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

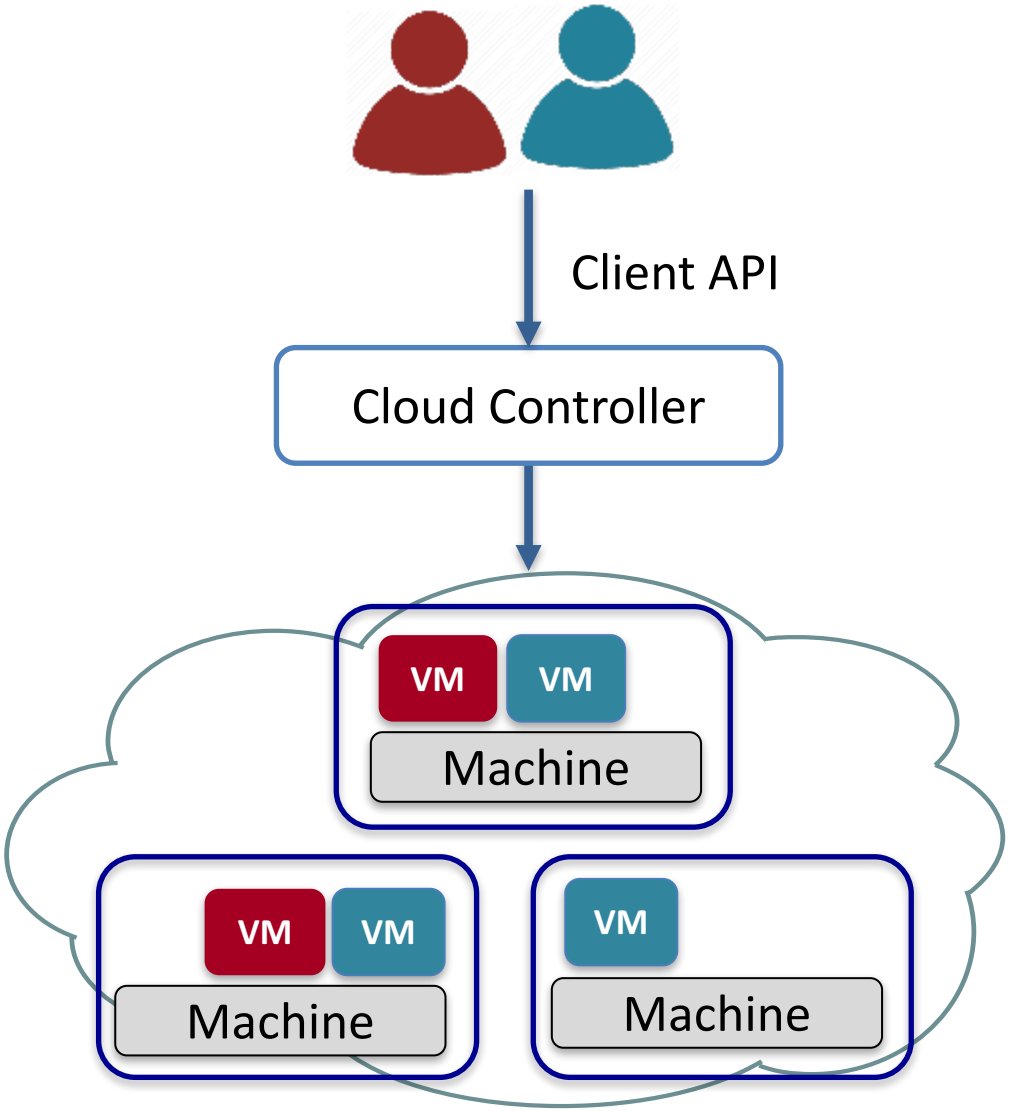
Soo-Jin Moon, Vyas Sekar Michael K. Reiter

Carnegie Mellon University

THE UNIVERSITY of NORTH CAROLINA at CHAPEL HILL

Project Silver

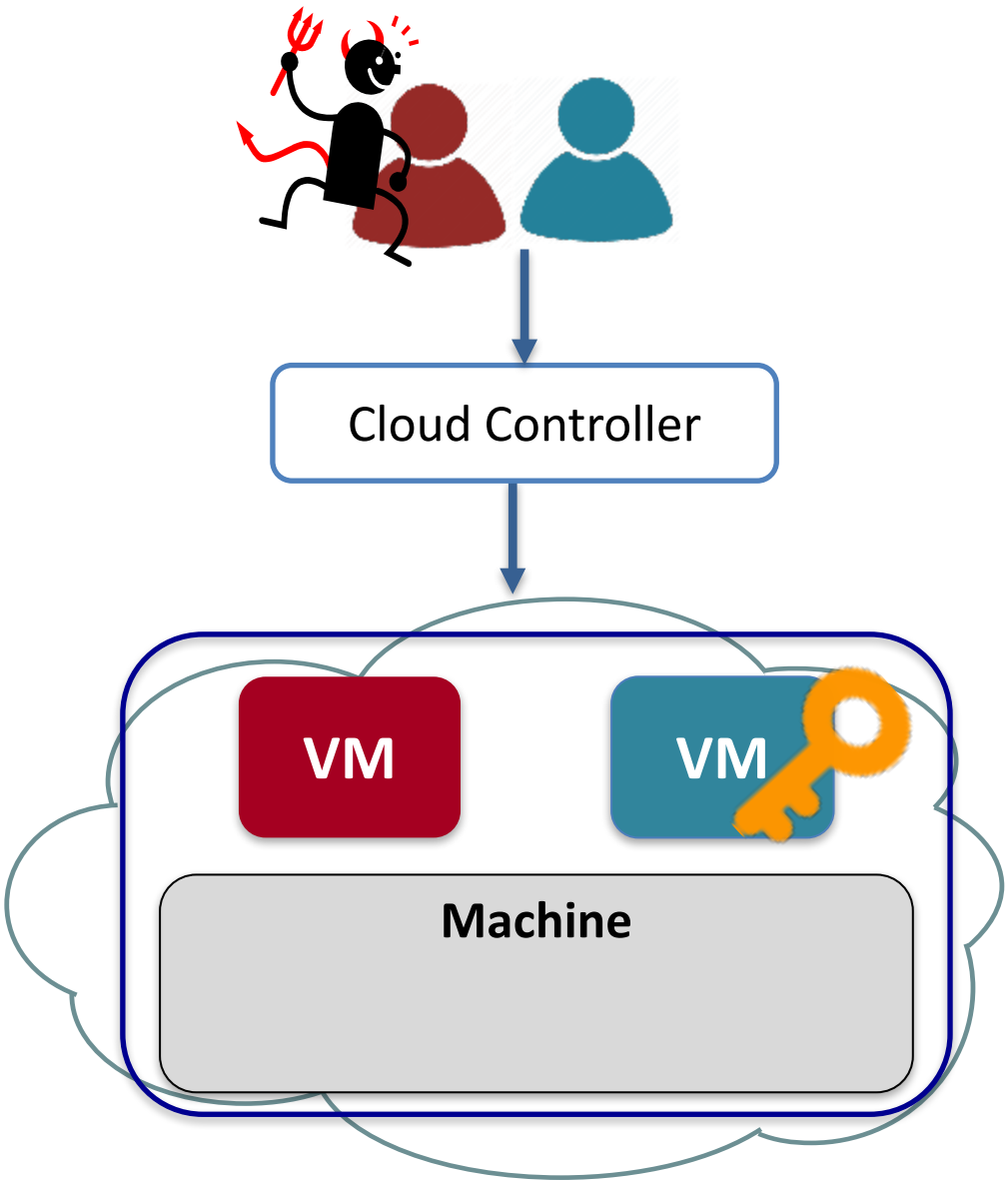
Context: Infrastructure-as-a-Service Clouds



amazon web services™ EC2

Google Compute Engine

Information Leakage via Co-Residency



Co-Residency

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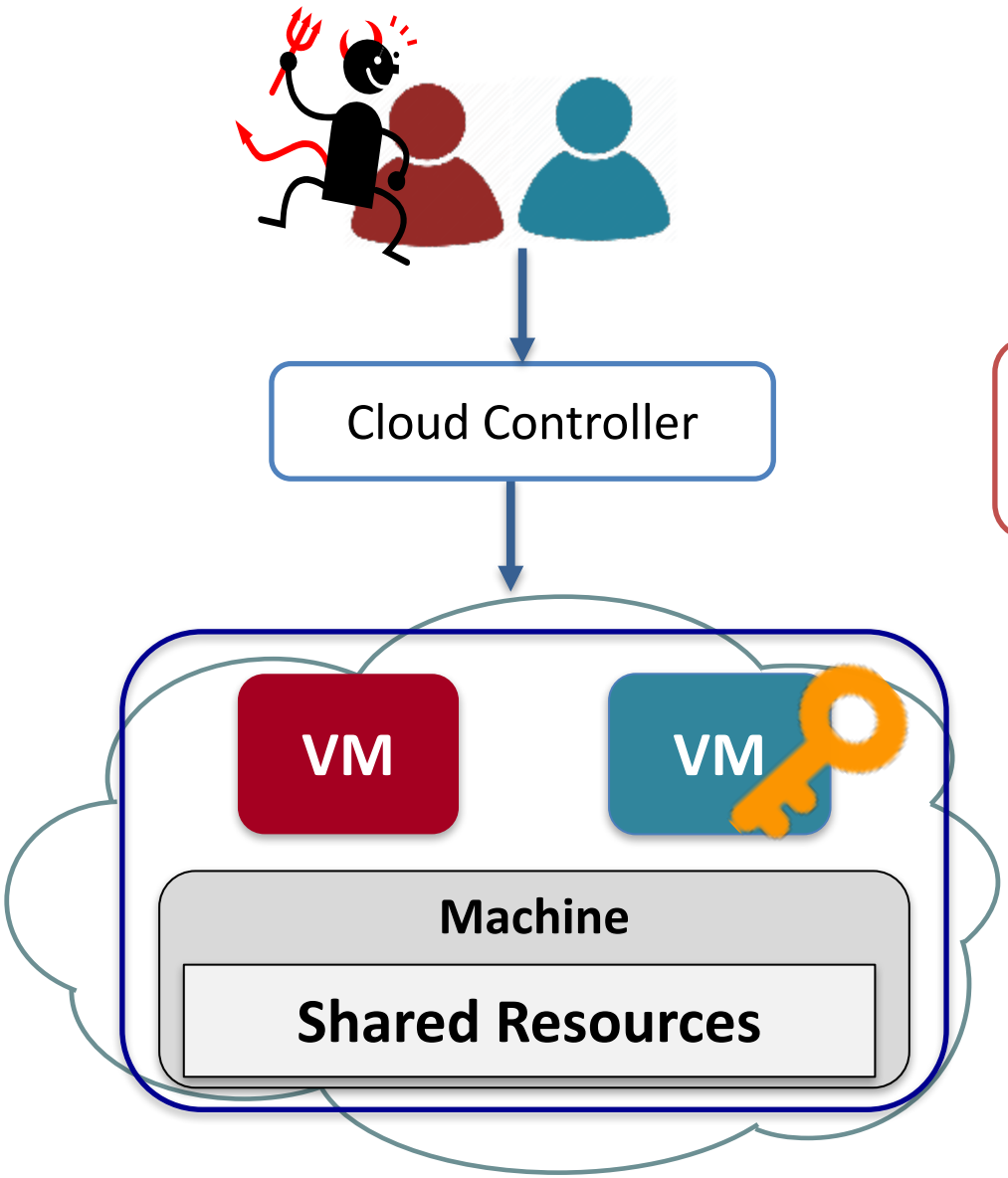

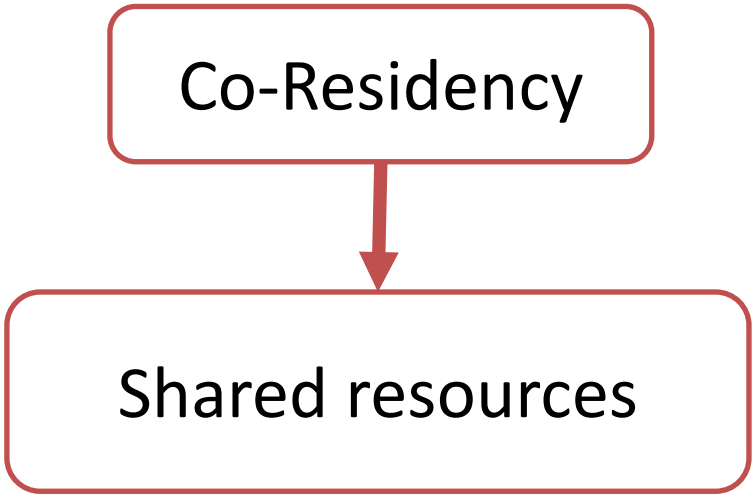

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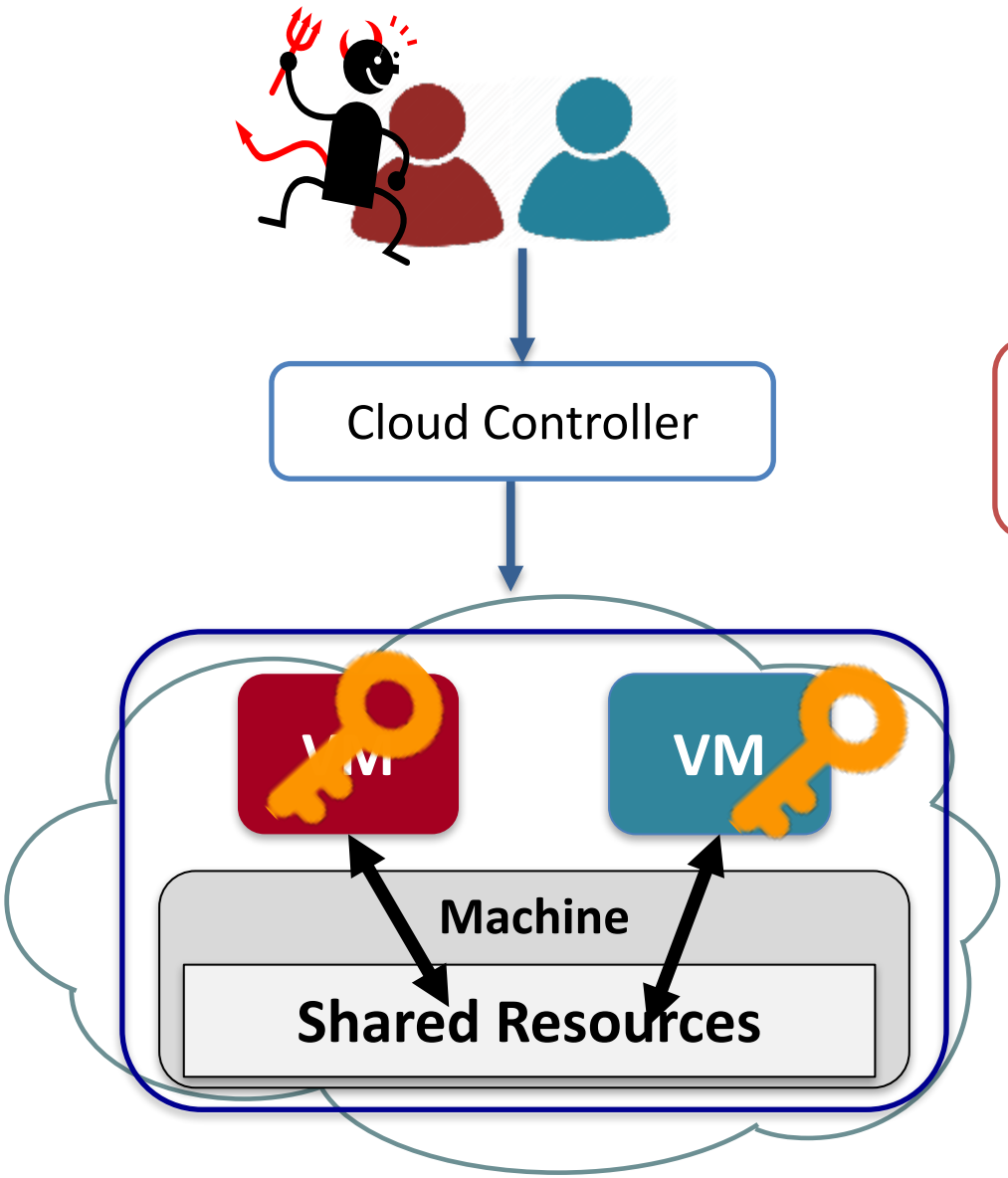

