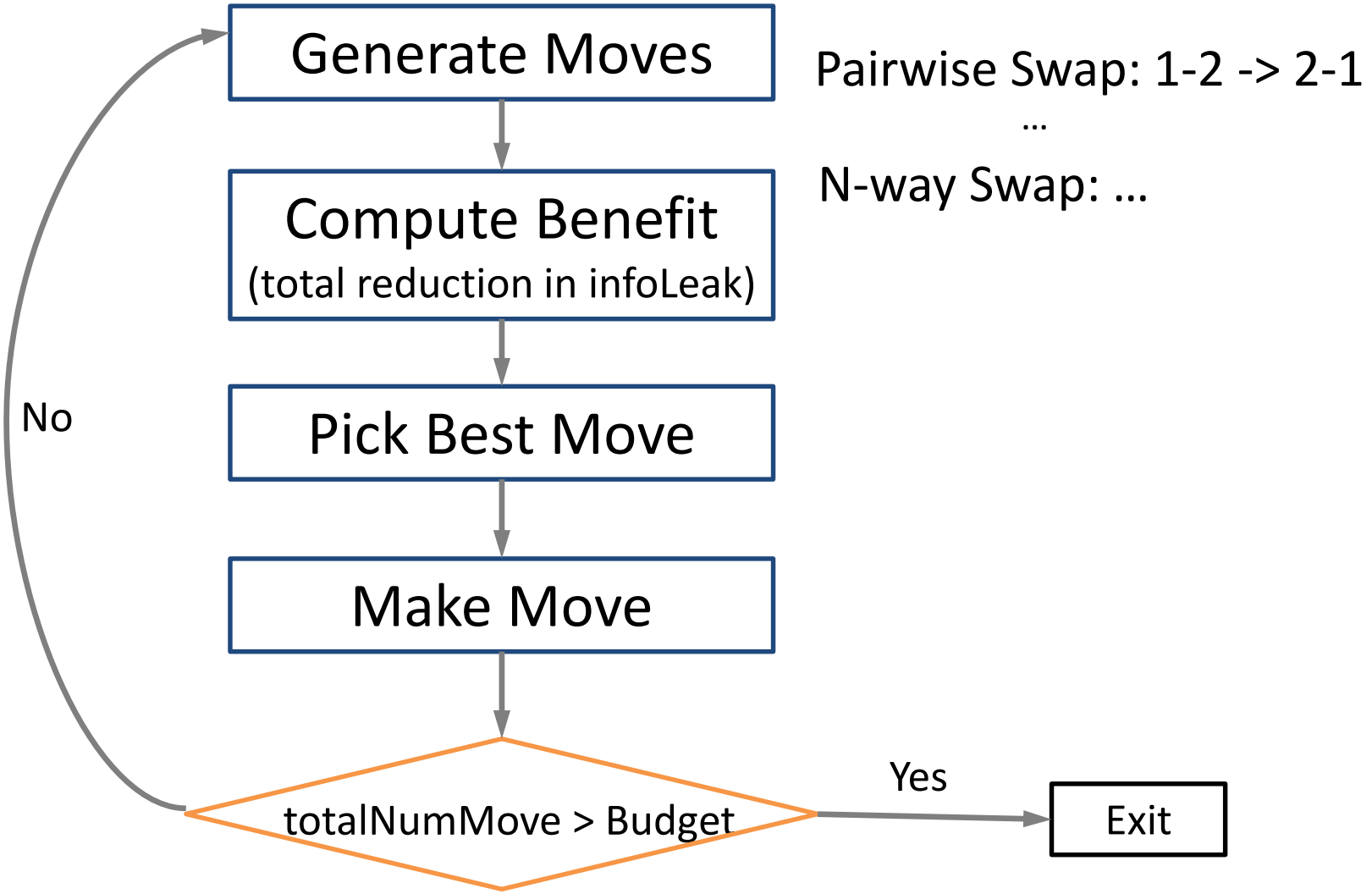
- Basic Greedy with our optimizations

Why is Basic Greedy not scalable?



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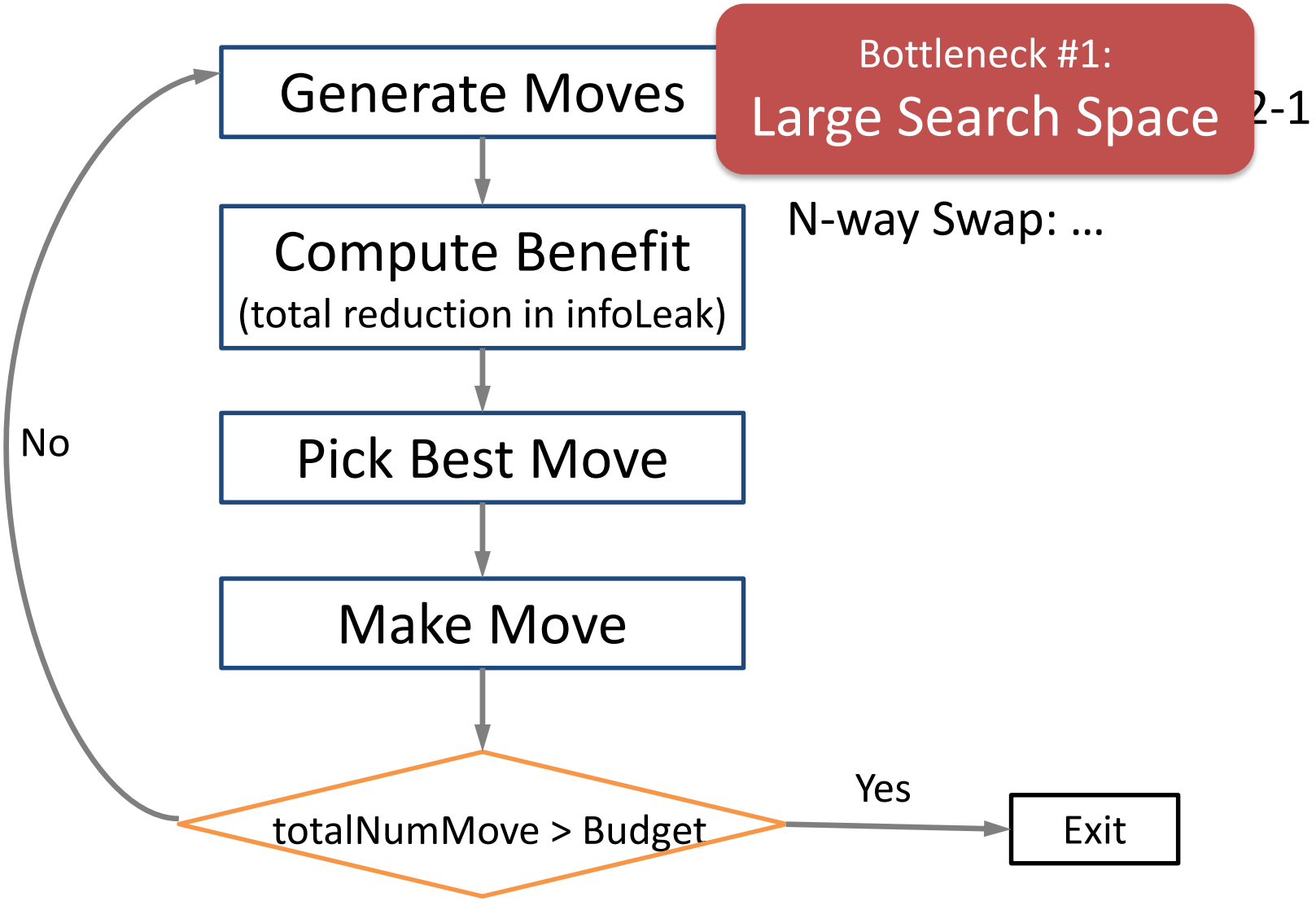

