Fine-Grained Fault Tolerance using Device Checkpoints

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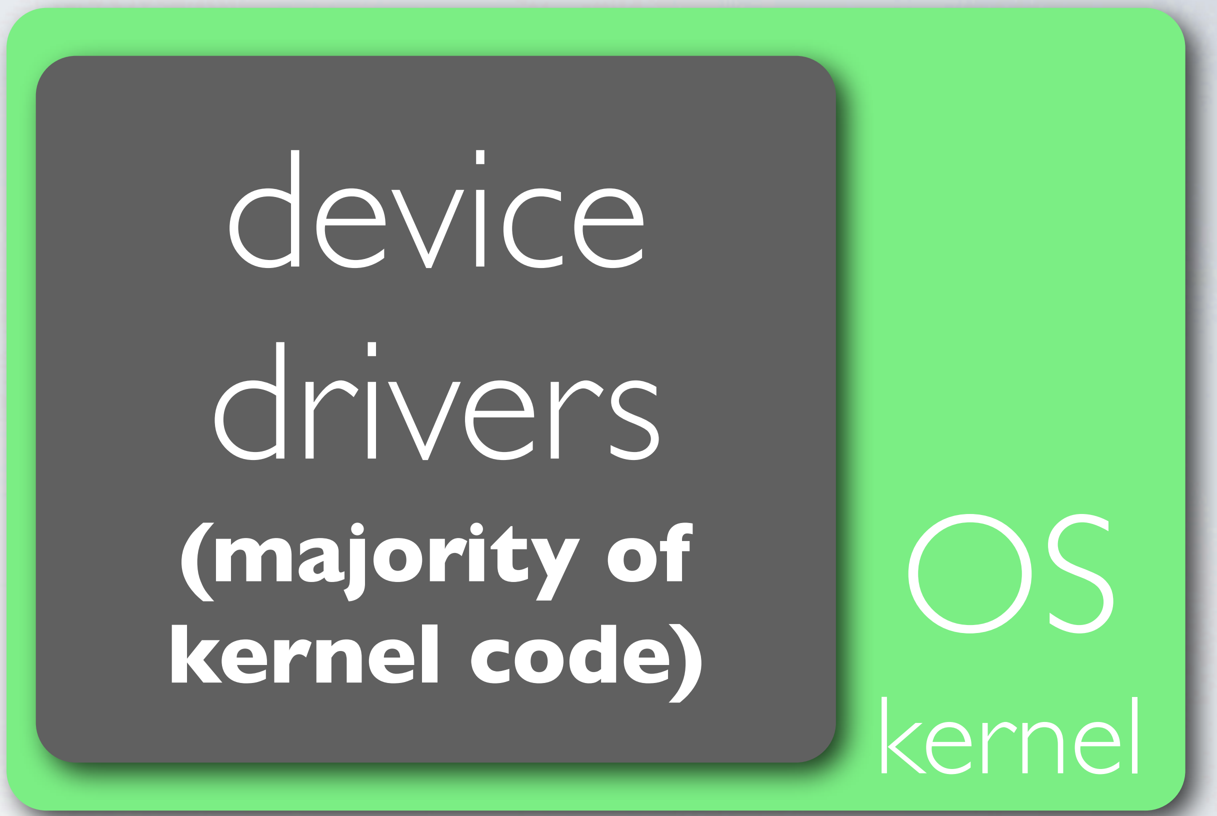
with Matthew Renzelmann and Michael M. Swift
University of Wisconsin-Madison

The (old) elephant in the room

3rd party developers

+



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device drivers

(majority of kernel code)

OS kernel

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Recipe for disaster

Extensive past work on reliability research

Improvement	System	Validation		
		Drivers	Bus	Classes
Isolation	Nooks [SOSP 03]	6	1	2
	XFI [OSDI 06]	2	1	1
	CuriOS [OSDI 08]	2	1	2
Type Safety	SafeDrive [OSDI 06]	6	2	3
	Singularity [Eurosys 06]	1	1	1
Specification	Nexus [OSDI 08]	2	1	2
	Termite [SOSP 09]	2	1	2
Recovery	Shadow Drivers [OSDI 04]	13	1	3
Static analysis tools	Windows SDV [Eurosys 06]	All	All	All
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Observation 1: Solutions that limit changes to kernel and apply to lots of drivers have real impact

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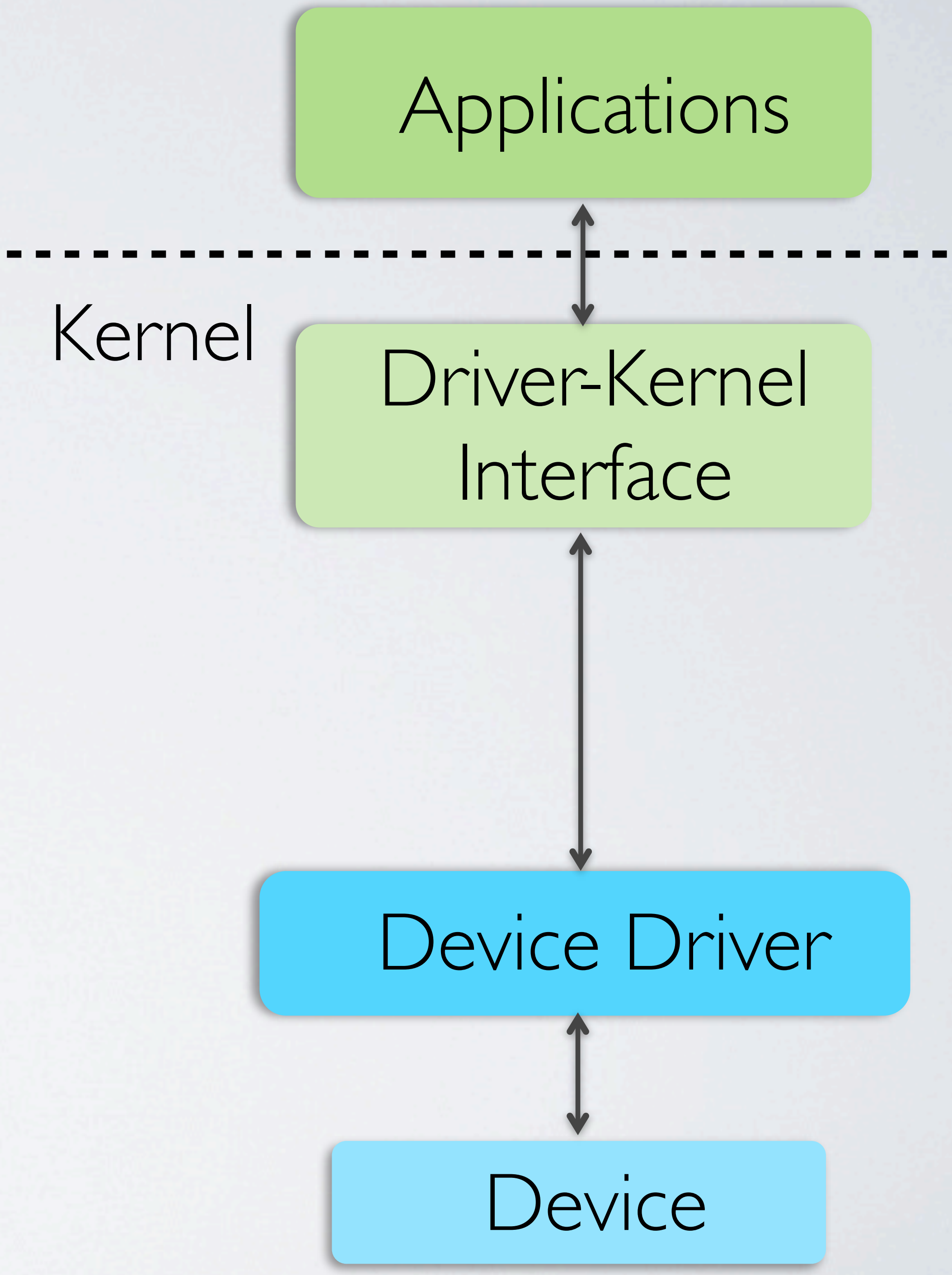
Observation 2: Most systems focus on improving isolation and detection and not on recovery

Driver failure recovery limited to driver restart

- Restart driver upon failure
  - Safedrive and MINIX approach
  - Can break applications



Shadow drivers

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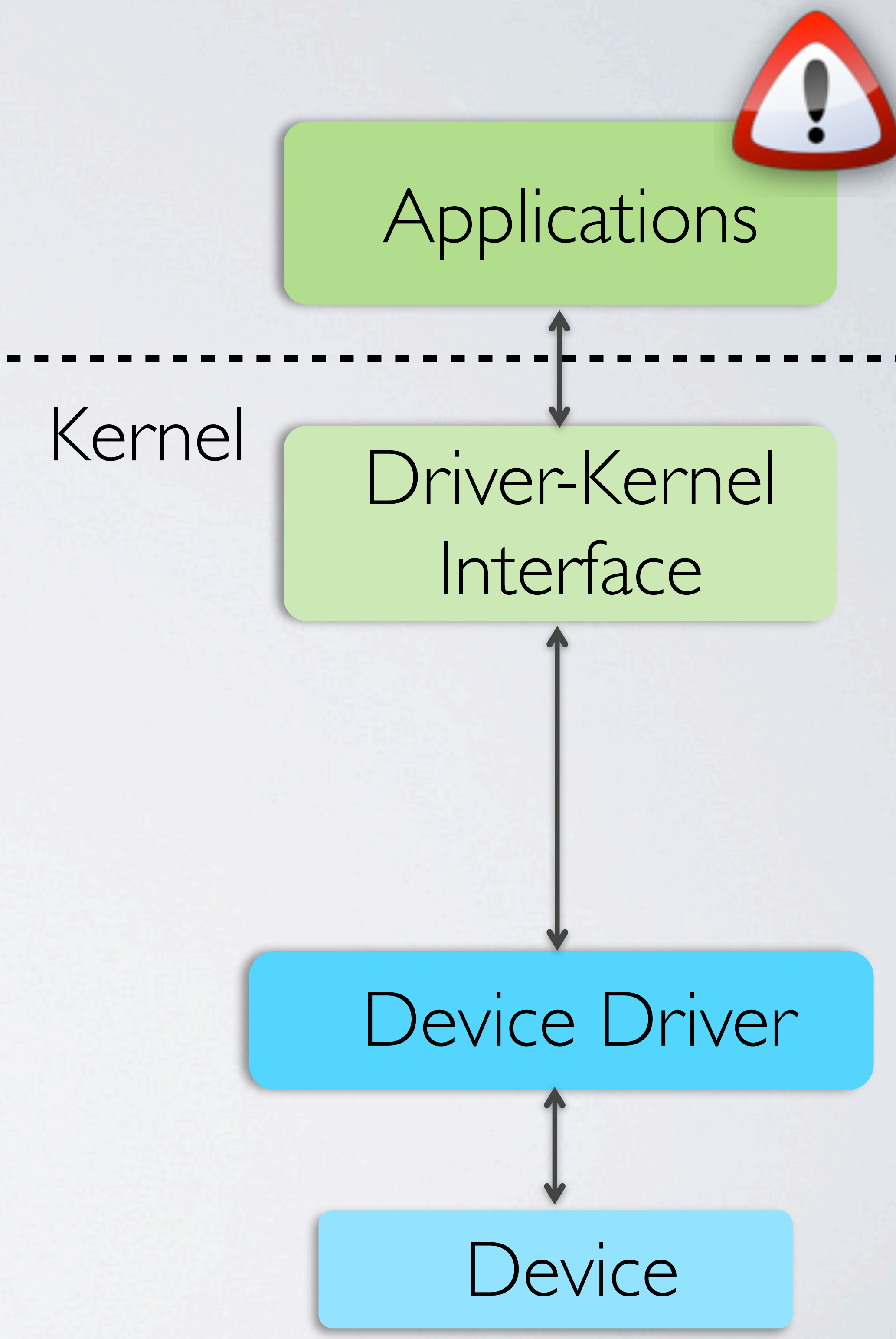

Shadow drivers

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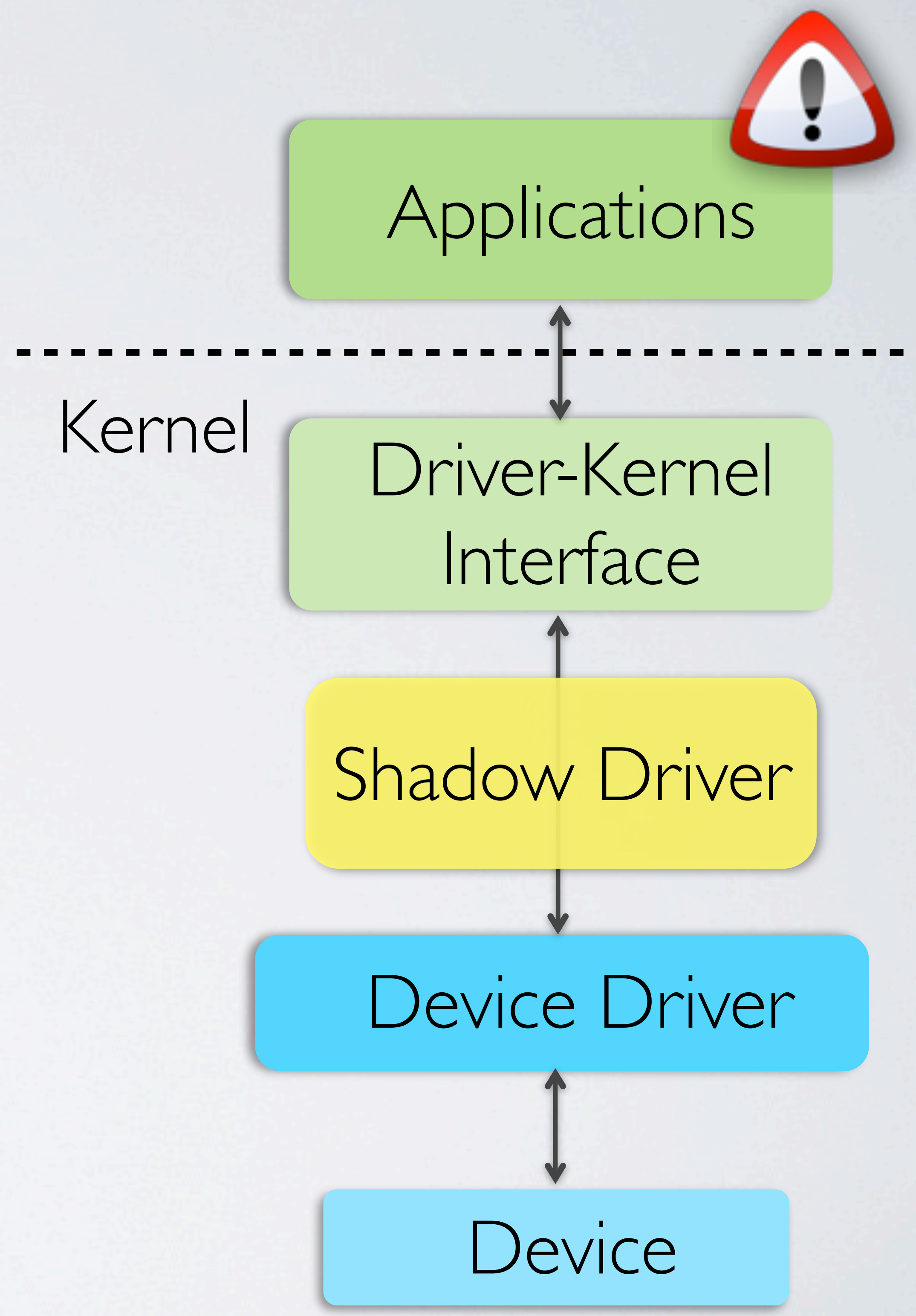
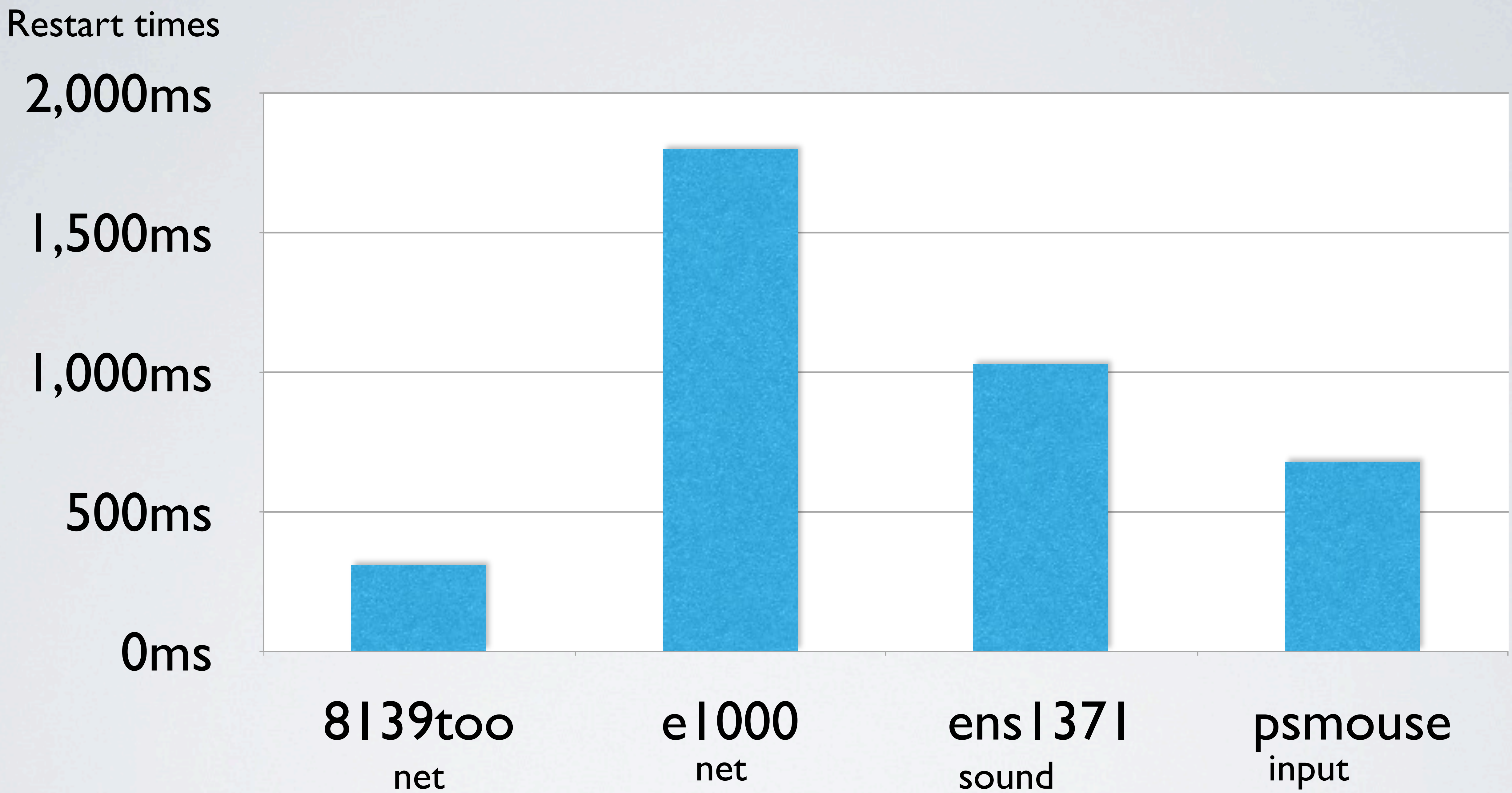
- Restart and replay upon failure
  - Shadow driver approach
  - Always record state of driver
  - Perform restart and log replay upon failure
  - Transparent to applications



Shadow drivers

Problem 1: Restart based driver recovery is slow



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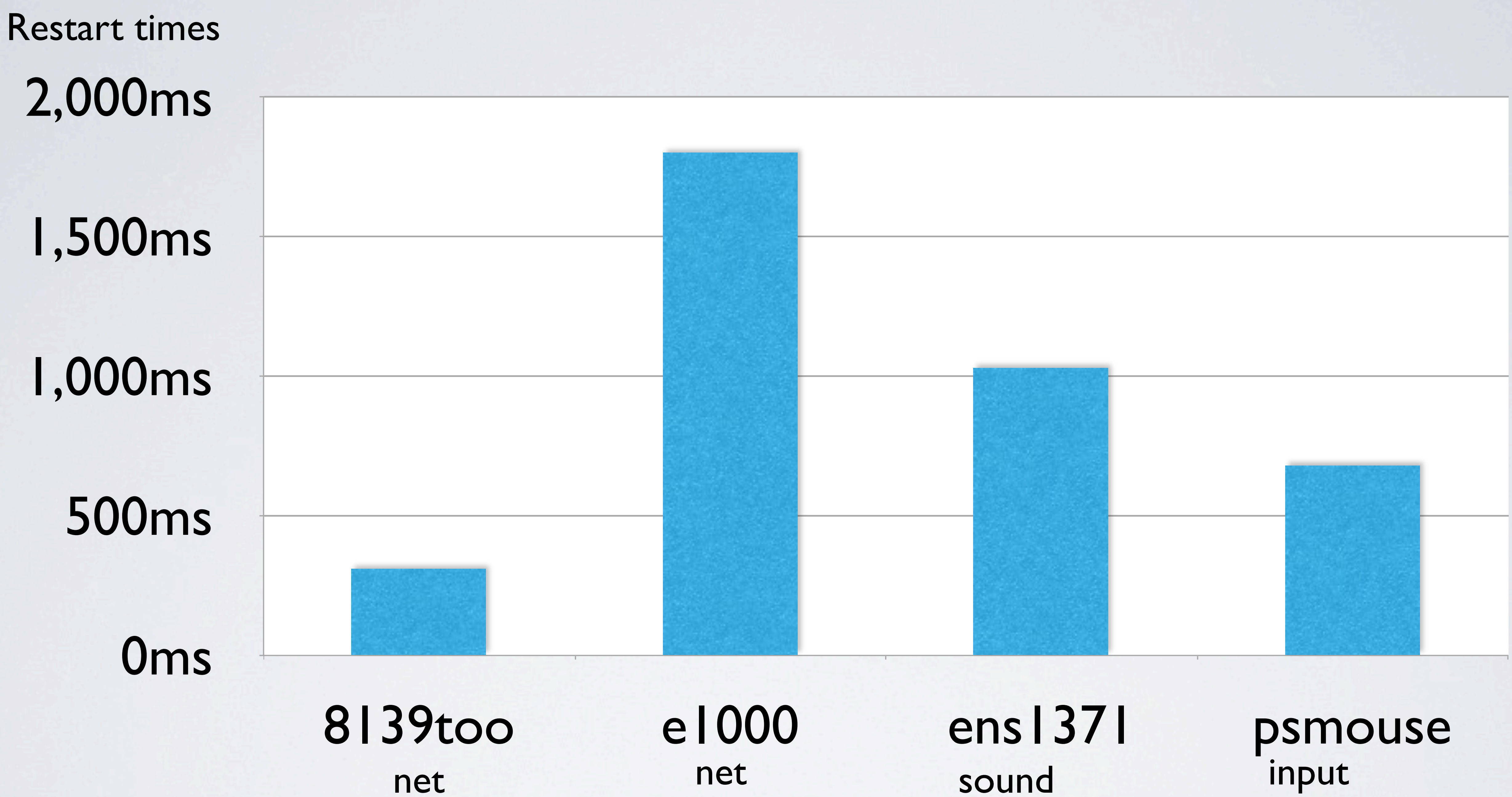
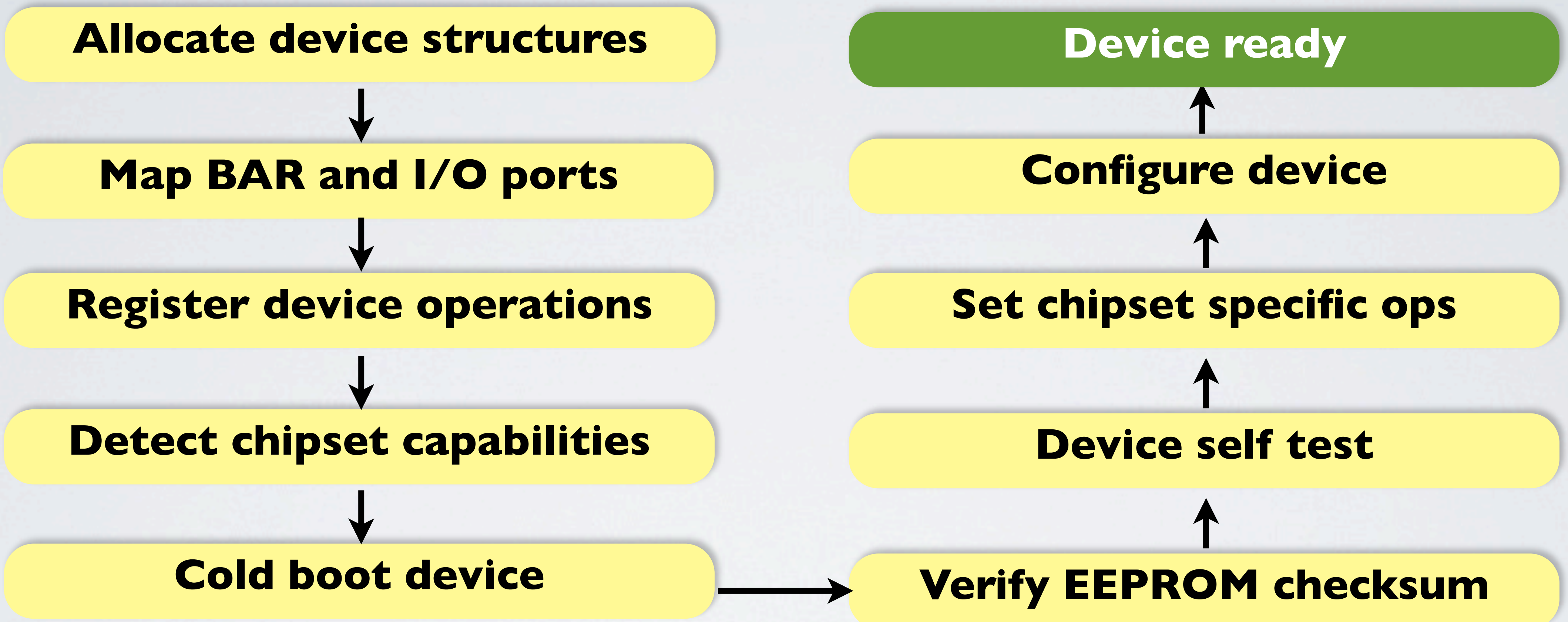


