Understanding and Improving Device Access Complexity

Asim Kadav
(with Prof. Michael M. Swift)
University of Wisconsin-Madison

Devices enrich computers

- **Keyboard**
- **Sound**
- **Printer**
- **Network**
- **Storage**

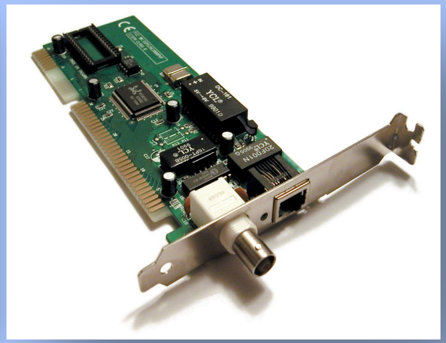
Devices enrich computers

- Keyboard
- Sound
- Printer
- Network
- Storage

- Keyboard
- Flash storage
- Graphics
- WIFI
- Headphones
- SD card
- Camera
- Accelerometers
- GPS
- Touch display
- NFC

Huge growth in number of devices

New I/O devices: accelerometers, GPUS, GPS, touch



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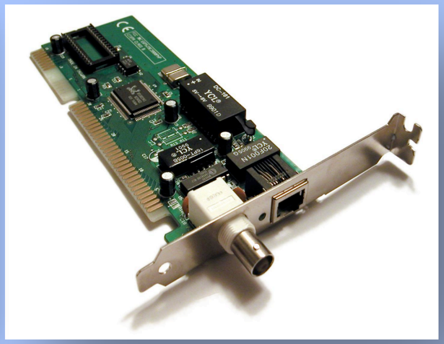

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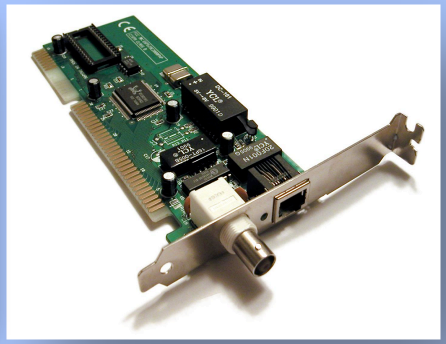
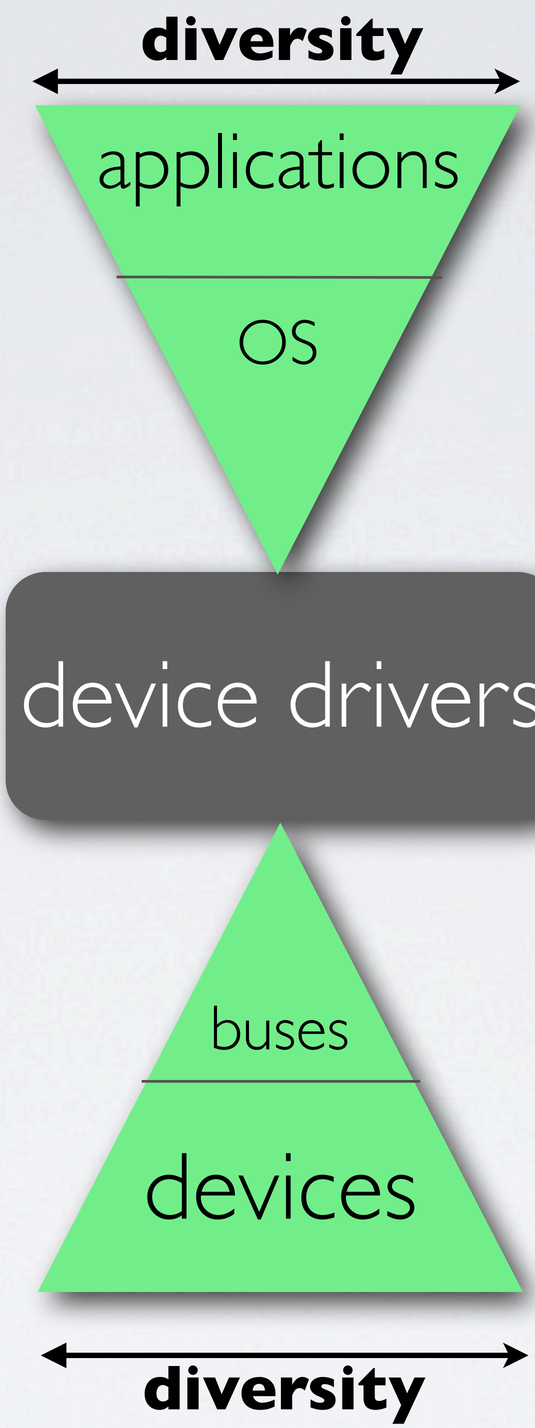