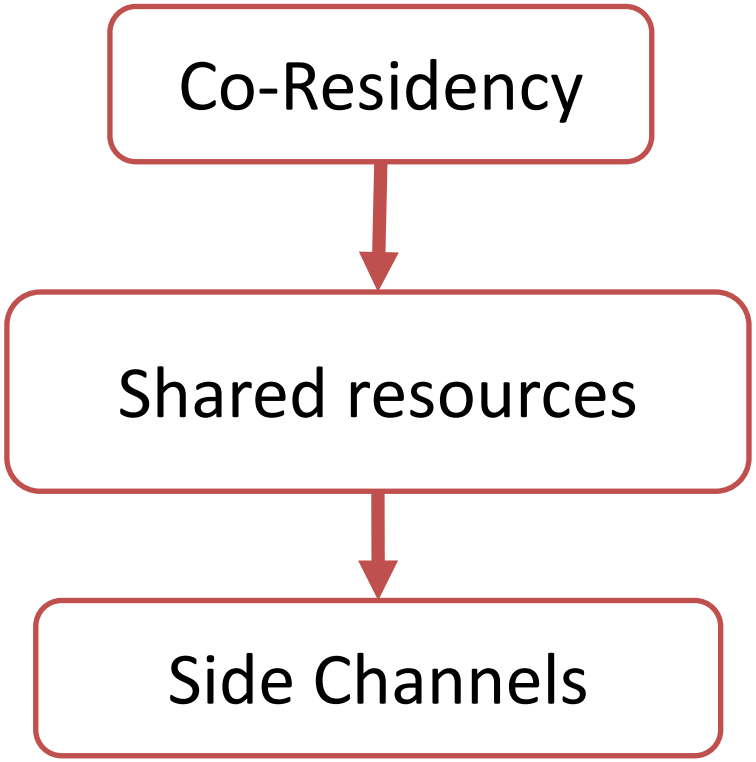

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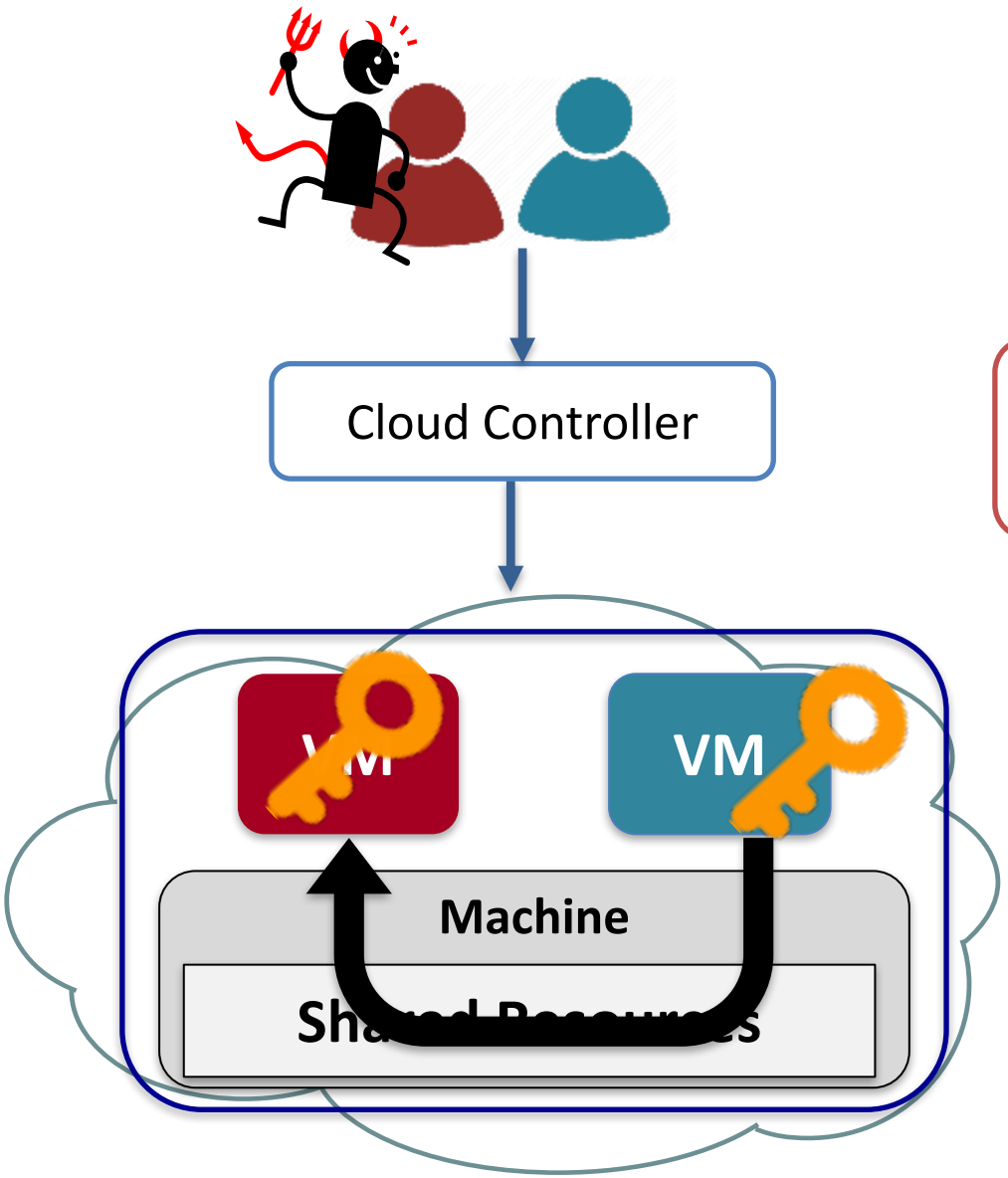


Co-Residency

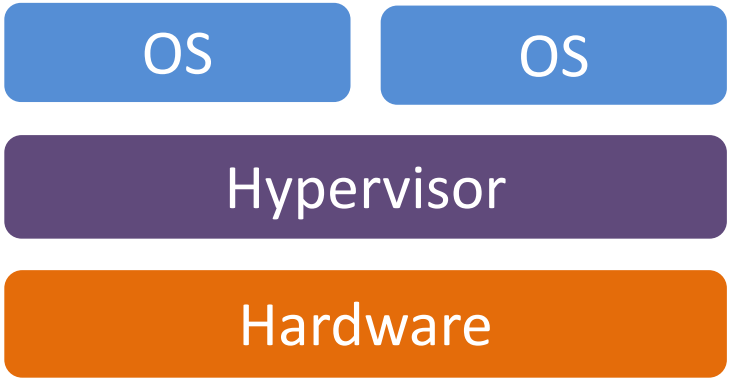
Shared resources

Side Channels

Information Leakage

Limitations of Current Defenses

1. Requires significant/detailed upgrades



e.g., Noise injection

e.g., Deterministic execution

e.g., New cache design

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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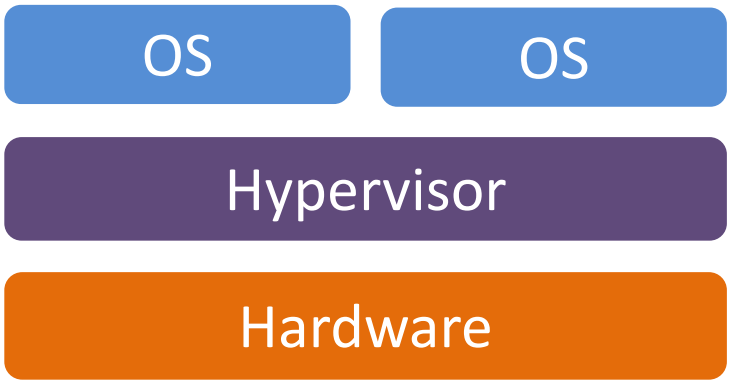

e.g., Noise injection

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2. Attack-specific

What about future side-channel attacks?

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Ideal Properties

1) General

2) Immediately deployable

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Single-tenancy?

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~~Single-tenancy?~~

Nomad Ideas

1) General

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Nomad Ideas

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Tackle root-cause

→ Minimize co-residency

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Nomad Ideas

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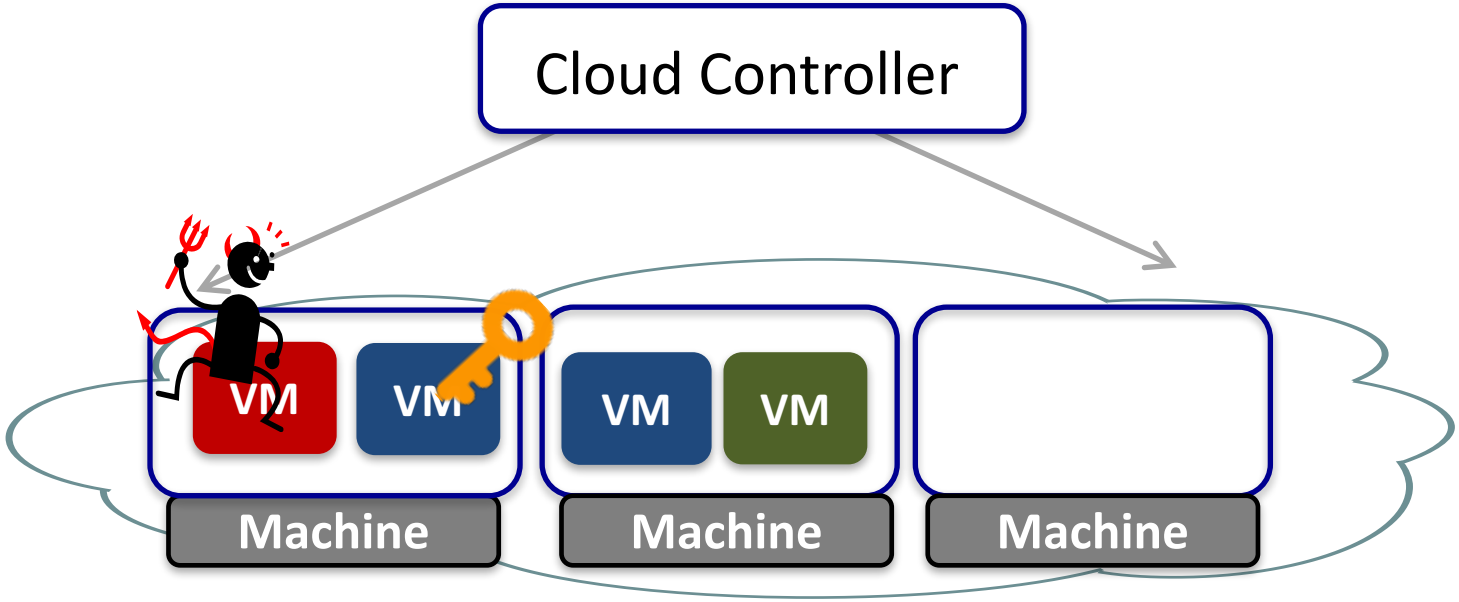
Migration

Nomad Vision: Migration-as-a-Service

- Provider-assisted



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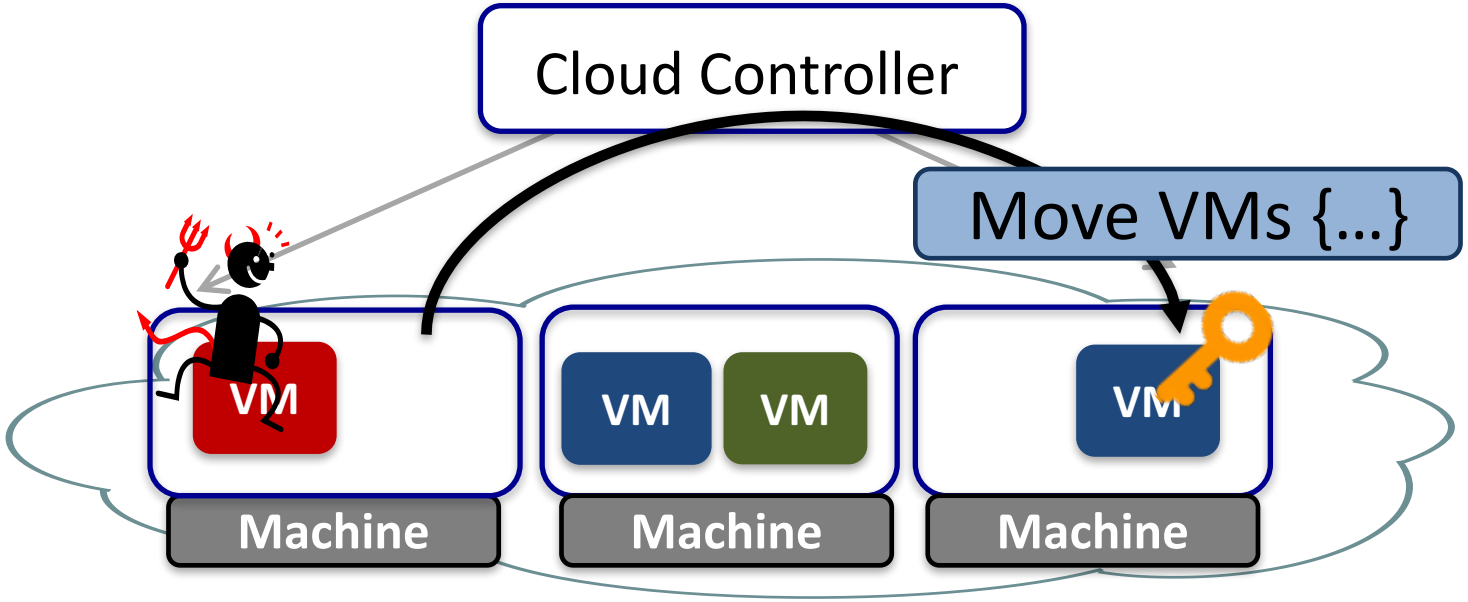
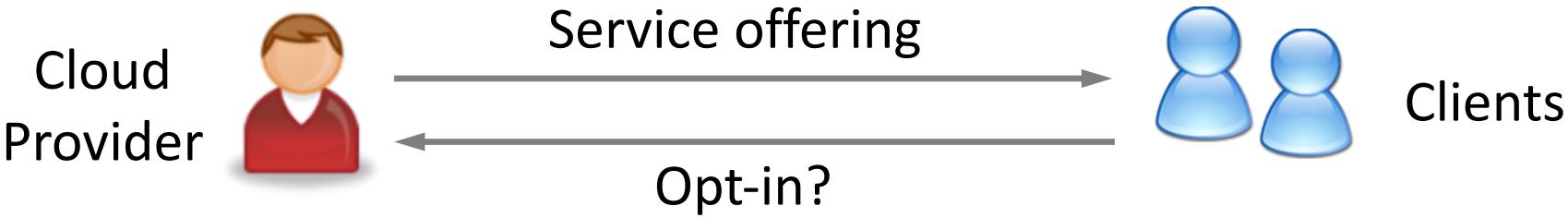


