HyperTP: Mitigating vulnerability windows with hypervisor transplant

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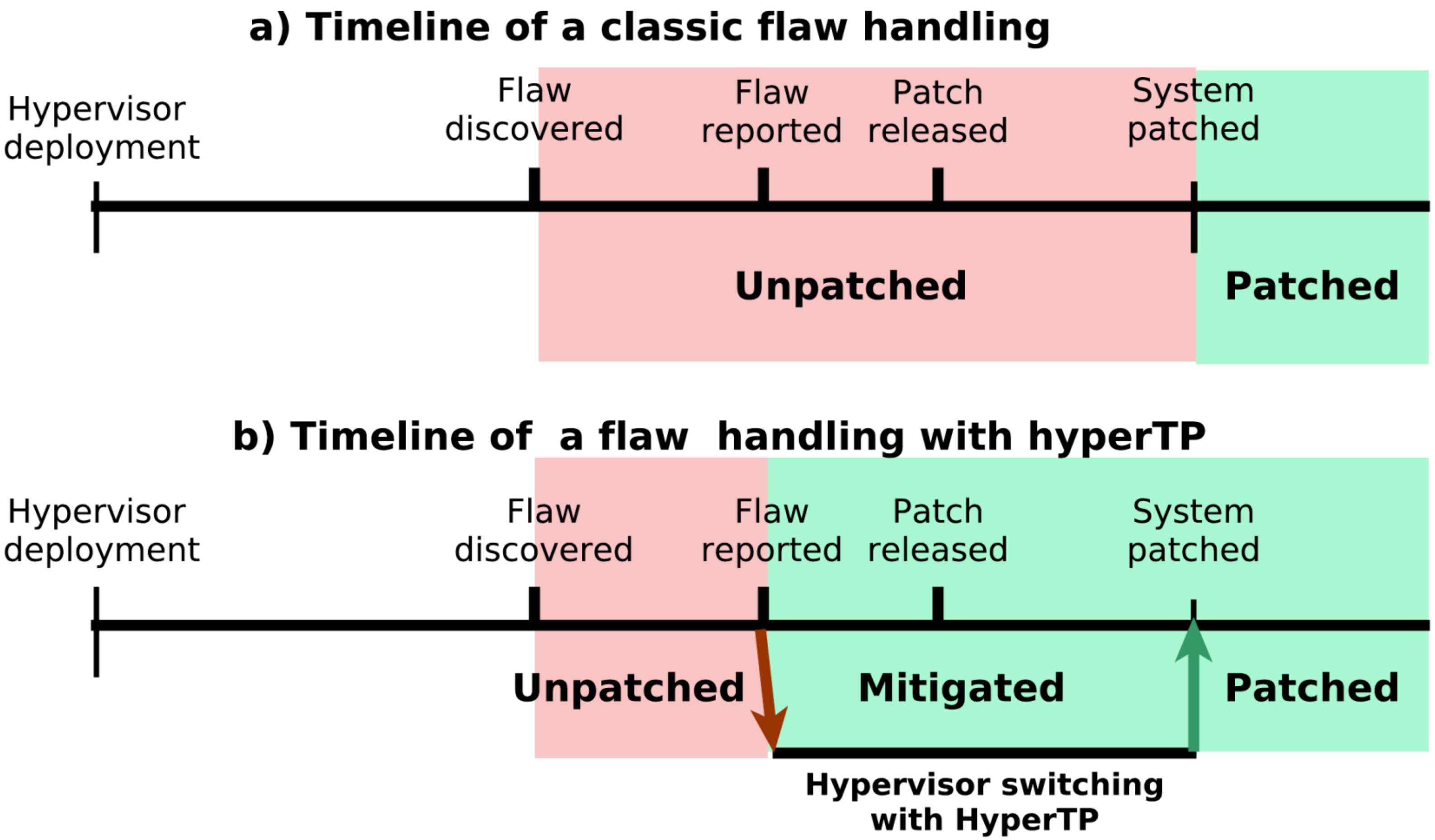
Motivation

- Need to reduce datacenter's window of vulnerability
  - Alibaba reports 15 days to upgrade one cluster
- Different hypervisors have different attack surfaces and vulnerability windows
  - Ideally select from a "pool" of hypervisors for the safest one
- Solution: hypervisor transplant
  - Switching from one hypervisor to another
- Combine with existing virtualization management tools (libvirt, OpenStack)

Vulnerability timeline



Key contribution: HyperTP

- Combination of 2 approaches: in-place hypervisor transplant ("InPlaceTP") and migration-based transplant ("MigrationTP")
- Built around two main principles: memory separation and unified intermediate VM representation