Many buses: USB, PCI-e, thunderbolt

Heterogeneous OS support: 10G ethernet vs card readers

Device drivers: OS interface to devices



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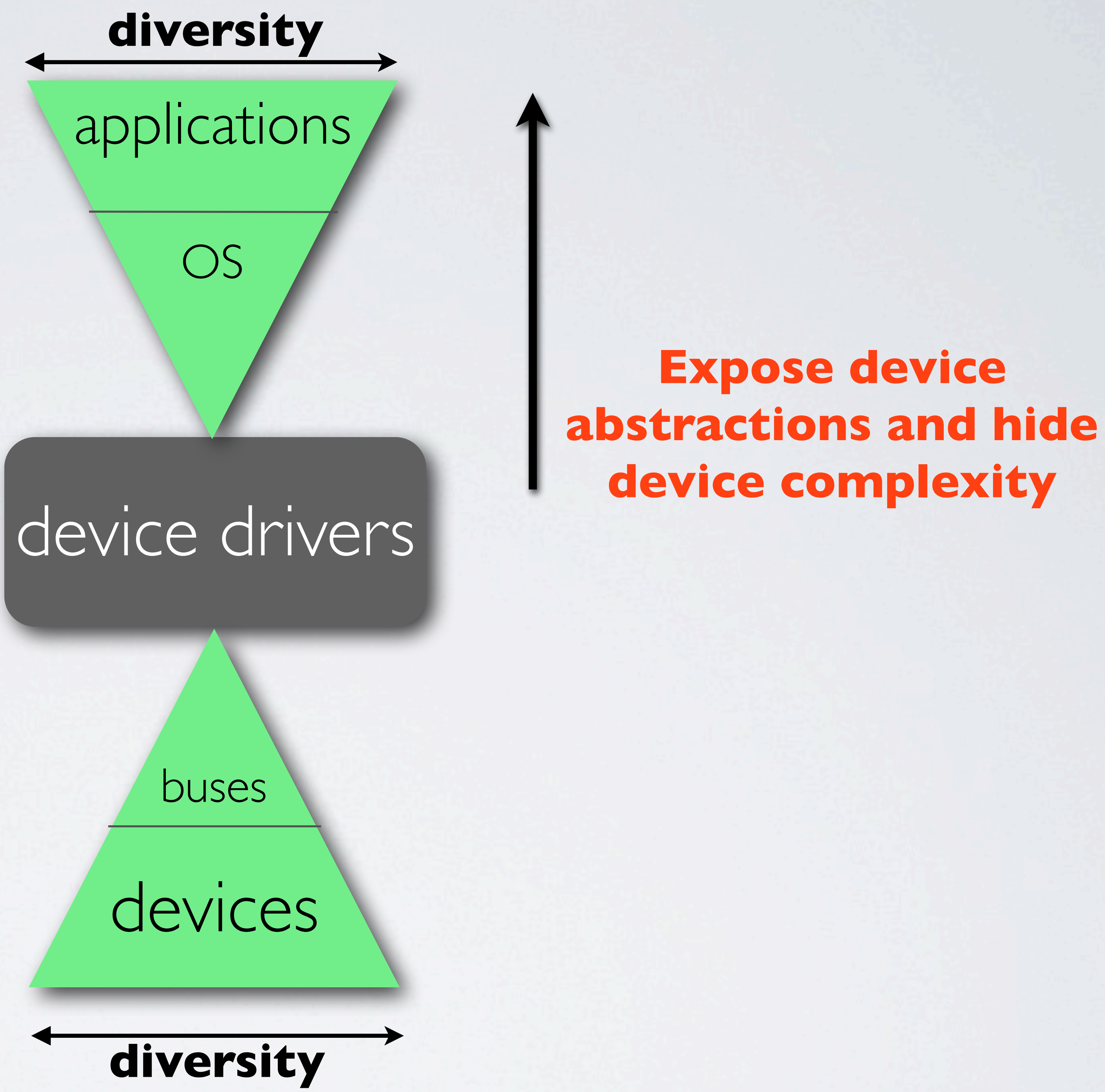

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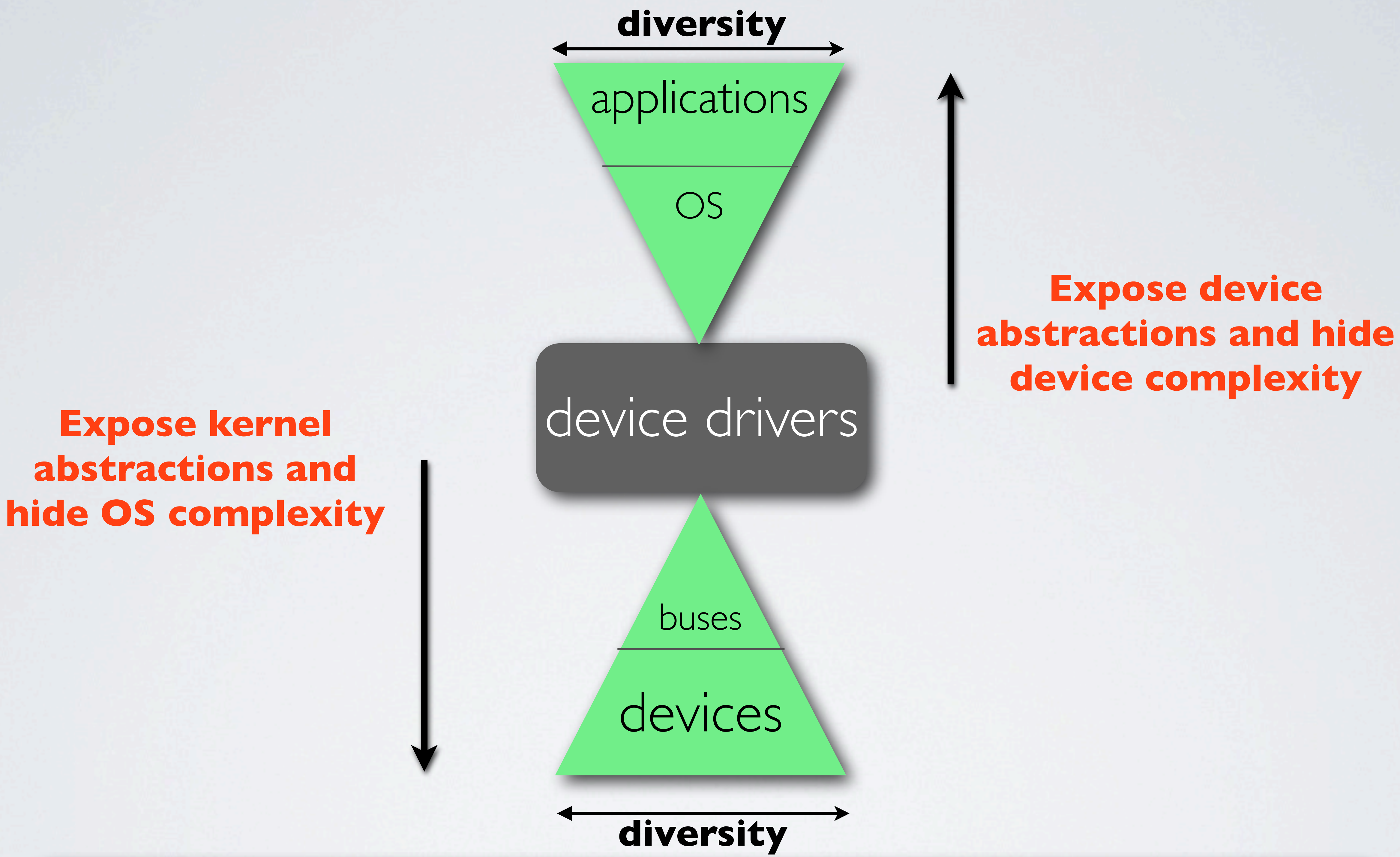
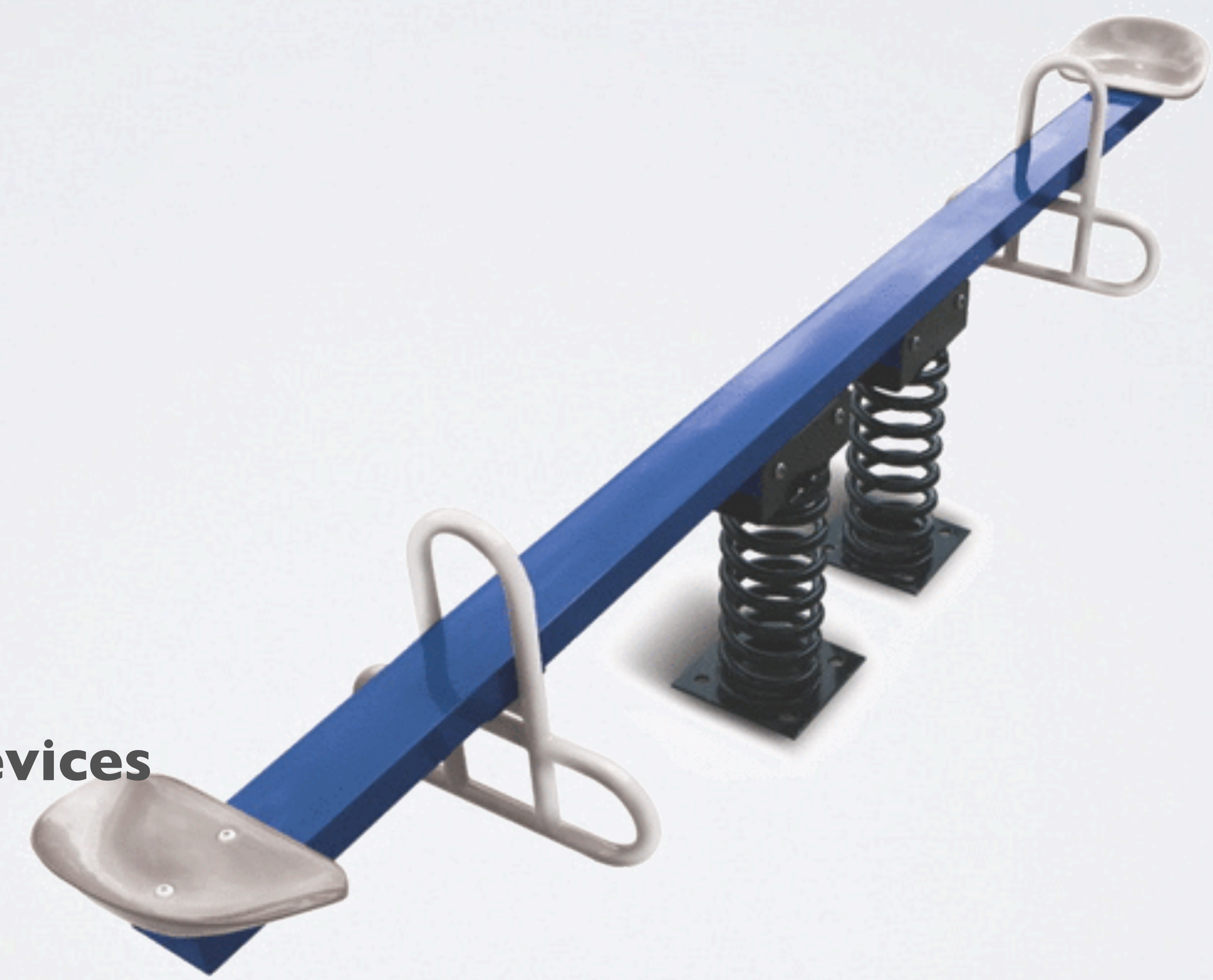