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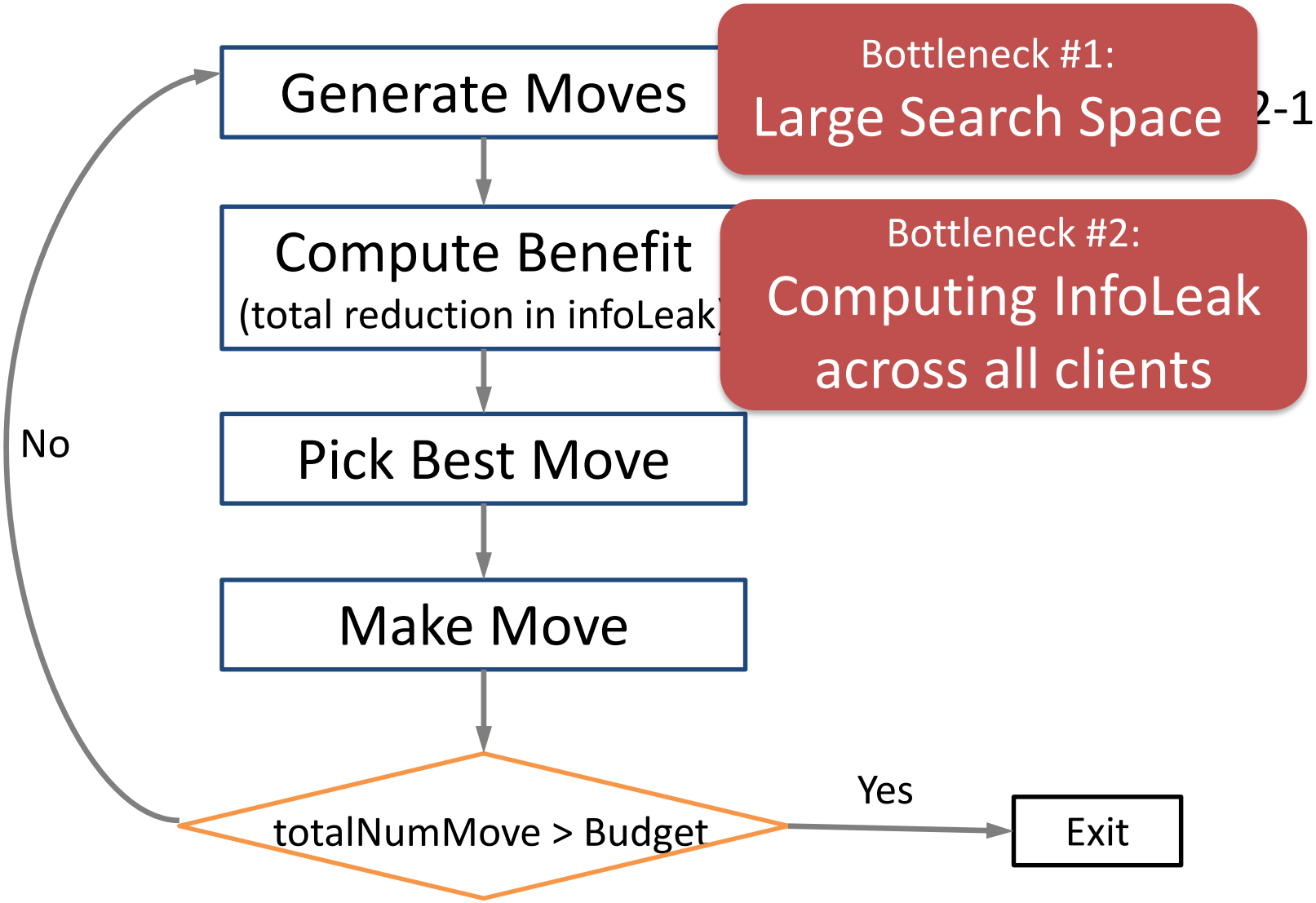