Shadow drivers restart the driver upon failure which can be slow

Driver re-initialization probes hardware again



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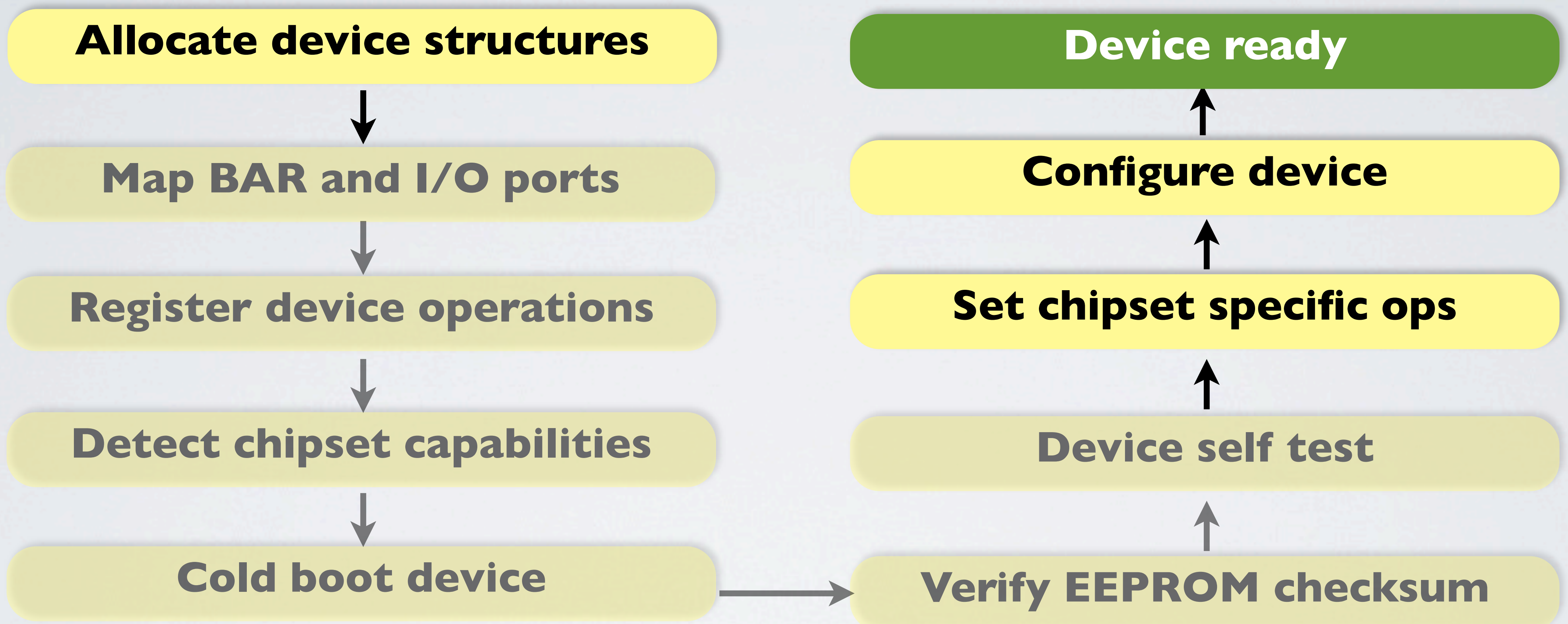

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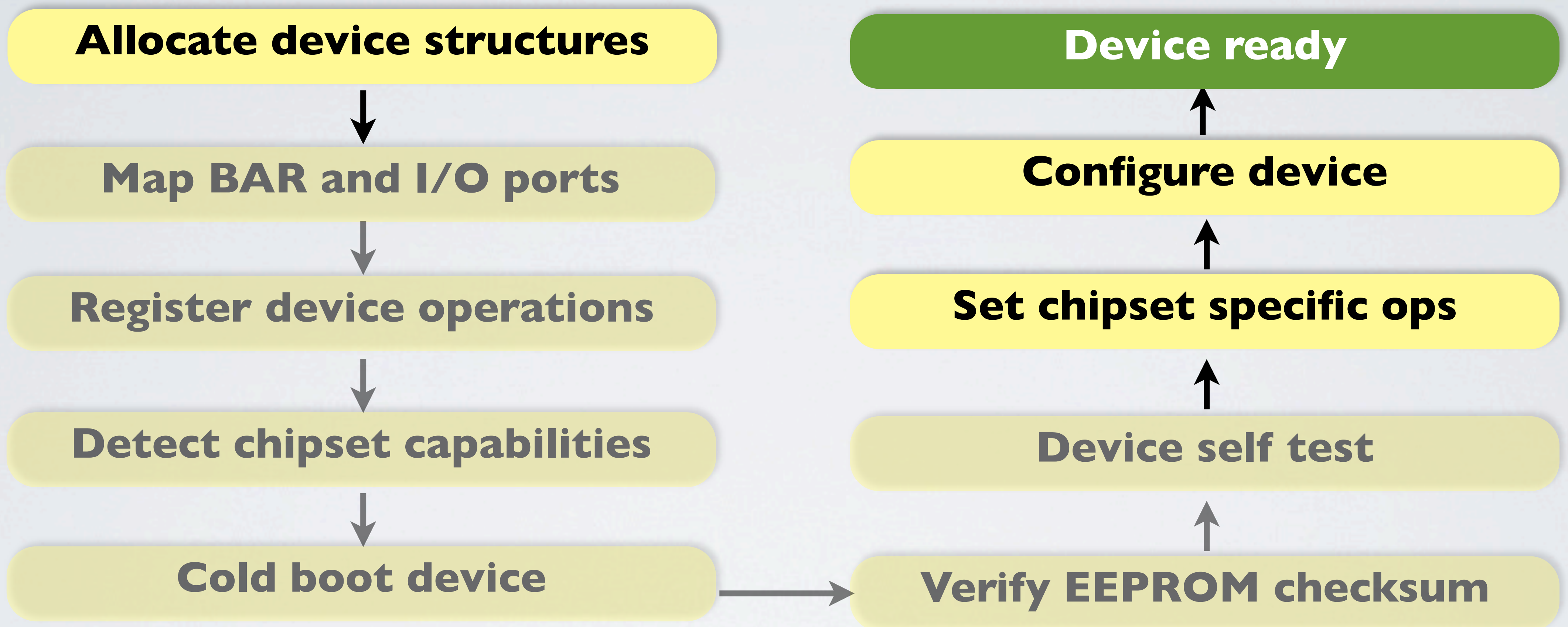
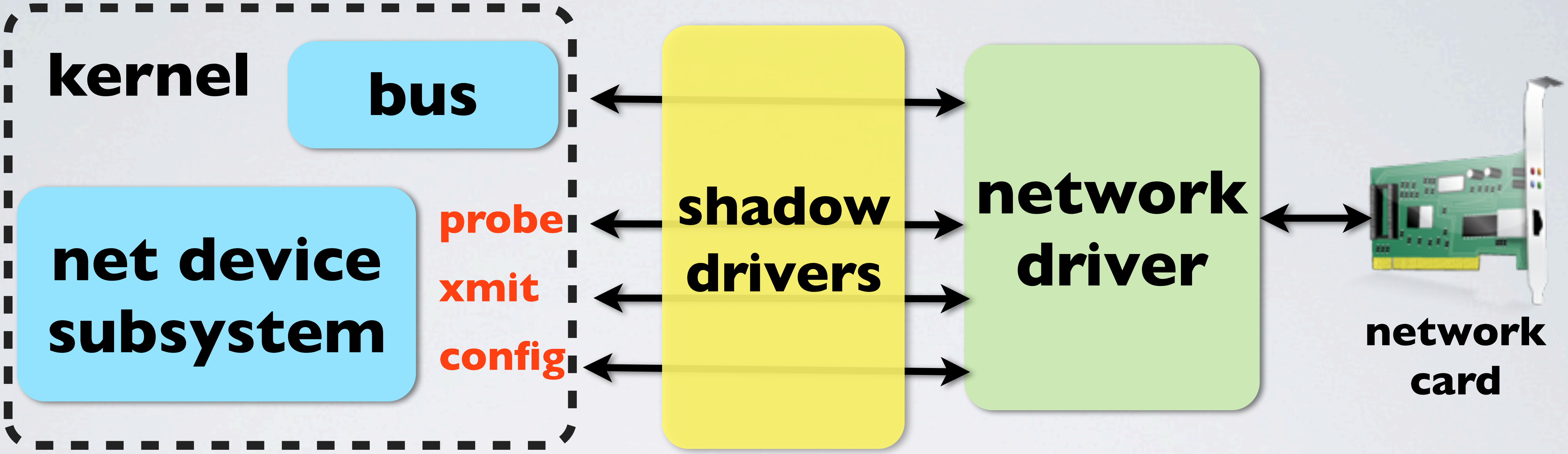


- What does slow device re-initialization hurt?
  - Fault tolerance: Driver recovery
  - Virtualization: Live migration
  - OS functions: Fast reboot

Problem 2: Shadow drivers assume drivers follow class behavior



- Class definition includes:
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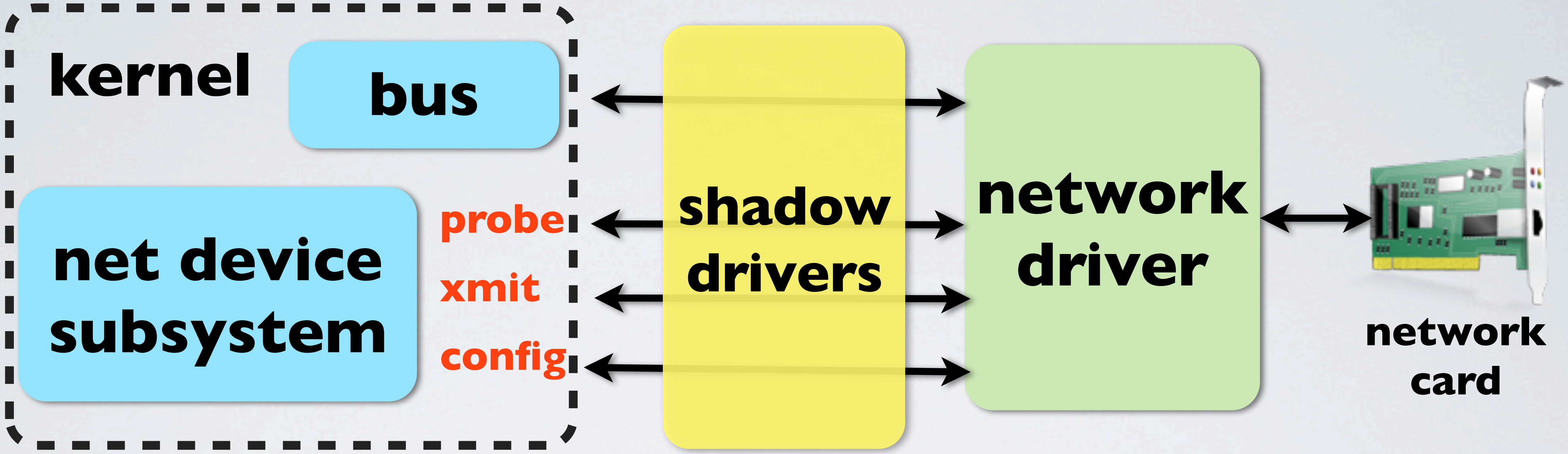

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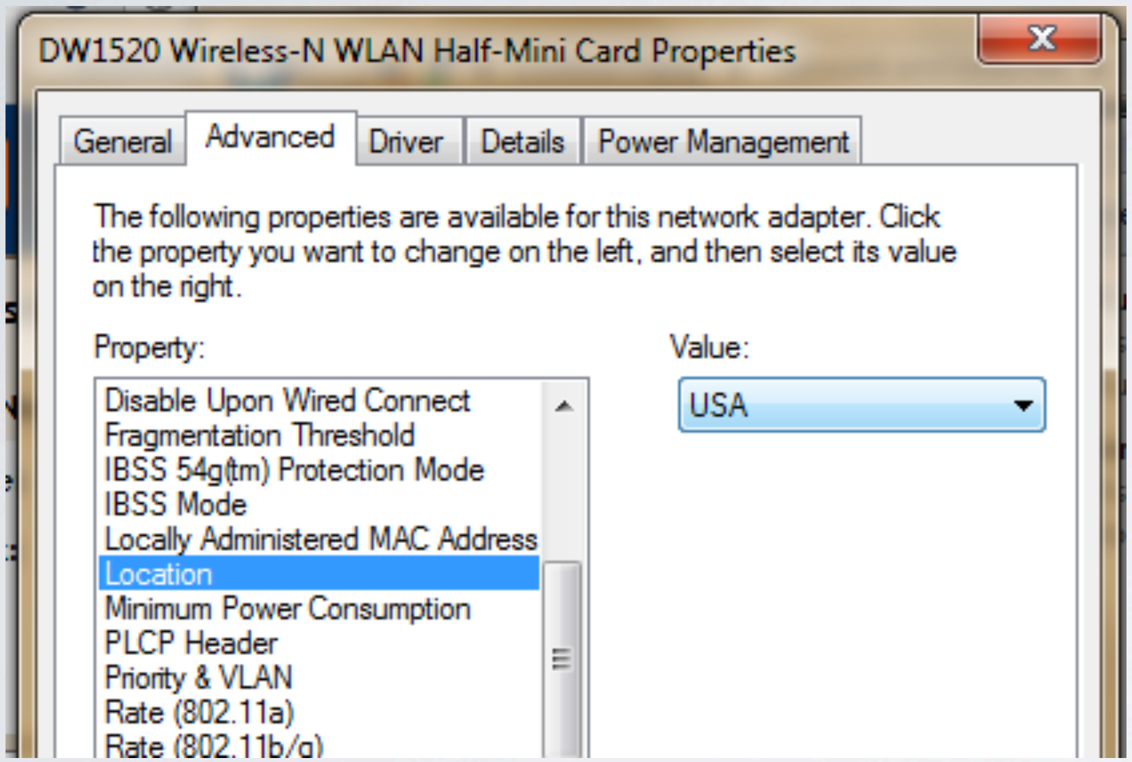
How many drivers follow class behavior and how much code does this add and

Problem 2(a): Drivers do behave outside class definitions

- **Non-class behavior that affects recovery:**
  - **procfs/sysfs interactions and unique ioctls**



Windows WLAN card config via private ioctls

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$ echo 1 > /sys/class/sound/mixer/
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Linux sound card config via sysfs

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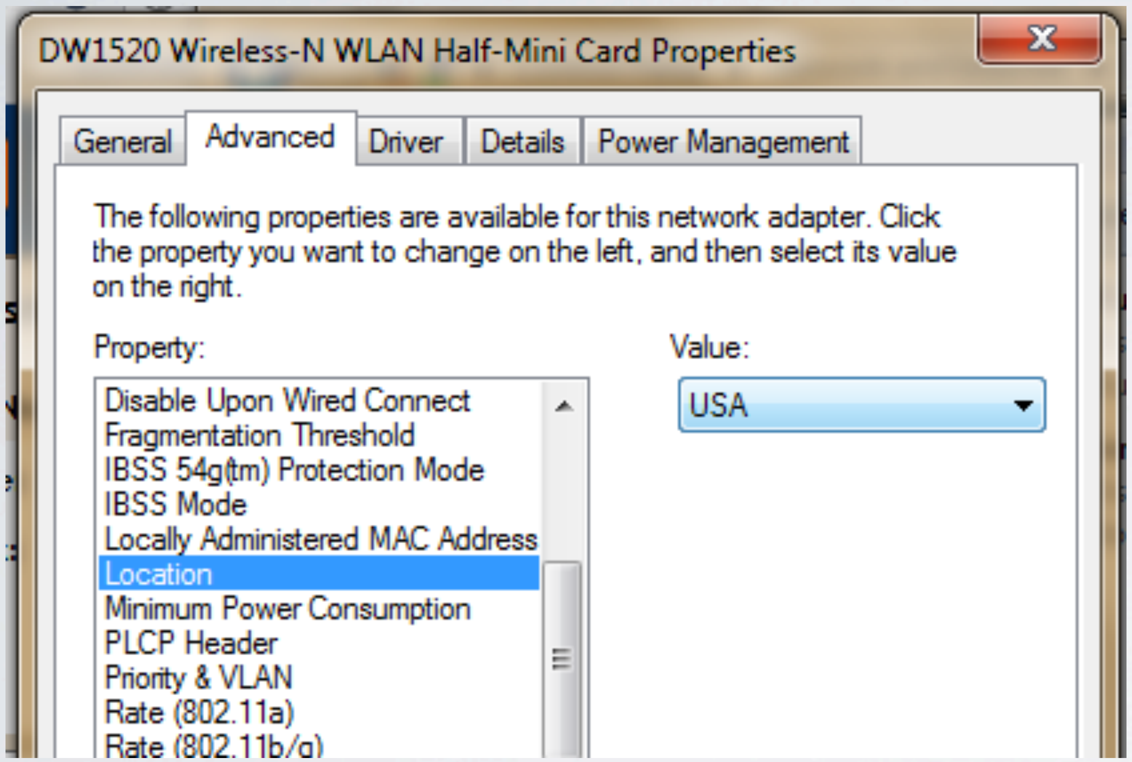

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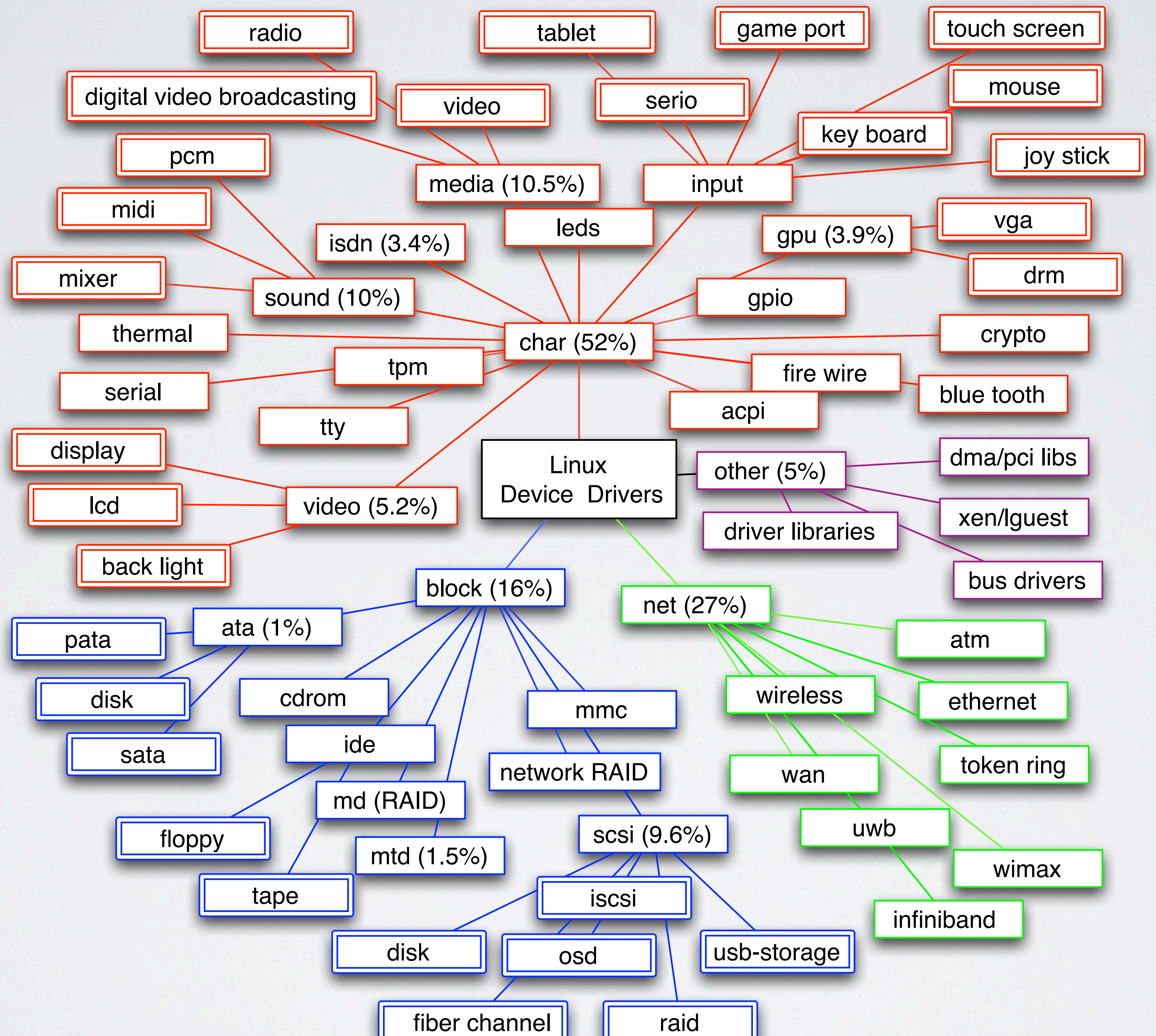
At least 16% of drivers have non-class behavior and may not recover correctly using shadow drivers