Allow diverse set of applications and OS services to access diverse set of devices

Evolution of devices hurts device access



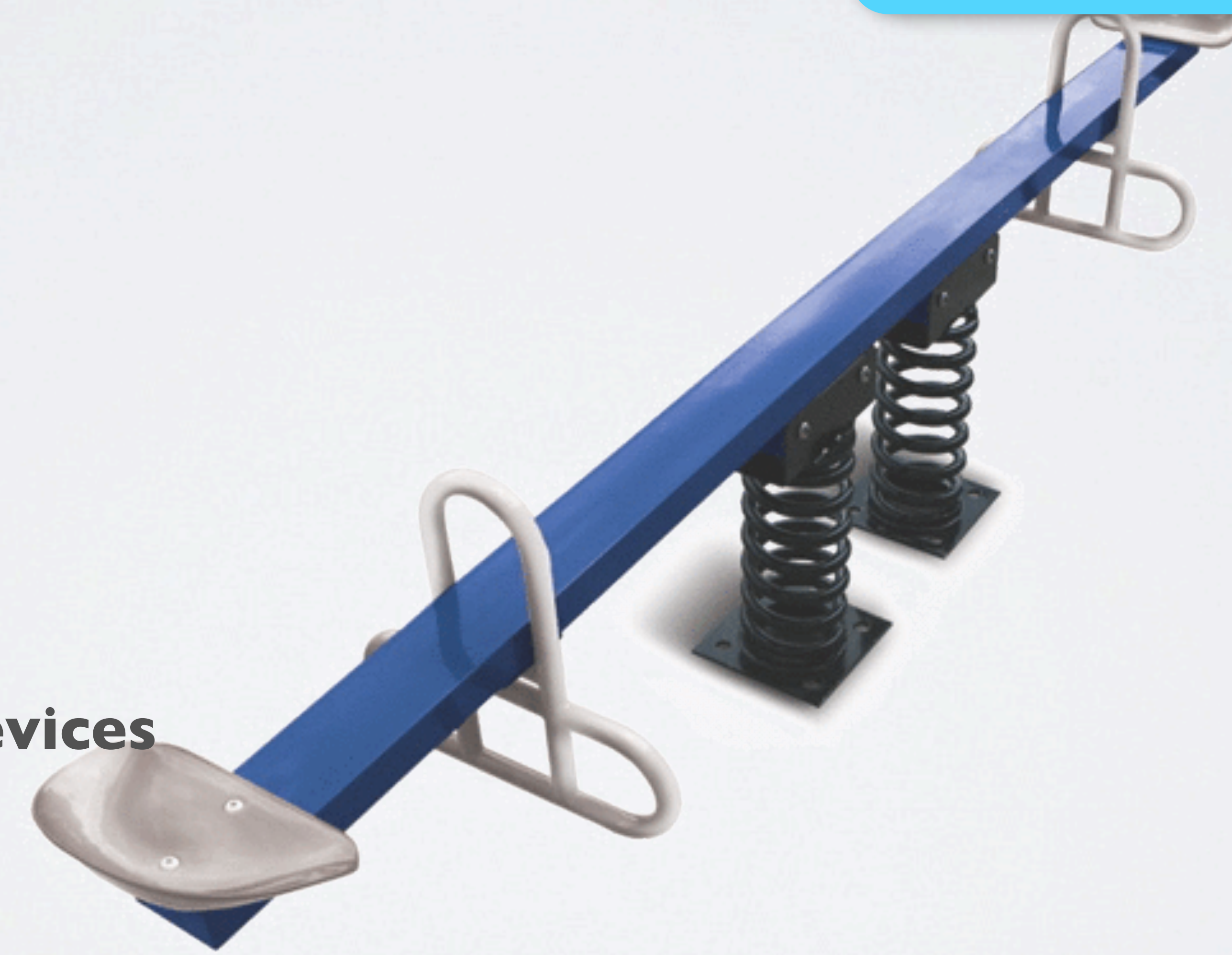
Evolution of devices hurts device access