Nomad Vision: Migration-as-a-Service

- Opt-in Service



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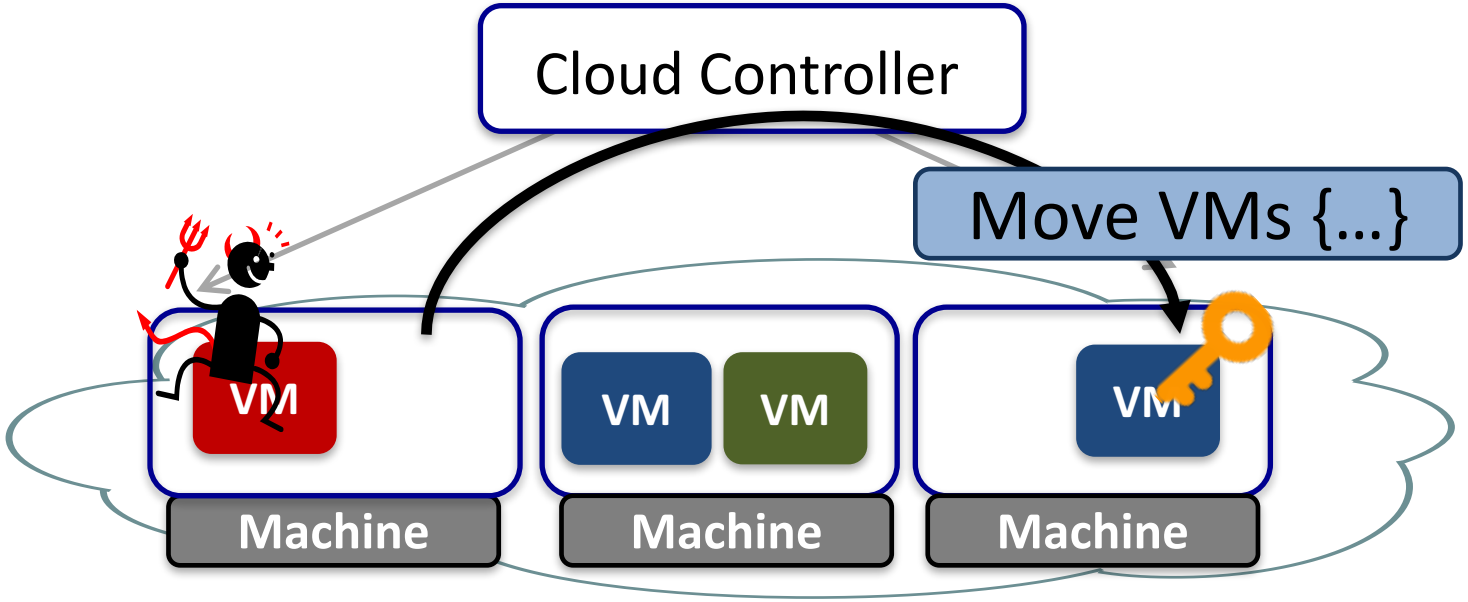
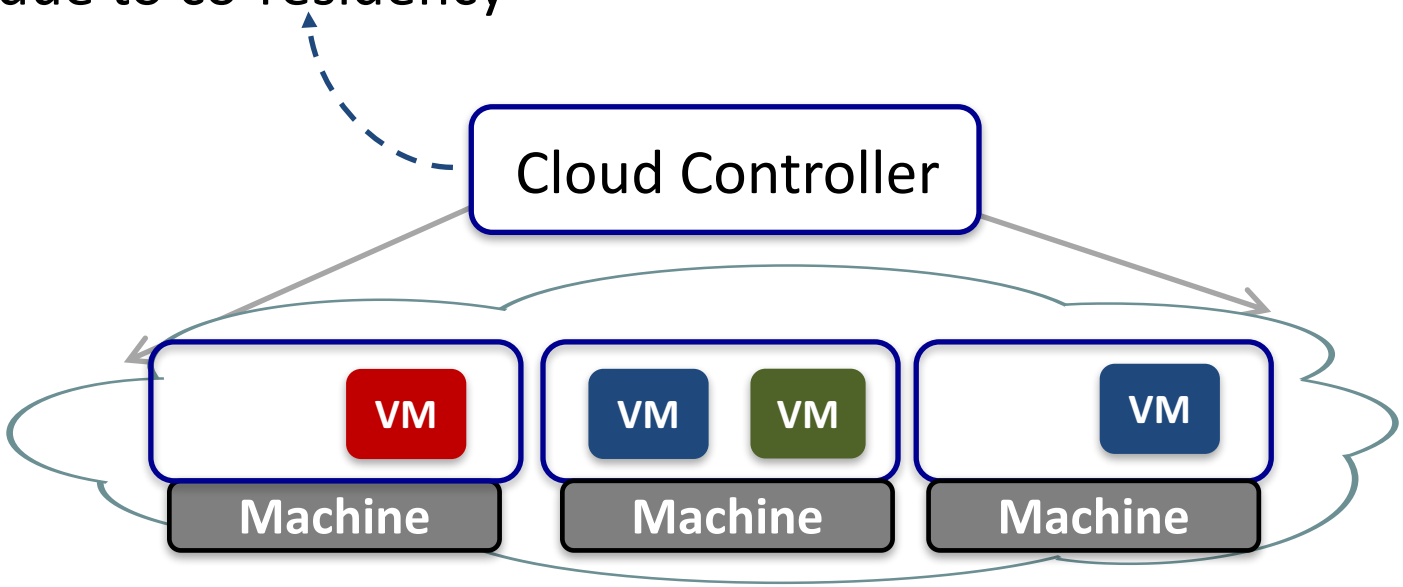


Nomad Practical Challenges

Logic

Characterize information leakage due to co-residency



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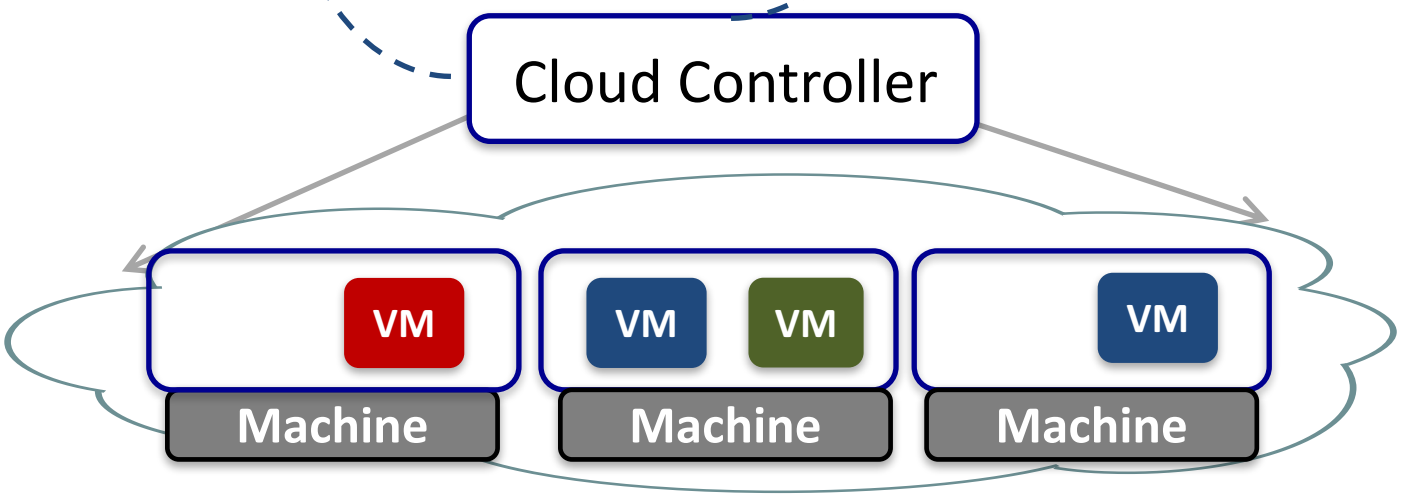
Scalable Design

e.g., can Amazon EC2 run this?



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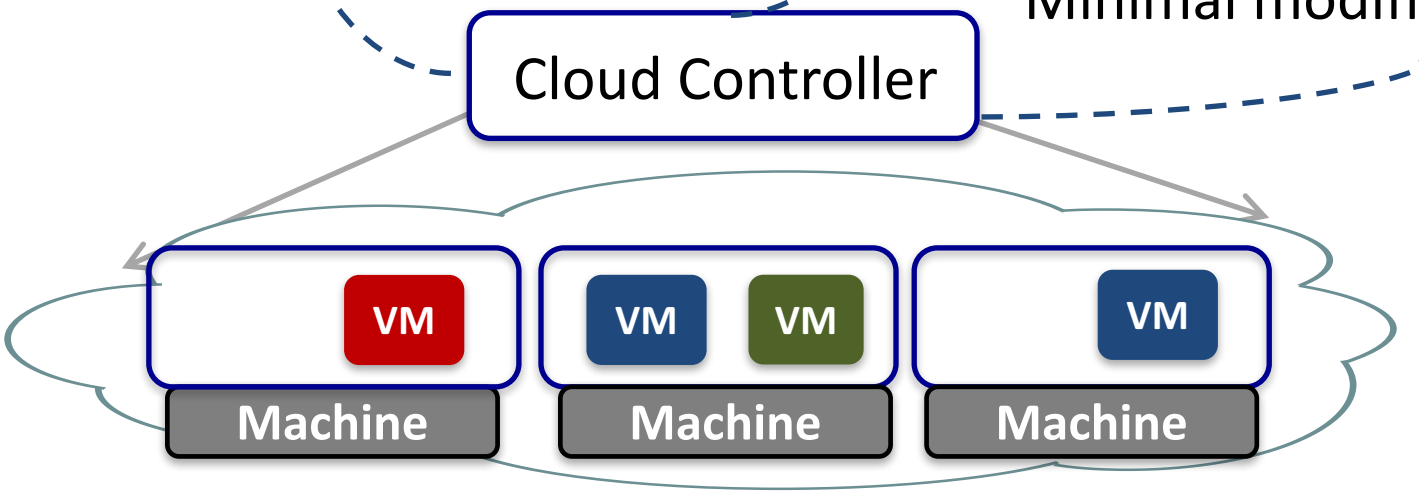
Minimal modifications?



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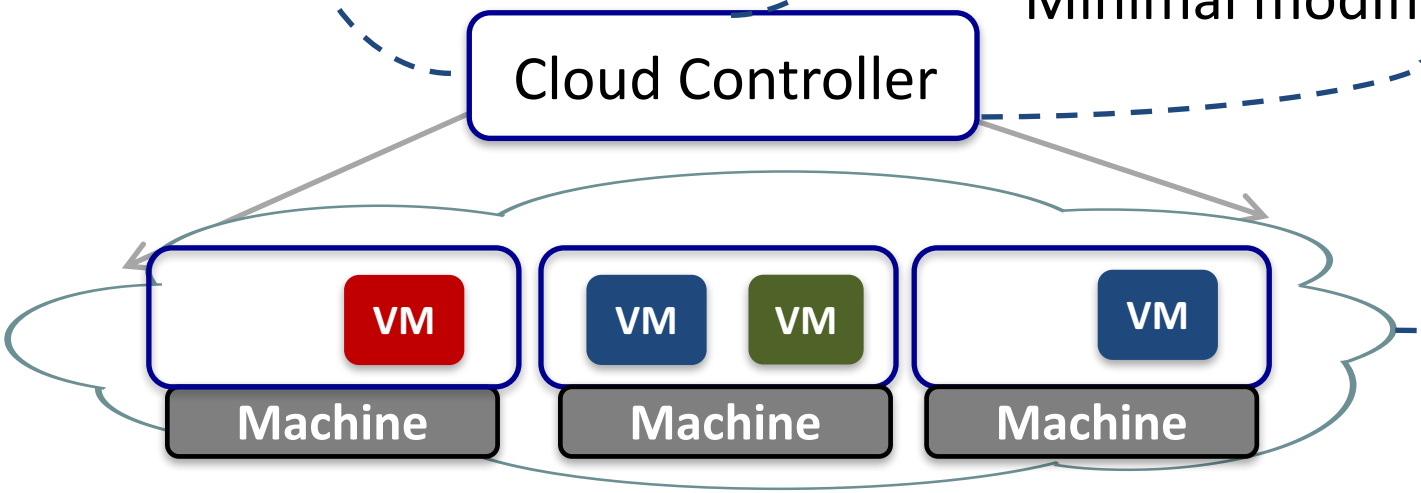

Practical Impact (applications)

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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Threat Model

Objective: Extract secrets via co-residency

- Can use any kind of resource
- Can launch/terminate VMs at will
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- VMs of a given client can collaborate

- Cannot control VM placement
- No info. sharing across distinct clients

Provider

- Don’t know which other clients are malicious

Information Leakage (InfoLeak) Model

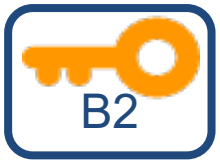
Clients

Information Leakage (InfoLeak) Model

Clients

Replicated? (R or NR)

VM-level view



R

Information Leakage (InfoLeak) Model

Clients

VM-level view

Replicated? (R or NR)

R

NR

Information Leakage (InfoLeak) Model

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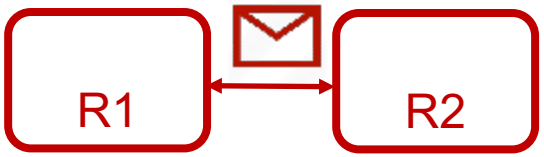
Replicated? (R or NR)

Collaborating? (C or NC)

VM-level view

R

C



NR

Information Leakage (InfoLeak) Model

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VM-level view

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R

NR

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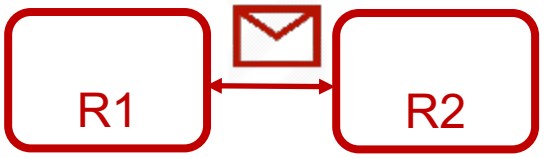
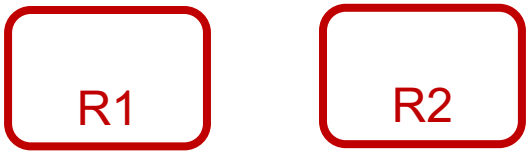