Problem 2(b): Too many classes



★ **"Understanding Modern Device Drivers"** **ASPLOS 2012**

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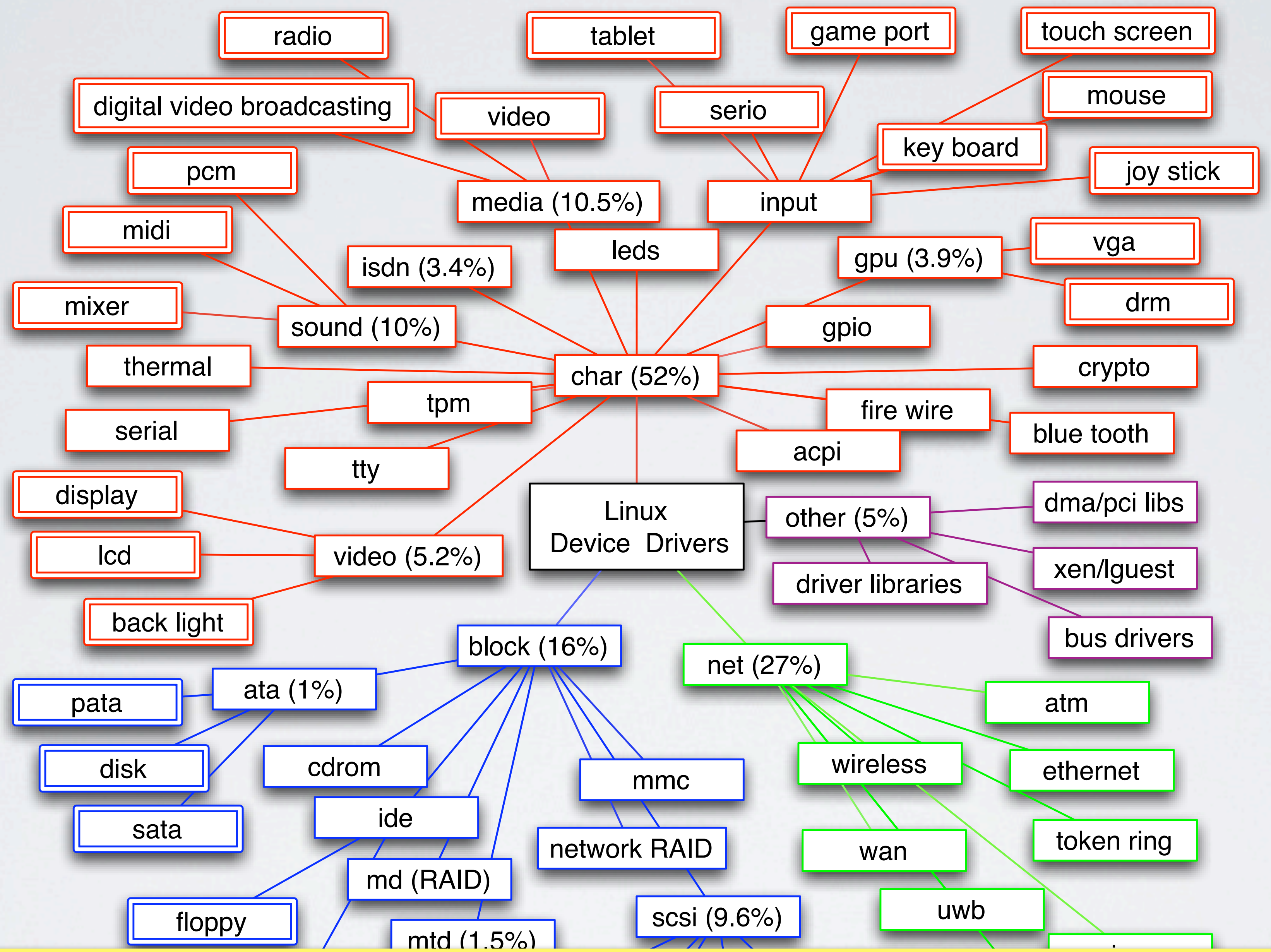

Class-specific driver recovery leads to a large kernel recovery subsystem

★ **"Understanding Modern Device Drivers"** **ASPLOS 2012**

Fine-Grained Fault Tolerance (FGFT)

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Fine-grained Isolation

- Runs driver entry points like transactions
- Relies on code generation to limit new code in kernel

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Checkpoint-based recovery

- ★ Provides fast and correct recovery semantics

- ★ Requires incremental overhead/changes to drivers
- ★ Shifts burden of fault tolerance to faulty code

Outline

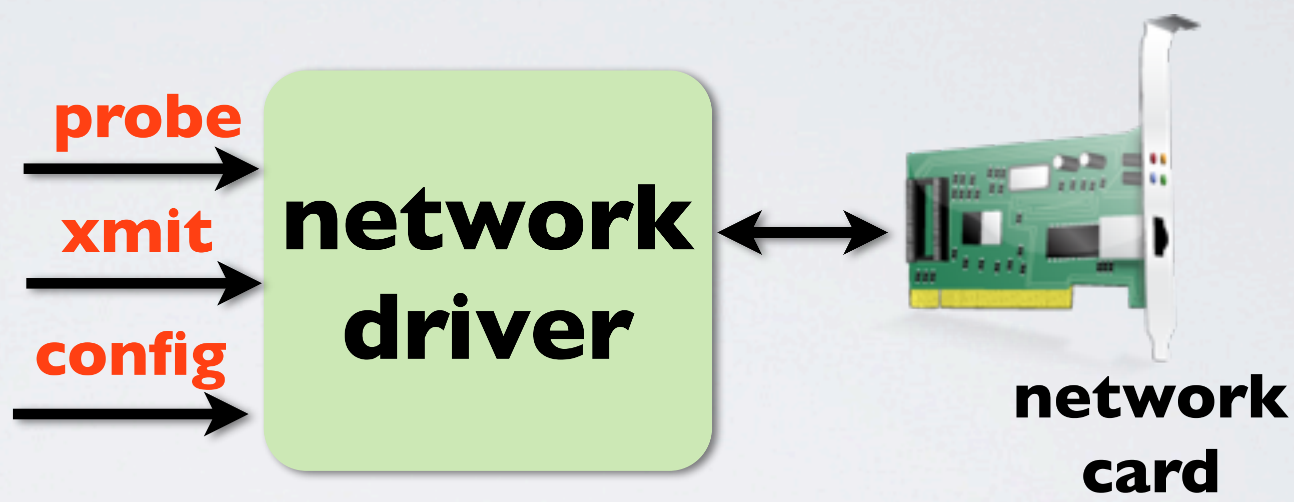
Introduction

Fine-grained isolation

Checkpoint-based recovery

Evaluation and Conclusions

Unit of fault tolerance: Driver entry point



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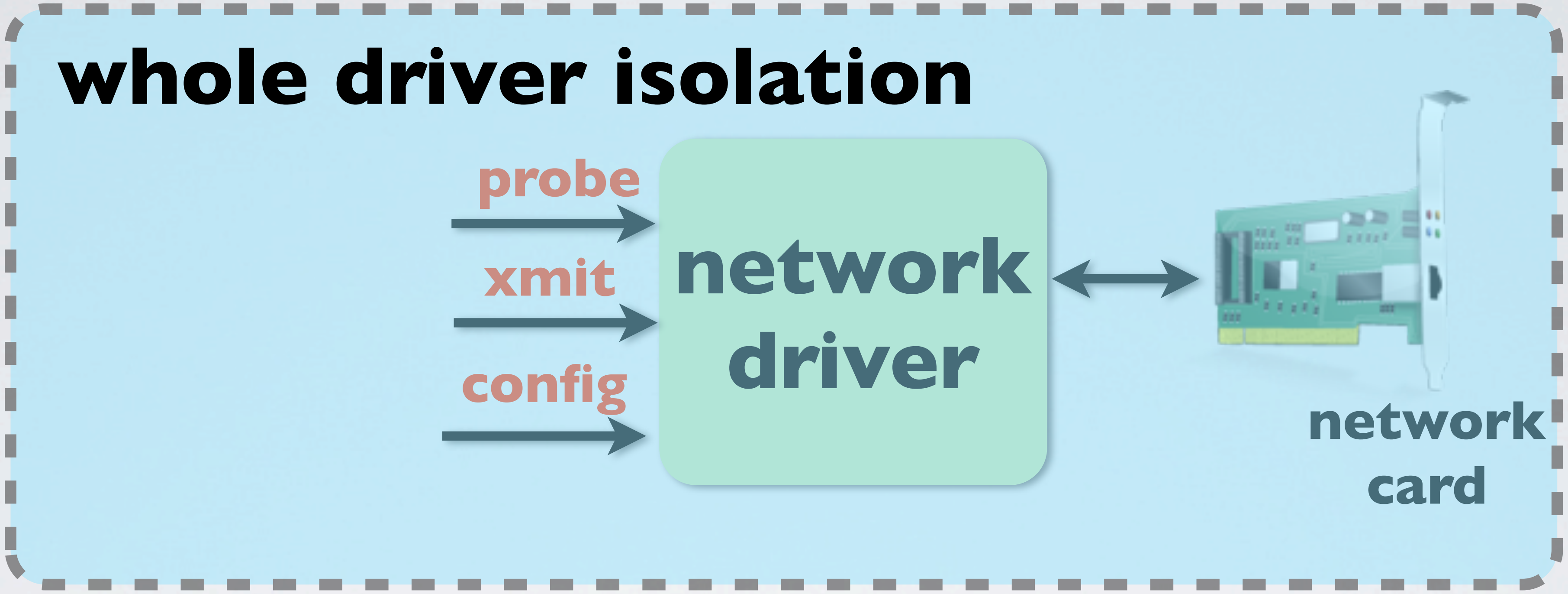

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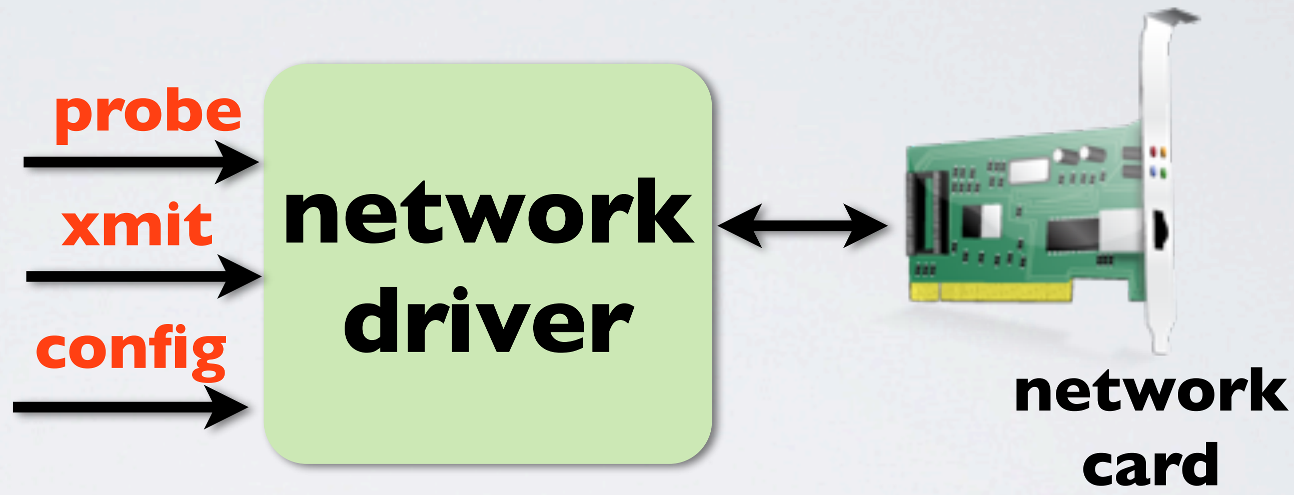

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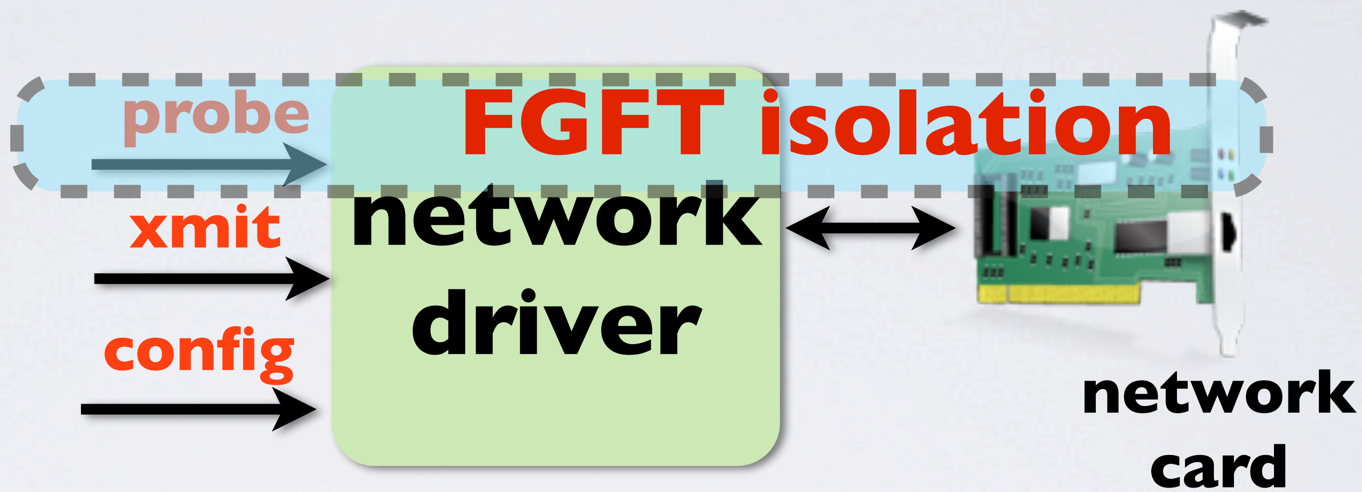

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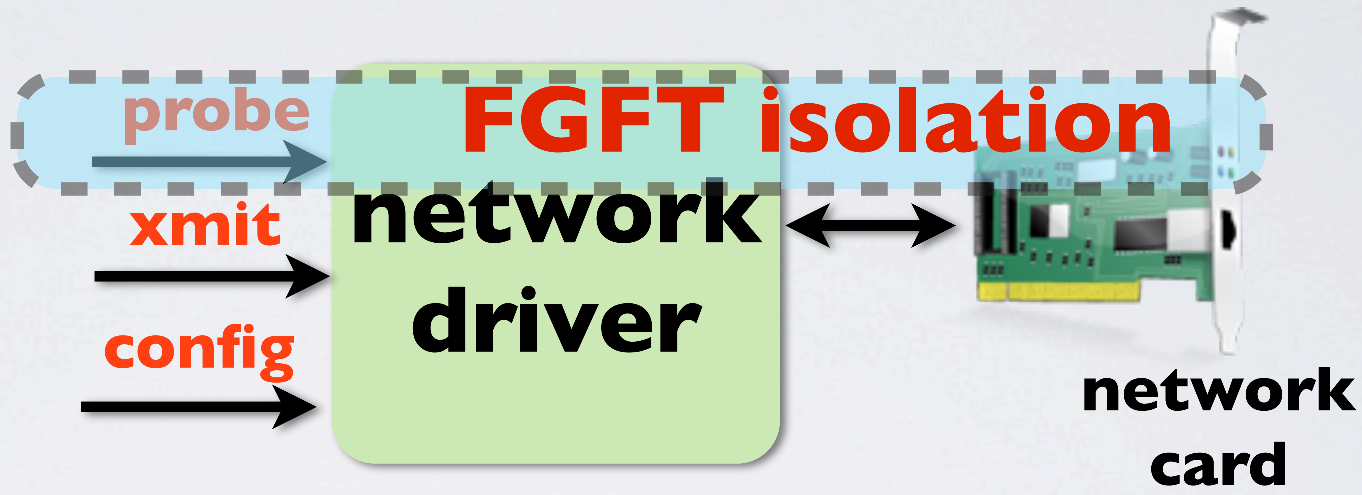

★ **Provide fault tolerance to specific driver entry points**

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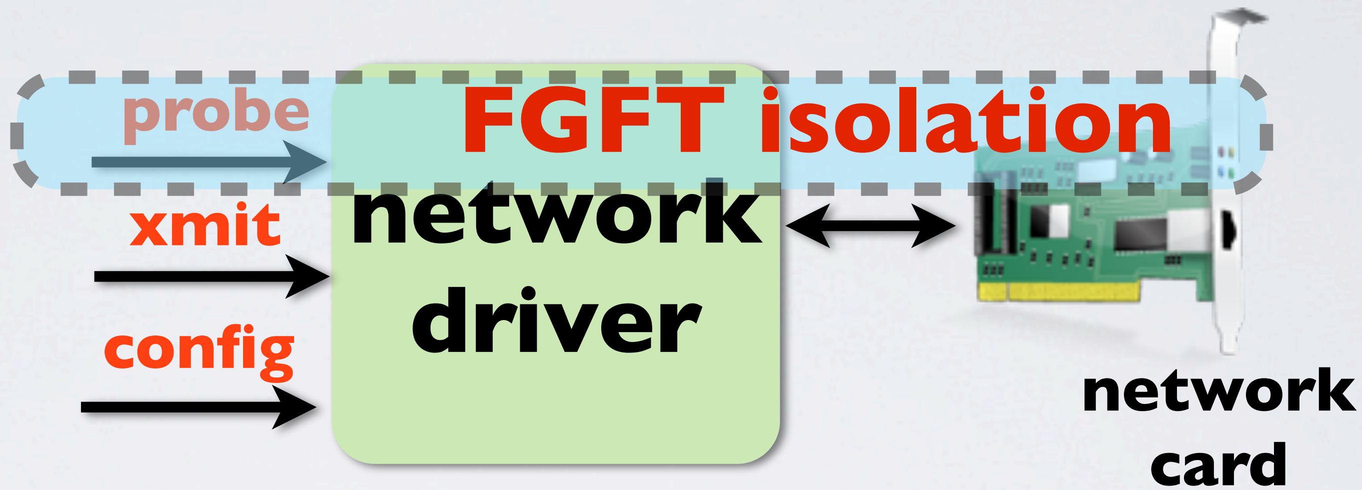
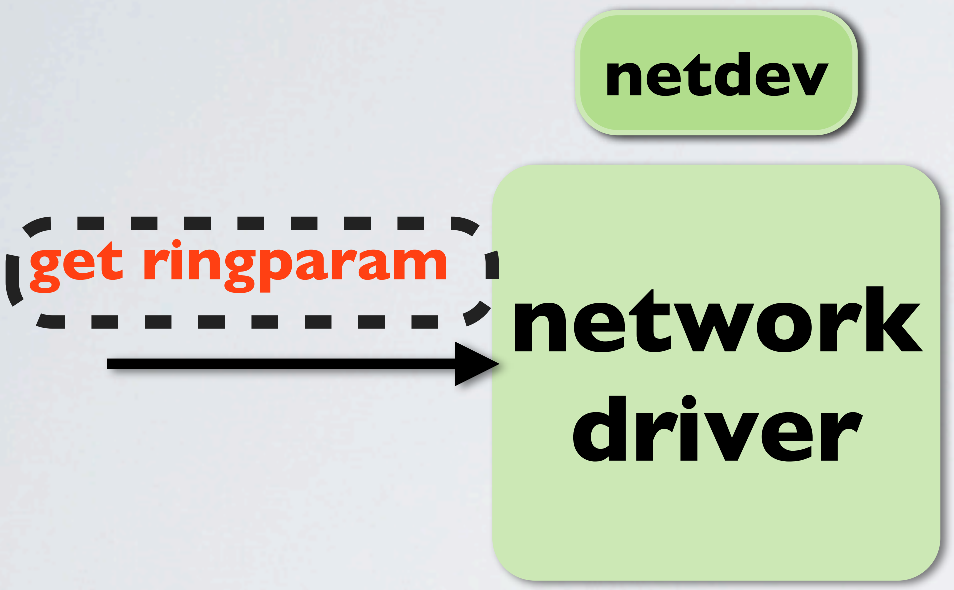


★ **Provide fault tolerance to specific driver entry points**

★ **Can be applied to untested code or code marked suspicious by static or runtime tools**

Transactional support through code generation



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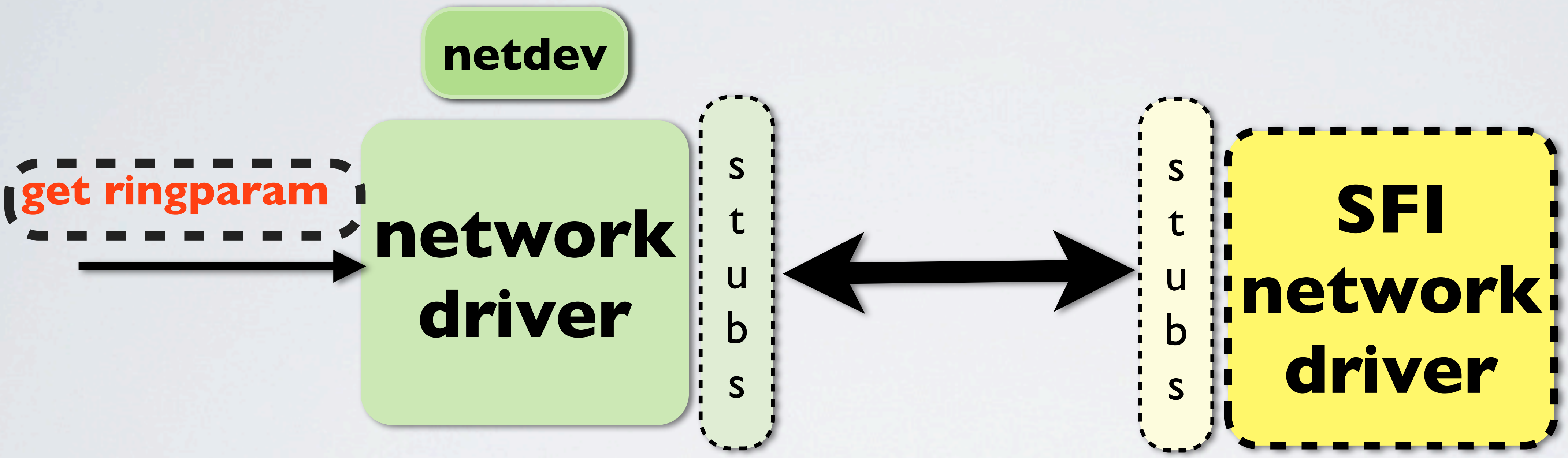