Simplicity

Low latency

Reliability

Cost effective



Efficient device support in OS

Evolution of devices

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- Simplicity
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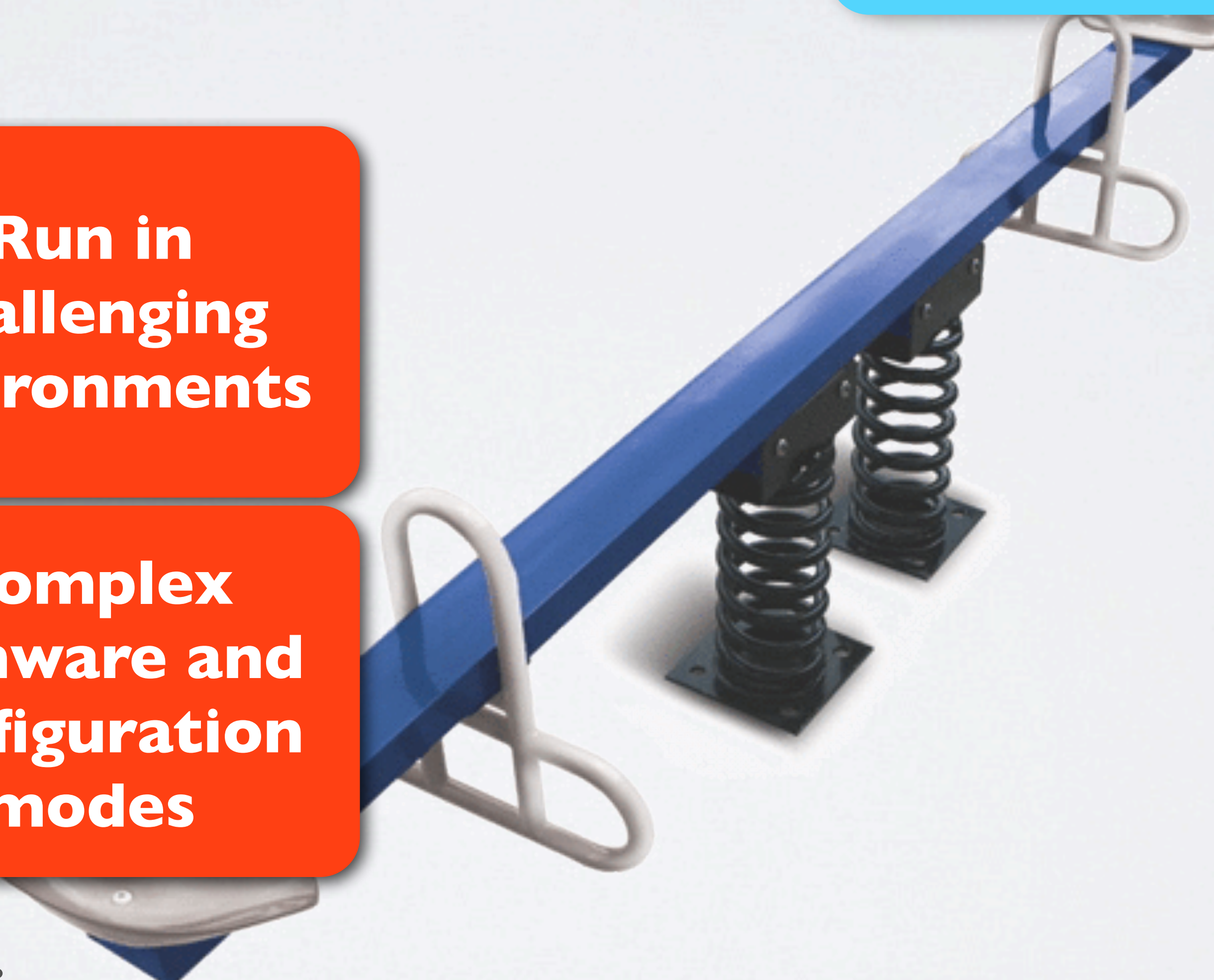
Efficient device support in OS



- Growth in number and diversity
- Run in challenging environments
- Hardware failures (like CMOS issues)
- Complex firmware and configuration modes

Evolution of devices

Evolution of devices hurts device access

Tools and mechanisms to address increasing device complexity

Simplicity

Low latency

Reliability

Cost effective

Efficient device support in OS

Growth in number and diversity

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Complex firmware and configuration modes