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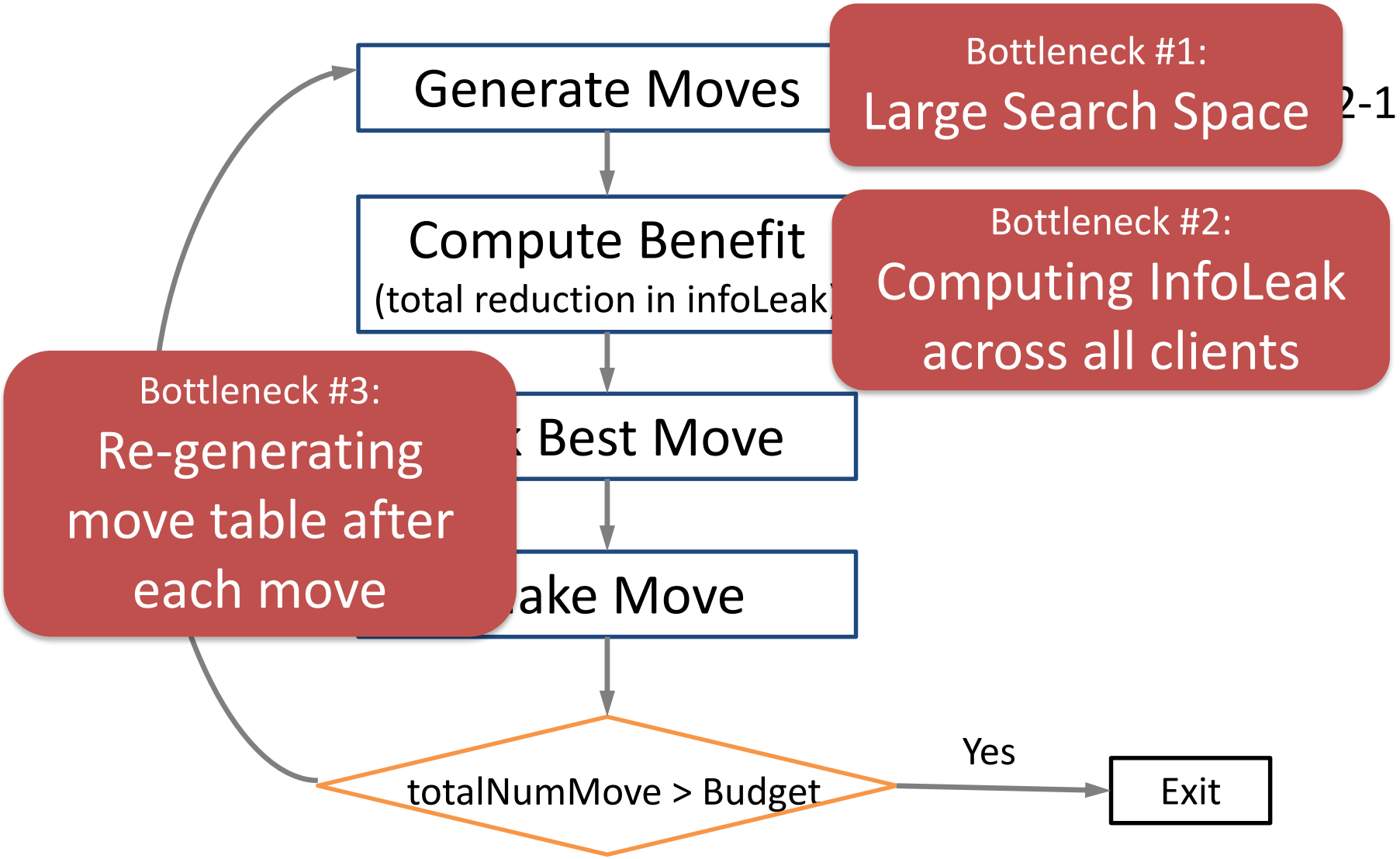
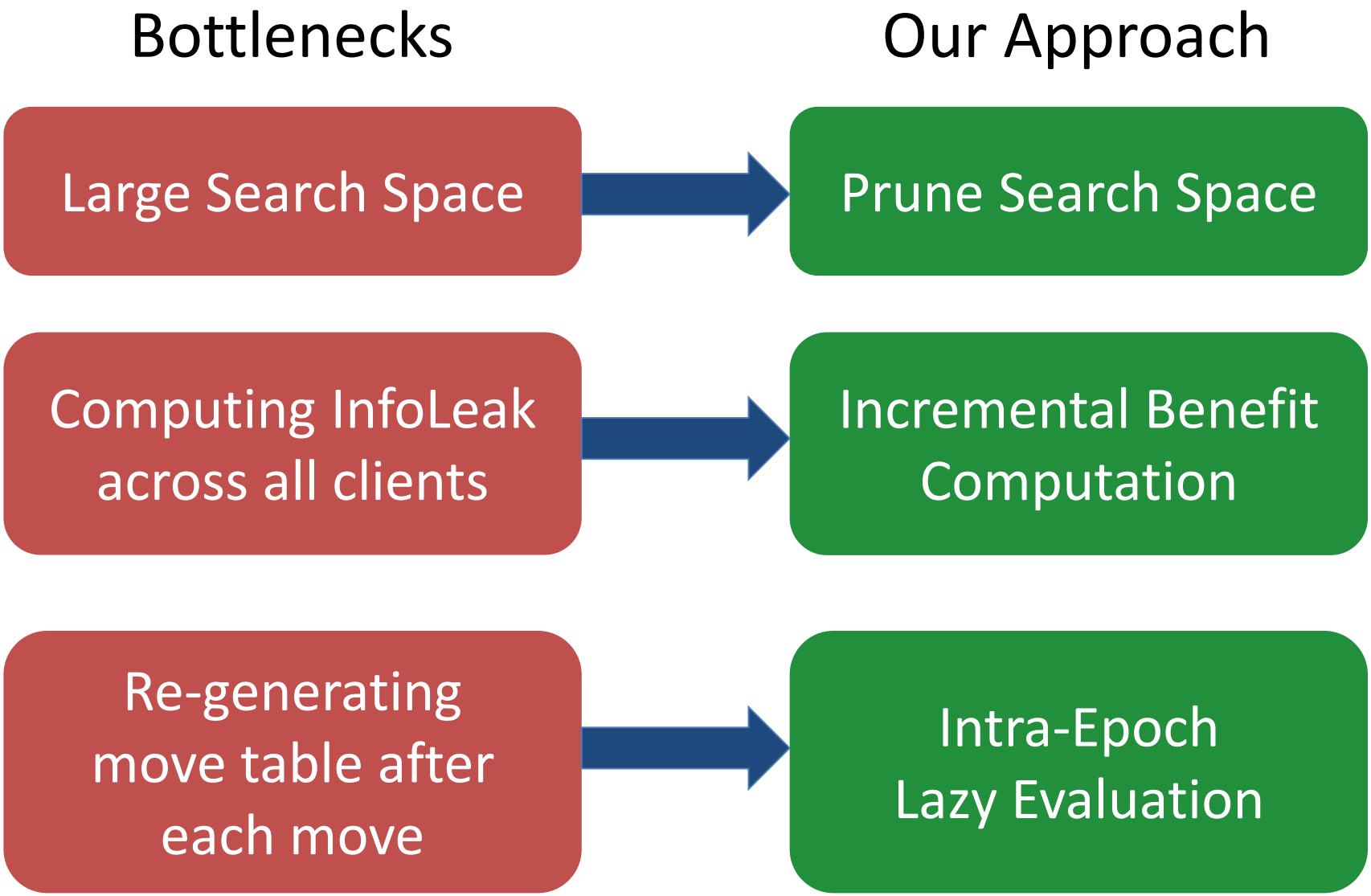


Our Approach



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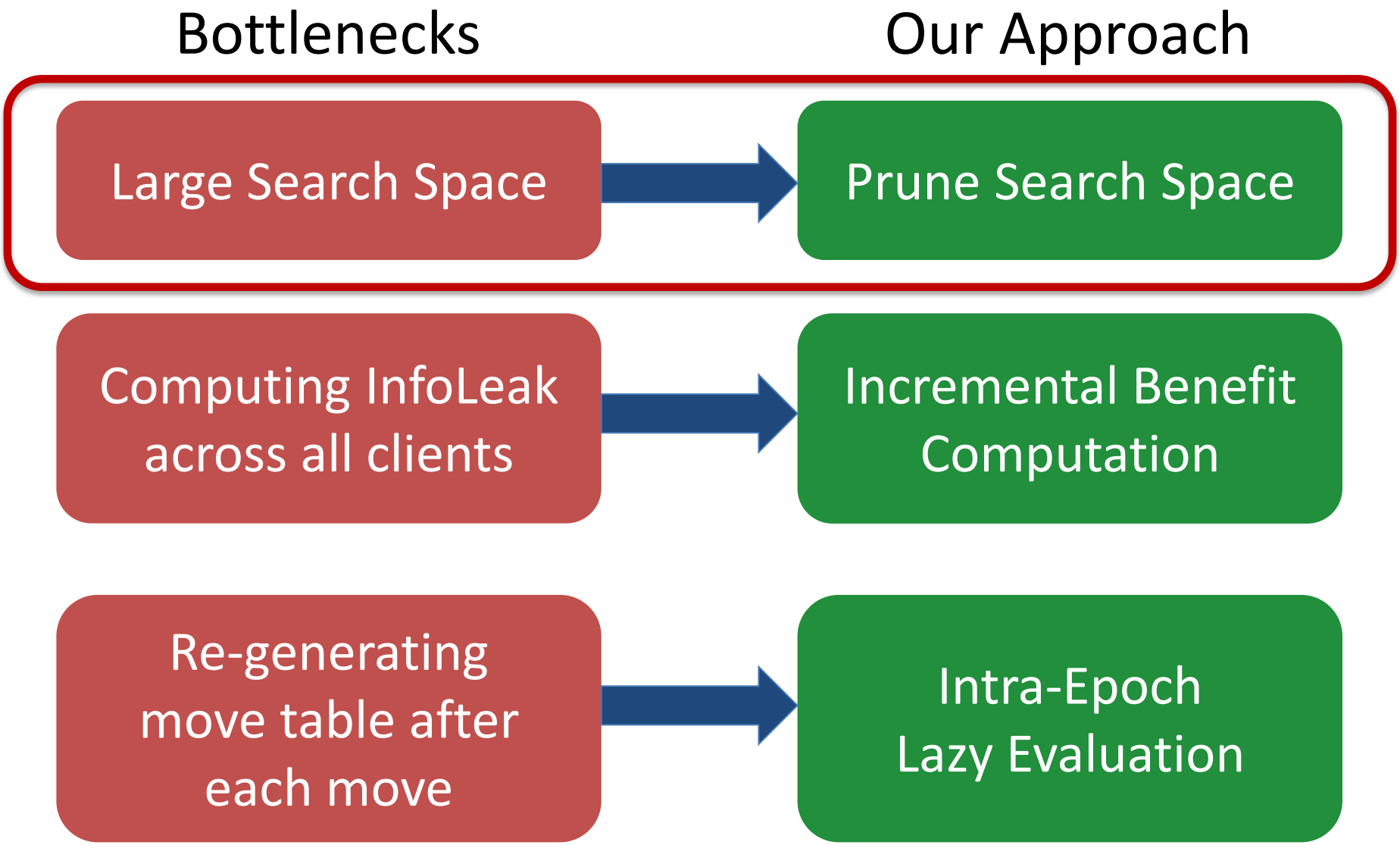
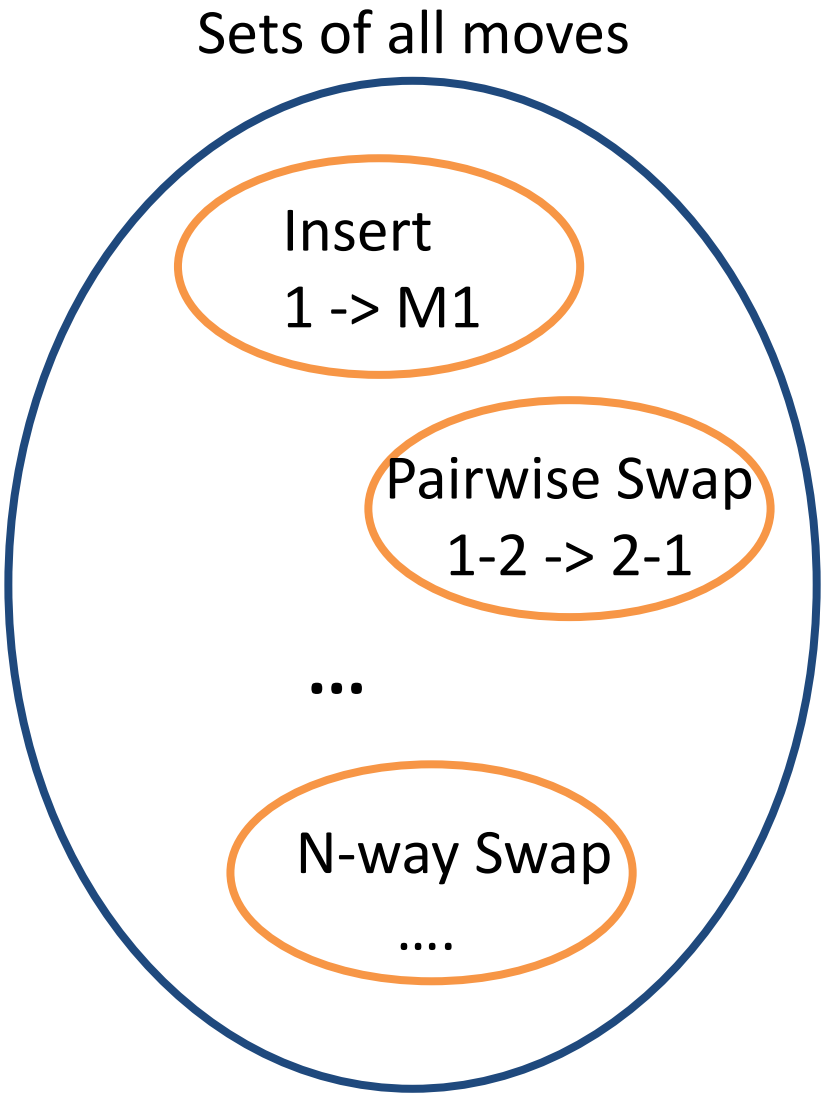