HyperTP general workflow

1. Save VM states and memory
2. Suspend running VMs
3. Transplant new hypervisor
4. Restore VM states
5. Resume VM

Memory separation

- We identified four categories of hypervisor memory:

  most VM-specific...
  - Guest state (i.e. guest-only memory)*
  - VM state (GPA-HPA maps, vCPU state, etc.)*
  - VM management state (list of running VM, hypervisor scheduler)
  - Hypervisor state (non-VM related)

  ...most hypervisor-specific

  *saved/translated by HyperTP

Unified VM state representation

- Intermediate representation of guest and VM states
  - vCPU
  - Memory
  - I/O devices
- Functions to translate to/from native hypervisor state
- Towards uniform "virtual machine API" across hypervisors

Prototype

- Implemented on Linux 5.3.1, kvmtool and Xen 4.12.1 HVM
- $\sim$8.5 KLOC (90% userspace-based)
- InPlaceTP for Xen $\leftrightarrow$ KVM, Xen $\rightarrow$ Xen
- MigrationTP for Xen $\rightarrow$ KVM

Saving guest devices

- Saving and restoring VM hardware state already possible in most hypervisors
  - Xen: reuse existing HVM state saving code
  - kvmtool: write saving code matching Xen HVM state format
- Incompatible devices (e.g. PV NICs): unplug device before transplanting

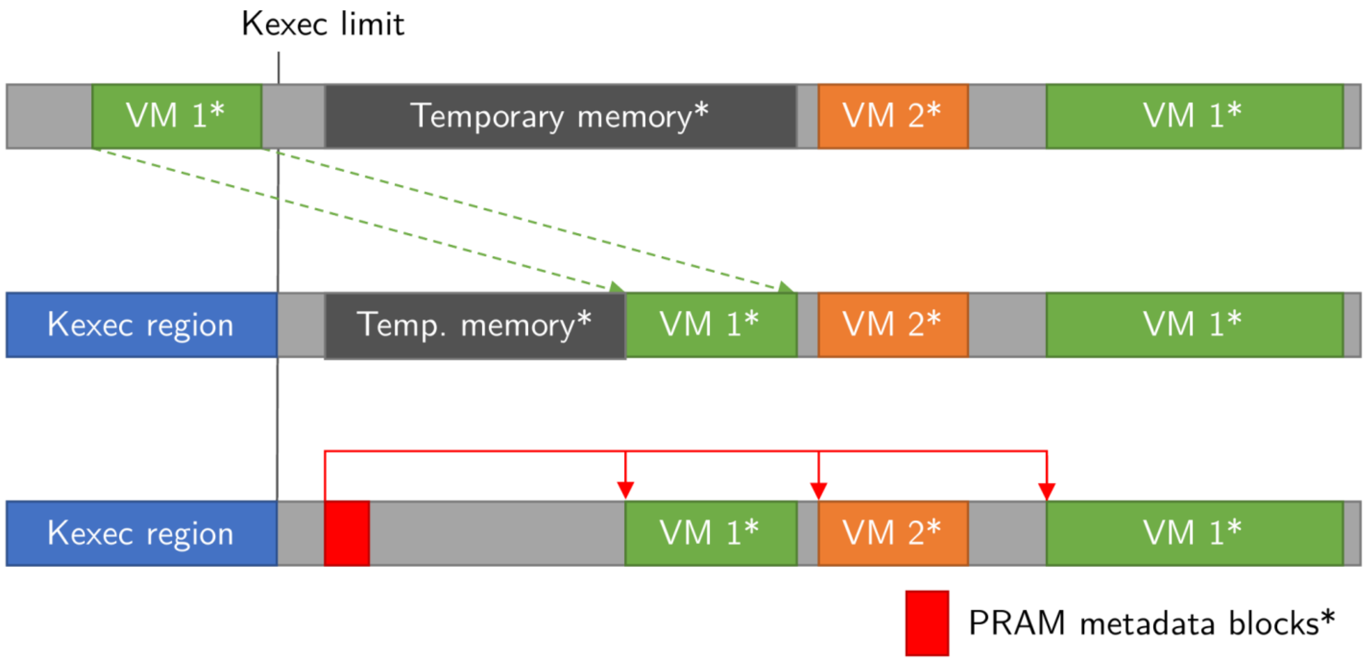
Saving guest memory (InPlaceTP)

- Saving guest memory to disk is too time consuming
- Keep guest memory in host RAM
- Manage VM memory in file table
  - Modified Vladimir Davydov's PRAM patchset and in-memory format
  - Supports 4K and 2M pages