Evolution of devices

Growth in drivers hurts understanding of drivers

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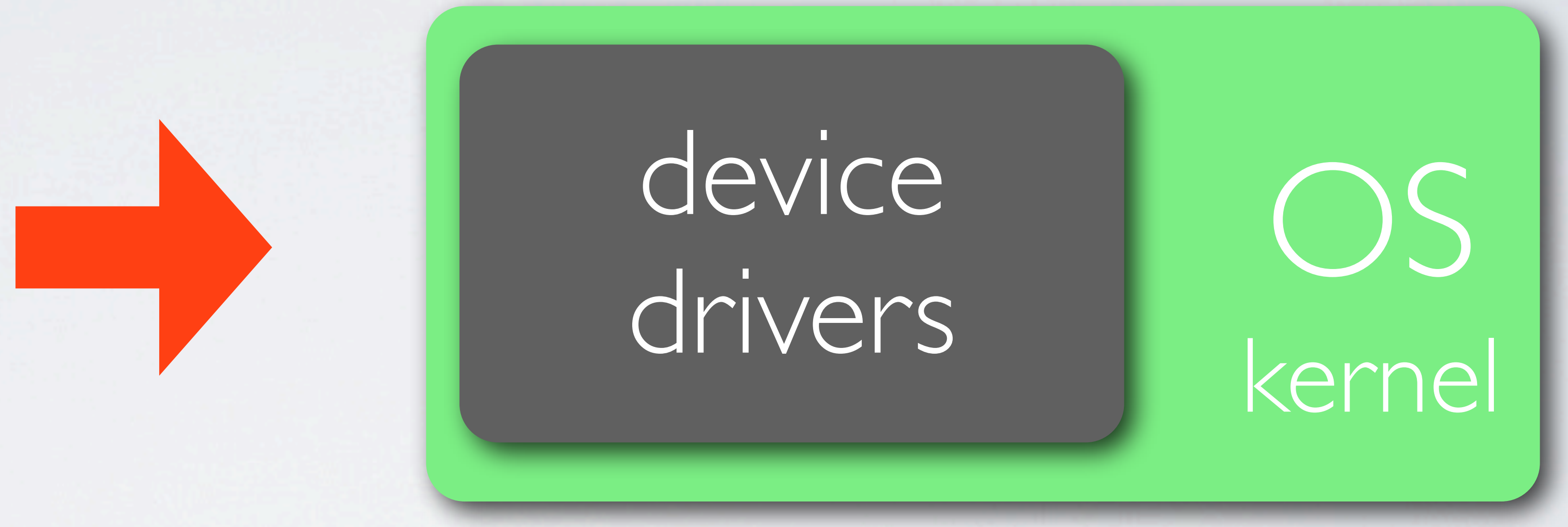
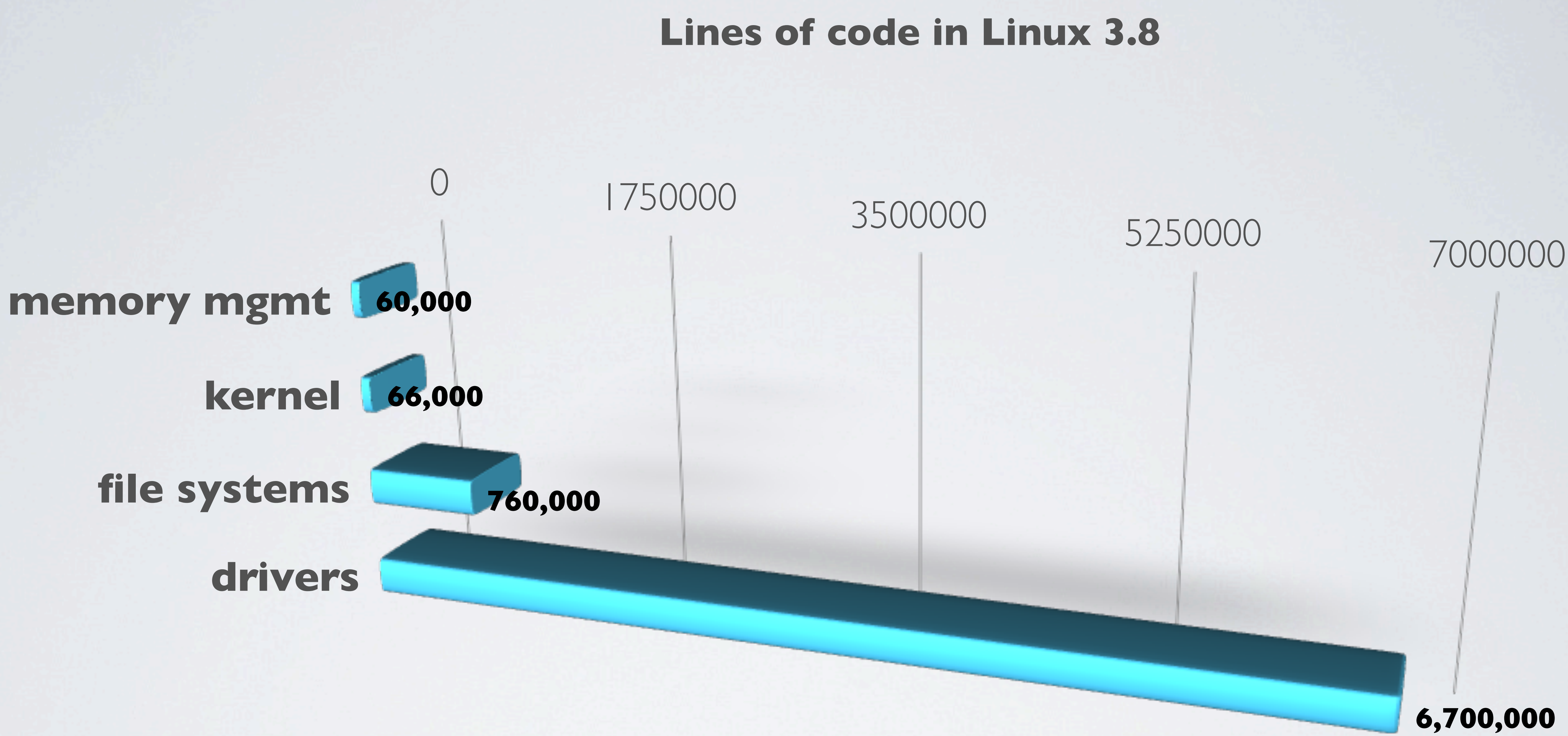