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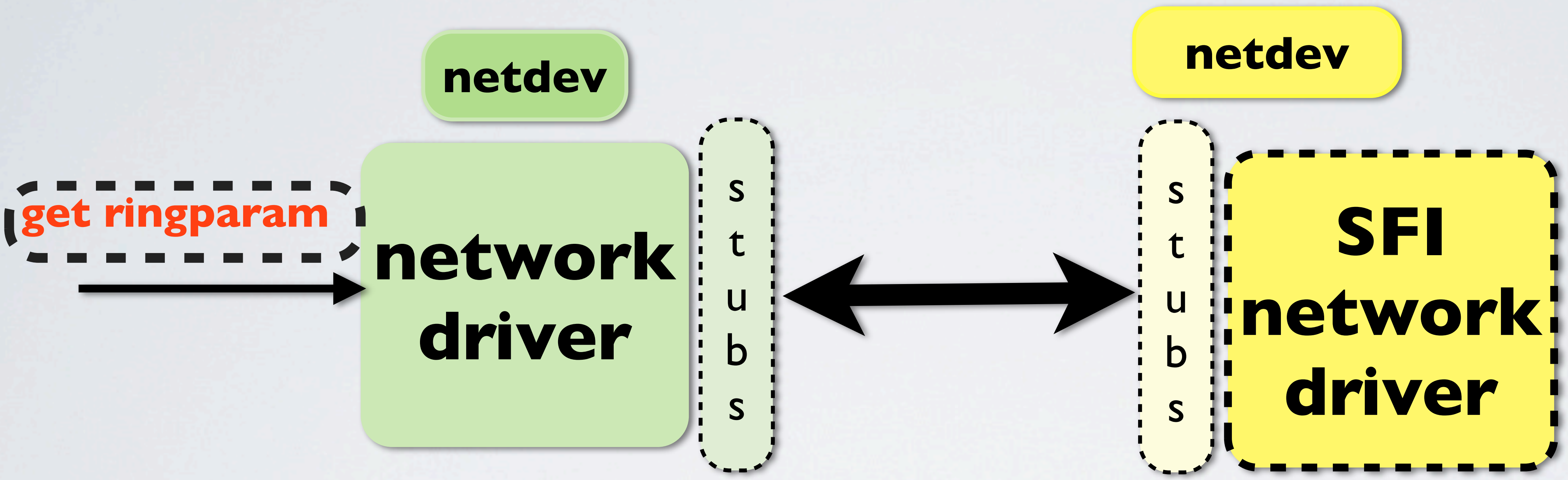

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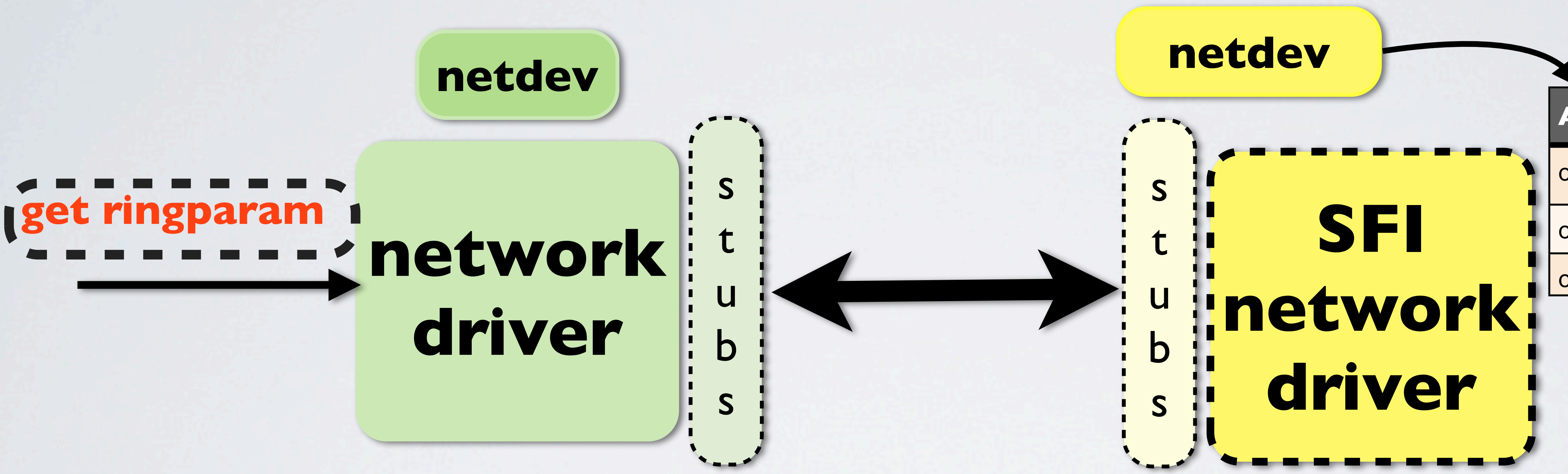

Range Table

Address	Access rights
oxffffaooo	Read
oxffffaoo8	Write
oxffffaooa	Read

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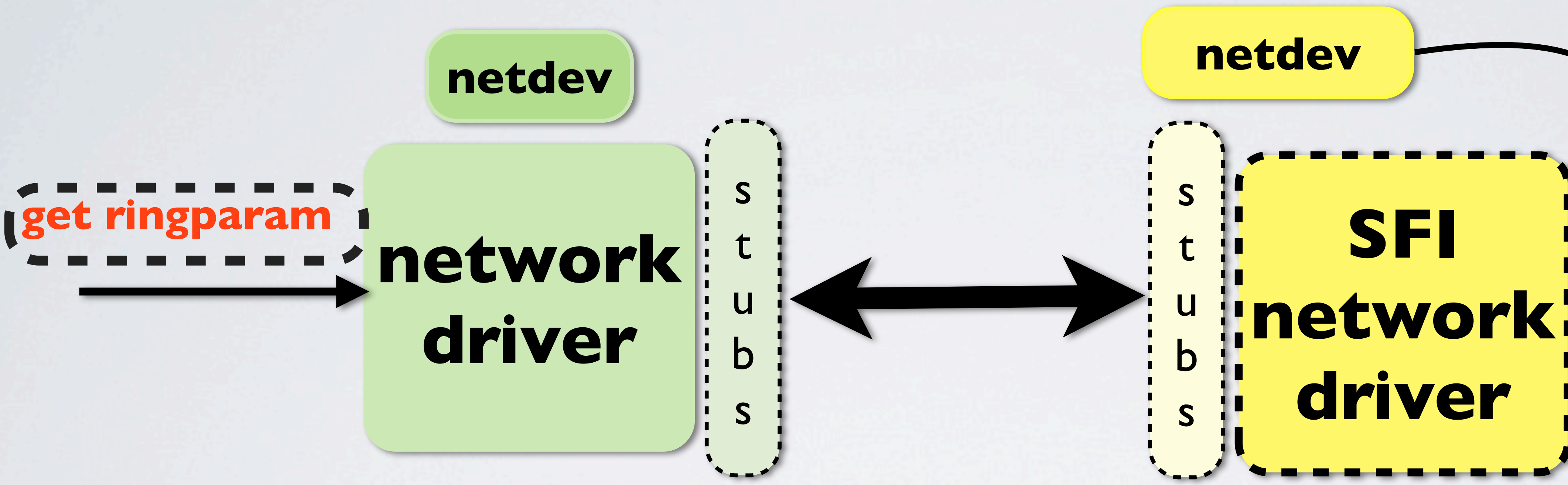

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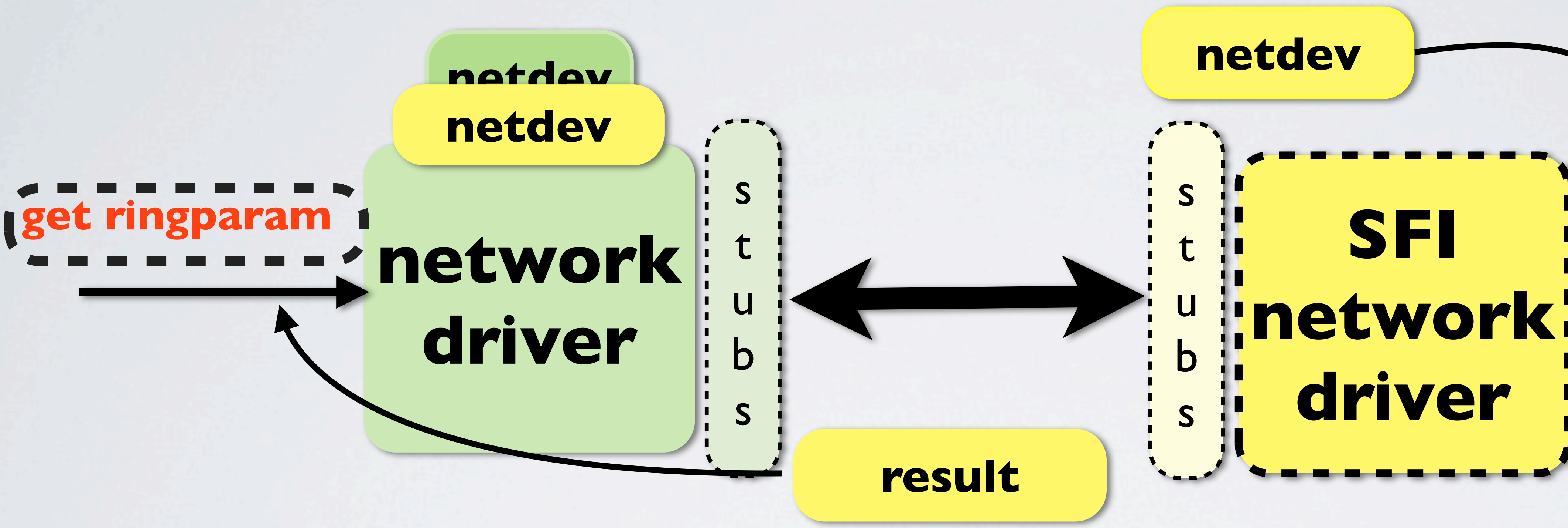

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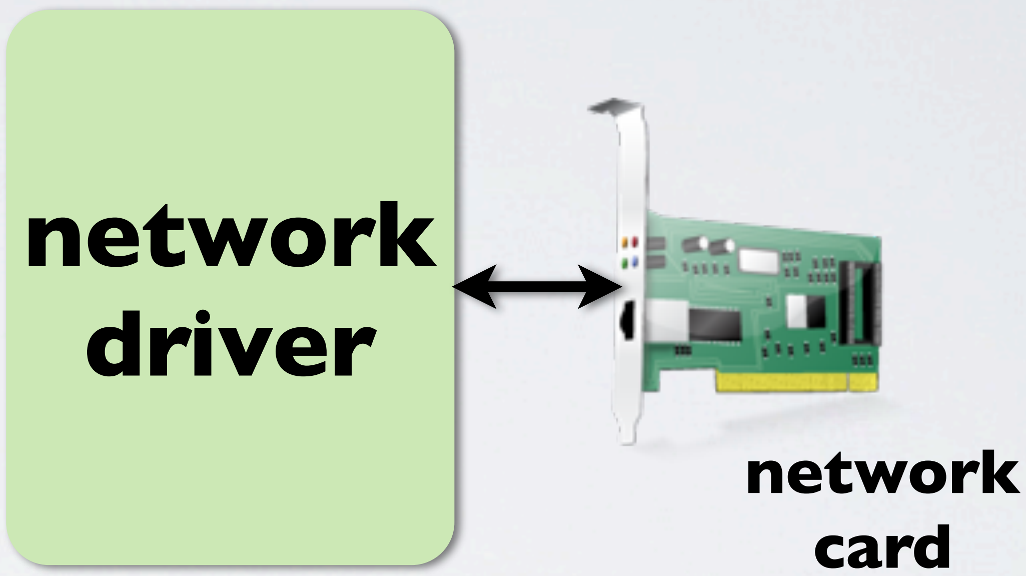

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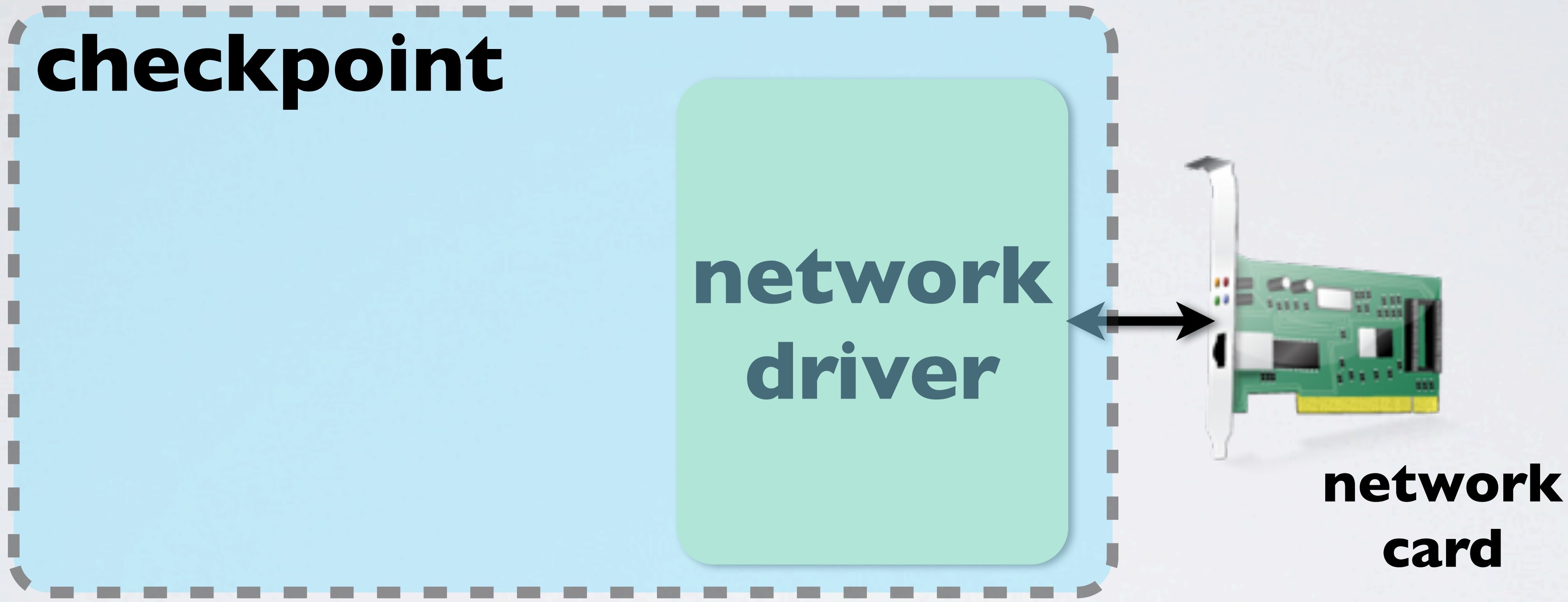

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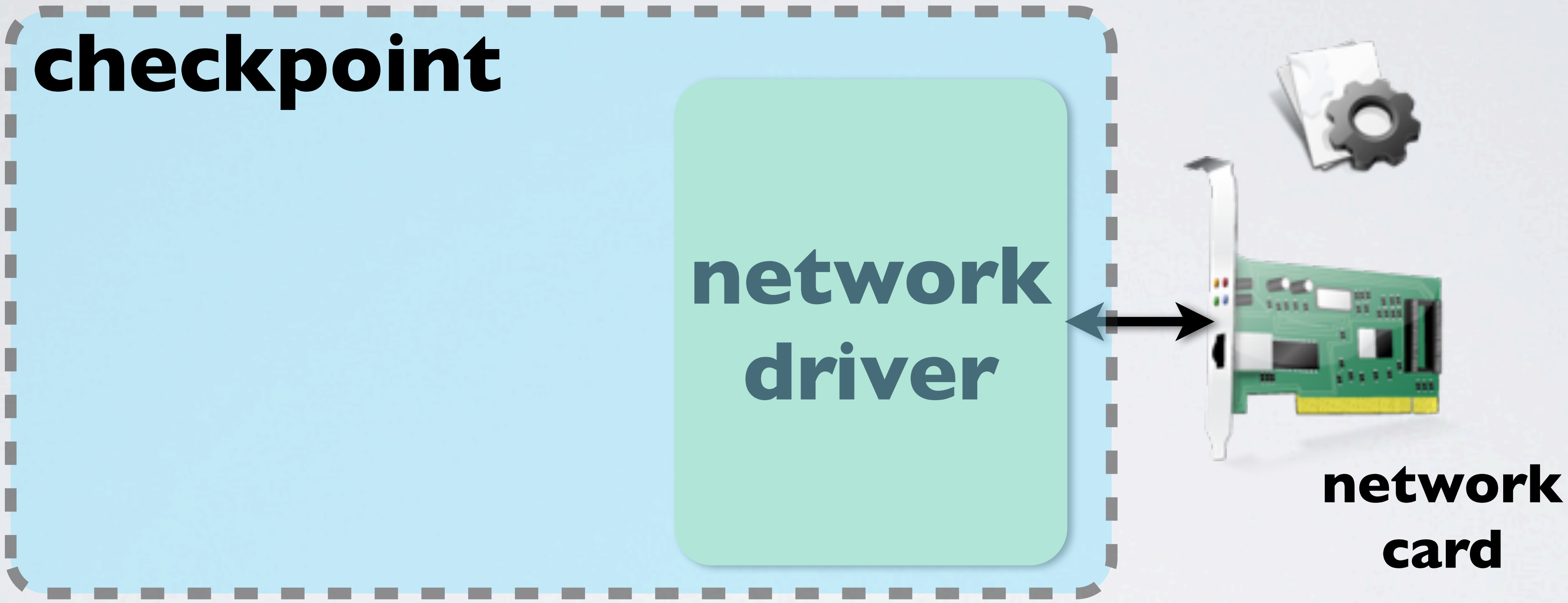

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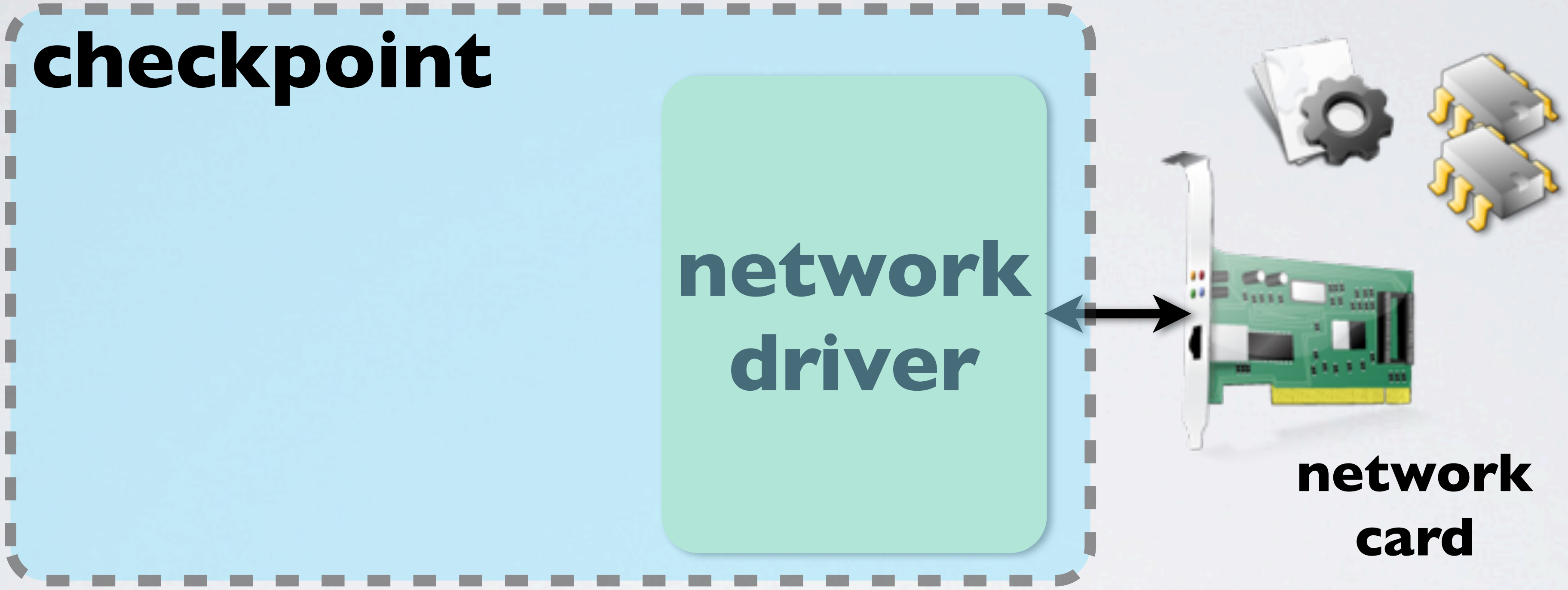

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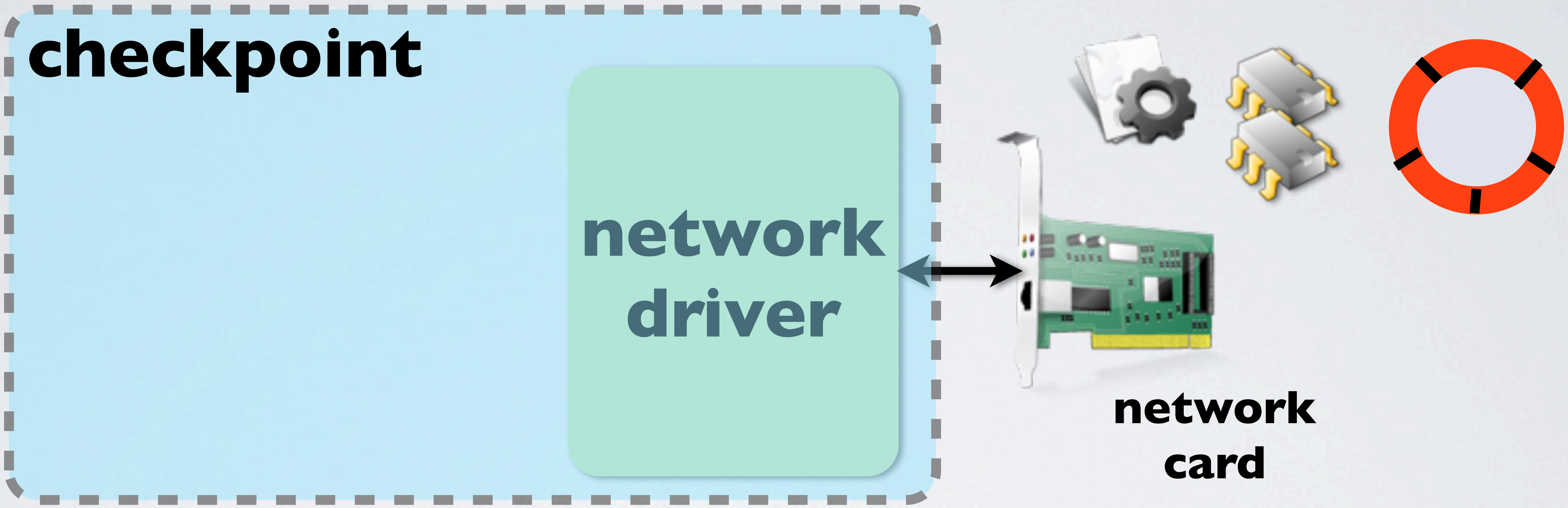