Prune #1: Pruning Move Space



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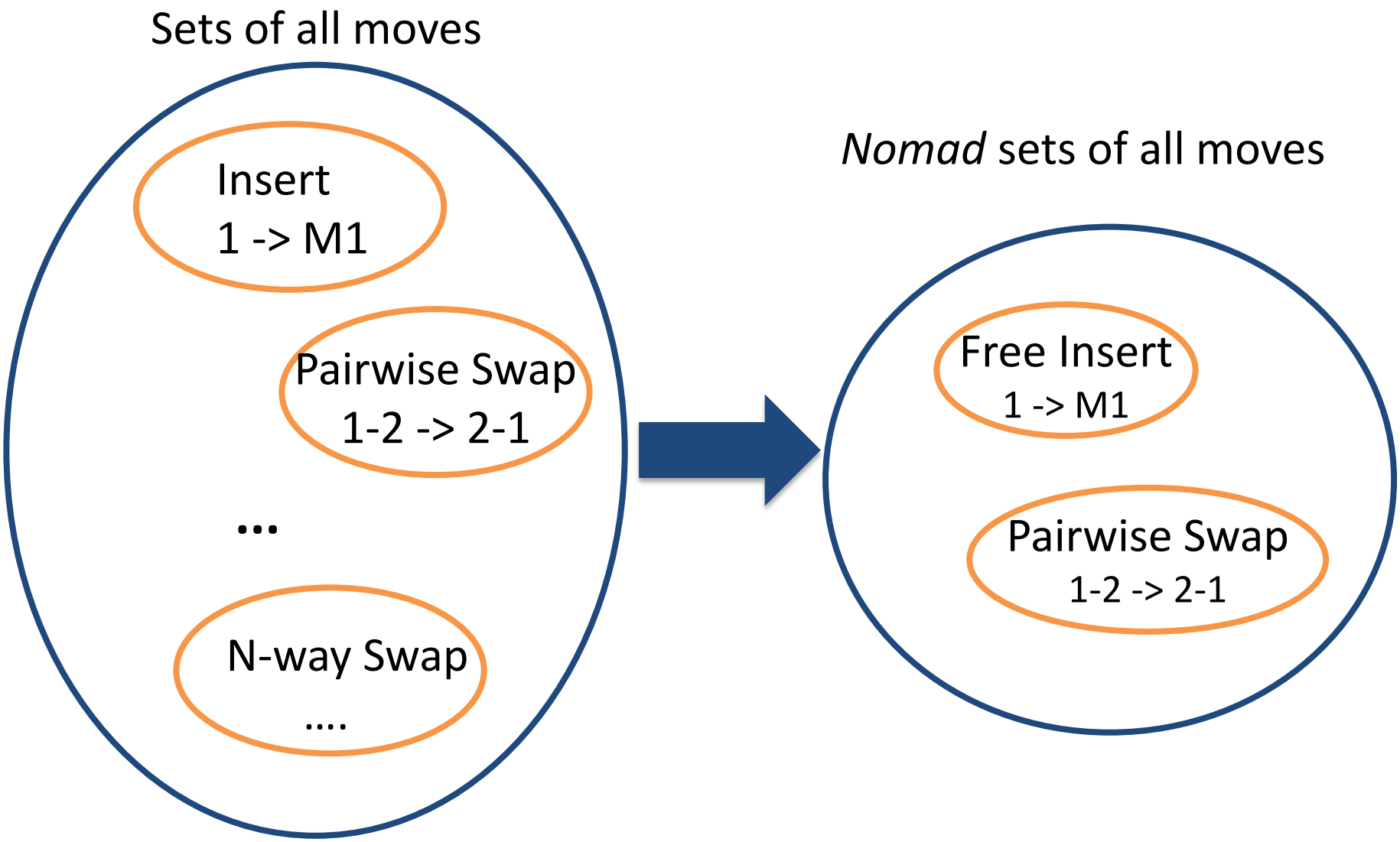
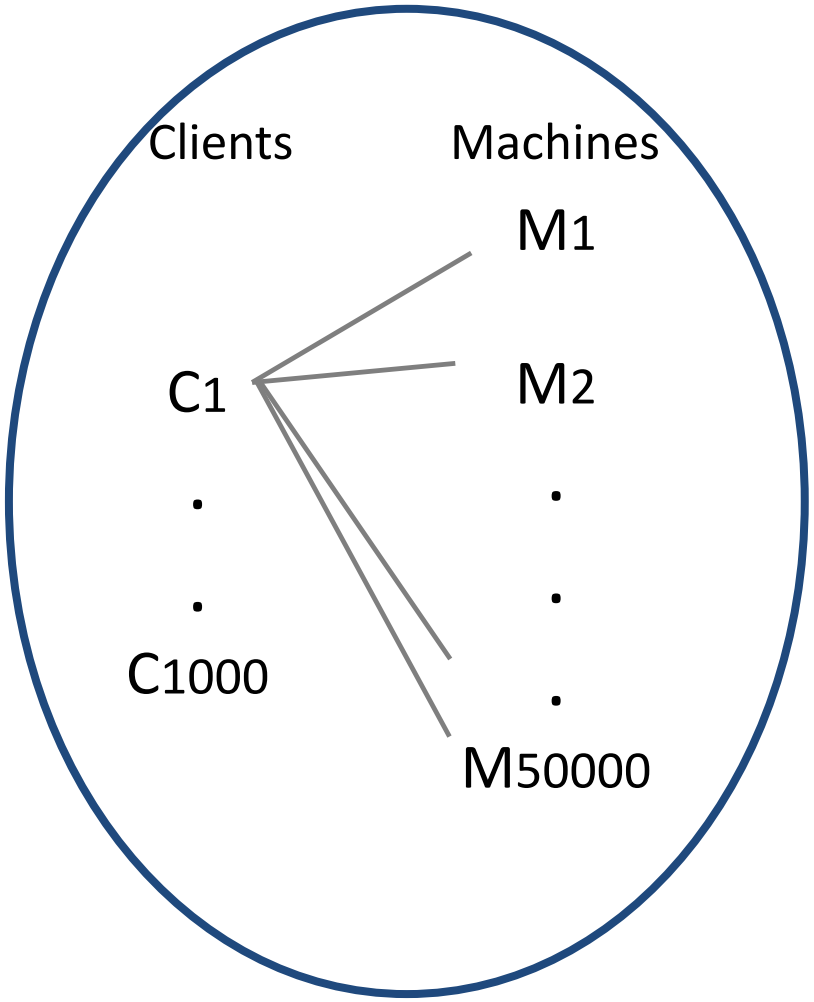