Contribute 60% of Linux kernel code

and more than 90% in Windows

Growth in drivers hurts understanding of drivers



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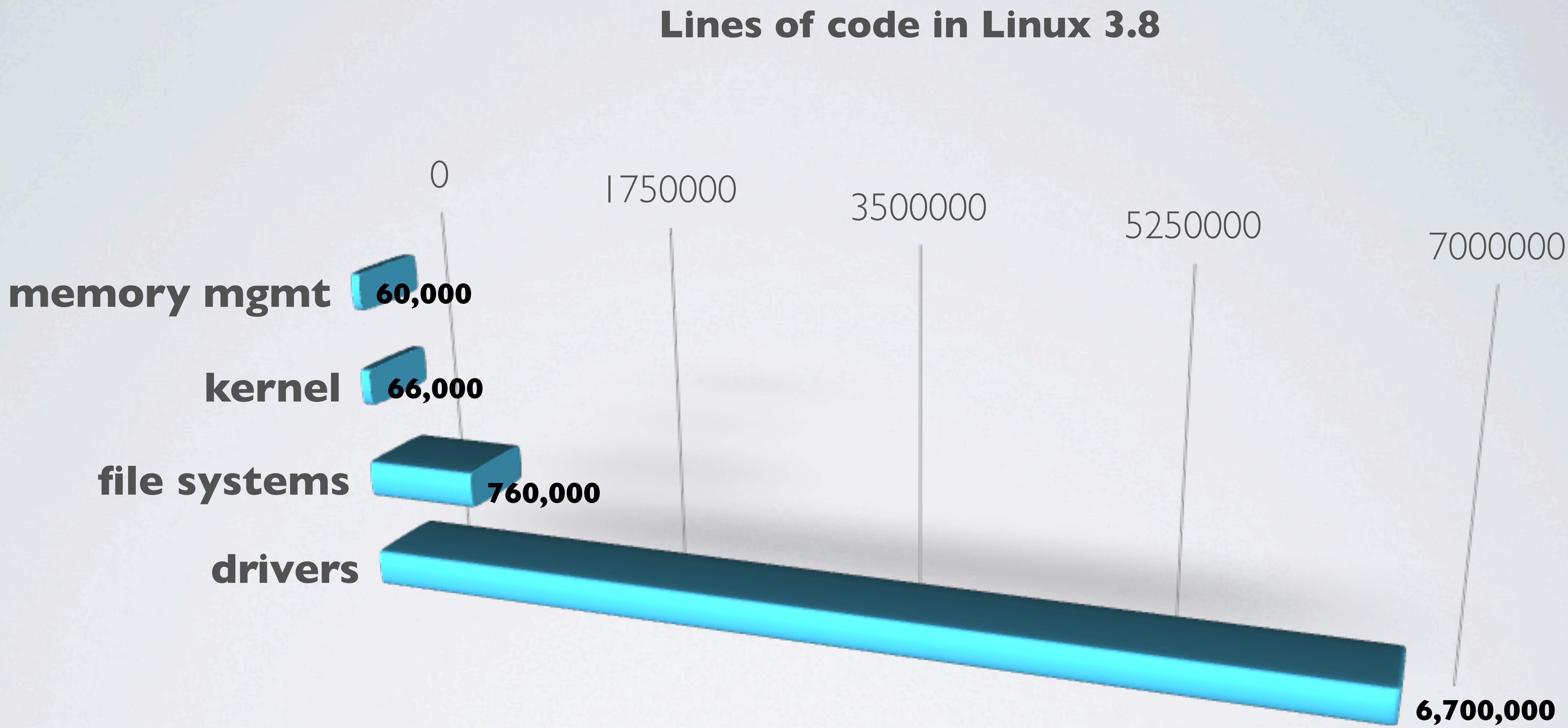

Understand the software complexity and improve driver code

Last decade: Focus on the driver-kernel interface

3rd party developers

+

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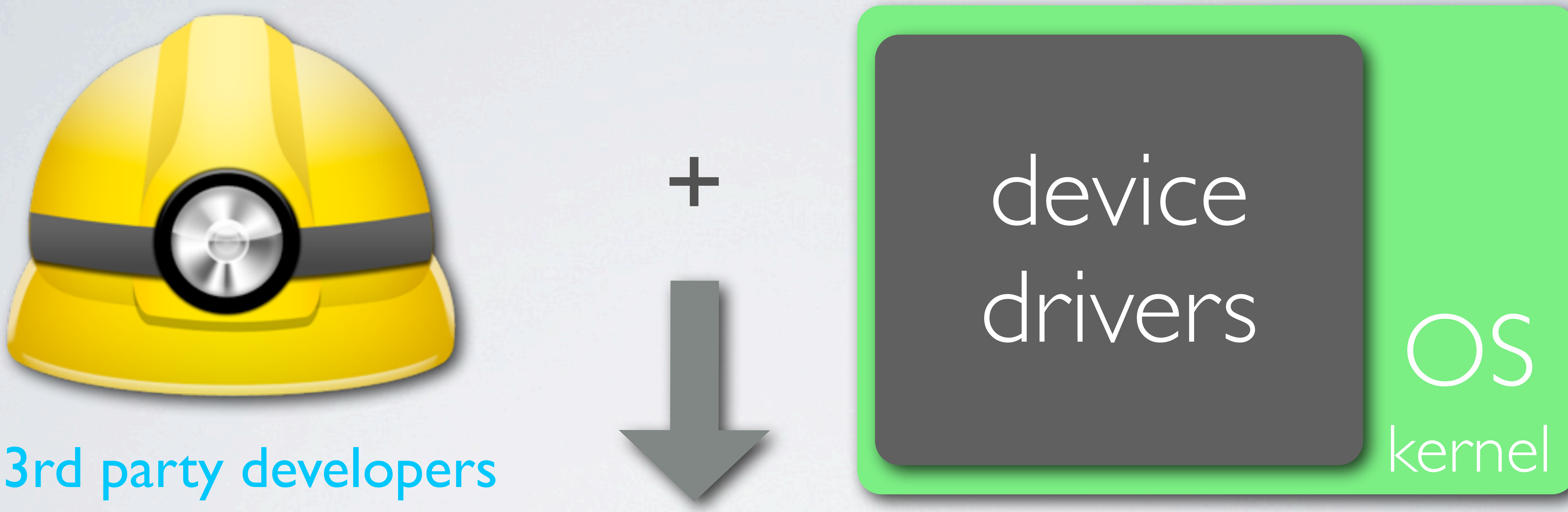

Last decade: Focus on the driver-kernel interface

3rd party developers

+

device drivers

OS kernel

Recipe for disaster

Re-use lessons from existing driver research

Improvement	System	Validation		
		Drivers	Bus	Classes
New functionality	Shadow driver migration [OSR09]	1	1	1
	RevNIC [Eurosys 10]	1	1	1
Reliability	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
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Static analysis tools	Windows SDV [Eurosys 06]	Many	Many	Many
	Coverity [CACM 10]	All	All	All
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Large kernel subsystems and validity of few device types result in limited adoption of research solutions