NC



Information Leakage (*InfoLeak*) Model

Collaborating? \ Replicated?	NR	R
NC	<NR,NC>	<R,NC>
	Least InfoLeak	
C	<NR,C>	<R,C>
		Most InfoLeak

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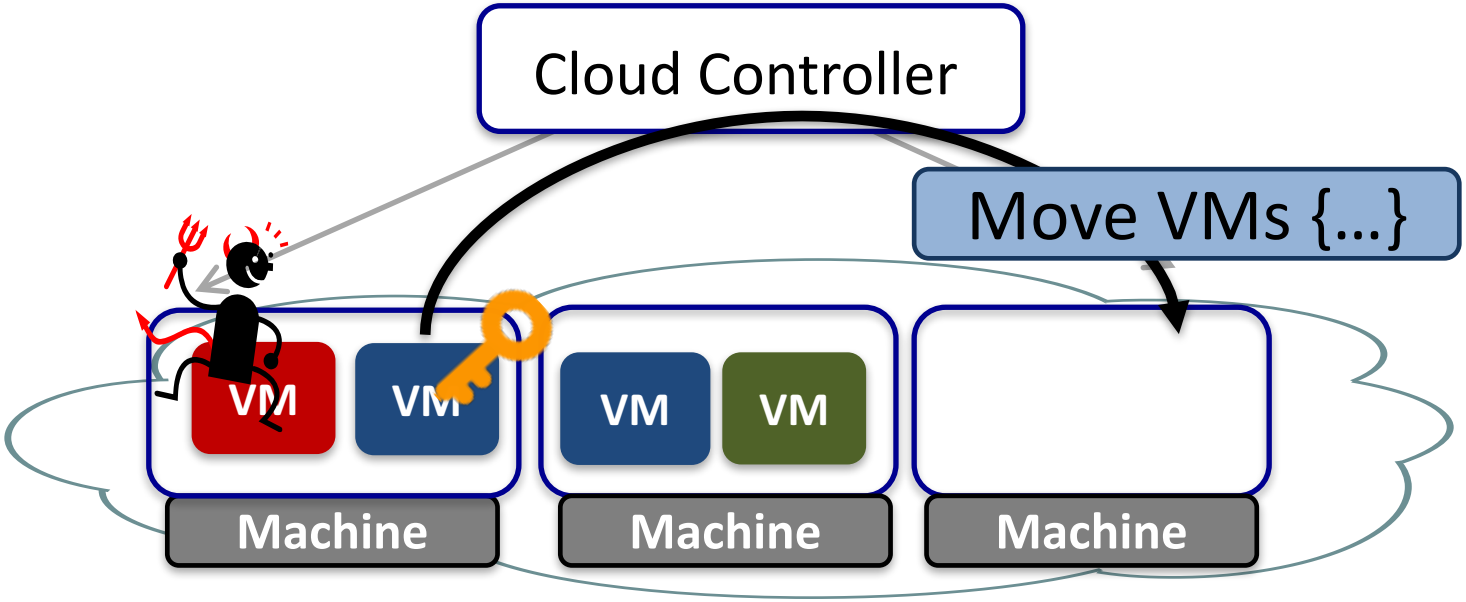
Practical OpenStack implementation with minimal modifications

System Overview



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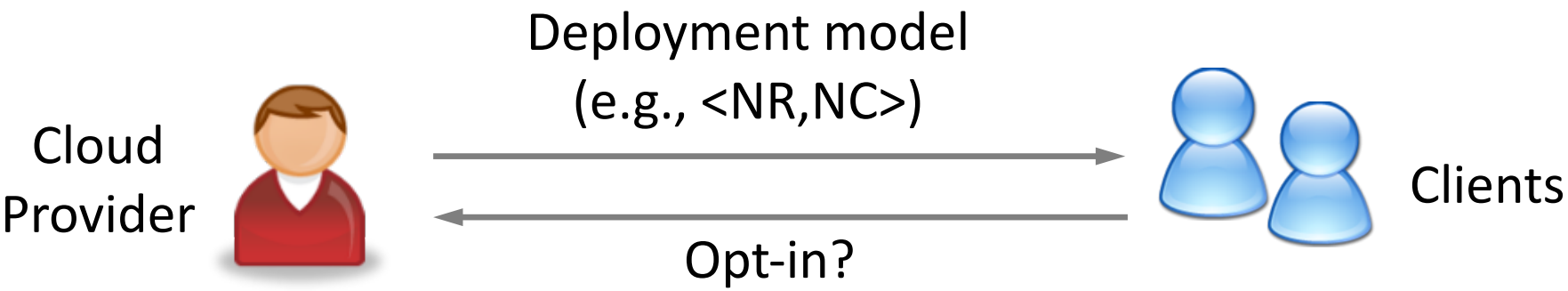
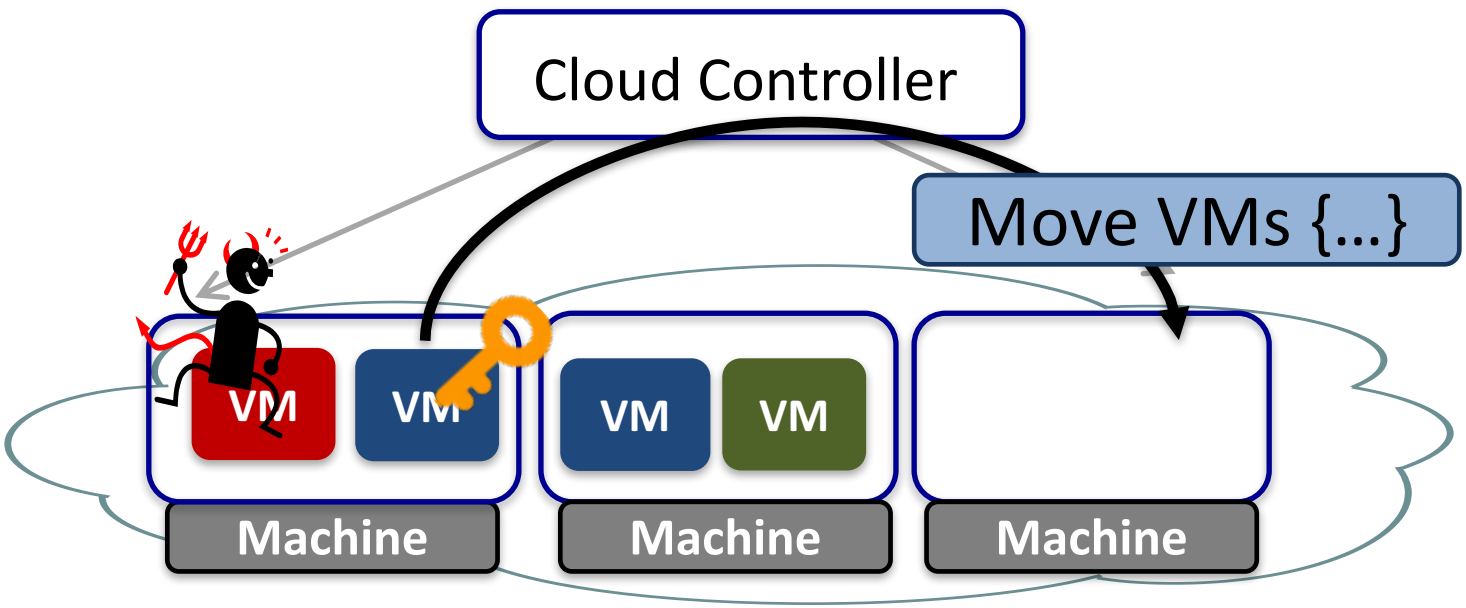
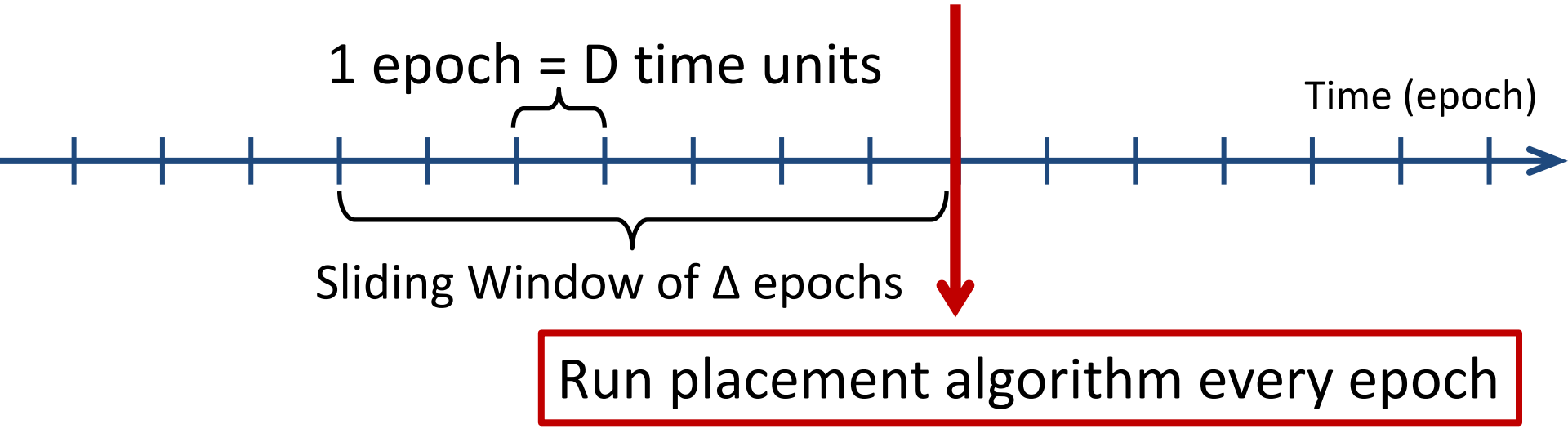




Operational Timeline



Run placement algorithm every epoch

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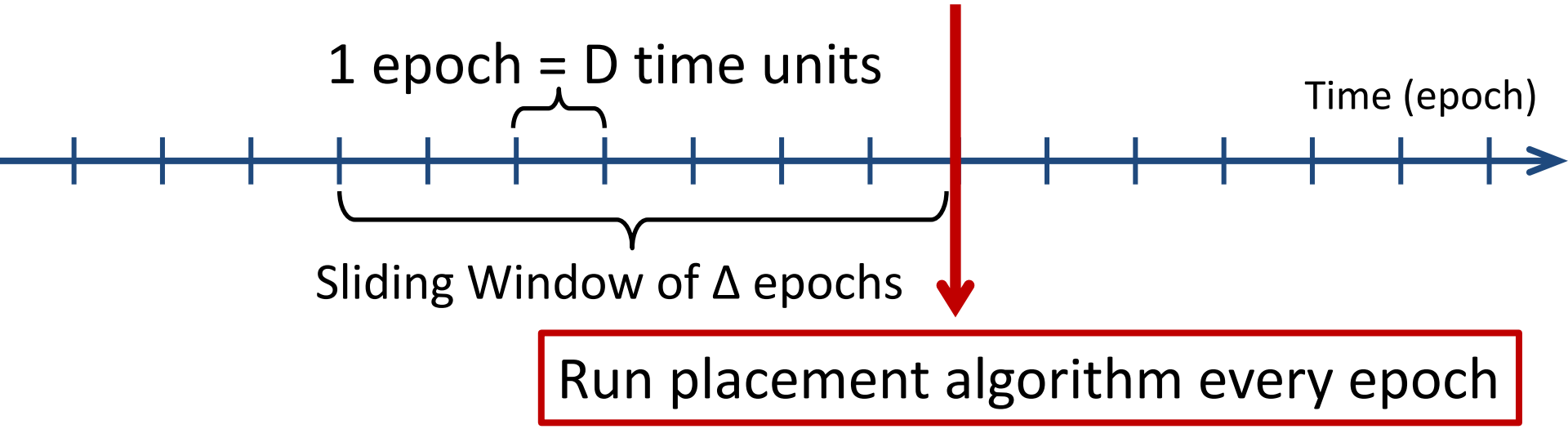

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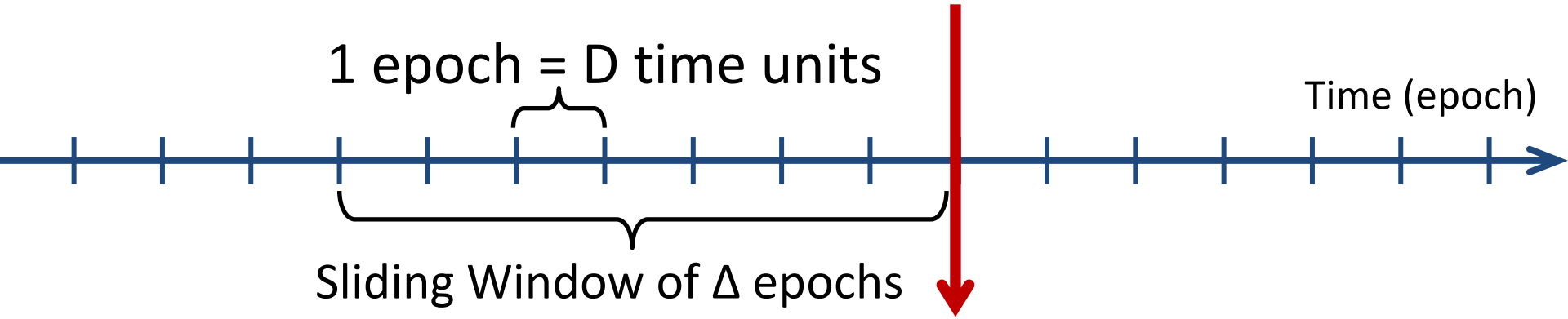
Side-channel Parameters:

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

Operational Timeline



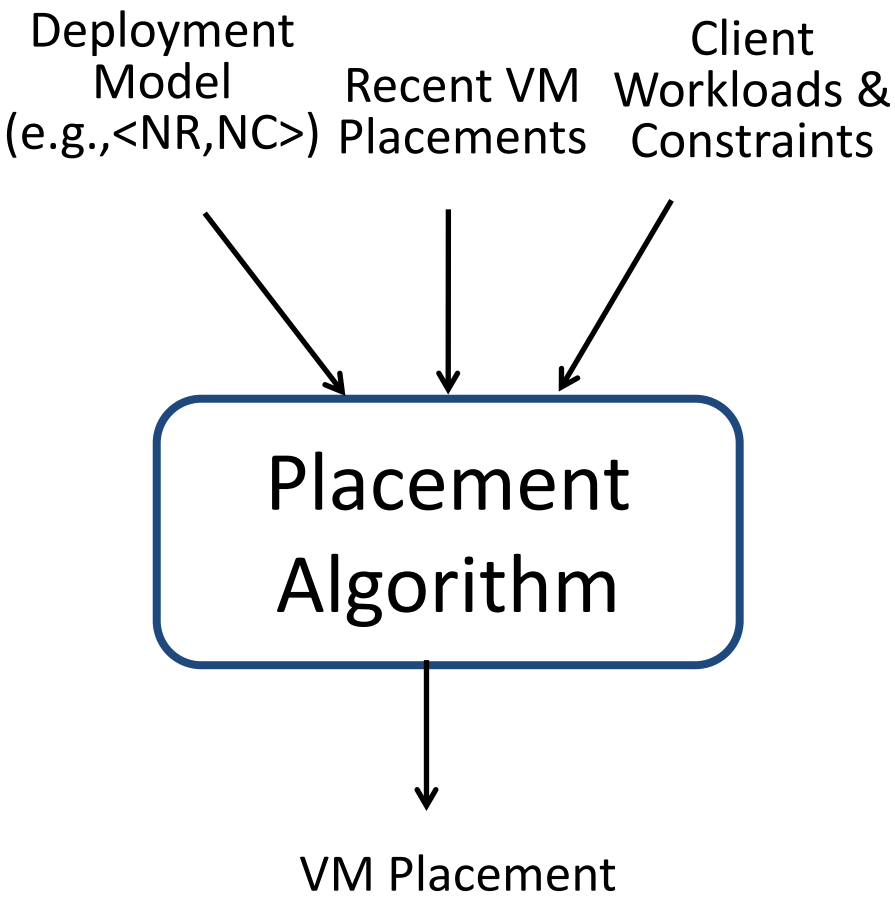
Run placement algorithm every epoch

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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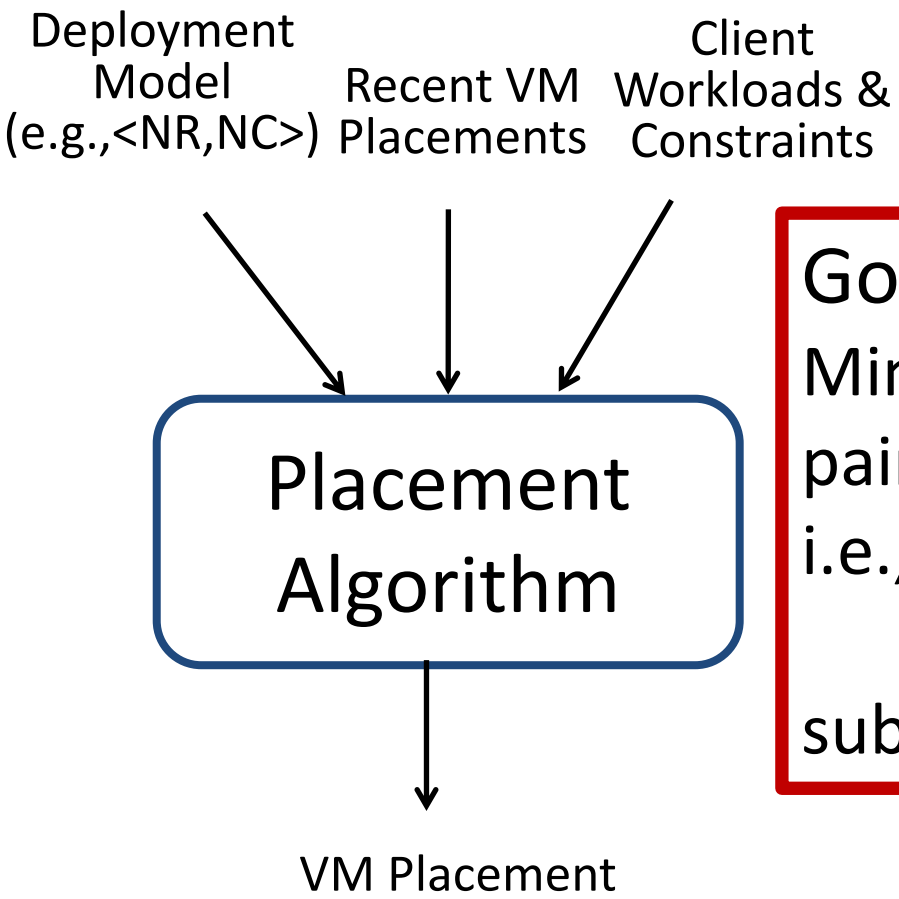


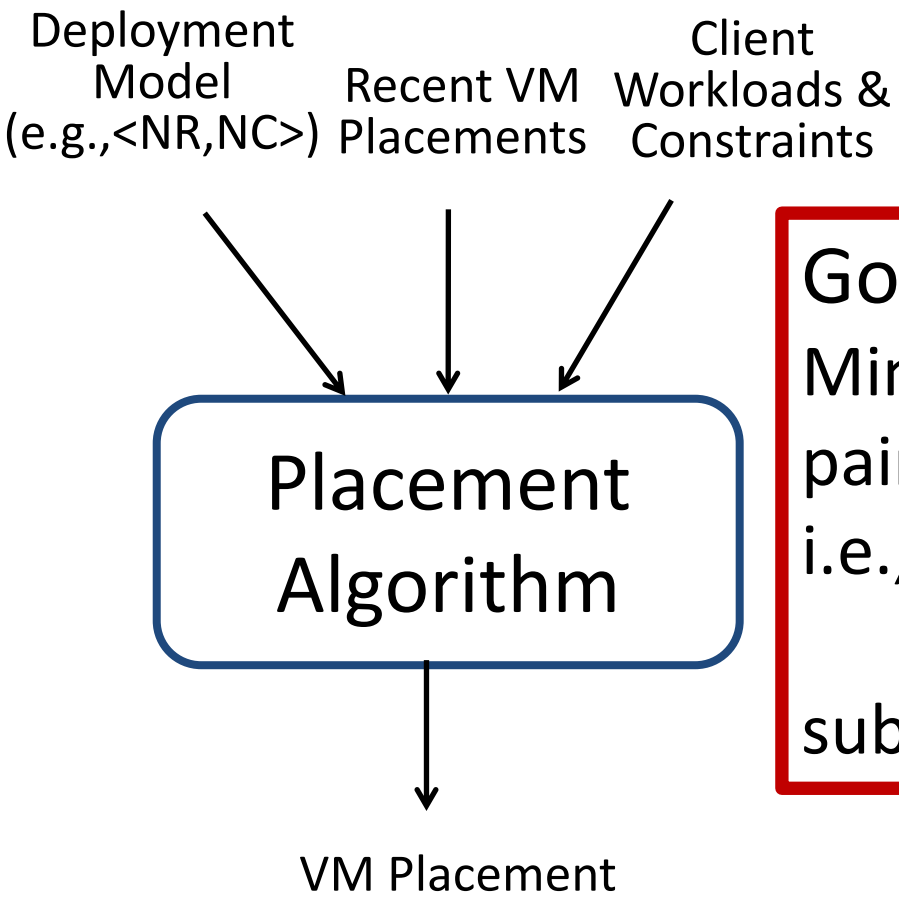
Goal (per epoch):

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



F(Deployment Model)

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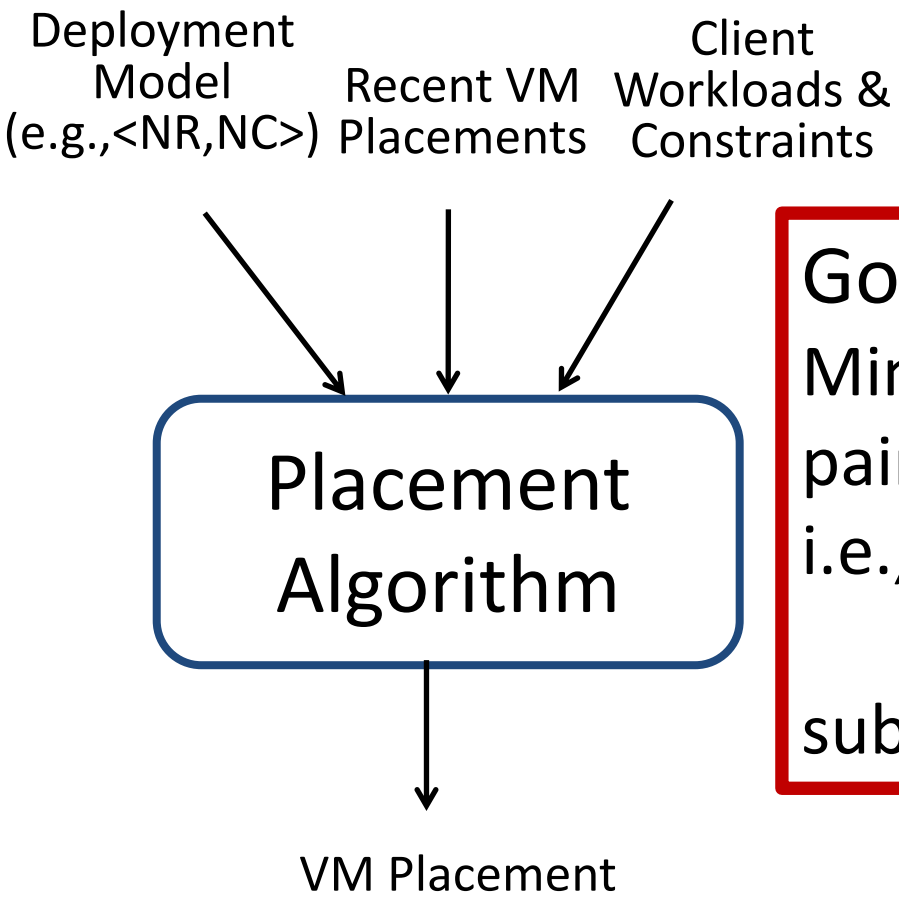

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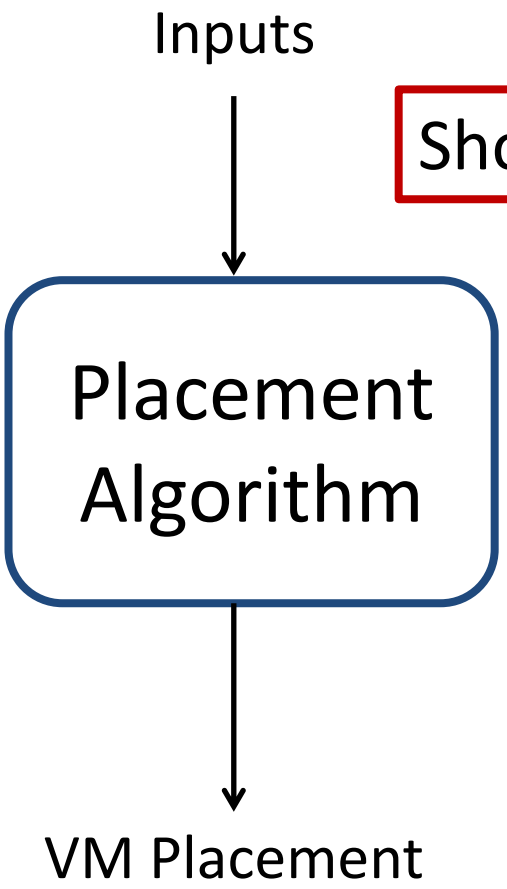
F(Network Capacity)

Challenge: Scalability



Should handle tens of thousands of servers

Challenge: Scalability

Inputs

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Placement Algorithm

- ILP (Integer Linear Programming)

For 40 machines, D > 1 day

VM Placement

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VM Placement

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Should handle tens of thousands of servers

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- Basic Greedy

For 400 machines, D > 1 day

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Placement Algorithm

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↓

Placement Algorithm

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VM Placement

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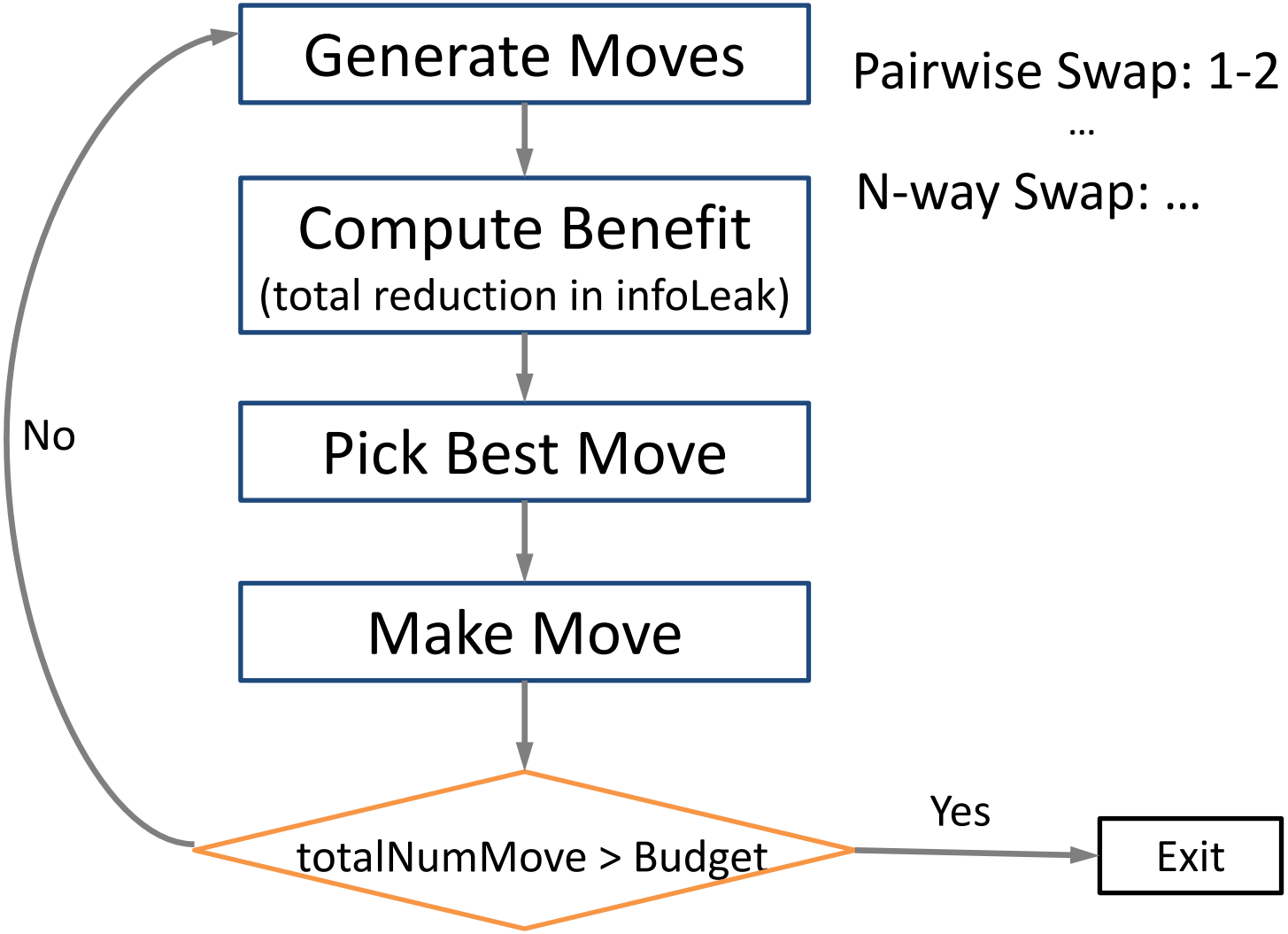
~~For 400 machines, D > 1 day~~

- Basic Greedy with our optimizations

Why is Basic Greedy not scalable?