Prune #2: Hierarchical Decomposition

Sets of all free inserts



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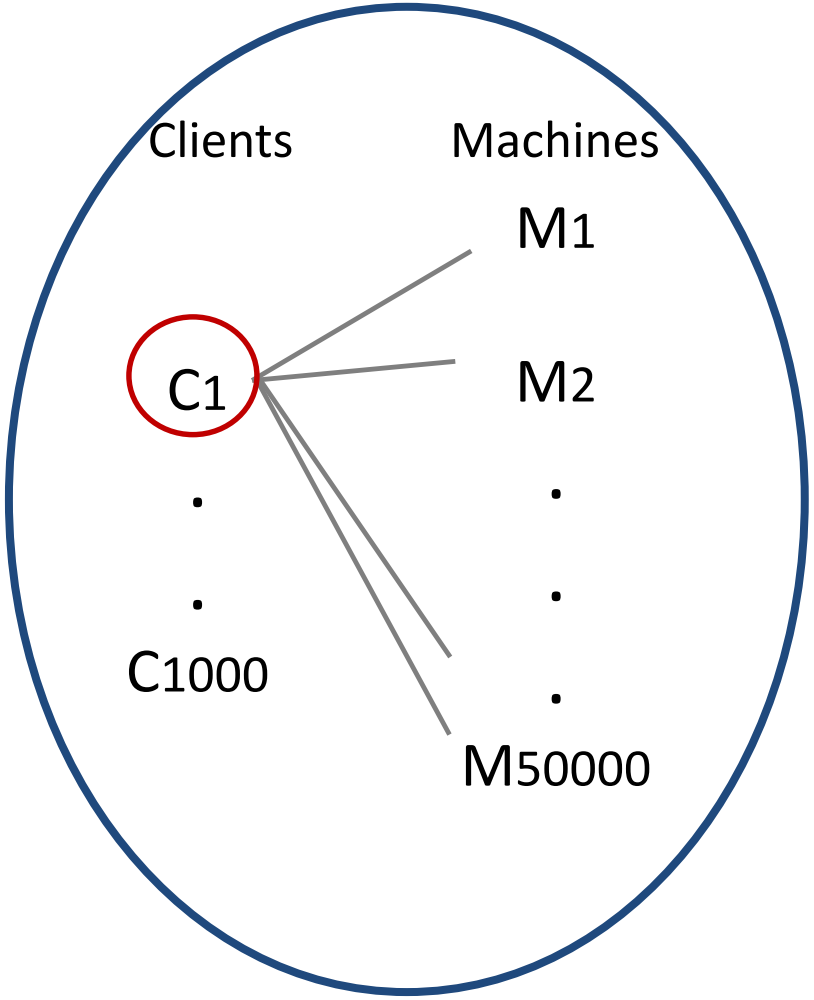