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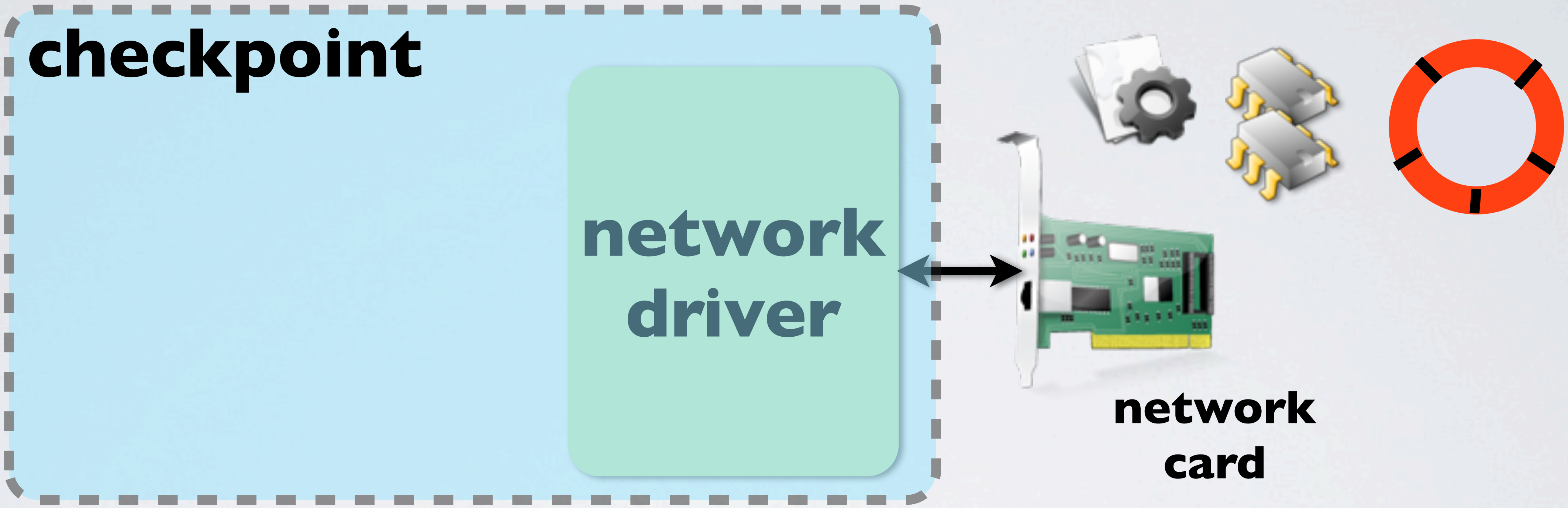

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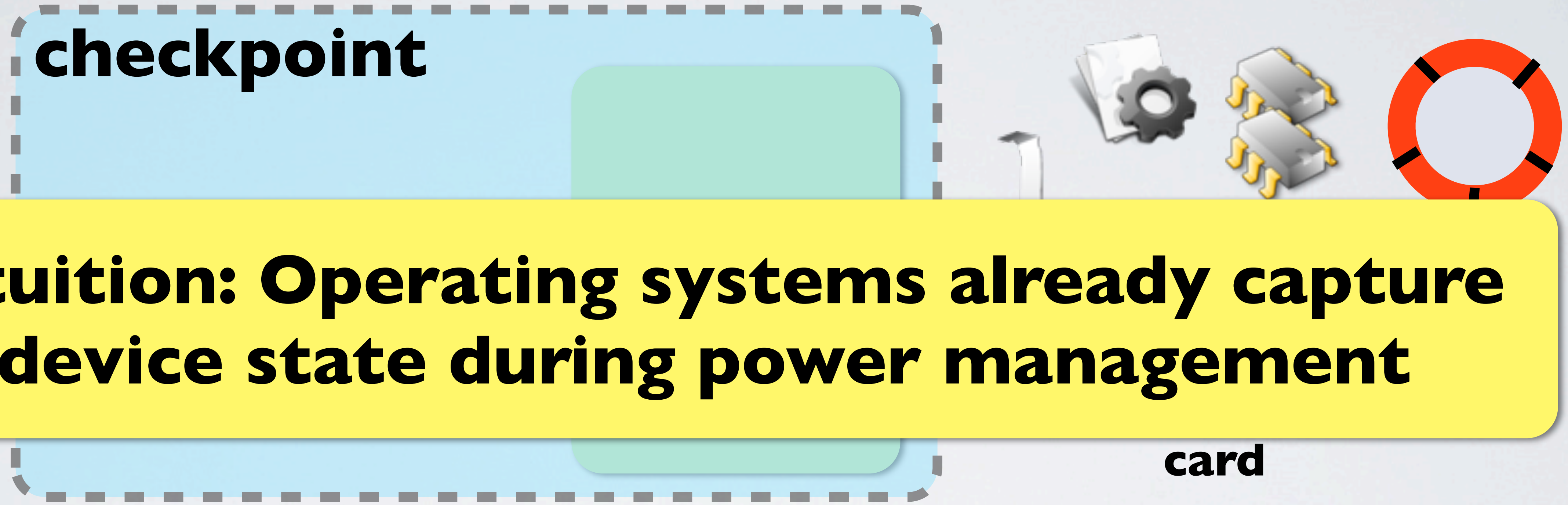

Intuition: Operating systems already capture device state during power management

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  - ★ **Memory buffer addresses used for DMA**
- ★ **Unique for every device**

Intuition with power management

- Refactor power management code for device checkpoints
  - Correct: Developer captures unique device semantics
  - Fast: Avoids probe and latency critical for applications
- Ask developers to export checkpoint/restore in their drivers

Device checkpoint/restore from PM code

Suspend	Resume
Save config state	Restore config state
Save register state	Restore register state
Disable device	Restore or reset DMA state
Save DMA state	Re-attach/Enable device
Suspend device	Device Ready

Device checkpoint/restore from PM code

Suspend

- Save config state
- Save register state
- Save DMA state
- Suspend device

Resume

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Suspend/resume code provides device checkpoint functionality

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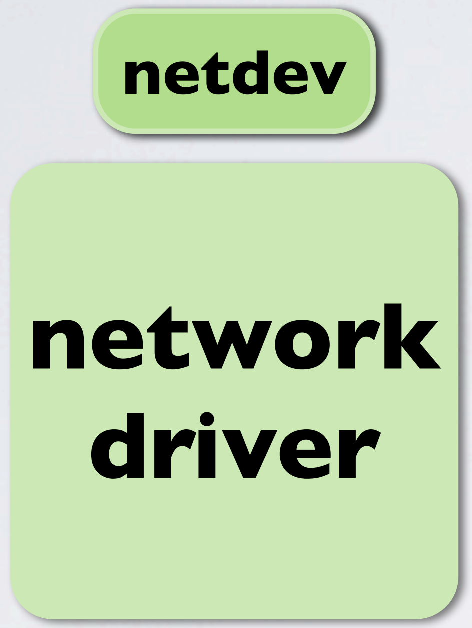
Synergy of isolation and fast checkpoints



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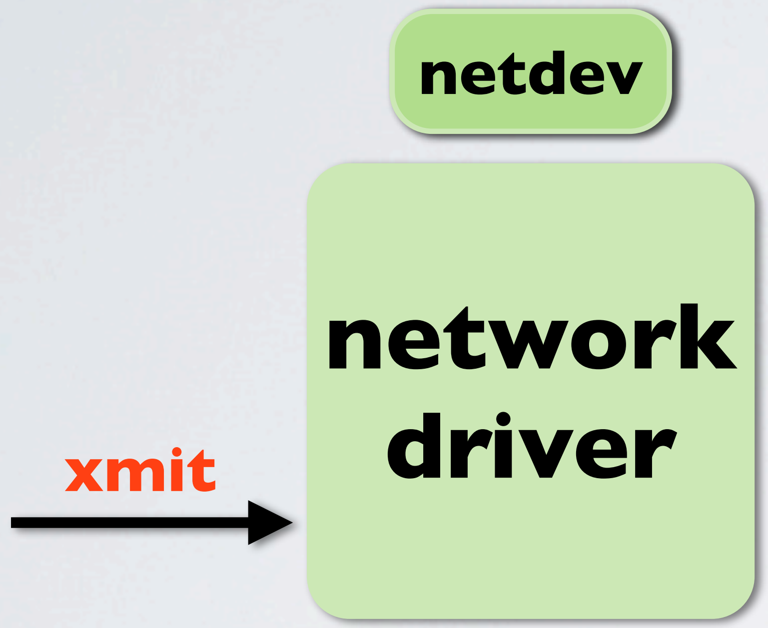

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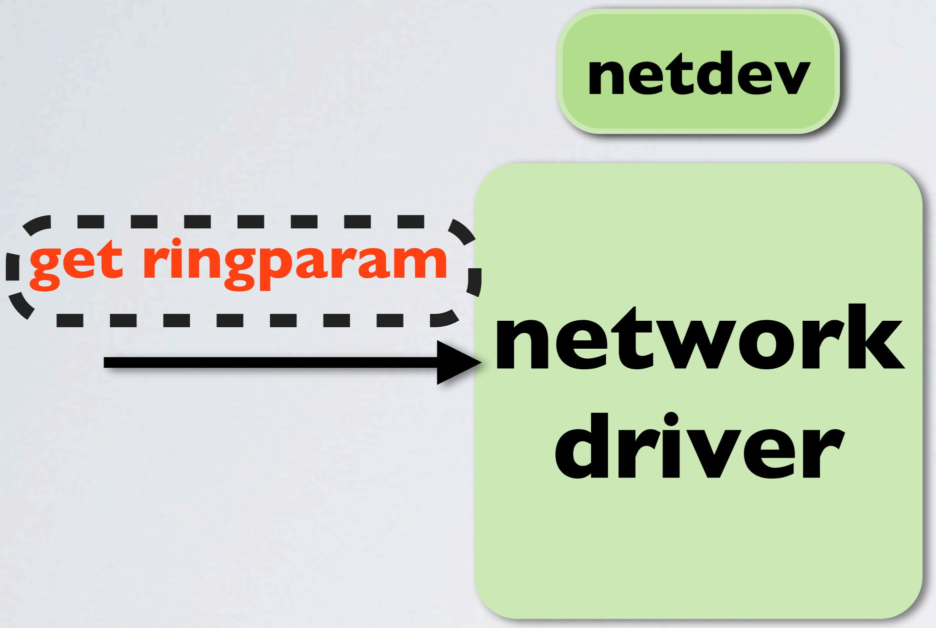

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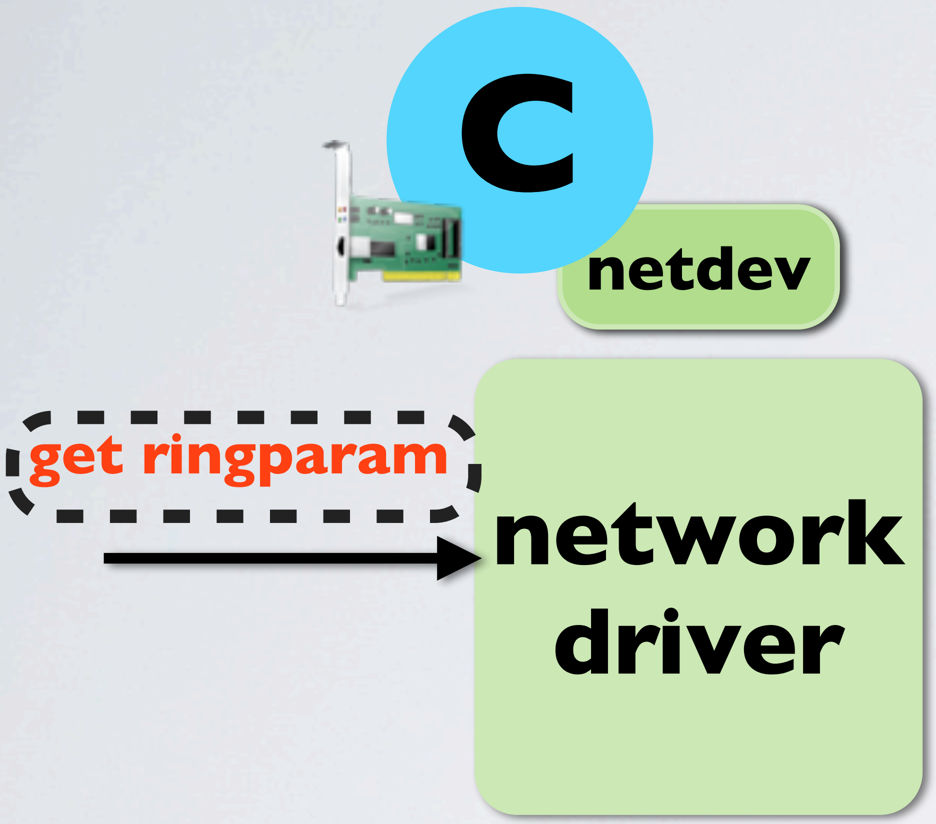

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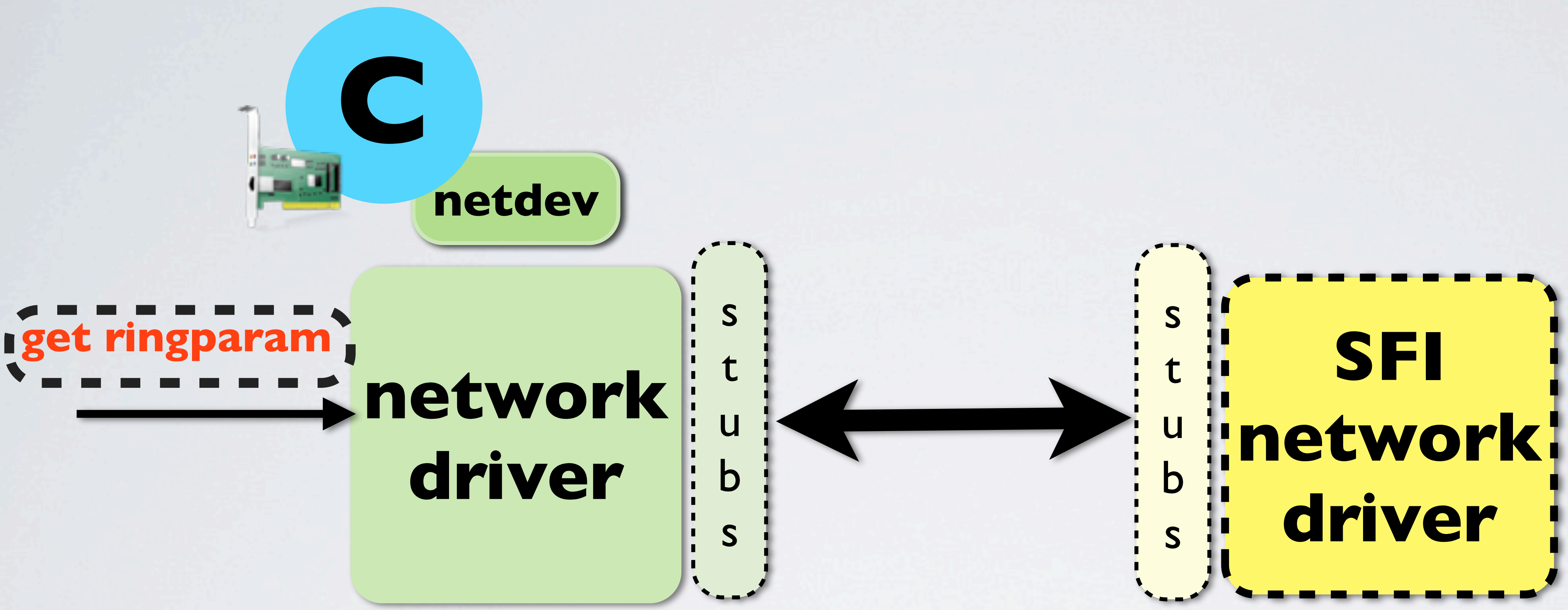

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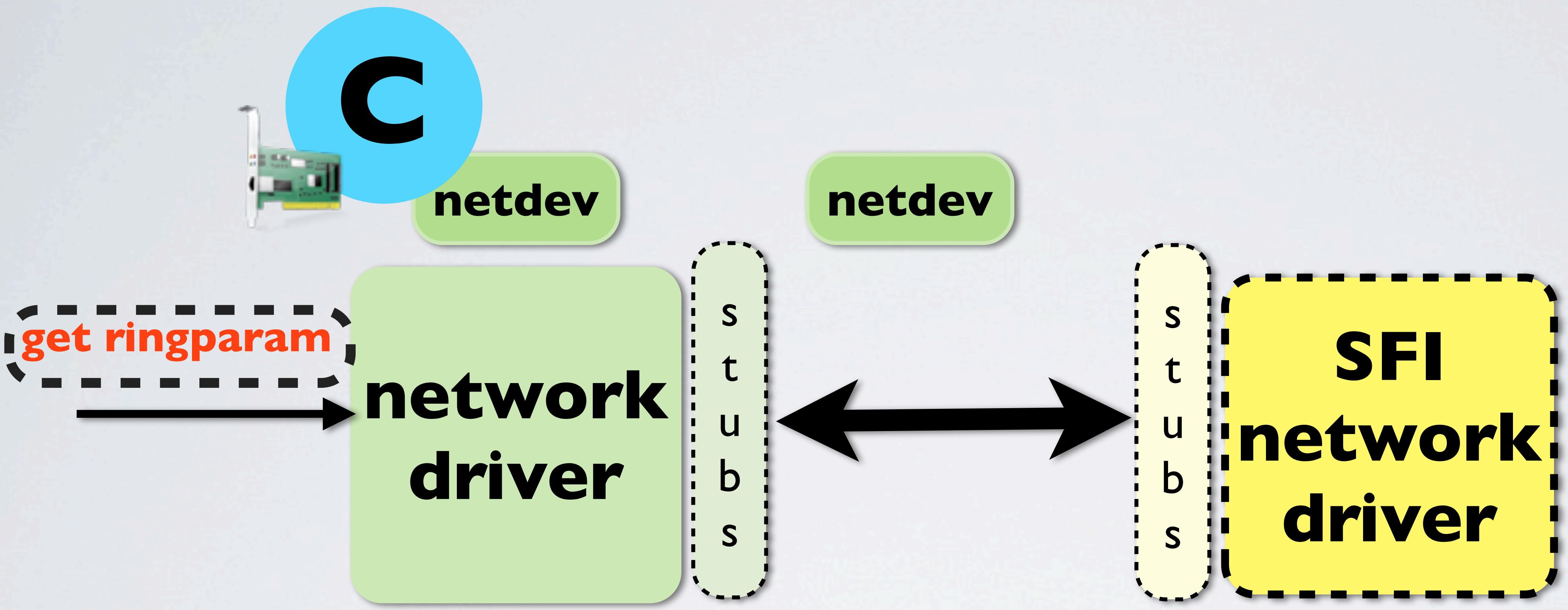

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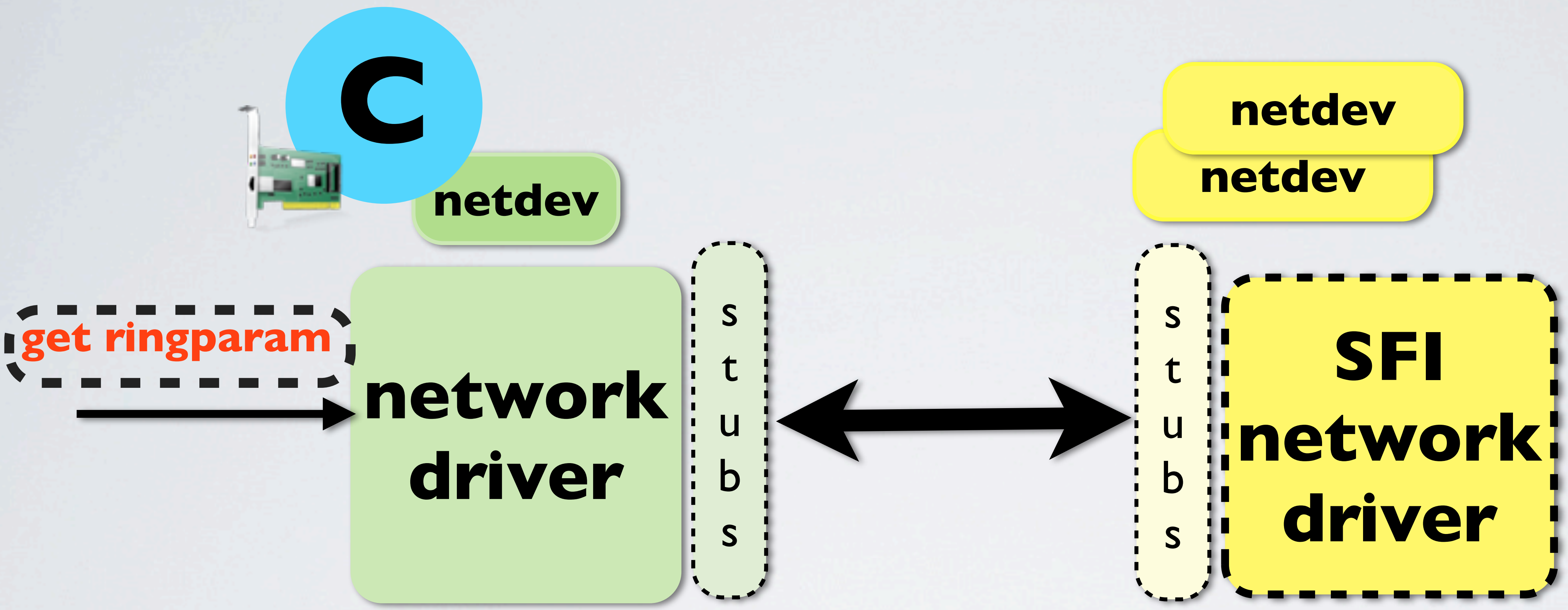

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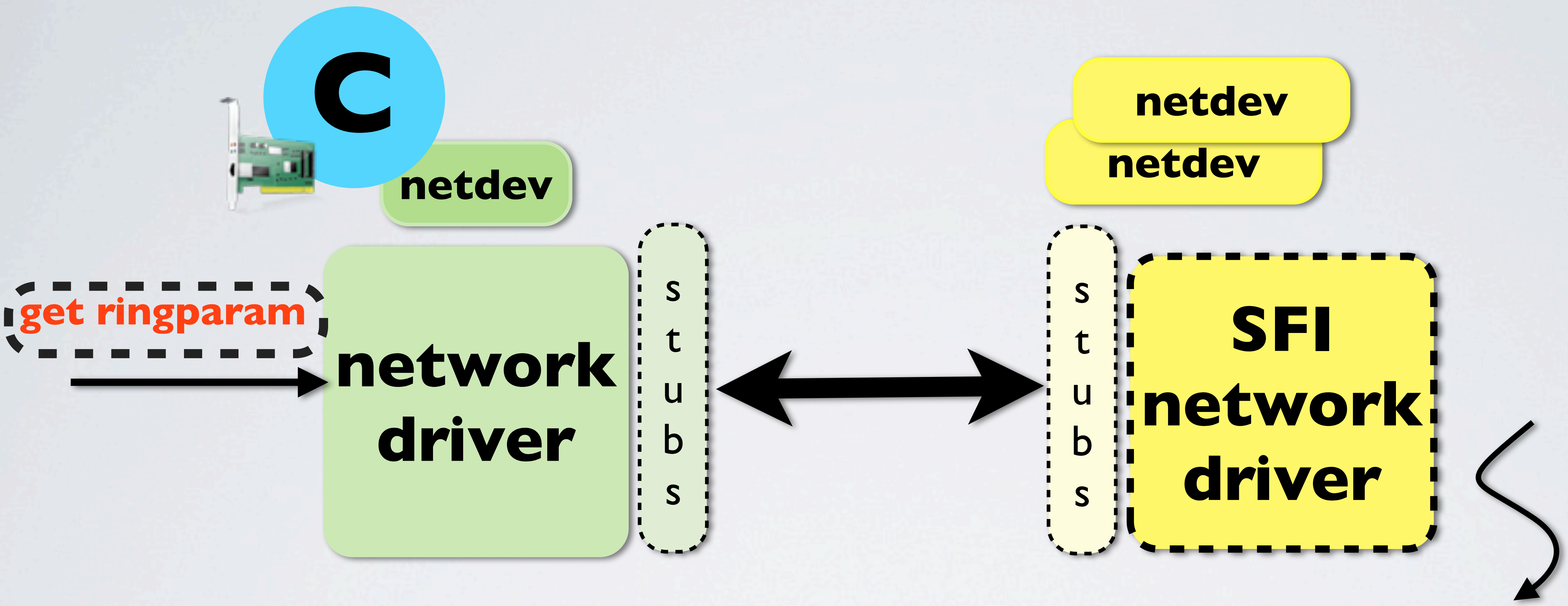