Pairwise Swap: 1-2 -> 2-1

…

N-way Swap: …

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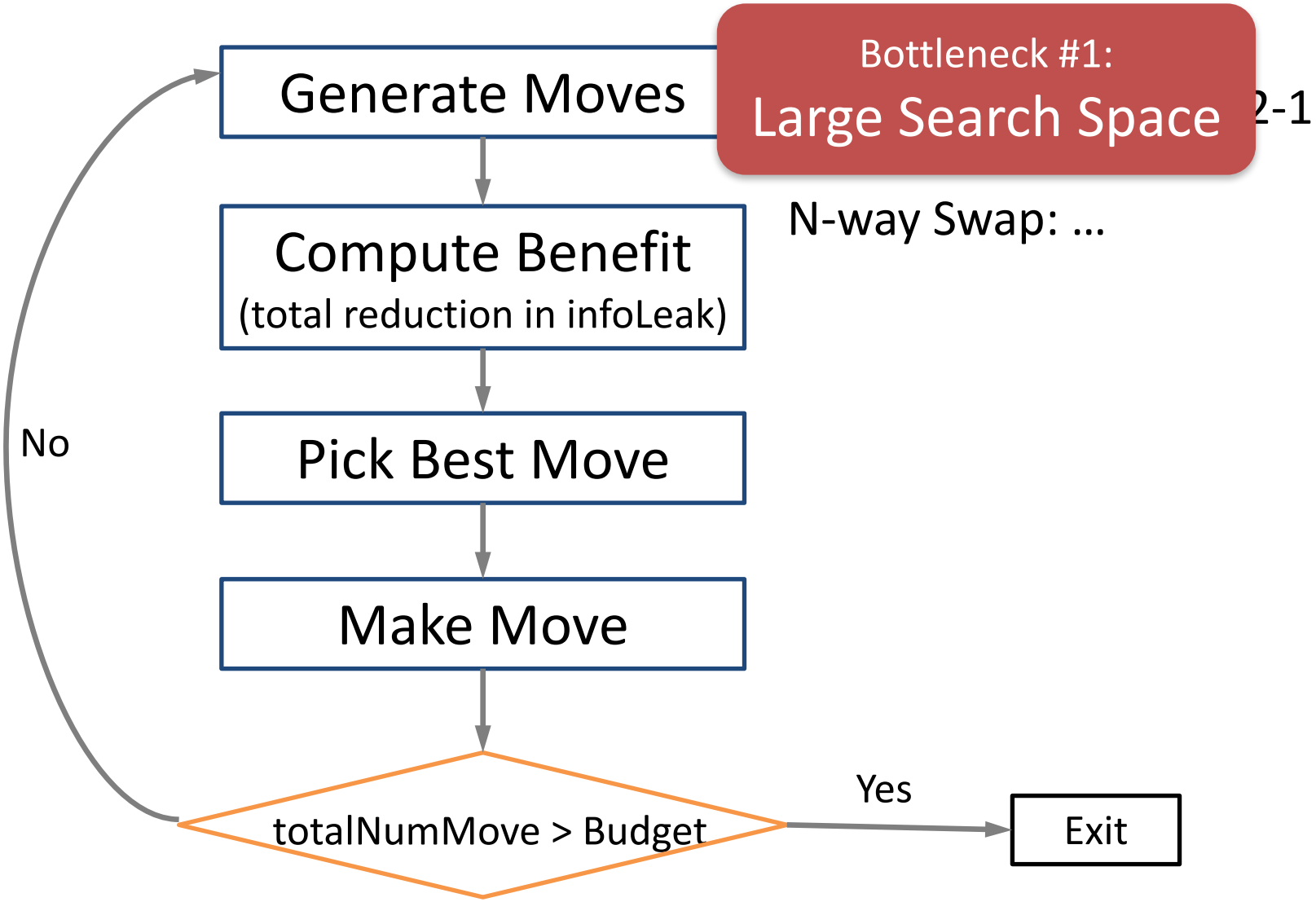

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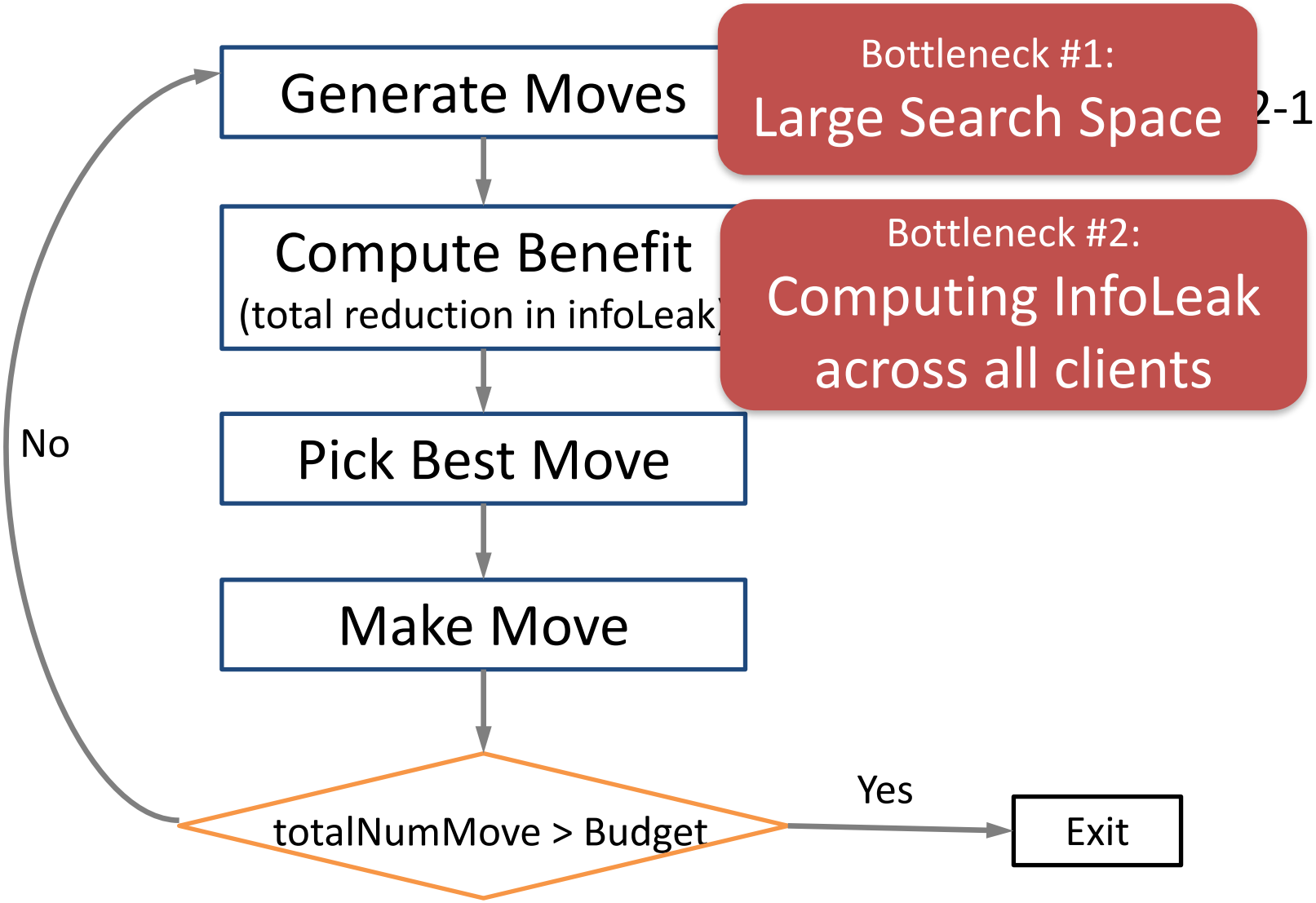

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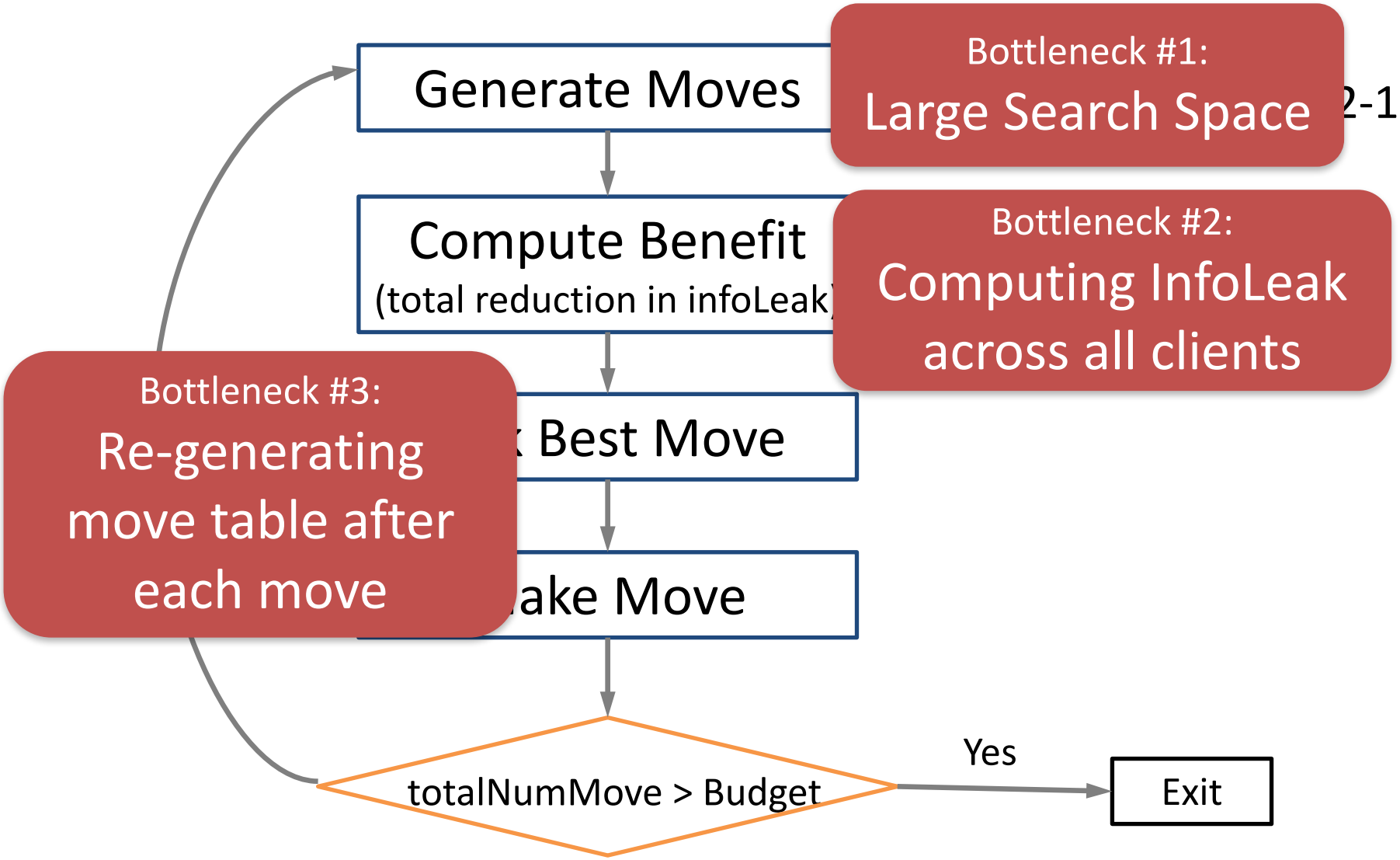

Our Approach

Bottlenecks	Our Approach
Large Search Space	Prune Search Space
Computing InfoLeak across all clients	Incremental Benefit Computation
Re-generating move table after each move	Intra-Epoch Lazy Evaluation

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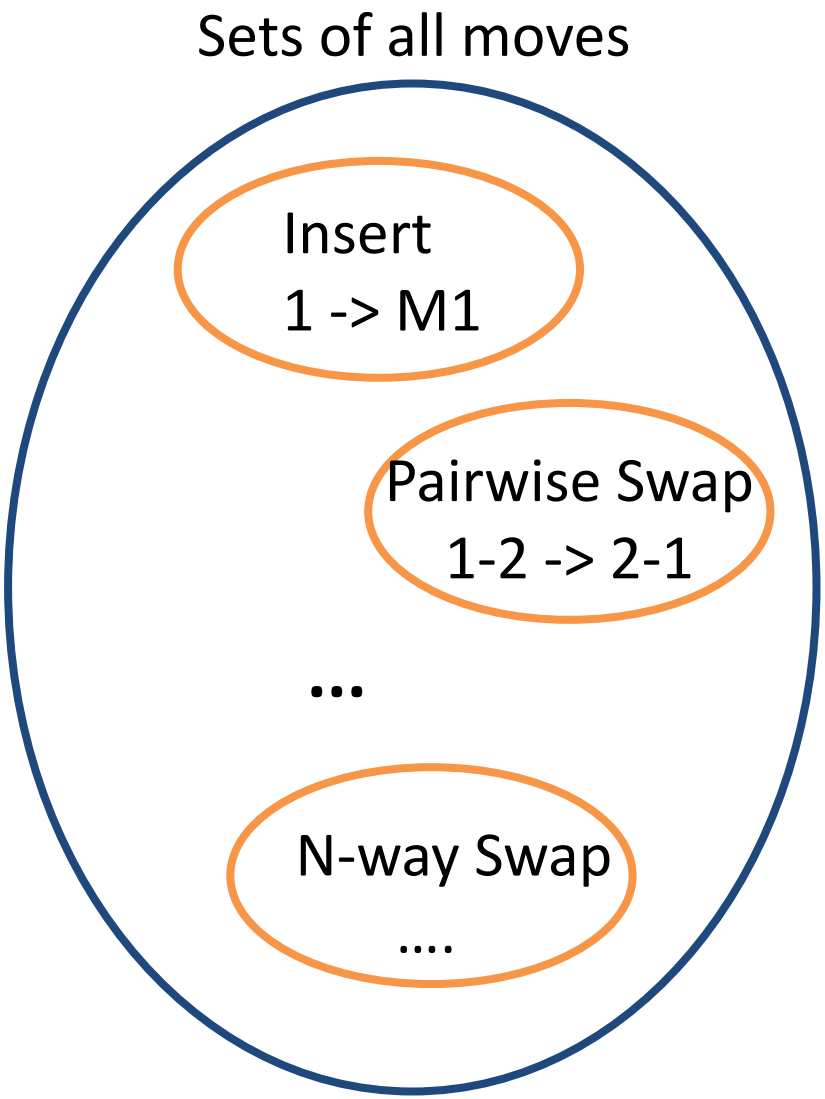