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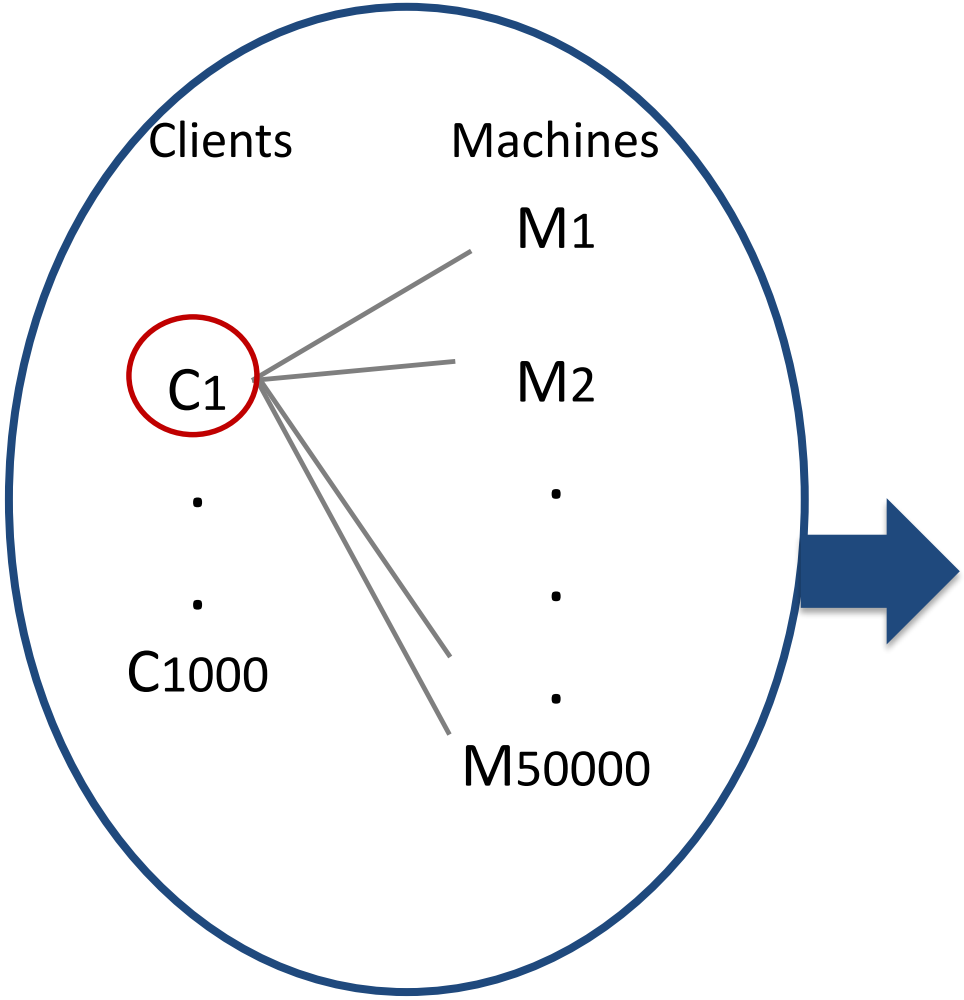
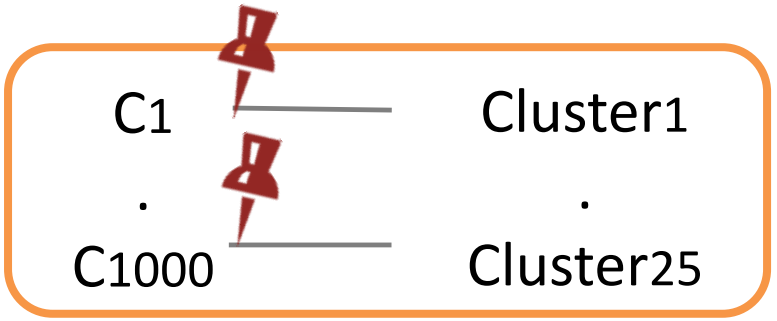
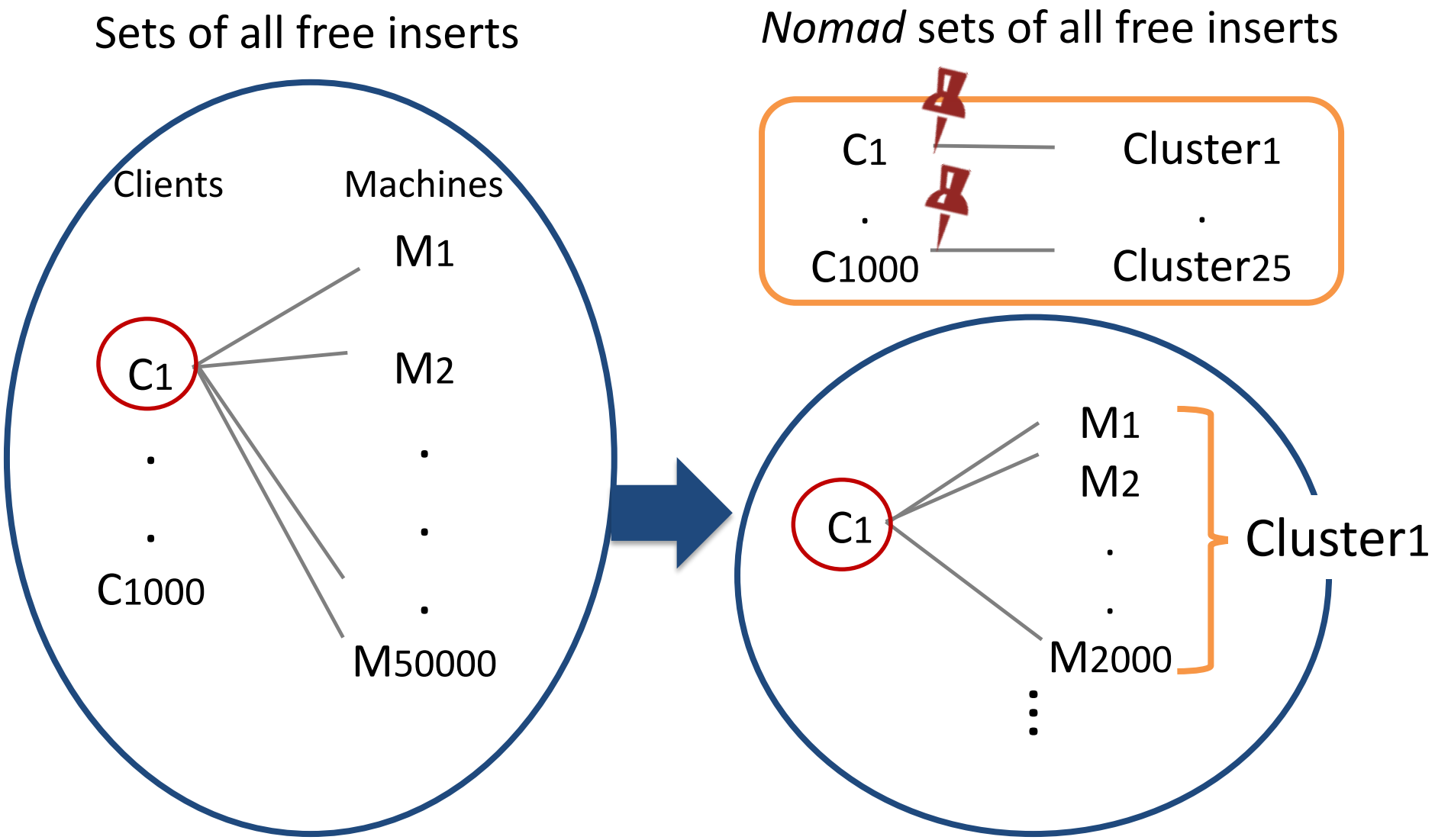