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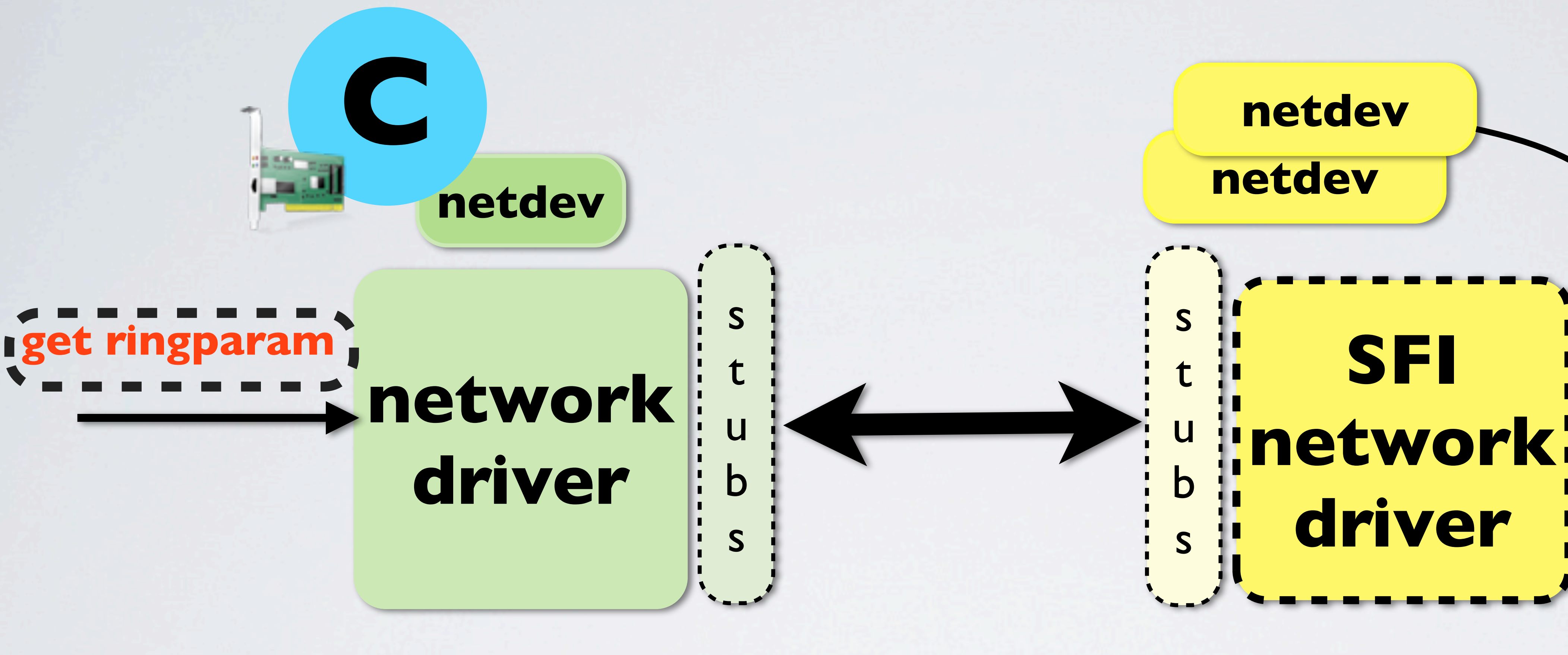

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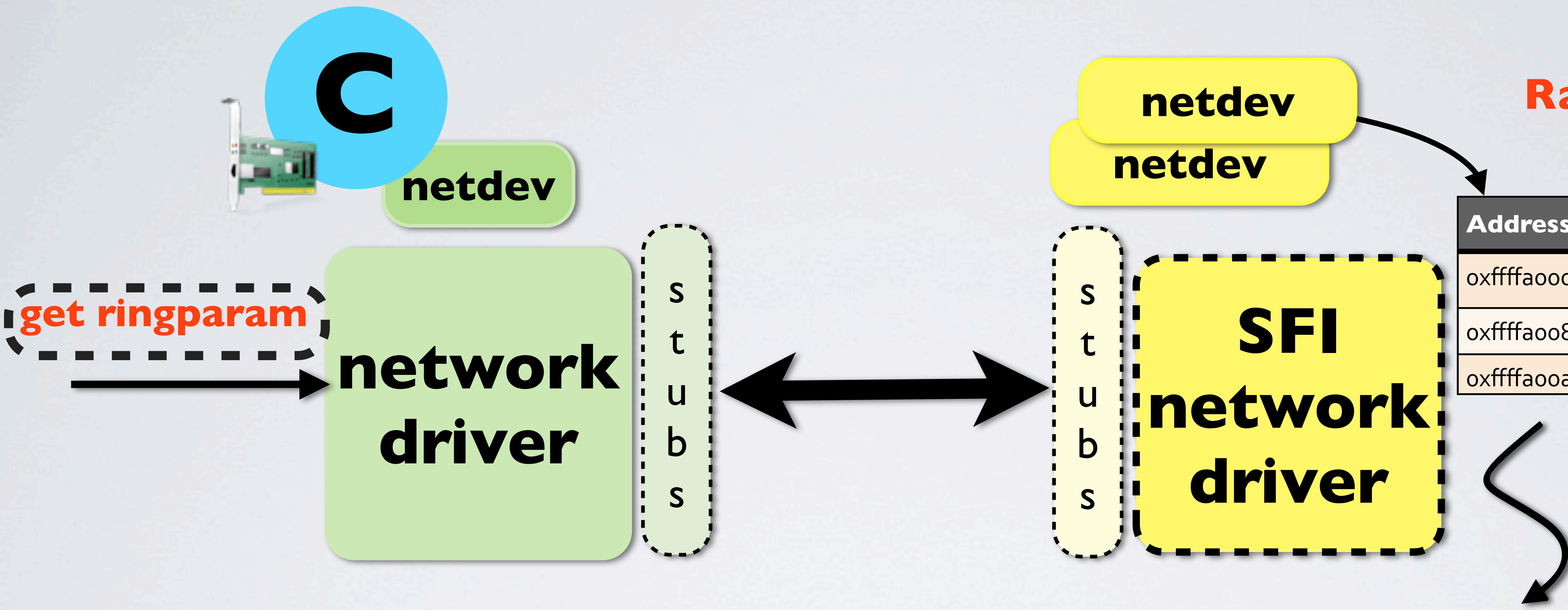
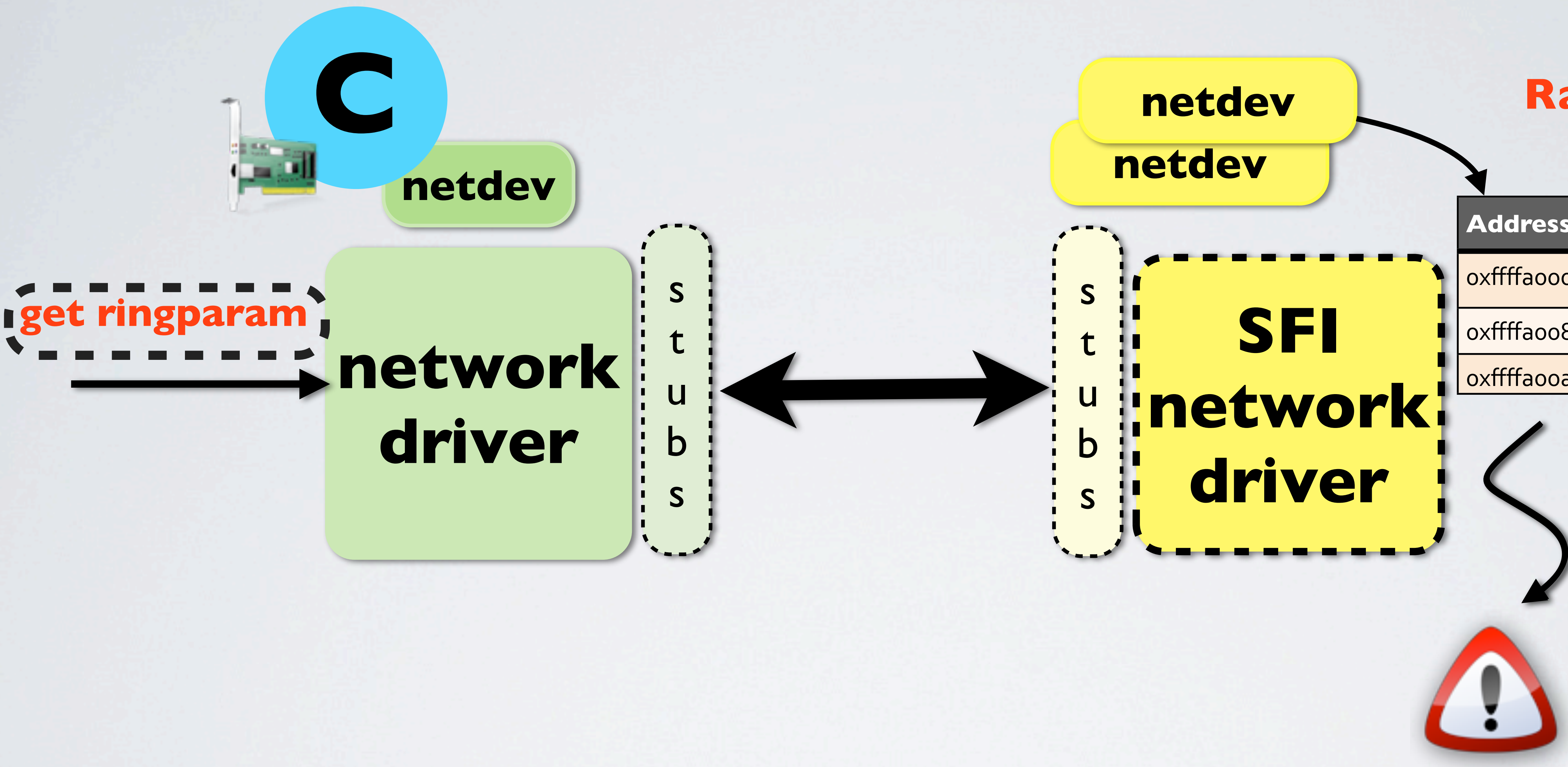
oxffffaooa	Read

Synergy of isolation and fast checkpoints



Address	Access rights
oxffffaooo	Read
oxffffaoo8	Write
oxffffaooa	Read

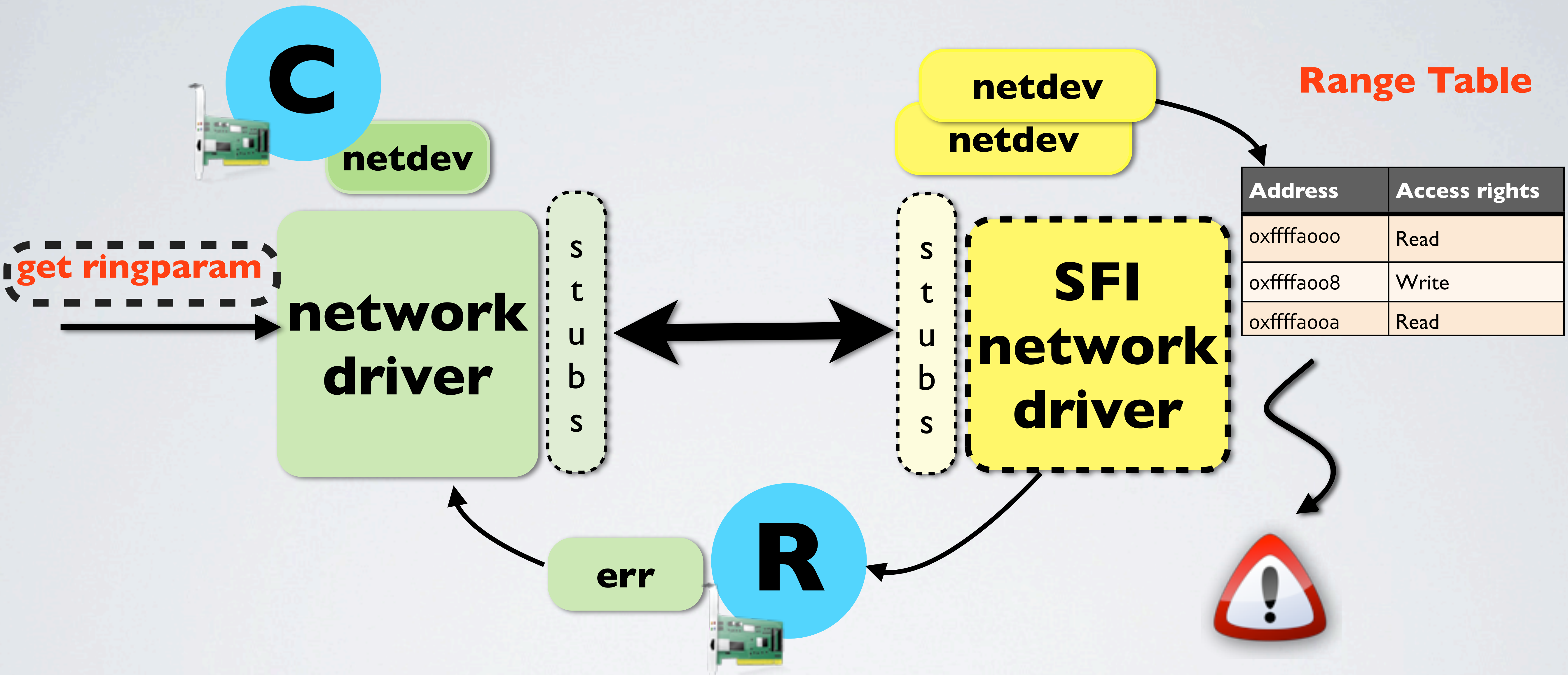
Synergy of isolation and fast checkpoints



Range Table

Address	Access rights
oxffffaooo	Read
oxffffaoo8	Write
oxffffaooa	Read

Synergy of isolation and fast checkpoints



Address	Access rights
oxffffaooo	Read
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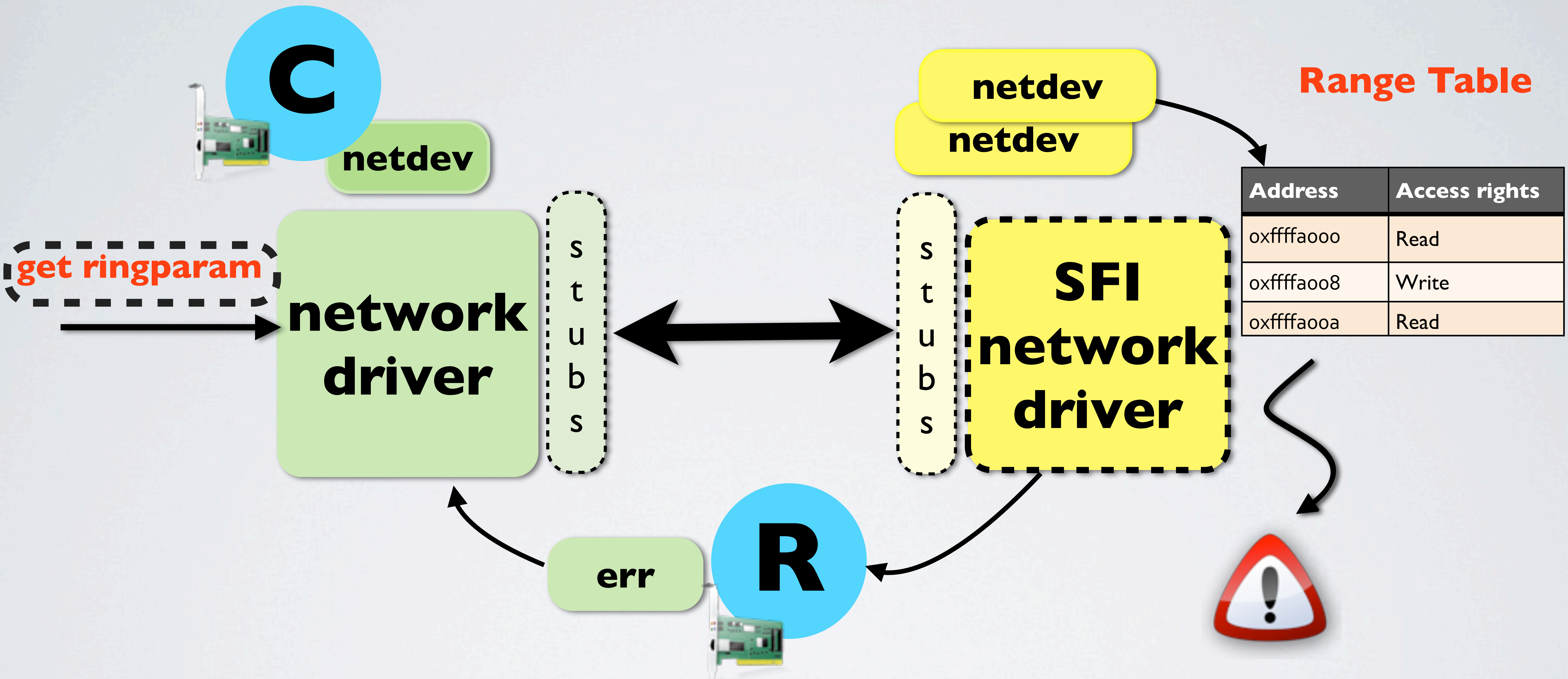
Synergy of isolation and fast checkpoints



Address	Access rights
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oxffffaoo8	Write
oxffffaooa	Read

FGFT provides transactional execution of driver entry points

How does this give us transactional execution?

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  - **Driver state: Run code in SFI module**
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- **Isolation: Serialization to hide incomplete transactions**
  - **Re-use existing device locks to lock driver**
  - **Two phase locking**
- **Consistency: Only valid (kernel, driver and device) states**
  - **Higher level mechanisms to rollback external actions**
  - **At most once device action guarantee to applications**

Outline

Introduction

Fine-grained isolation

Checkpoint-based recovery

Evaluation & Conclusions

Evaluation platform

- **Criterion :**
  - **Latency of recovery: How fast is it?**
  - **Correctness of recovery: How well does it work?**
  - **Incremental effort: How much work is it?**
  - **Performance: How much does it cost?**

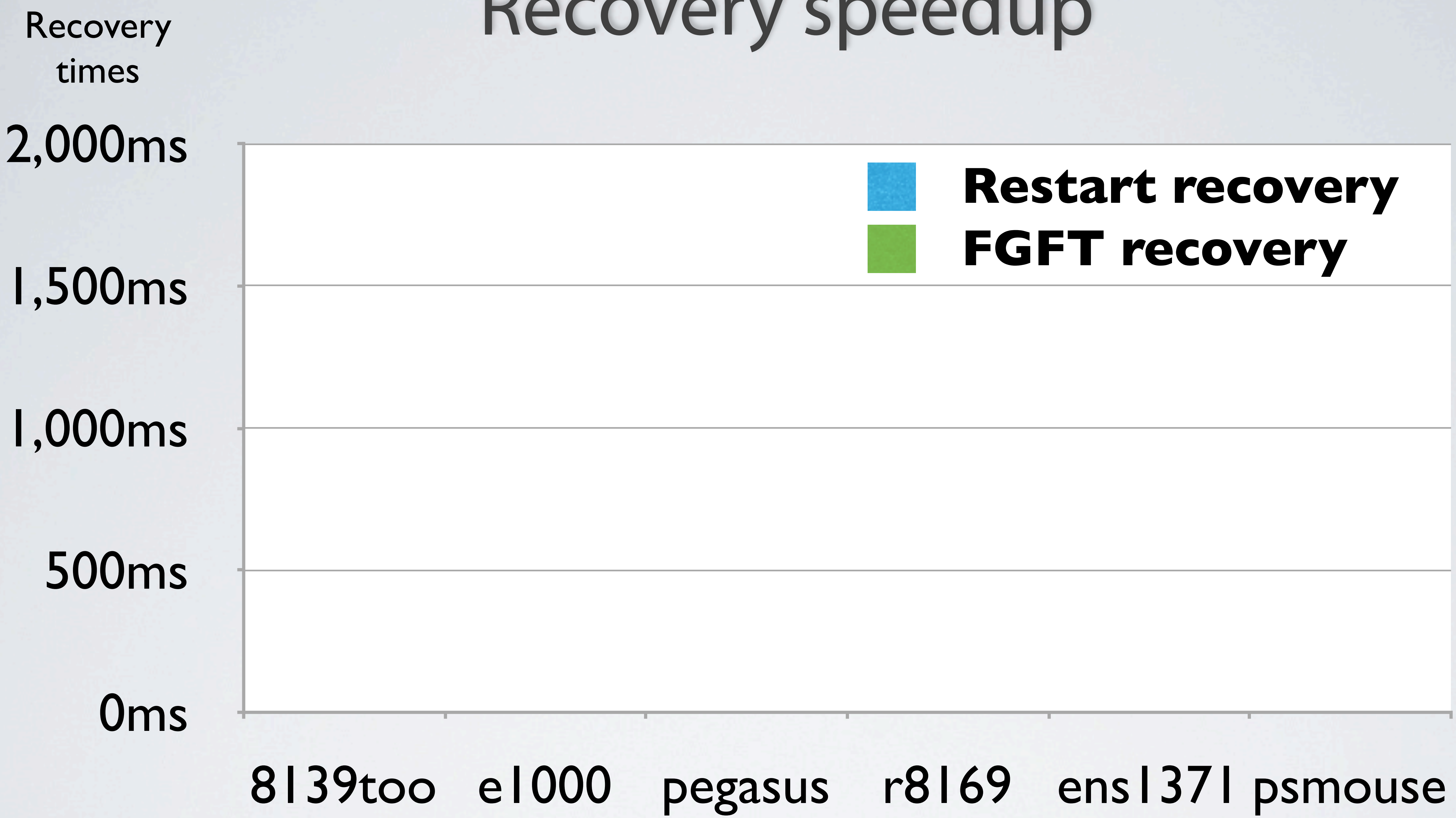
Evaluation platform

- Criterion :
  - Latency of recovery: How fast is it?
  - Correctness of recovery: How well does it work?
  - Incremental effort: How much work is it?
  - Performance: How much does it cost?