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Design goal: Complete solution that limits kernel changes and applies to all drivers

Goal: Address software and hardware complexity

- ★ **Understand and improve device access in the face of rising hardware and software complexity**

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Increasing hardware complexity

Reliability against hardware failures

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Reliability against hardware failures

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Increasing hardware complexity

Low latency device availability

2

Goal: Address software and hardware complexity

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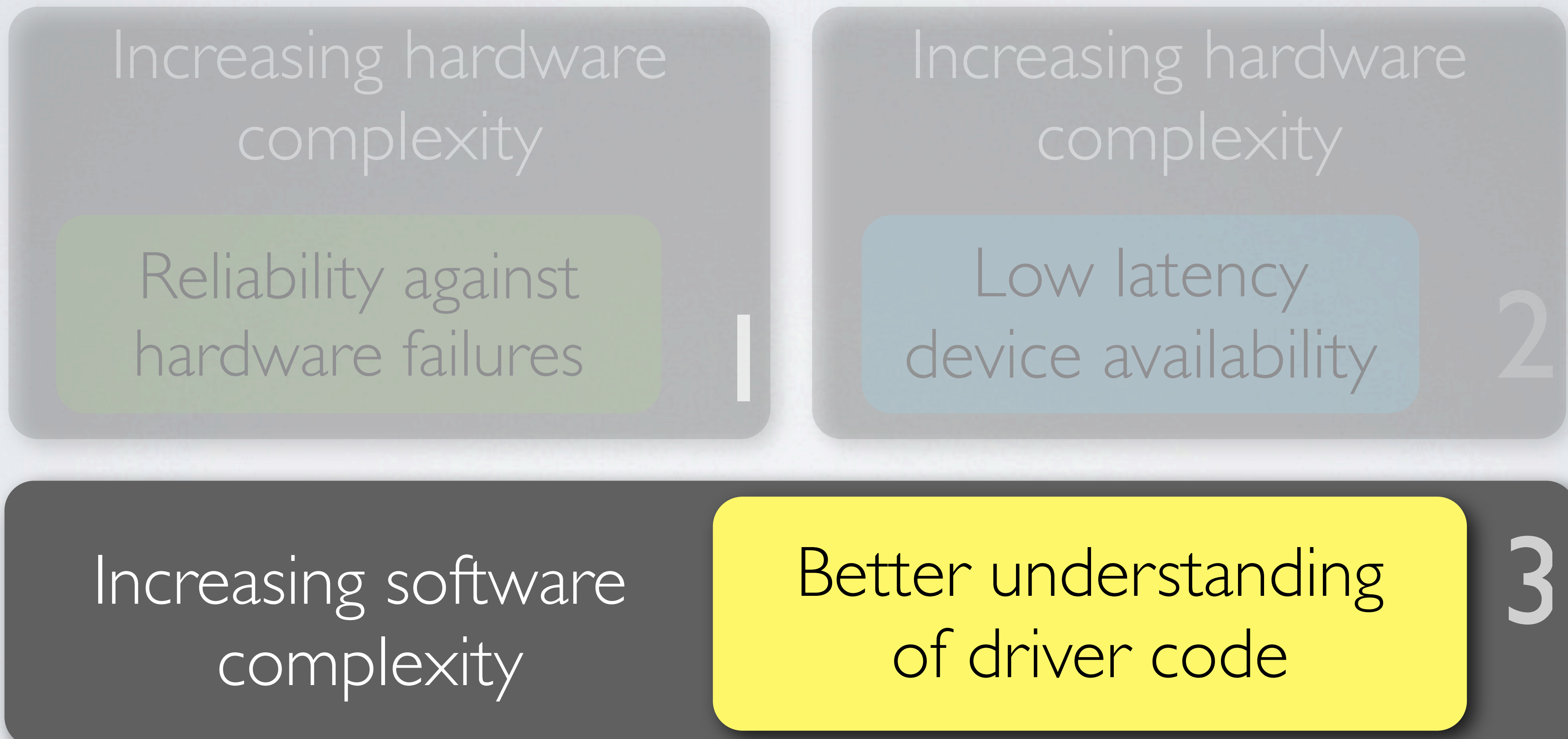

Contributions/Outline

First research consideration of hardware failures in drivers

SOSP '09

Tolerate device failures

Largest study of drivers to understand their behavior and verify research assumptions

ASPLOS '12

Understand drivers and potential opportunities

Introduce checkpoint/restore in drivers for low latency fault tolerance

ASPLOS '13

Transactional approach for low latency recovery

What happens when devices misbehave?