Nomad sets of all free inserts



Prune #2: Hierarchical Decomposition



Our Work

1. Idea

General side-channel defense via migration

2. Logic

Characterize information leakage due to co-residency

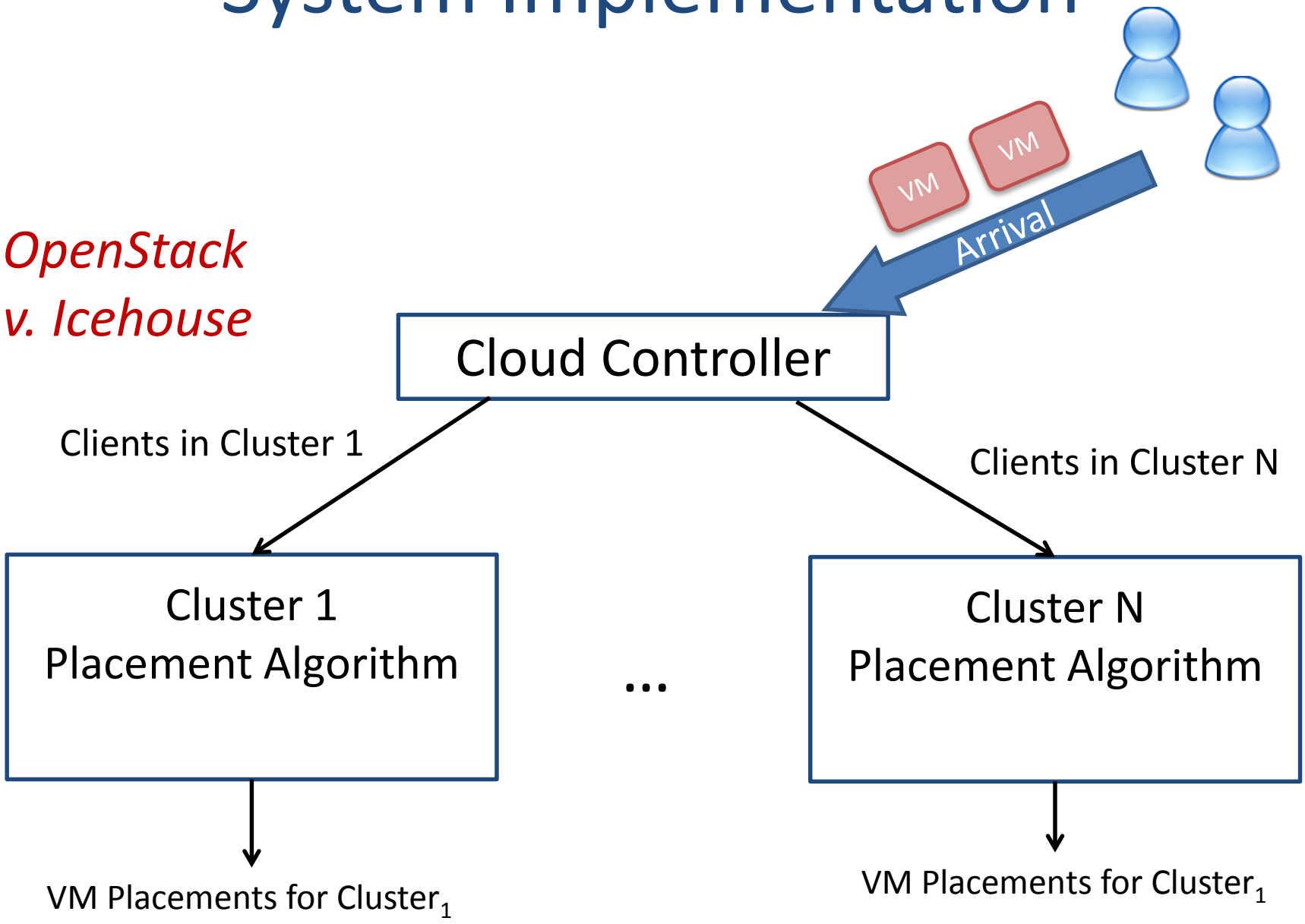
3. Scalable Design

Scalable VM migration strategy that can handle large cloud deployments

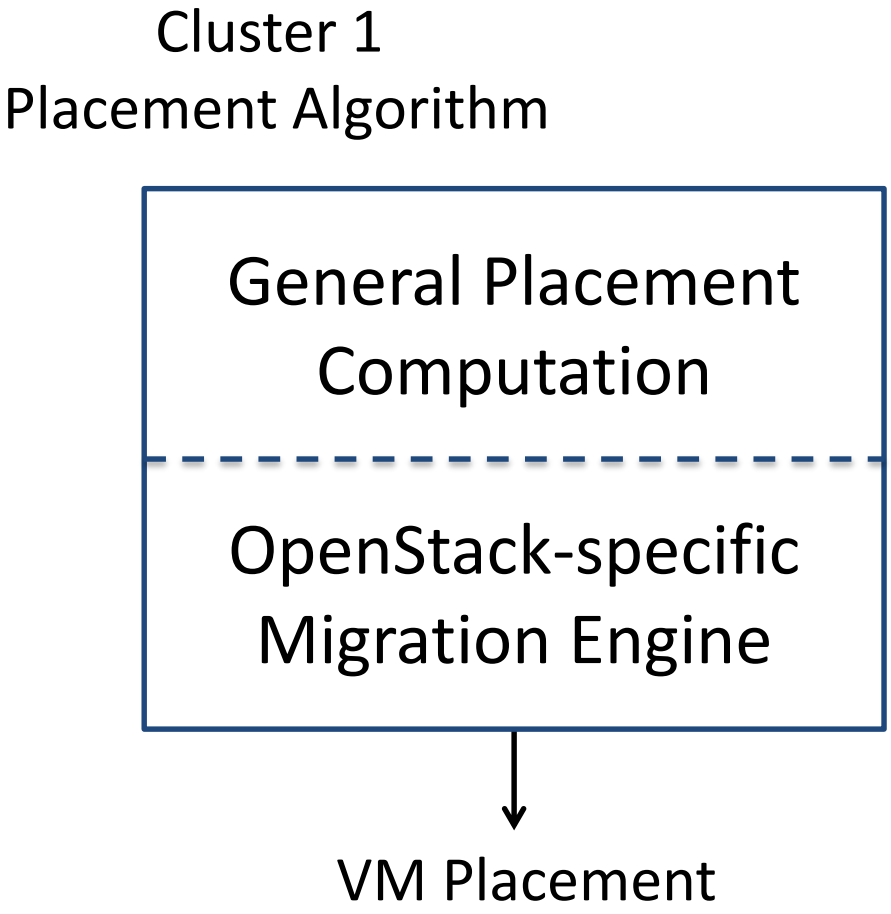
4. Practical Impact

Practical OpenStack implementation with minimal modifications

System Implementation



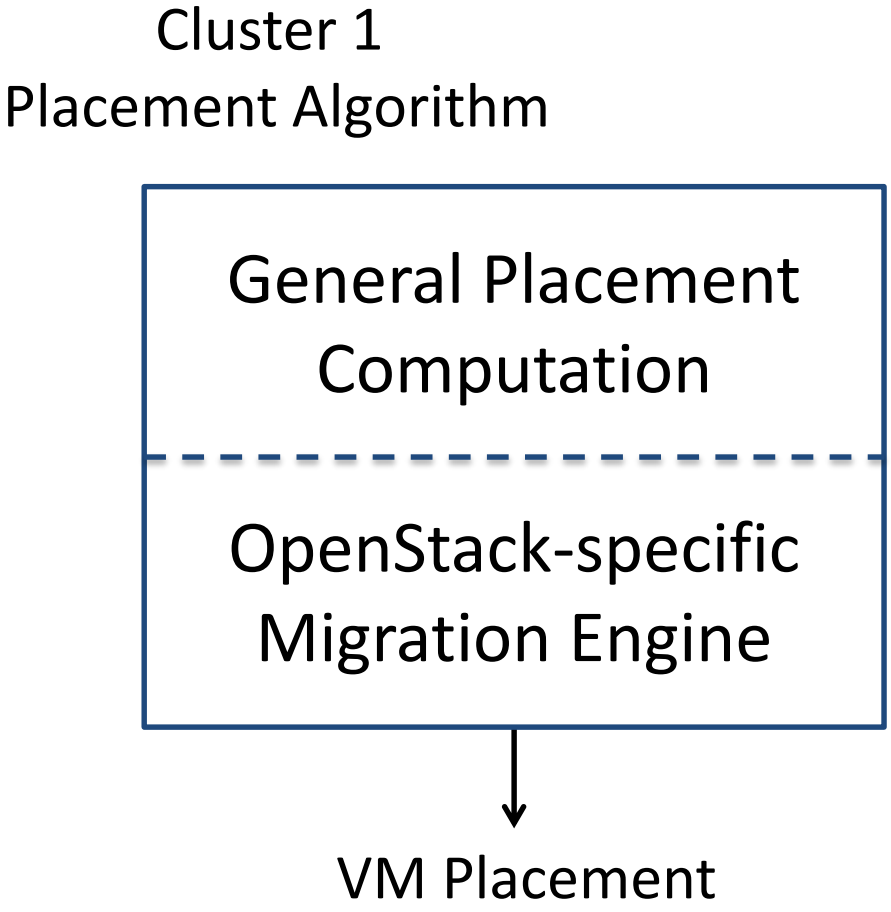
System Implementation (One Cluster)



Custom C++
~2000 LOC

OpenStack Icehouse:
~200 LOC in Controller Scheduler code

System Implementation (One Cluster)