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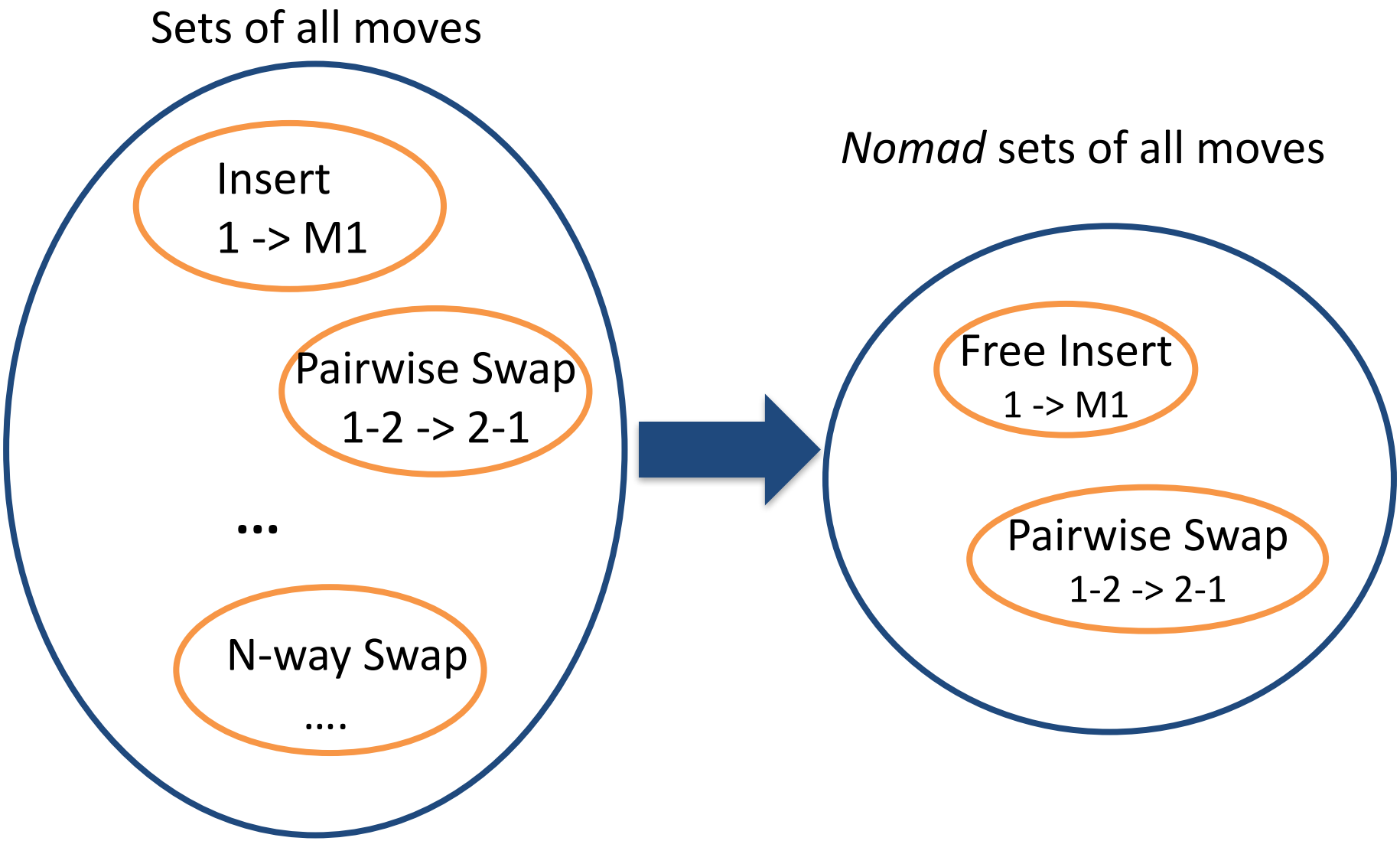
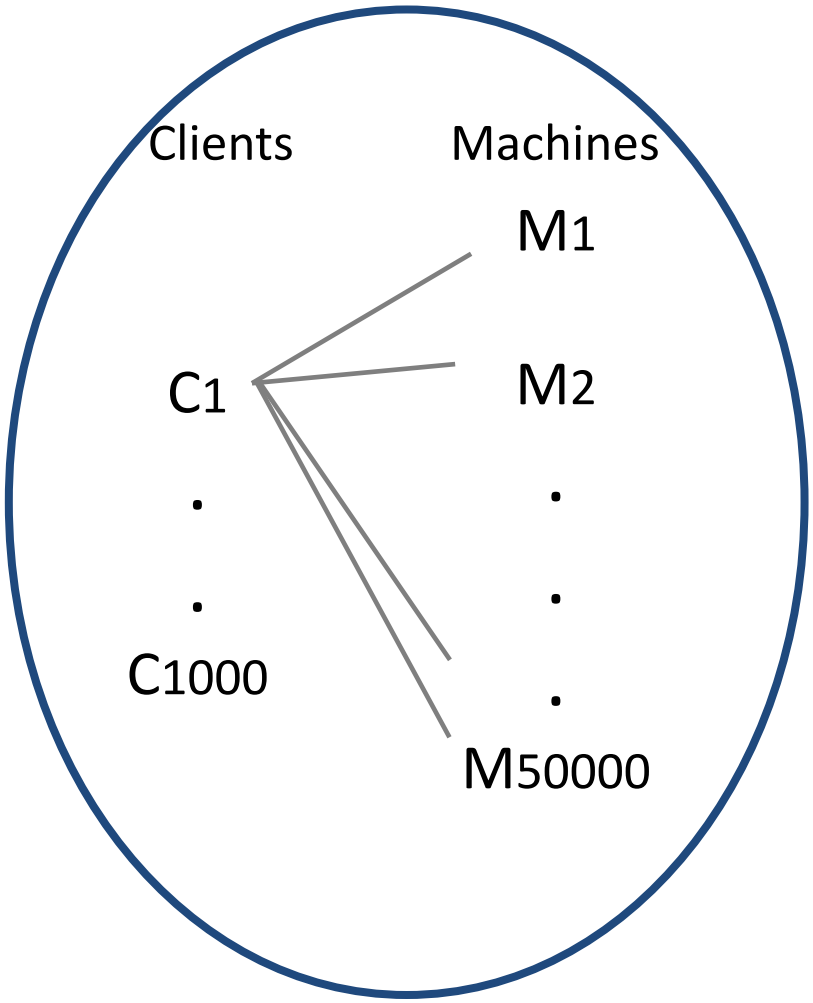


Prune #2: Hierarchical Decomposition

Sets of all free inserts



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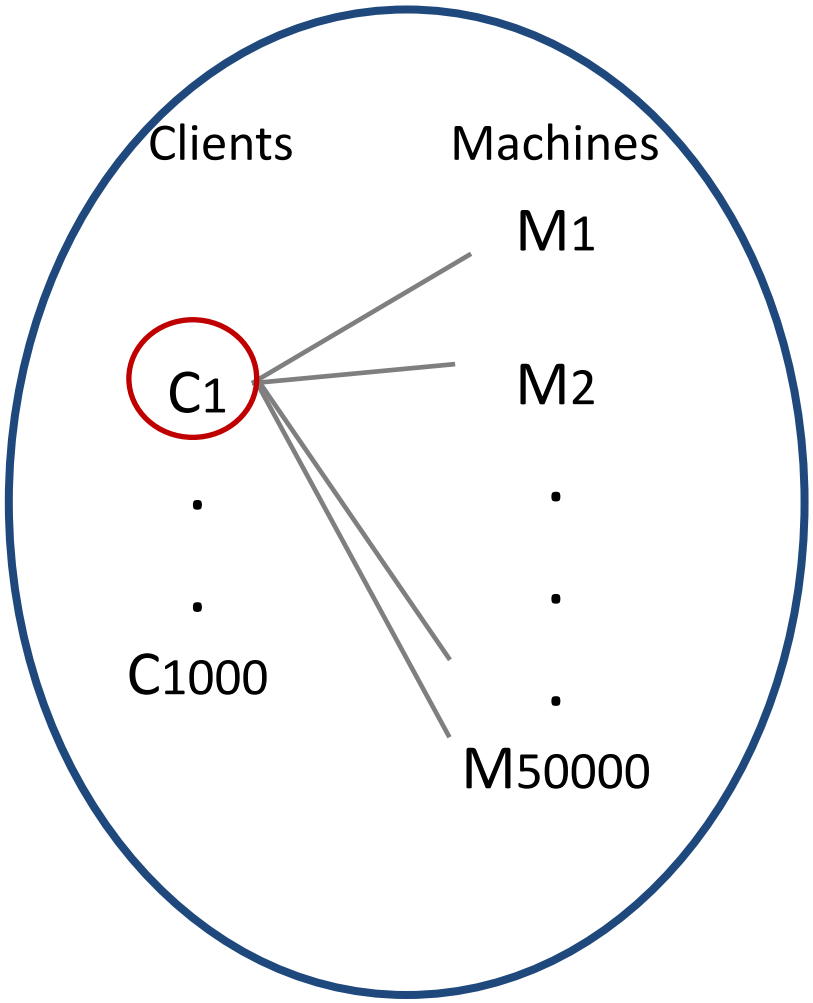

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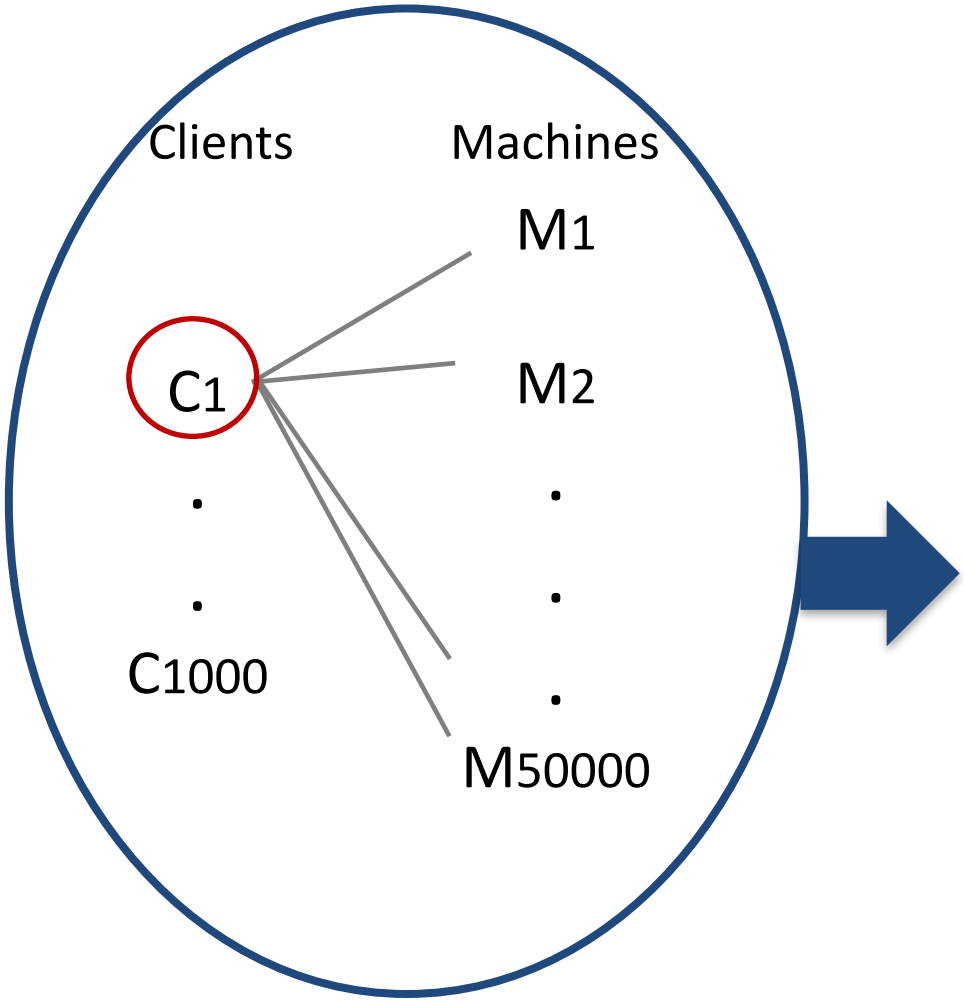

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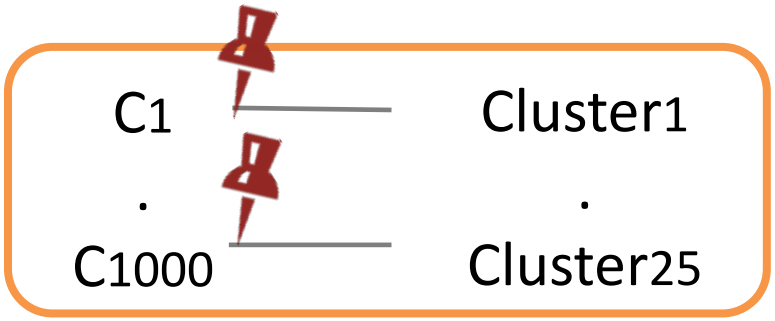

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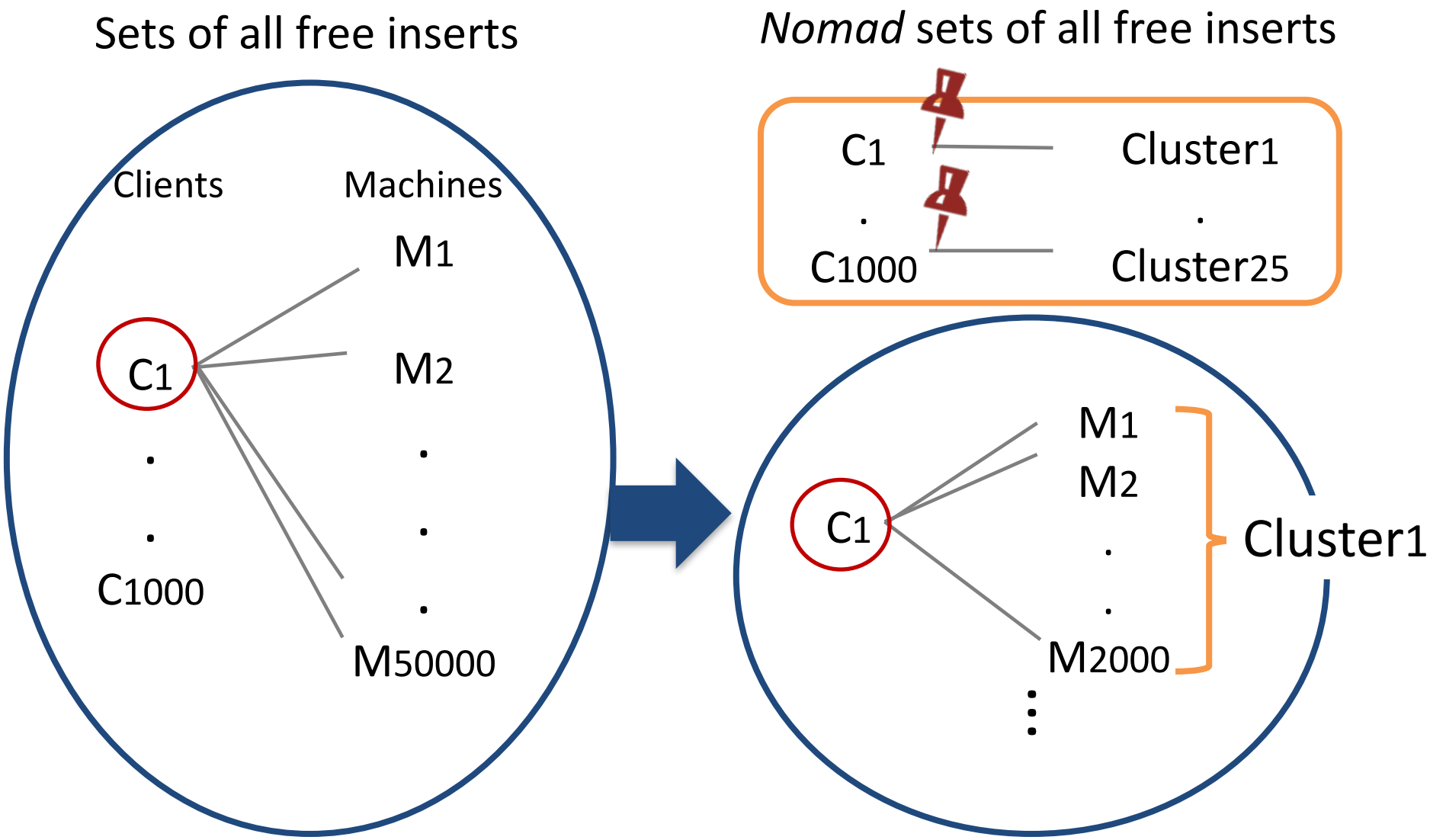