- Platform :
  - Implemented in Linux 2.6.29
  - 2.5 GHz Intel Core 2 Quad core w/ 4 GB DDR2 DRAM
  - Six drivers across three classes

Driver	Class	Bus
8139too	net	PCI
e1000	net	PCI
r8169	net	PCI
pegasus	net	USB
psmouse	sound	PCI
ens1371	input	serio

Recovery speedup



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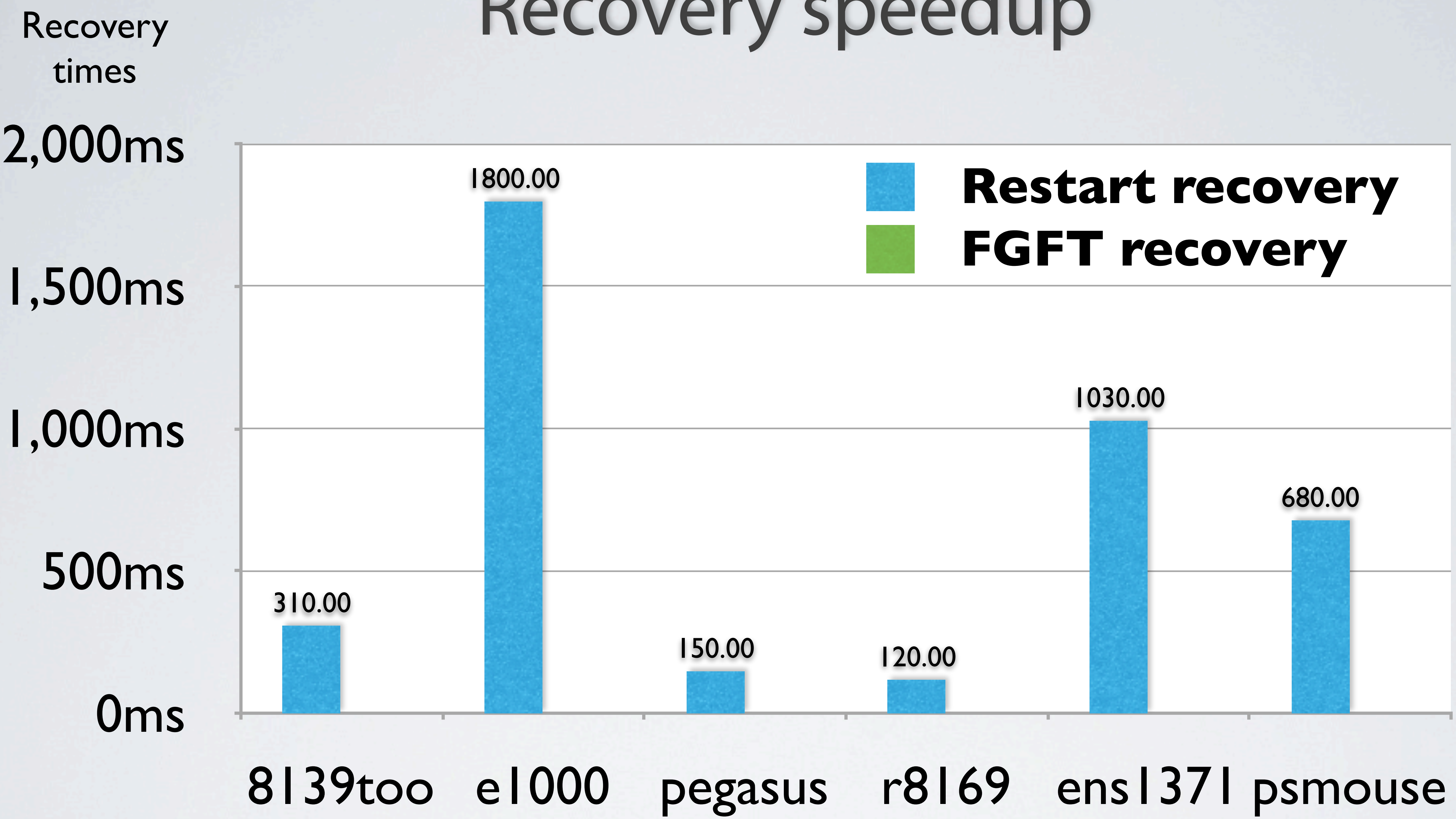
Recovery speedup



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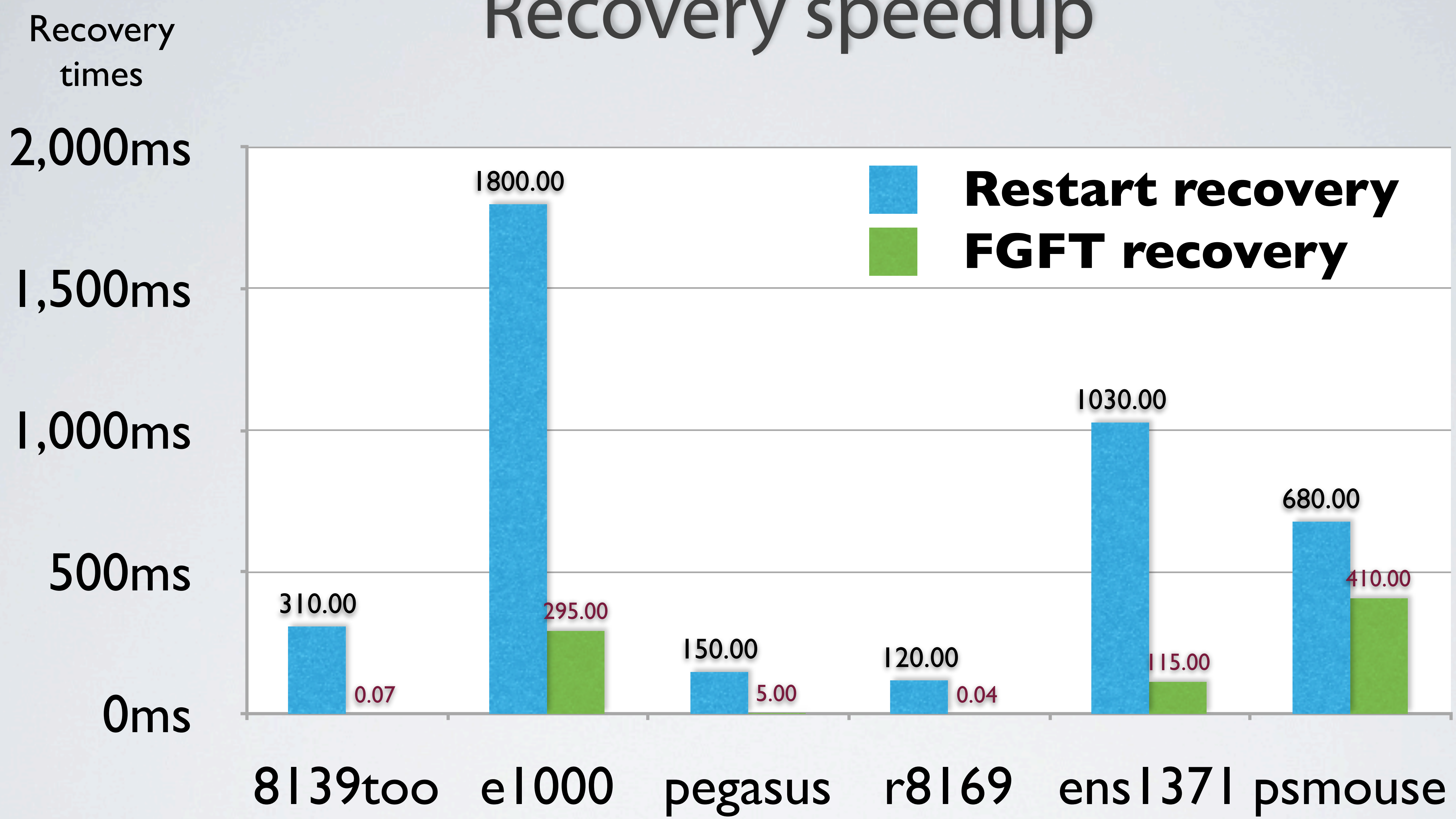
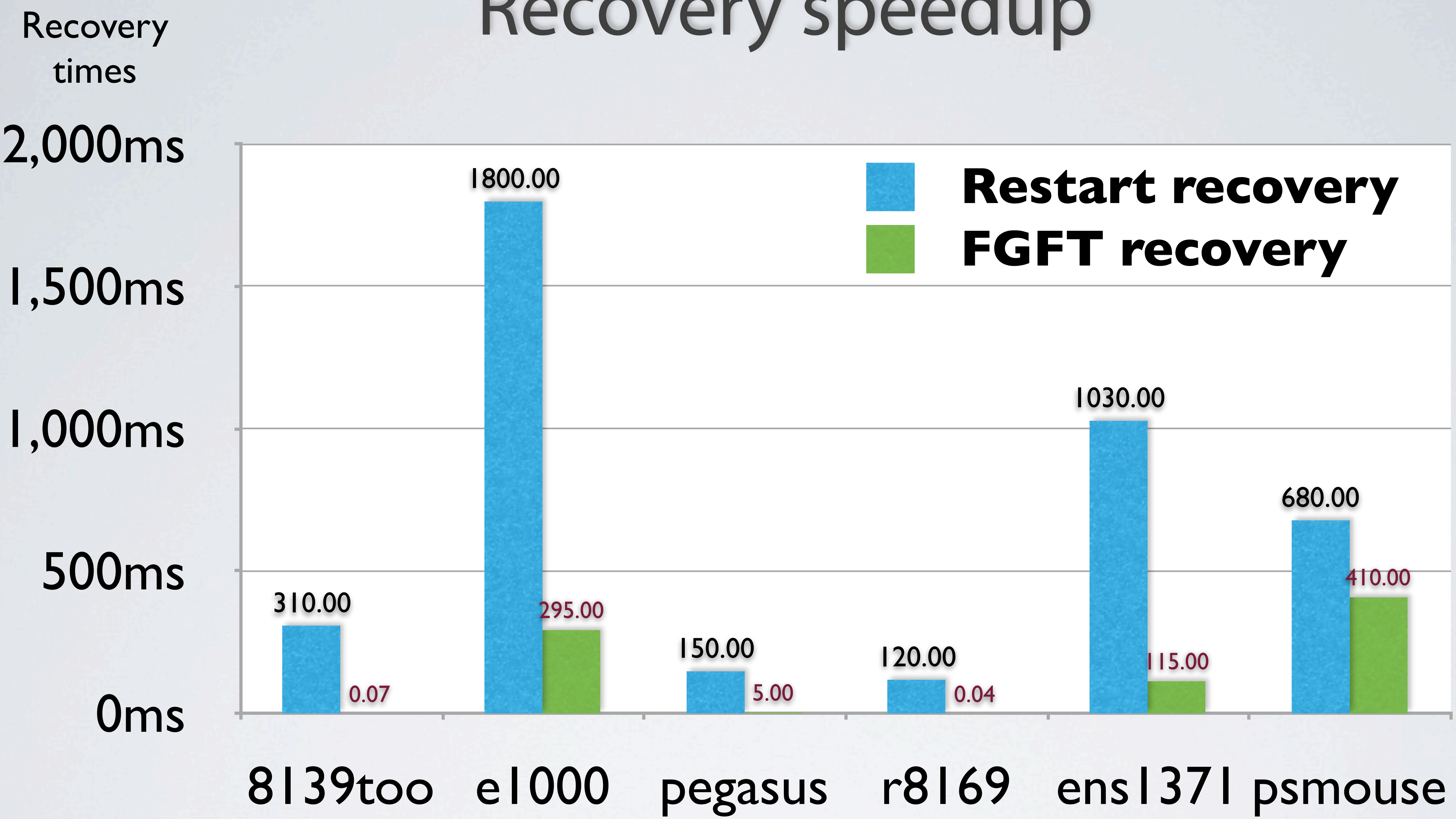


Recovery speedup



FGFT provides significant speedup in driver recovery and improves system availability

Static and dynamic fault injection

Driver	Injected Faults	Native Crashes
8139too	43	43
e1000	47	47
r8169	36	36
pegasus	34	33
ens1371	22	21
psmouse	46	46
TOTAL	258	256

Static and dynamic fault injection

Driver	Injected Faults	Native Crashes	FGFT Crashes
8139too	43	43	NONE
e1000	47	47	NONE
r8169	36	36	NONE
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TOTAL	258	256	NONE

Static and dynamic fault injection

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8139too	43	43	NONE
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psmouse	46	46	NONE
TOTAL	258	256	NONE

FGFT recovers from multiple failures : 1) restores non-class state and 2) does not affect other threads

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Programming effort

Driver	LOC	Isolation annotations		Recovery additions	
		Driver annotations	Kernel annotations	LOC Moved	LOC Added
8139too	1, 904	15	20	26	4
e1000	13, 973	32		32	10
r8169	2, 993	10		17	5
pegasus	1, 541	26	12	22	5
ens1371	2, 110	23	66	16	6
psmouse	2, 448	11	19	19	6

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Programming effort

Driver	LOC	Isolation annotations		Recovery additions	
		Driver annotations	Kernel annotations	LOC Moved	LOC Added
8139too	1,904	15	20	26	4
e1000	13,973	32		32	10
r8169	2,993	10		17	5
pegasus	1,541	26	12	22	5
ens1371	2,110	23	66	16	6
psmouse	2,448	11	19	19	6

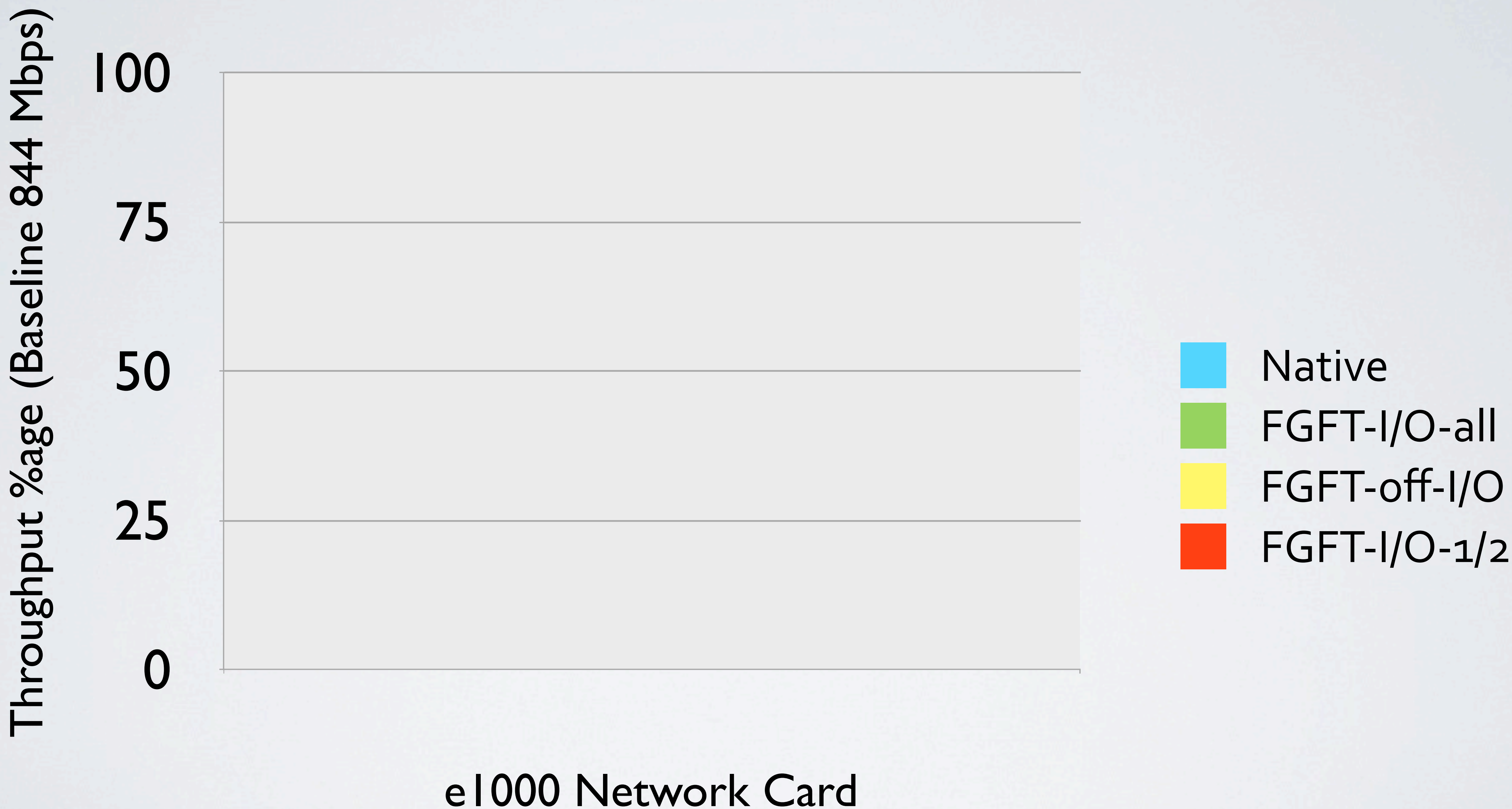
FGFT requires a loadable kernel module (1200 LOC) and 38 lines of kernel changes to trap processor exceptions

Throughput with isolation and recovery

Native
FGFT-I/O-all
FGFT-off-I/O
FGFT-I/O-1/2

netperf on Intel quad-core machines

Throughput with isolation and recovery



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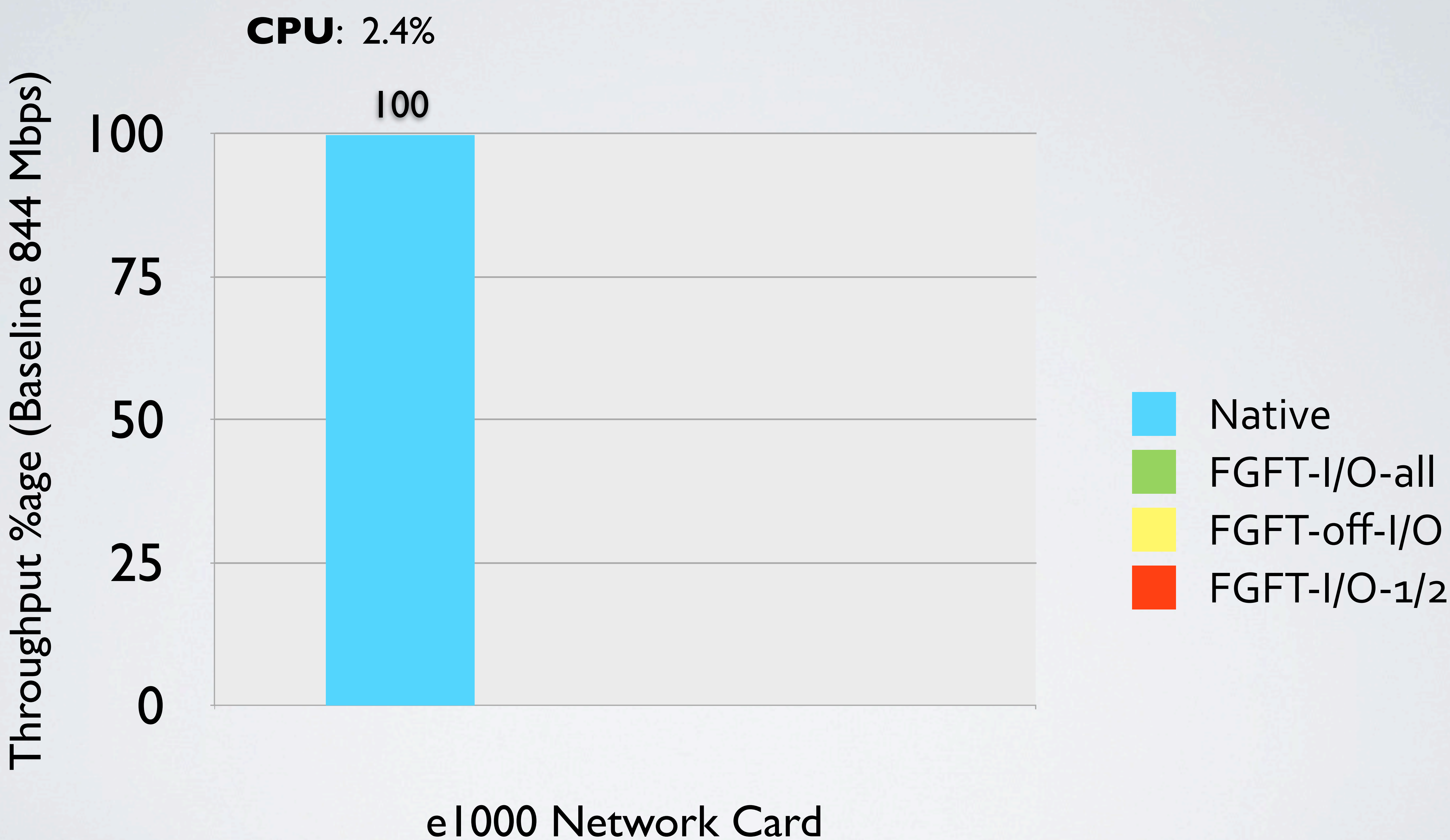
Throughput with isolation and recovery



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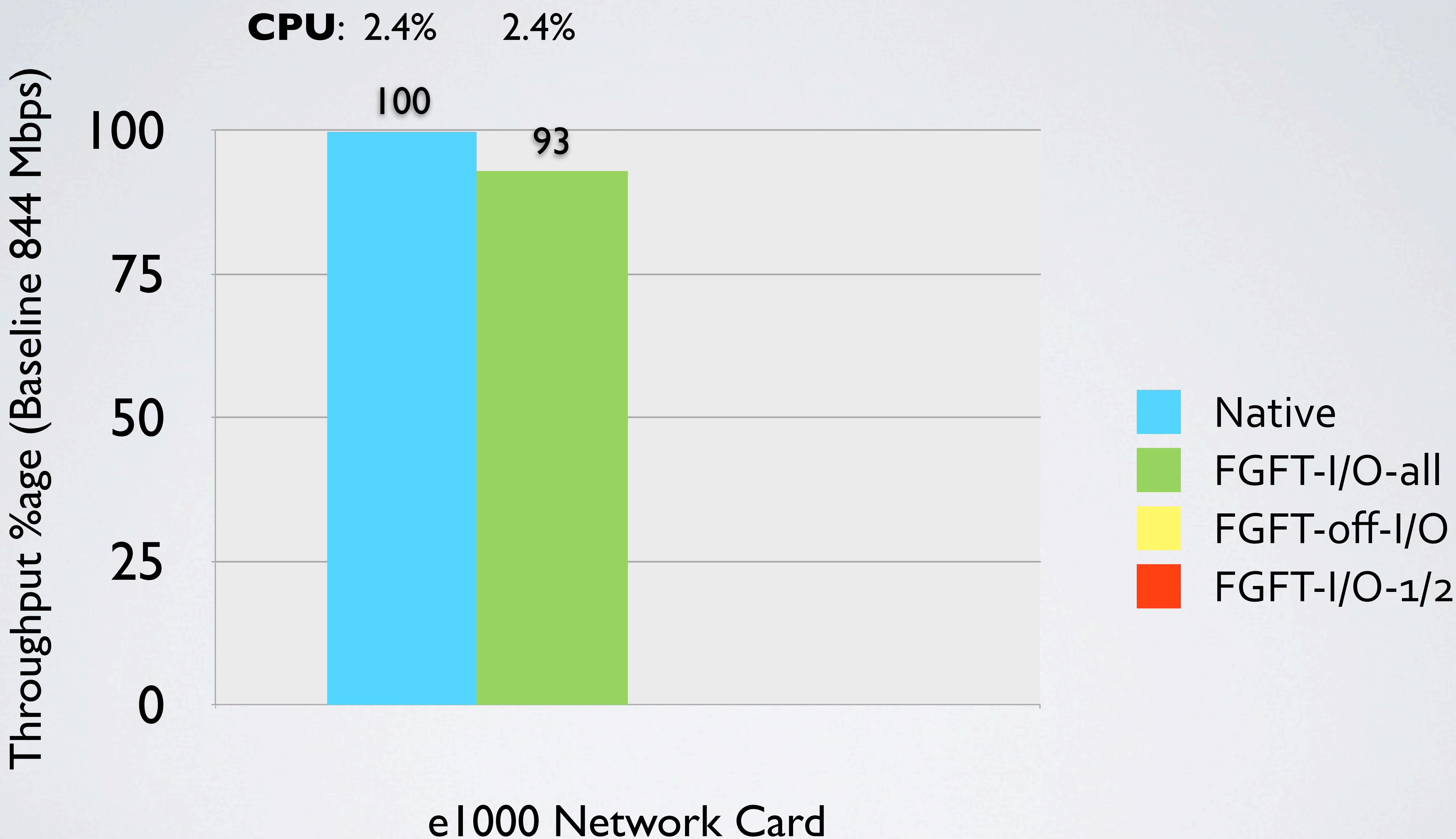