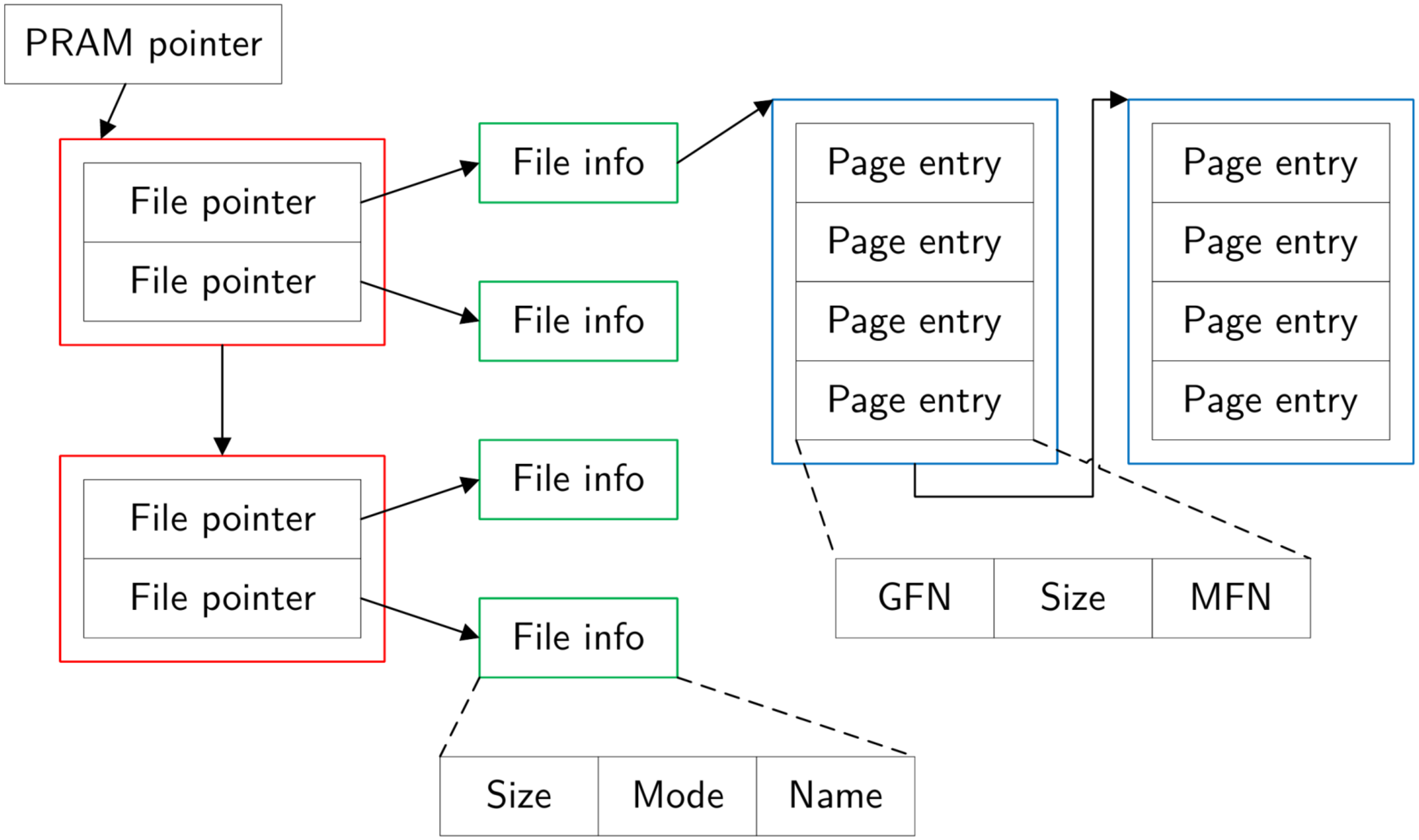
PRAM table construction

1. Allocate temporary memory
2. Relocate VM memory regions
3. Construct PRAM table

*Non-contiguous regions



PRAM in-memory format



Transplanting (InPlaceTP)

- Need to preserve memory contents
- Solution: Use Kexec
    - Fast boot without going through BIOS
    - Supported for Xen $\leftrightarrow$ Linux transition
    - Keeps RAM relatively intact
- Pass PRAM table address through kernel parameter
- Compatibility fixes for Kexec with Xen $\leftrightarrow$ KVM

Restoring guest devices

- Modified kvmtool to read/write unified state:

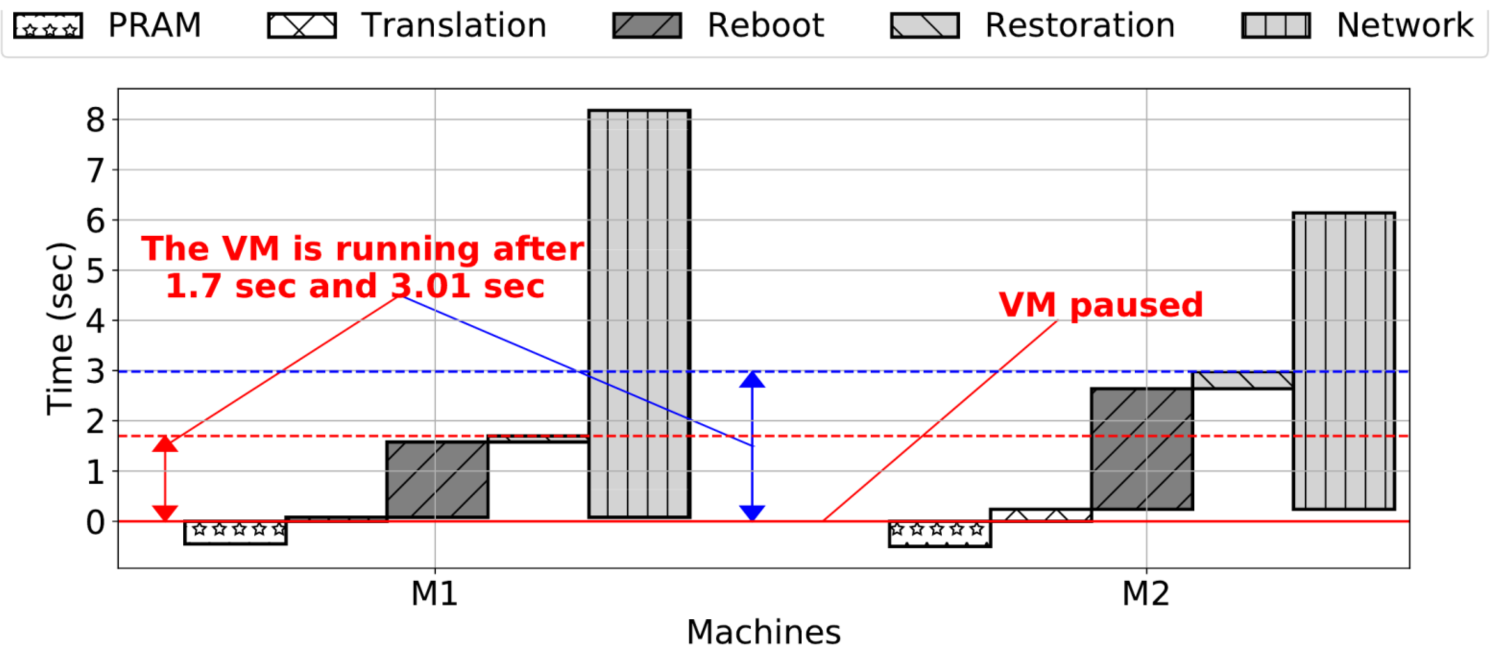
State	Xen	kvmtool
CPU regs	CPU	KVM (S)REGS, MSRS
Local APIC	LAPIC	KVM MSRS
Local APIC regs	LAPIC_REGS	KVM LAPIC_REGS
MTRR	MTRR	KVM MSRS
XSAVE	XSAVE	KVM XCRS, XSAVE
IO-APIC	IOAPIC	KVM IRQCHIP
PIT	PIT	KVM PIT2
TSC	TSC	KVM TSC
RTC	RTC	kvmtool RTC

Restoring memory (InPlaceTP)

- Mount PRAM structure as virtual filesystem at boot time
- Each VM's memory regions together represented as one file
- KVM: VM memory file directly mmap()ed
- Xen: Implement hypercall to assign memory file to restored domain