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1. Idea

General side-channel defense via migration

2. Logic

Characterize information leakage due to co-residency

3. Scalable Design

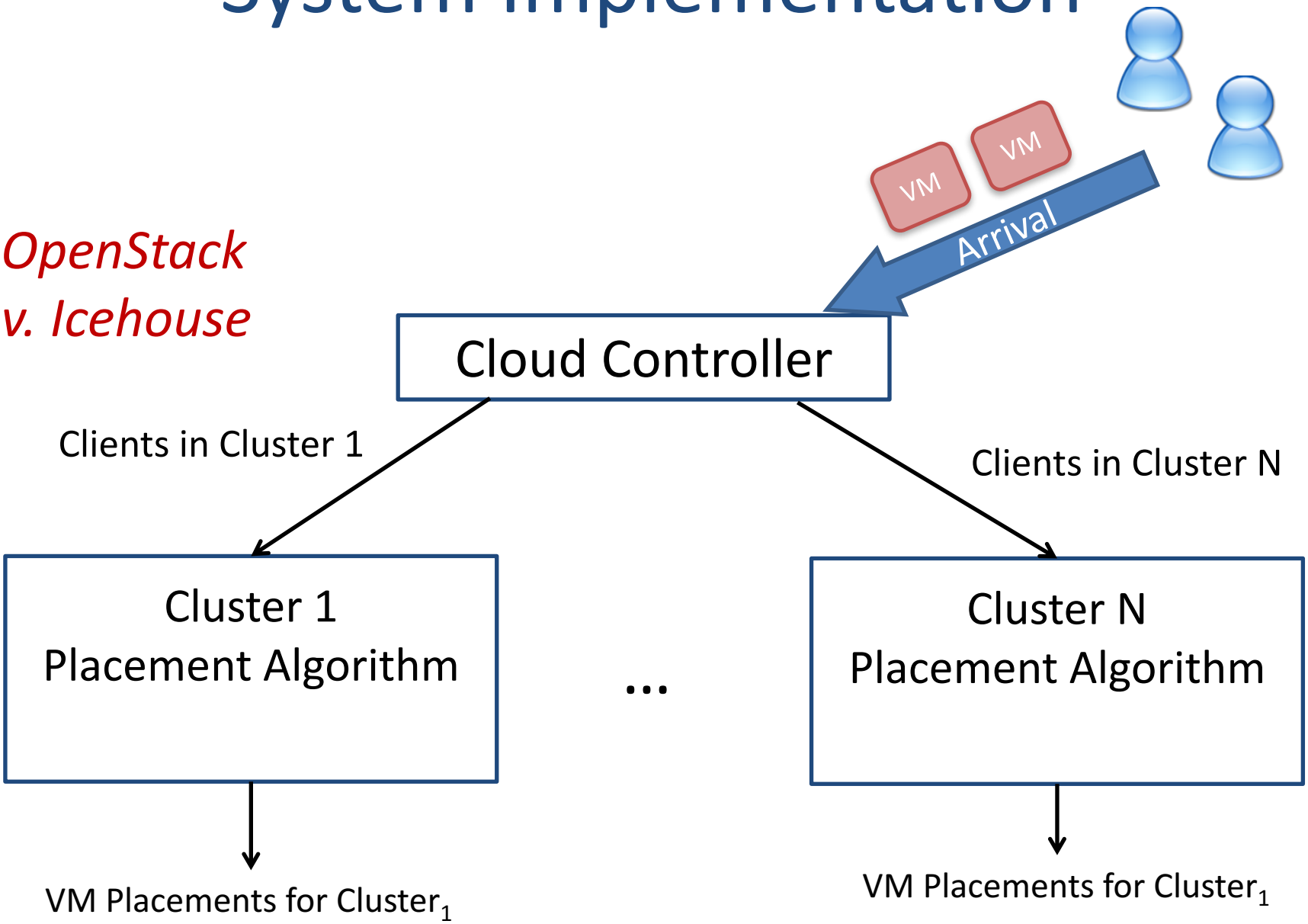
Scalable VM migration strategy that can handle large cloud deployments

4. Practical Impact

Practical OpenStack implementation with minimal modifications

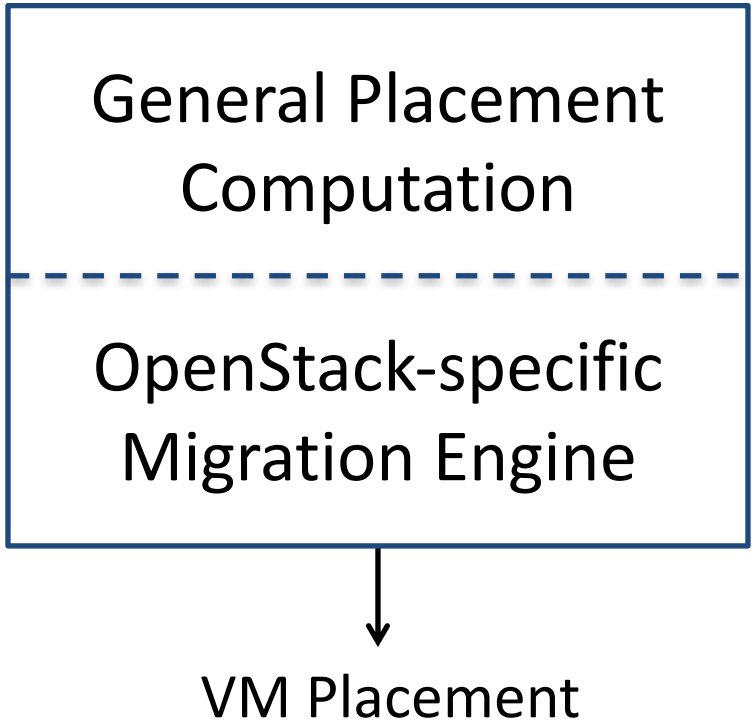
System Implementation

OpenStack v. Icehouse



System Implementation (One Cluster)

Cluster 1
Placement Algorithm



Custom C++
~2000 LOC

OpenStack Icehouse:
~200 LOC in Controller Scheduler code

System Implementation (One Cluster)

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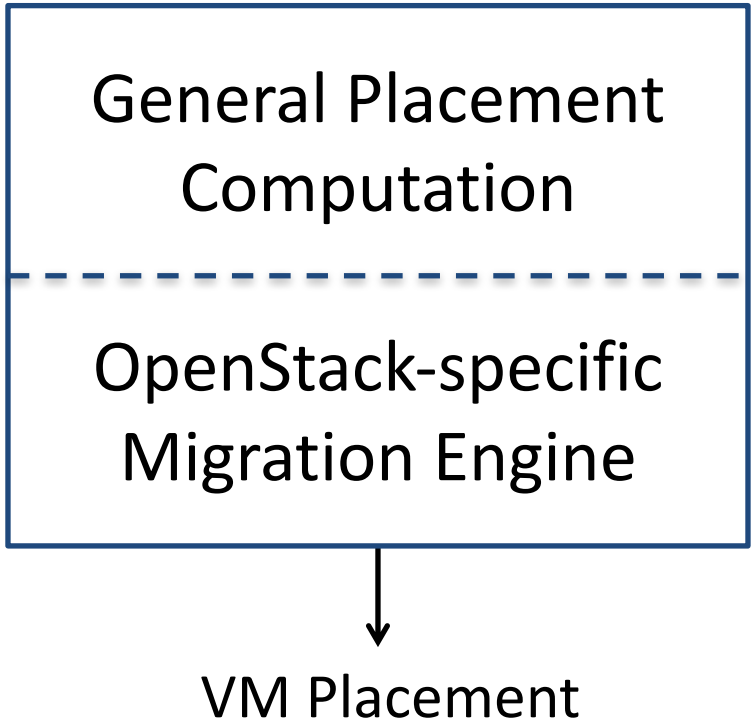

Custom C++
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OpenStack Icehouse:
~200 LOC in Controller Scheduler code

Requires minimal modifications to existing deployments

Key Evaluation Questions

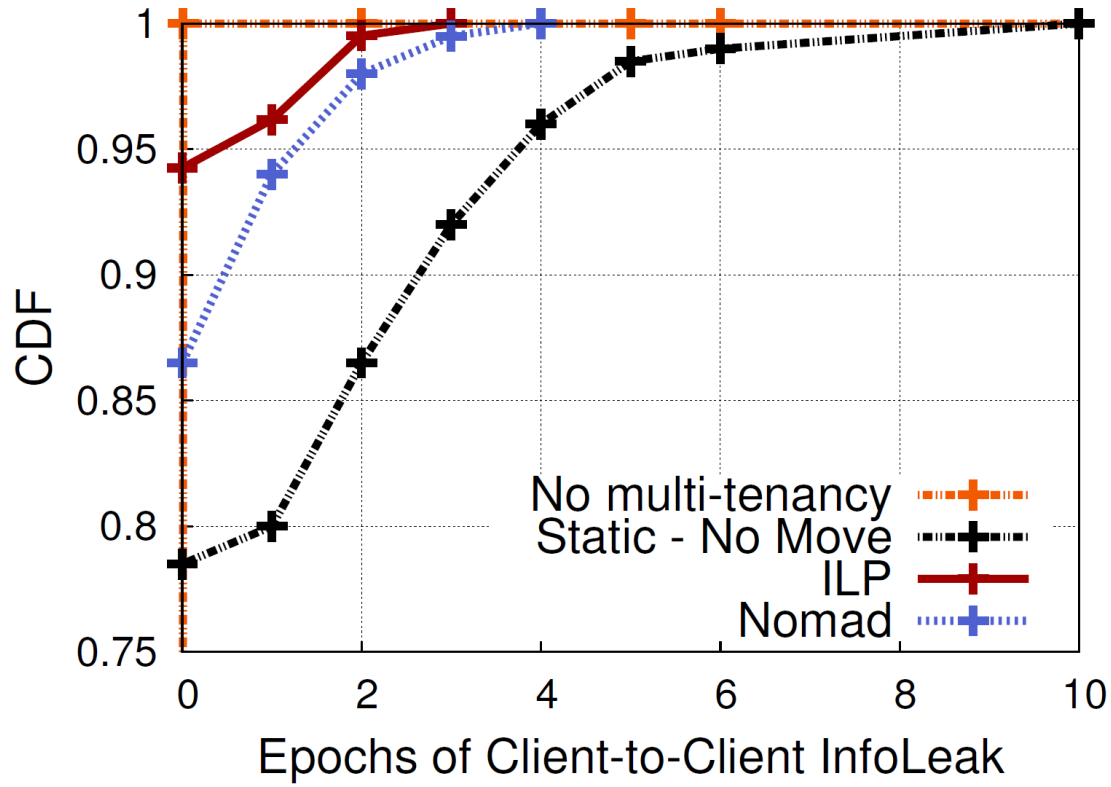
- Information leakage resilience
- Scalability
- Impact on cloud applications
- Benefit/Cost of each design idea
- Resilience to strategic adversary

Information Leakage resilience

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

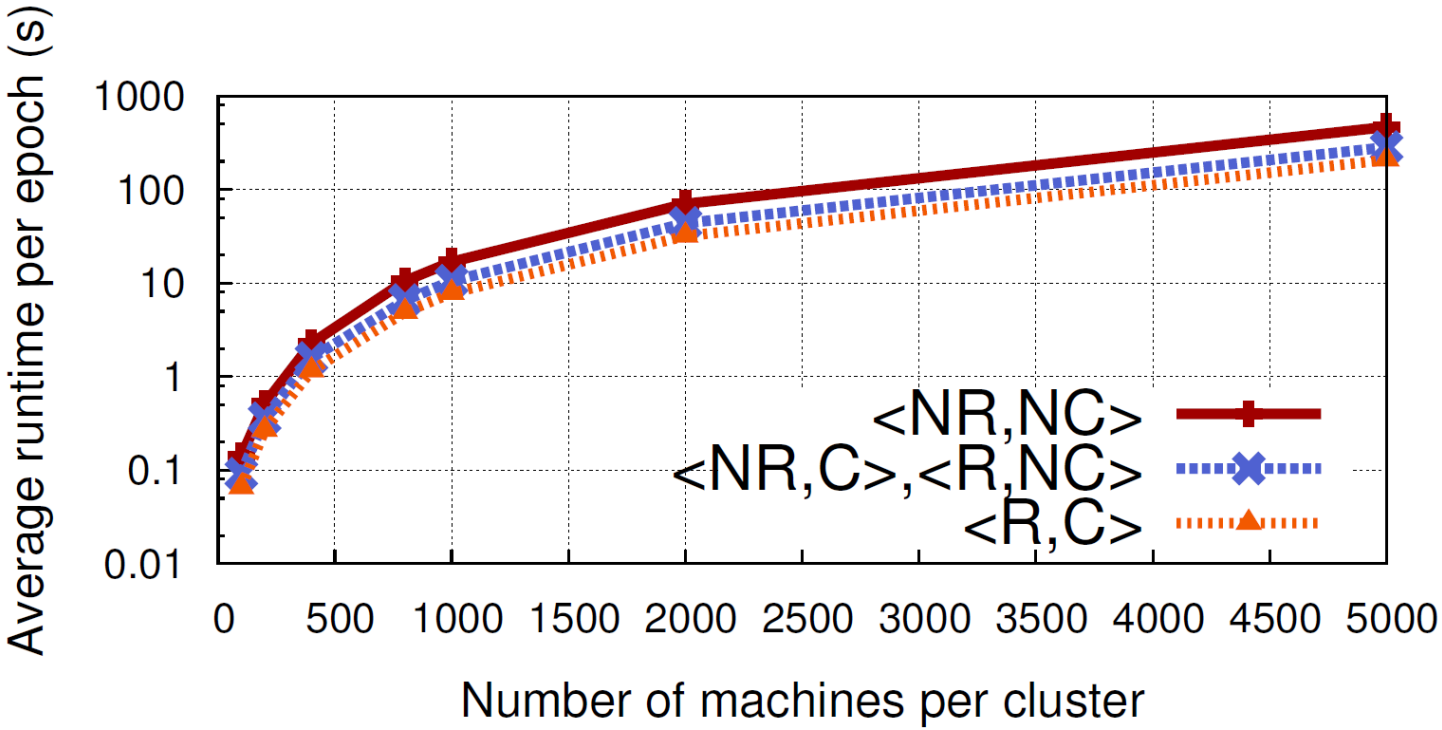
Metric:

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



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