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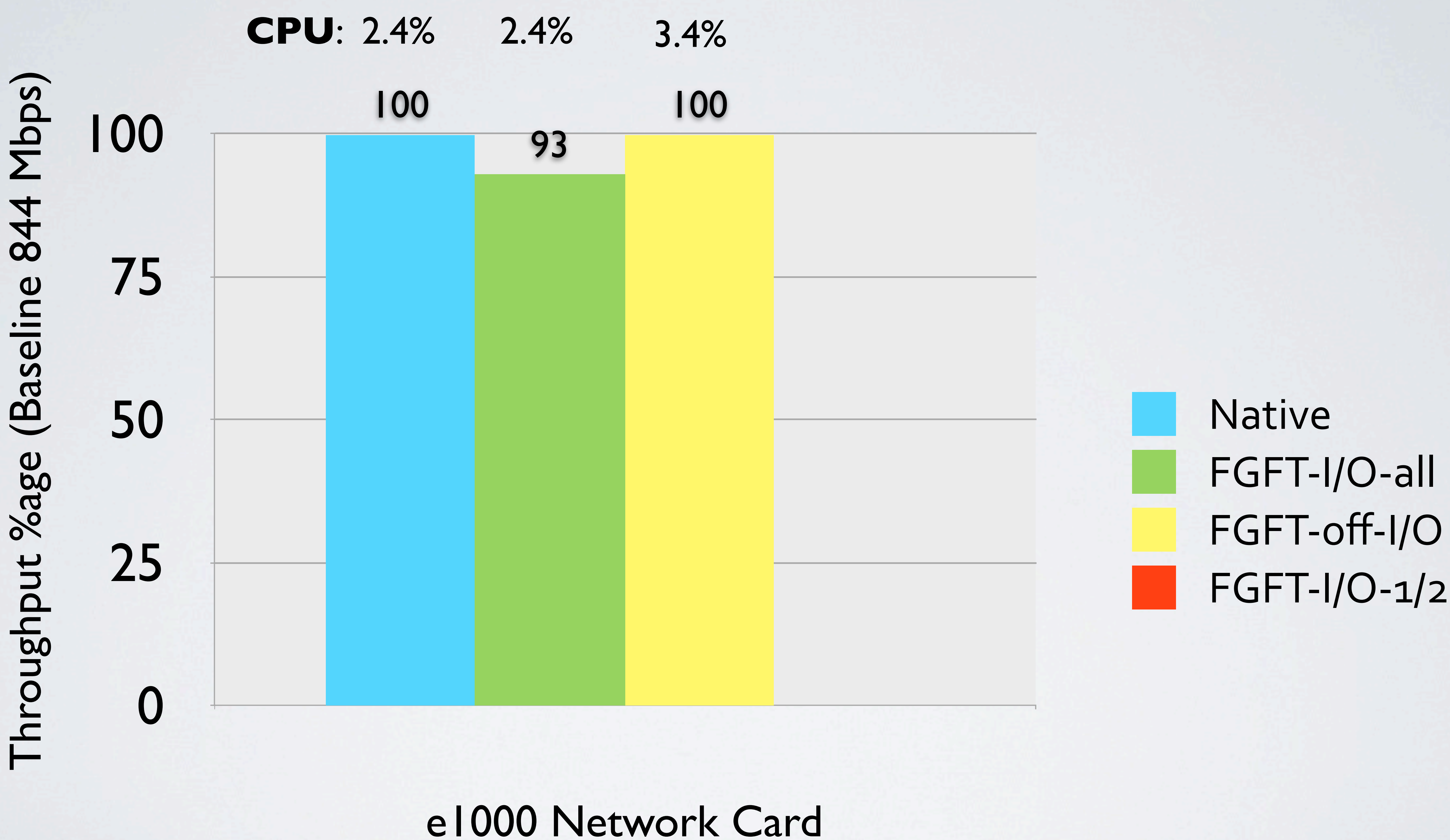

netperf on Intel quad-core machines

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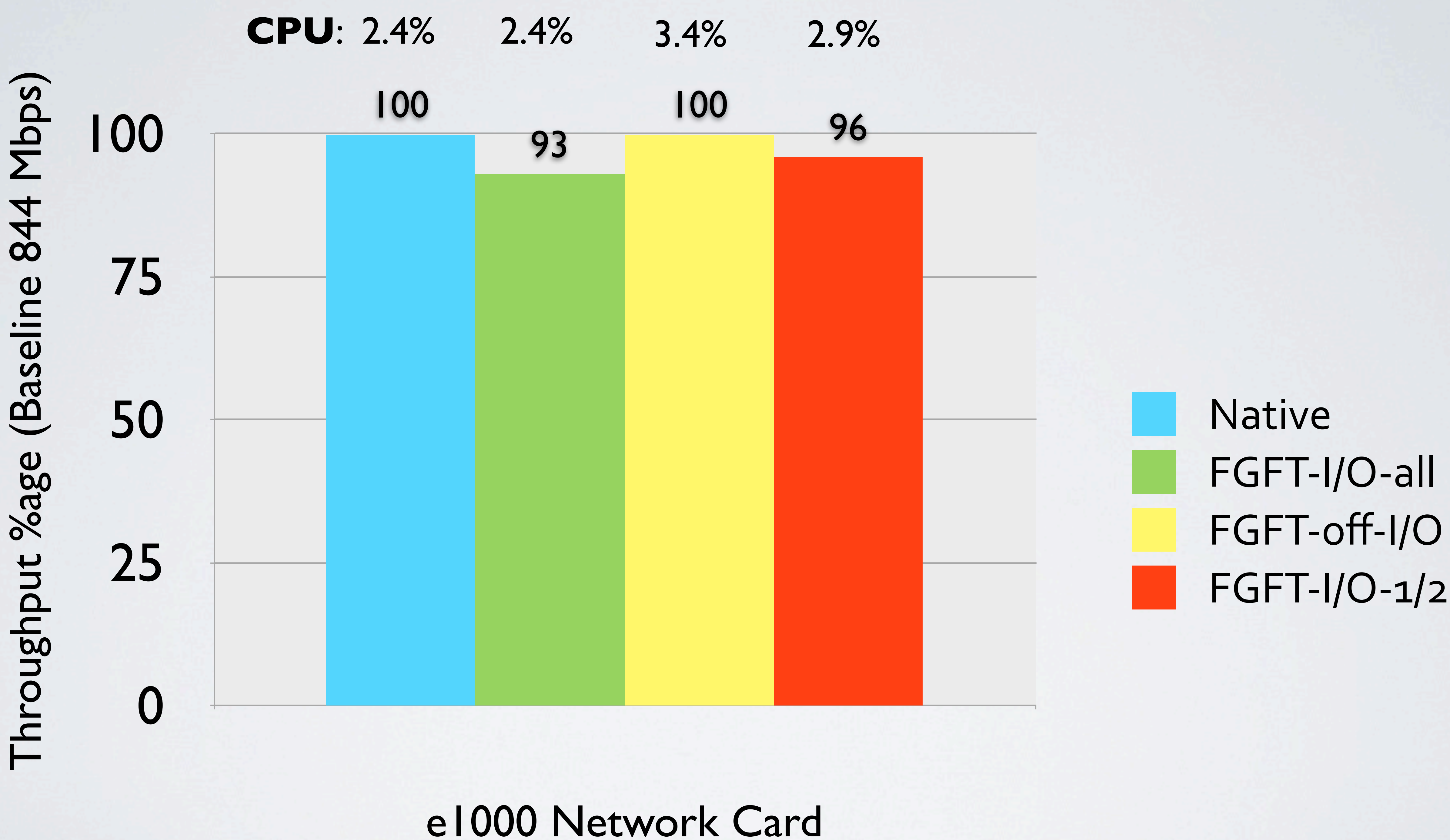
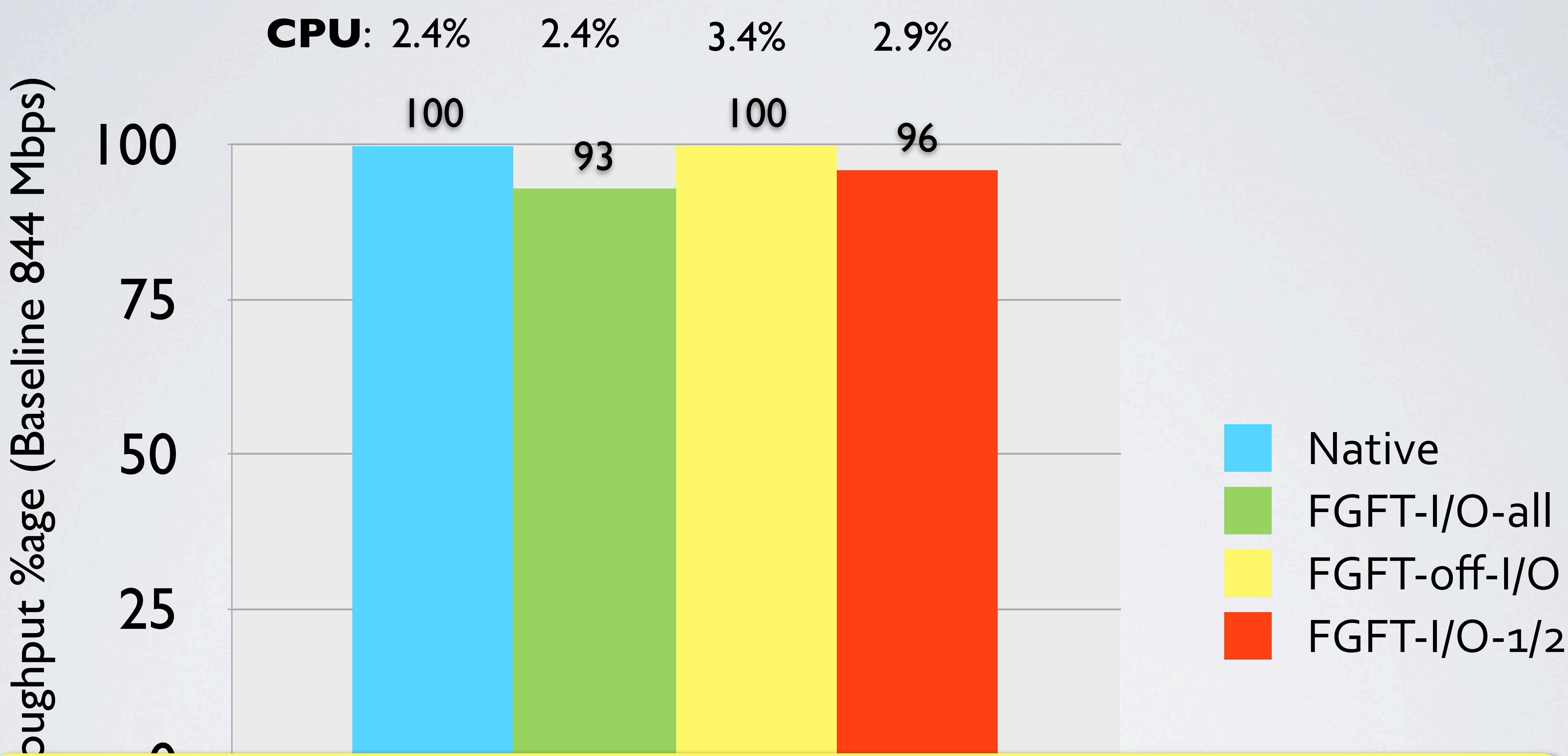
Throughput with isolation and recovery



netperf on Intel quad-core machines

Throughput with isolation and recovery



FGFT can isolate and recover high bandwidth devices at low overhead without adding kernel subsystems

netperf on Intel quad-core machines

Summary

Summary

- FGFT runs driver code as transactions
  - Provides fault tolerance at incremental performance and programmer efforts
- Introduced device checkpoints
  - Provides fast and complete recovery semantics
- Fast device checkpoints should be explored in other domains like fast reboot, upgrade etc.

Questions

Asim Kadav

- **http://cs.wisc.edu/~kadav**
- **kadav@cs.wisc.edu**
- **Graduating in spring!**

Extra slides

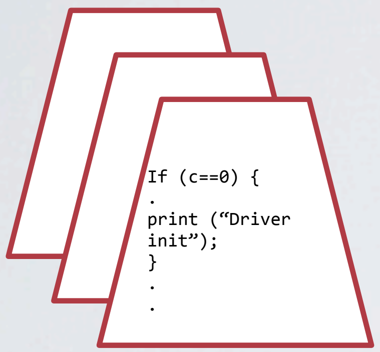
- Unlike suspend, devices continue to be accessed after a checkpoint
  - Rely on drivers following ACPI specifications for correctness

Latency for device checkpoint/restore

Driver	Class	Bus	Checkpoint Times	Restore Times
8139too	net	PCI	33µs	62µs
e1000	net	PCI	32µs	280ms
r8169	net	PCI	26µs	30µs
pegasus	net	USB	0µs	4ms
ens1371	sound	PCI	33µs	111ms
psmouse	input	serio	0µs	390ms

Fast checkpoint/restore using suspend/resume

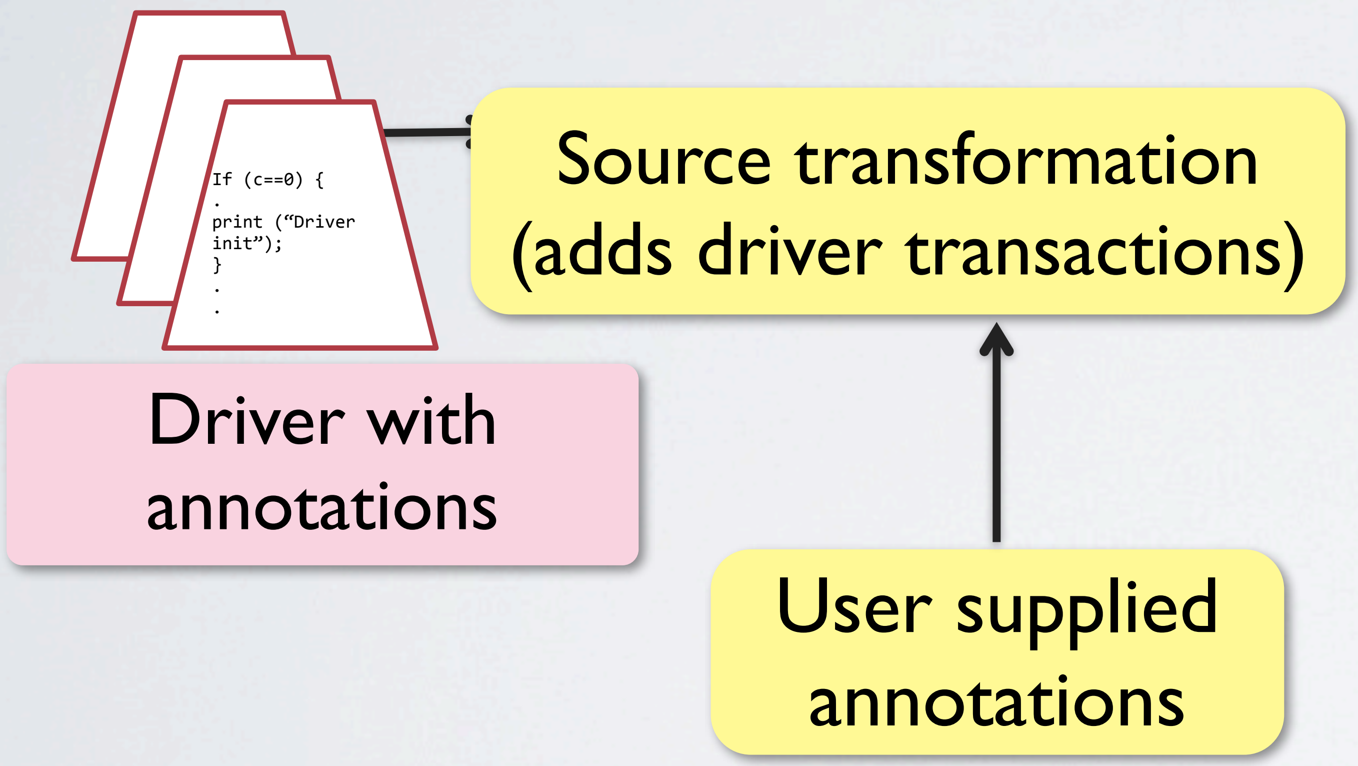
Transforming drivers to run as FGFT



Driver with annotations

Static modifications

Transforming drivers to run as FGFT



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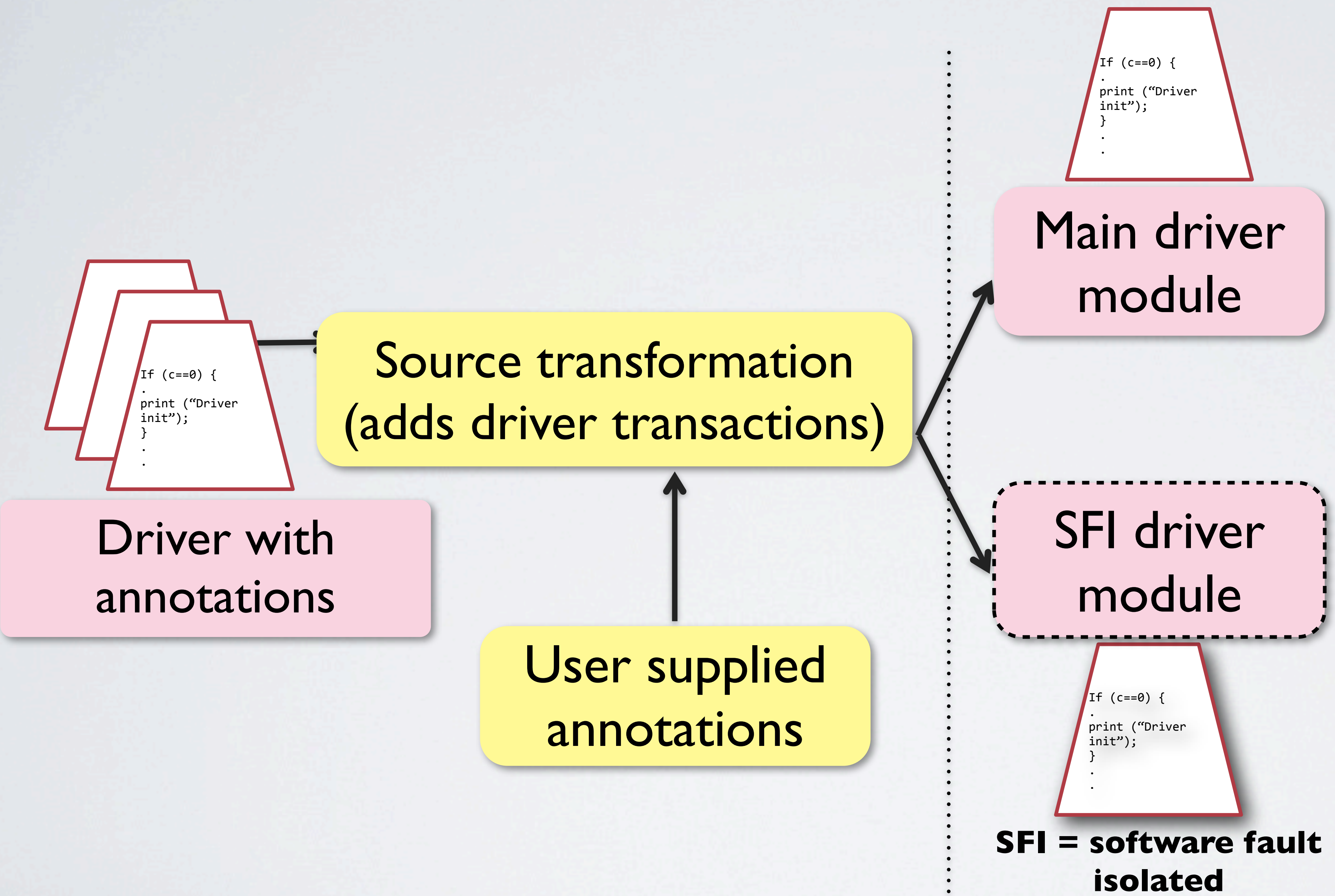

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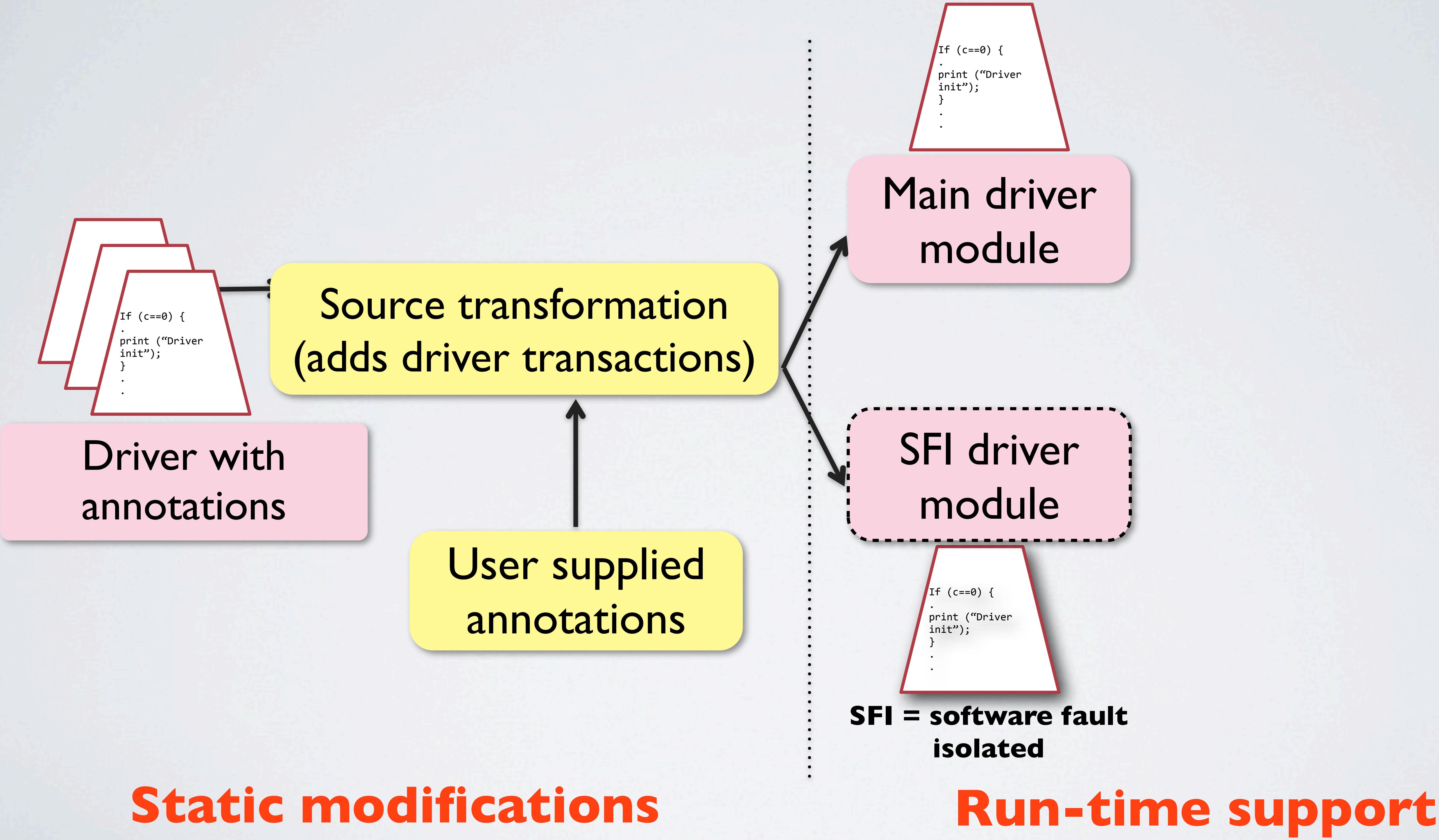

Transforming drivers to run as FGFT