Evaluations: InPlaceTP Xen $\rightarrow$ KVM

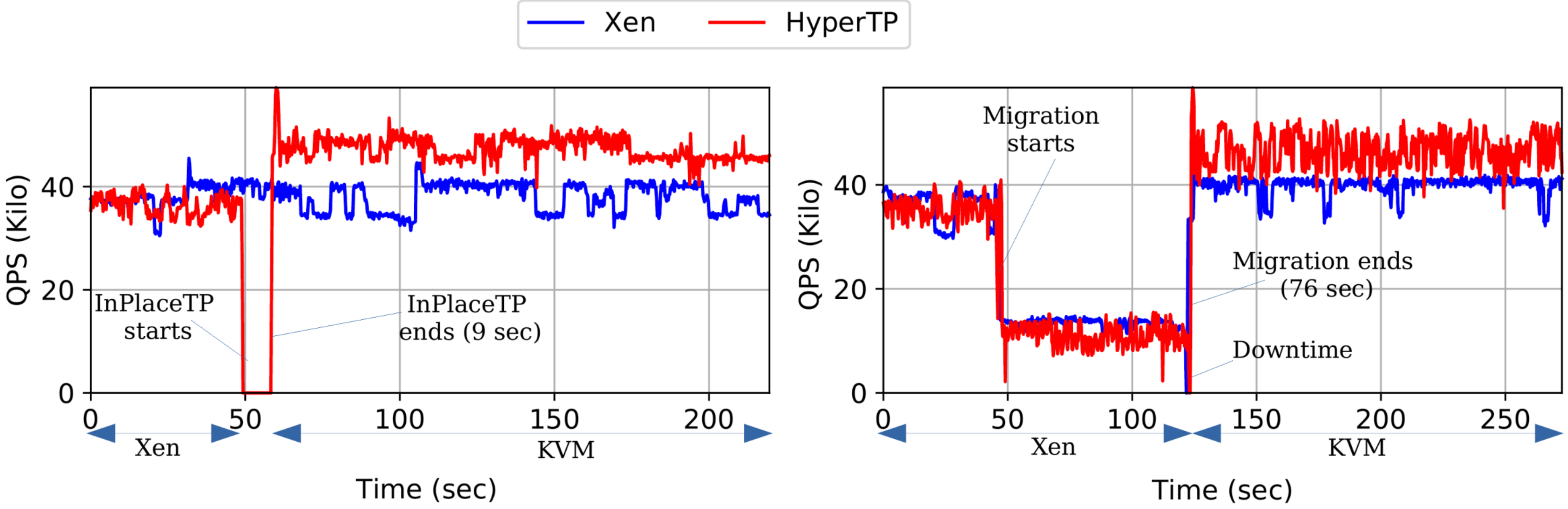
- Two different machines: M1/M2
- Downtime: 1.70 seconds on M1; 3.01 seconds on M2



- Networking card takes additional time to restart

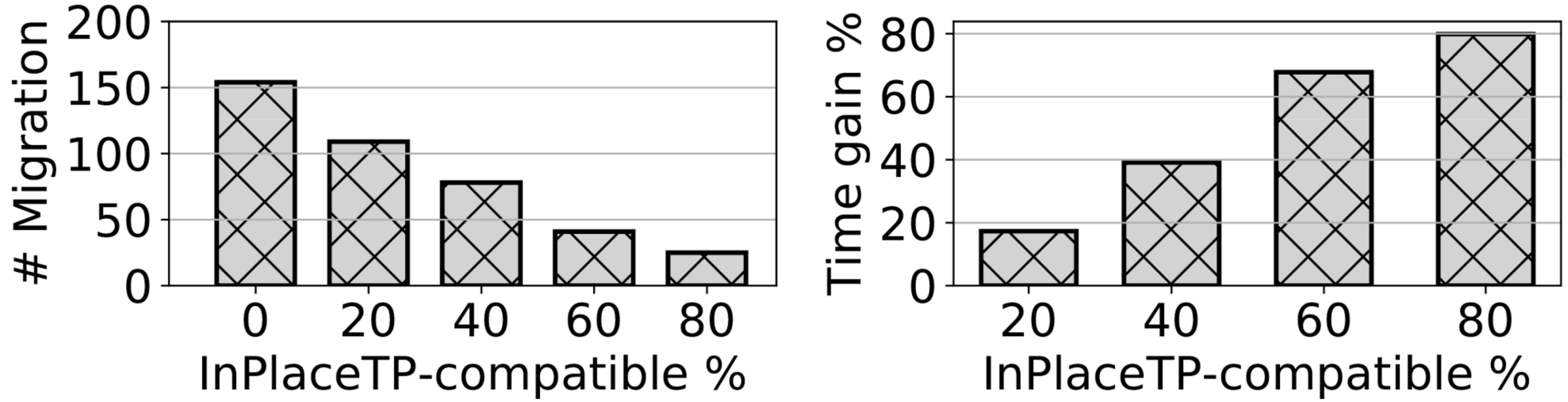
Evaluations

- InPlaceTP (left) offers low VM disruption and acceptable VM downtime
- MigrationTP (right) performs similarly to live migration: minimal downtime but long migration time comes with performance impact



Cluster-level upgrade times

- Used BtrPlace to simulate cluster upgrade event
- Cluster contains a mix of InPlaceTP-compatible and non-compatible VMs
- The more InPlaceTP-compatible VMs, the less time it takes to upgrade the cluster



Thank you for listening!