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

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Context: Infrastructure-as-a-Service Clouds

Client API

Cloud Controller

VM
VM
Machine

VM
VM
Machine

VM
Machine

Amazon EC2

Google Compute Engine
Information Leakage via Co-Residency
Information Leakage via Co-Residency
Information Leakage via Co-Residency

Co-Residency

Shared resources

Side Channels

Cloud Controller

Shared Resources

Machine

VM

VM
Information Leakage via Co-Residency

Co-Residency

Shared resources

Side Channels

Information Leakage
Limitations of Current Defenses

1. Requires significant/detailed upgrades

   - OS
     - e.g., Noise injection
   - Hypervisor
     - e.g., Deterministic execution
   - Hardware
     - 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
Limitations of Current Defenses

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     - e.g., Noise injection
   - Hypervisor
     - e.g., Deterministic execution
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     - 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
Ideal Properties

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2) Immediately deployable

Single-tenancy?
Ideal Properties

1) General

2) Immediately deployable

Single-tenancy?
Nomad Ideas

1) General

2) Immediately deployable
Nomad Ideas

1) General

Tackle root-cause
→ Minimize co-residency

2) Immediately deployable
Nomad Ideas

1) General
   - Tackle root-cause
     → Minimize co-residency

2) Immediately deployable
   - Migration
Nomad Vision: Migration-as-a-Service

- Provider-assisted
Nomad Vision: Migration-as-a-Service

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Cloud Controller

Move VMs {...}
Nomad Vision: Migration-as-a-Service

- Opt-in Service
  - Cloud Provider
    - Service offering
    - Opt-in?
  - Clients

- Provider-assisted

  Cloud Controller

  Move VMs {...}
Nomad Practical Challenges

Logic

Characterize information leakage due to co-residency
Nomad Practical Challenges

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Scalable Design
e.g., can Amazon EC2 run this?
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Practical Impact (cloud)
Minimal modifications?

Cloud Controller

VM
Machine

VM
Machine

VM
Machine
**Nomad Practical Challenges**

**Logic**
Characterize information leakage due to co-residency

**Scalable Design**
e.g., can Amazon EC2 run this?

**Practical Impact (cloud)**
Minimal modifications?

**Cloud Controller**

**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
Our Work

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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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4. Practical Impact
   Practical OpenStack implementation with minimal modifications
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Threat Model

Objective: Extract secrets via co-residency

- Can use any kind of resource
- Can launch/terminate VMs at will
- VMs of a given client can collaborate
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- Cannot control VM placement
- No info. sharing across distinct clients
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Objective: Extract secrets via co-residency

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

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

• Don’t know which other clients are malicious

Provider
Information Leakage (InfoLeak) Model

Clients → InfoLeak ? → Malicious Actor
Information Leakage (InfoLeak) Model

Clients

Replicated? (R or NR)

VM-level view

B1

B2

R

InfoLeak?
Information Leakage (InfoLeak) Model

Clients

Replicated? (R or NR)

VM-level view

B1  B2

R

B1  B2

NR
Information Leakage (InfoLeak) Model

Clients

Replicated? (R or NR)

Collaborating? (C or NC)

VM-level view

R

C

NR
Information Leakage (InfoLeak) Model

Clients

Replicated? (R or NR)

Collaborating? (C or NC)

VM-level view

B1

B2

R

C

R1

R2

B1

B2

NR

NC

R1

R2
Information Leakage (InfoLeak) Model

Collaborating?

<table>
<thead>
<tr>
<th>Collaborating</th>
<th>Replicated?</th>
</tr>
</thead>
<tbody>
<tr>
<td>NR</td>
<td>R</td>
</tr>
<tr>
<td>NC</td>
<td>&lt;NR,NC&gt;</td>
</tr>
<tr>
<td>C</td>
<td>&lt;NR,C&gt;</td>
</tr>
<tr>
<td></td>
<td>&lt;R,NC&gt;</td>
</tr>
<tr>
<td></td>
<td>Most InfoLeak</td>
</tr>
<tr>
<td></td>
<td>Least InfoLeak</td>
</tr>
</tbody>
</table>
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System Overview

Cloud Controller

Move VMs {...}
System Overview

Cloud Provider

Deployment model (e.g., <NR,NC>)

Opt-in?

Clients

Cloud Controller

Move VMs {...}

Machine

VM

Machine

VM

VM

Machine

VM
Operational Timeline

1 epoch = D time units

Sliding Window of Δ epochs

Run placement algorithm every epoch
Operational Timeline

1 epoch = D time units

Sliding Window of Δ epochs

Run placement algorithm every epoch

Side-channel Parameters:
• K: Information leakage rate (i.e., bits per time unit)
• P: secret length (i.e., bits)
Operational Timeline

1 epoch = D time units

Sliding Window of $\Delta$ epochs

Run placement algorithm every epoch

Extracted secret (bits) if two VMs are co-resident for $\Delta$ epochs

Provider chooses D and $\Delta$ to AT LEAST satisfy:

$$D \times \Delta \times K < P$$
Placement Algorithm

Deployment Model (e.g., <NR,NC>)
Recent VM Placements
Client Workloads & Constraints

Placement Algorithm

VM Placement
Placement Algorithm

Deployment Model (e.g., <NR,NC>) → Recent VM Placements → Client Workloads & Constraints → Placement Algorithm

Goal (per epoch):
Minimize a *global* sum of a client-pair InfoLeak across past $\Delta$ epochs i.e.,
$$\sum_{c,c'} \text{InfoLeak}_{c \rightarrow c'}([t - \Delta, t])$$

subject to a fixed migration budget
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i.e.,
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Placement Algorithm