Custom C++
~2000 LOC

OpenStack Icehouse:
~200 LOC in Controller Scheduler code

Requires minimal modifications to existing deployments

Key Evaluation Questions

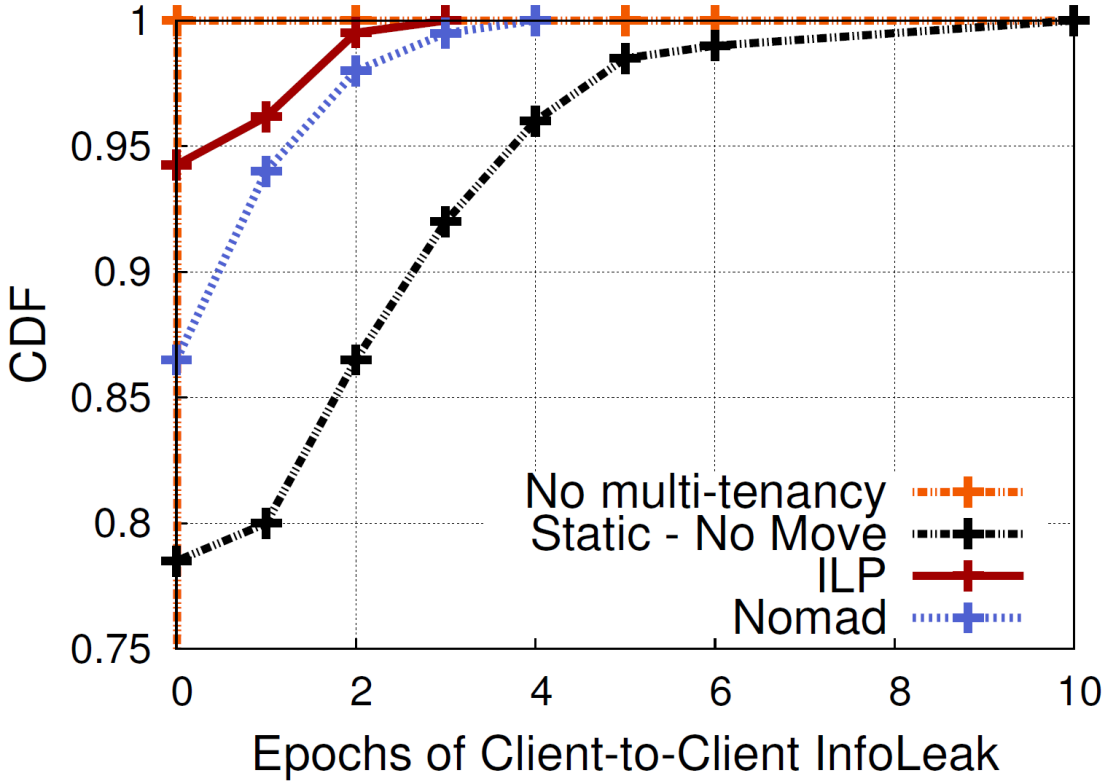
- Information leakage resilience
- Scalability
- Impact on cloud applications
- Benefit/Cost of each design idea
- Resilience to strategic adversary

Information Leakage resilience

<R,C>: Problem size of 20-machines

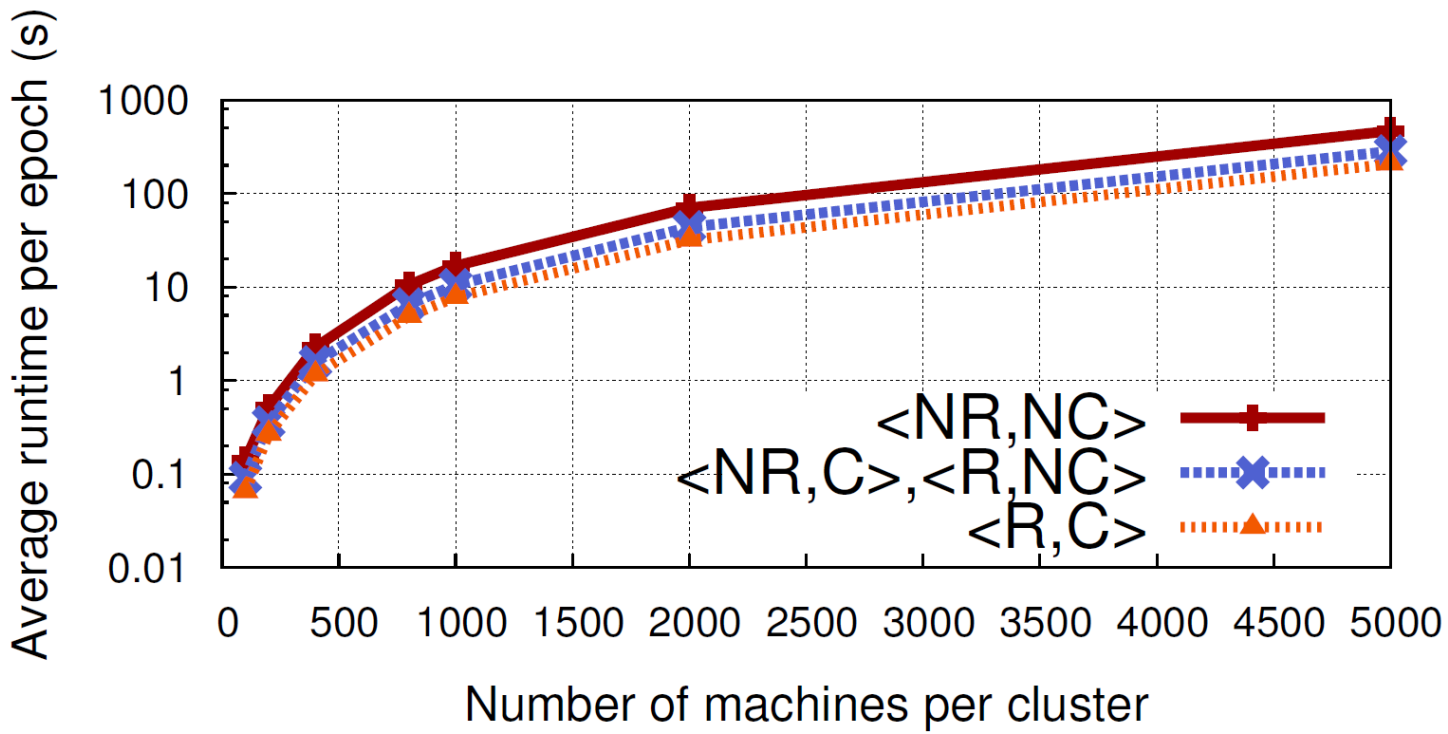
Metric:

$InfoLeak_{c \rightarrow c'}([t-\Delta, t])$



Nomad brings ~4.5x reduction in InfoLeak for 98th percentile compared to static w.r.t. ILP.

Scalability



Nomad placement algorithm is scalable to large deployments

Impact on cloud applications

Replicated web-server (Wikibench)

- Each client : 3 replicated web servers, 1 worker
  - In one epoch, *at least* 1 server migrates

$$Norm.Throughput\ (Norm.T) = \frac{T_{w/o} - T_w}{T_{w/o}} x\ 100$$

- Overhead (Norm. T)
  - ~0% for 95th Norm T.
  - 0.096% for 50th (median) Norm. T.
  - 1.8% for 5th Norm. T

Discussion

- Fast side-channel attacks
  - Need out-of-band defense
  - e.g., introduce cache noise, refresh secret
- Network Impact
  - With techniques like incremental diffs, the transfer size is much less than base VM image
- Incentives for adoption
  - Security-conscious clients opt-in
  - Providers have new revenue streams
- More opportunities
  - Fairness across clients

Conclusions

- Co-residency side-channel attacks: real/growing threats

Current World : 

No Migration

1. Per-attack fixes
2. Require significant upgrades

Nomad: 

"Migration-as-a-Service"

1. General solution
2. Needs minimal changes

- *Nomad* achieves:
  - Information leakage resilience close to the ILP
  - Scalable VM placement algorithm
  - Practical system atop OpenStack with minimal modifications