Goal (per epoch):
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i.e.,
\[
\sum_{c,c'} \text{InfoLeak}_{c \rightarrow c'}([t - \Delta, t])
\]
subject to a fixed migration budget

\[ F(\text{Deployment Model}) \]

\[ F(\text{Network Capacity}) \]
Challenge: Scalability

Inputs

Should handle tens of thousands of servers

Placement Algorithm

VM Placement
Challenge: Scalability

Inputs

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Placement Algorithm

• ILP (Integer Linear Programming)

For 40 machines, D > 1 day

VM Placement
Challenge: Scalability

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- For 40 machines, $D > 1$ day

VM Placement
Challenge: Scalability

Inputs

Placement Algorithm

Should handle tens of thousands of servers

- ILP (Integer Linear Programming)
  For 40 machines, $D > 1$ day
- Basic Greedy
  For 400 machines, $D > 1$ day
Challenge: Scalability

Should handle tens of thousands of servers

Placement Algorithm

Inputs

VM Placement

- ILP (Integer Linear Programming)
  For 40 machines, $D > 1$ day
- Basic Greedy
  For 400 machines, $D > 1$ day
Challenge: Scalability

Inputs

Should handle tens of thousands of servers

Placement Algorithm

- ILP (Integer Linear Programming)
  - For 40 machines, $D > 1$ day

- Basic Greedy
  - For 400 machines, $D > 1$ day

- Basic Greedy with our optimizations

VM Placement
Why is Basic Greedy not scalable?

Generate Moves

Compute Benefit (total reduction in infoLeak)

Pick Best Move

Make Move

totalNumMovement > Budget

Exit

Pairwise Swap: 1-2 -> 2-1

N-way Swap: ...
Why is Basic Greedy not scalable?

Generate Moves

Compute Benefit (total reduction in infoLeak)

Pick Best Move

Make Move

Yes

totalNumMove > Budget

No

Bottleneck #1: Large Search Space

N-way Swap: ...
Why is Basic Greedy not scalable?

Generate Moves

Compute Benefit
(total reduction in infoLeak)

Pick Best Move

Make Move

totalNumMove > Budget

Yes

Exit

Bottleneck #1:
Large Search Space

Bottleneck #2:
Computing InfoLeak across all clients
Why is Basic Greedy not scalable?

- Generate Moves
- Compute Benefit (total reduction in infoLeak)
- Pick Best Move
- Make Move

Bottleneck #1: Large Search Space
Bottleneck #2: Computing InfoLeak across all clients
Bottleneck #3: Re-generating move table after each move

- totalNumMove > Budget

Yes → Exit
Our Approach

Bottlenecks

- Large Search Space
- Computing InfoLeak across all clients
- Re-generating move table after each move

Our Approach

- Prune Search Space
- Incremental Benefit Computation
- Intra-Epoch Lazy Evaluation
Our Approach

Bottlenecks

- Large Search Space
- Computing InfoLeak across all clients
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Our Approach

- Prune Search Space
- Incremental Benefit Computation
- Intra-Epoch Lazy Evaluation
Prune #1: Pruning Move Space

Sets of all moves

- Insert
  1 -> M1

- Pairwise Swap
  1-2 -> 2-1

- N-way Swap
  ....

...
Prune #1: Pruning Move Space

Sets of all moves

- Insert 1 -> M1
- Pairwise Swap 1-2 -> 2-1
- N-way Swap ...

Nomad sets of all moves

- Free Insert 1 -> M1
- Pairwise Swap 1-2 -> 2-1
Prune #2: Hierarchical Decomposition

Sets of all free inserts

Clients

Machines

C1

M1

M1

M2

M2

C1000

M50000
Prune #2: Hierarchical Decomposition

Sets of all free inserts

- Clients
  - C1
  - .
  - .
  - .
  - C1000

- Machines
  - M1
  - .
  - .
  - .
  - M2
  - .
  - .
  - M50000
Prune #2: Hierarchical Decomposition

Sets of all free inserts

Clients

M1

M2

M50000

C1

. 

C1000

Machines

Nomad sets of all free inserts

C1

. 

C1000

Cluster1

Cluster25
Prune #2: Hierarchical Decomposition

Sets of all free inserts

Clients

C1

.

.

C1000

Machines

M1

M2

.

.

M50000

Nomad sets of all free inserts

Client1

.

.

Cluster25

C1

C1000

Cluster1

M1

M2

.

.

M2000

Cluster1
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System Implementation

OpenStack v. Icehouse

Cloud Controller

Clients in Cluster 1
- Cluster 1 Placement Algorithm
- VM Placements for Cluster 1

Clients in Cluster N
- Cluster N Placement Algorithm
- VM Placements for Cluster 1

Arrival

VM
VM
System Implementation (One Cluster)

Cluster 1
Placement Algorithm

General Placement Computation

OpenStack-specific Migration Engine

VM Placement

Custom C++
~2000 LOC

OpenStack Icehouse:
~200 LOC in Controller Scheduler code
System Implementation (One Cluster)

Cluster 1
Placement Algorithm

General Placement Computation

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VM Placement

Custom C++
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~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

\(<R,C>: \text{Problem size of 20-machines}\)

Metric:

\[\text{InfoLeak}_{c \rightarrow c'}([t - \Delta, t])\]

Nomad brings \(~4.5x\) reduction in InfoLeak for 98\(^{th}\) percentile compared to static w.r.t. ILP.
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

\[
\text{Norm. Throughput (Norm. T)} = \frac{T_{w/o} - T_w}{T_{w/o}} \times 100
\]

• Overhead (Norm. T)
  – \(\sim 0\%\) for 95\(^{th}\) Norm T.
  – 0.096\% for 50\(^{th}\) (median) Norm. T.
  – 1.8\% for 5\(^{th}\) 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