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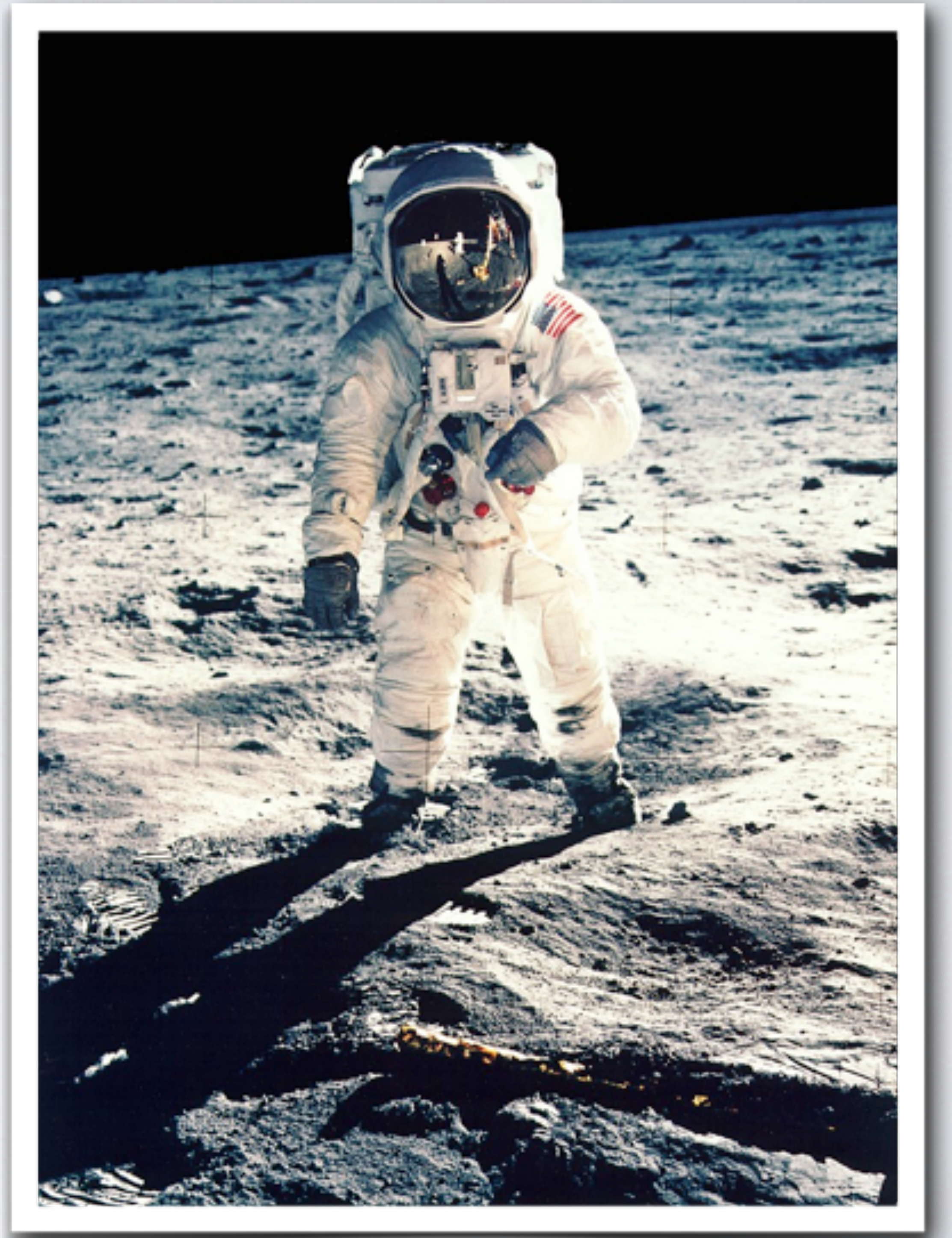
What happens when devices misbehave?

- ★ Drivers make it better
- ★ Drivers make it worse

Early example: Apollo 11 1969

- ★ Hardware design bug almost aborted the landing
- ★ Assumptions about antenna in driver led to extra CPU
- ★ Scientists on-board had to manually prioritize critical tasks



Current state of OS-hardware interaction

2013

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- ⋆ **Many device drivers often assume device perfection**
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Hardware dependence bug: Device malfunction can crash the system

Sources of hardware misbehavior

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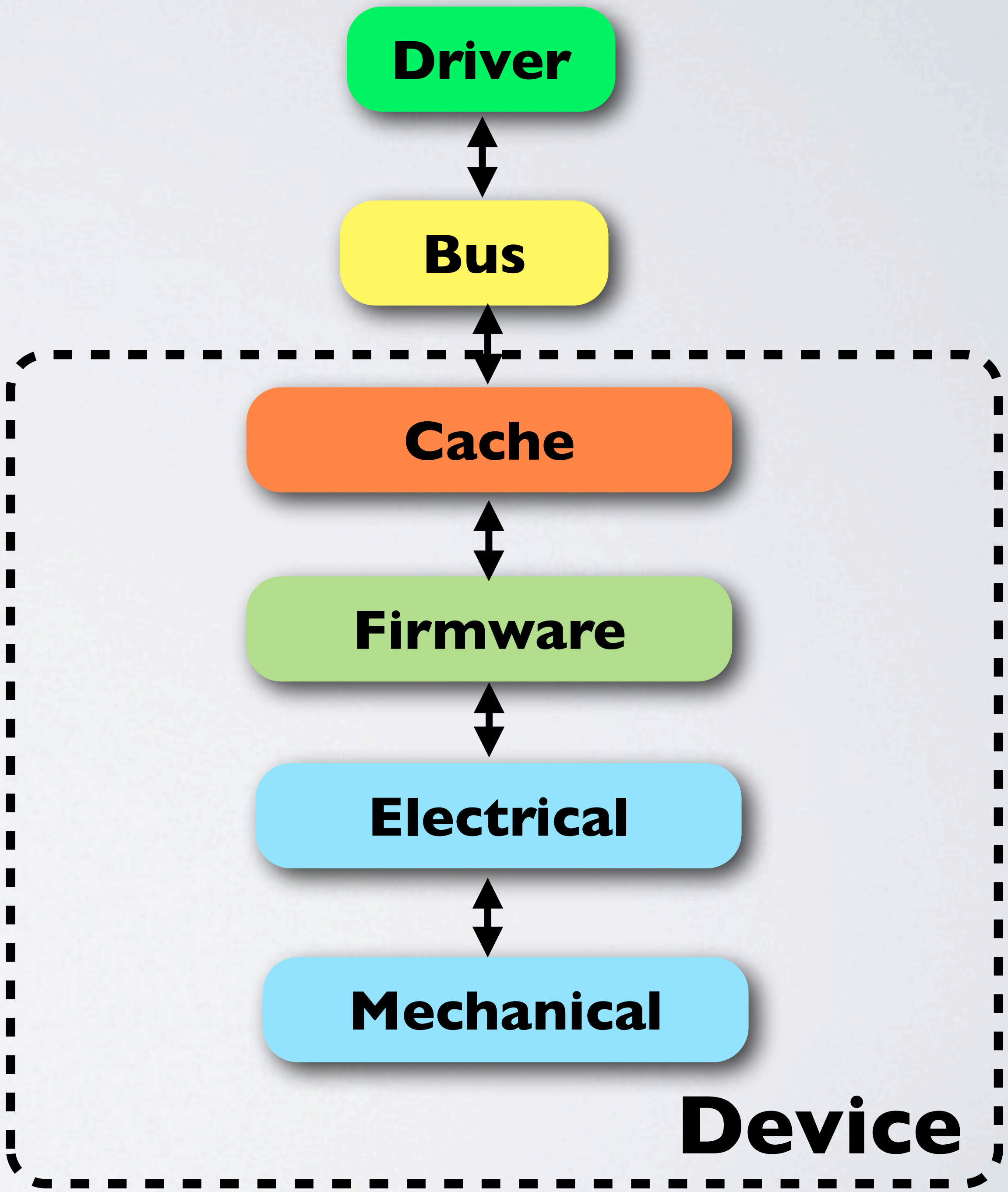

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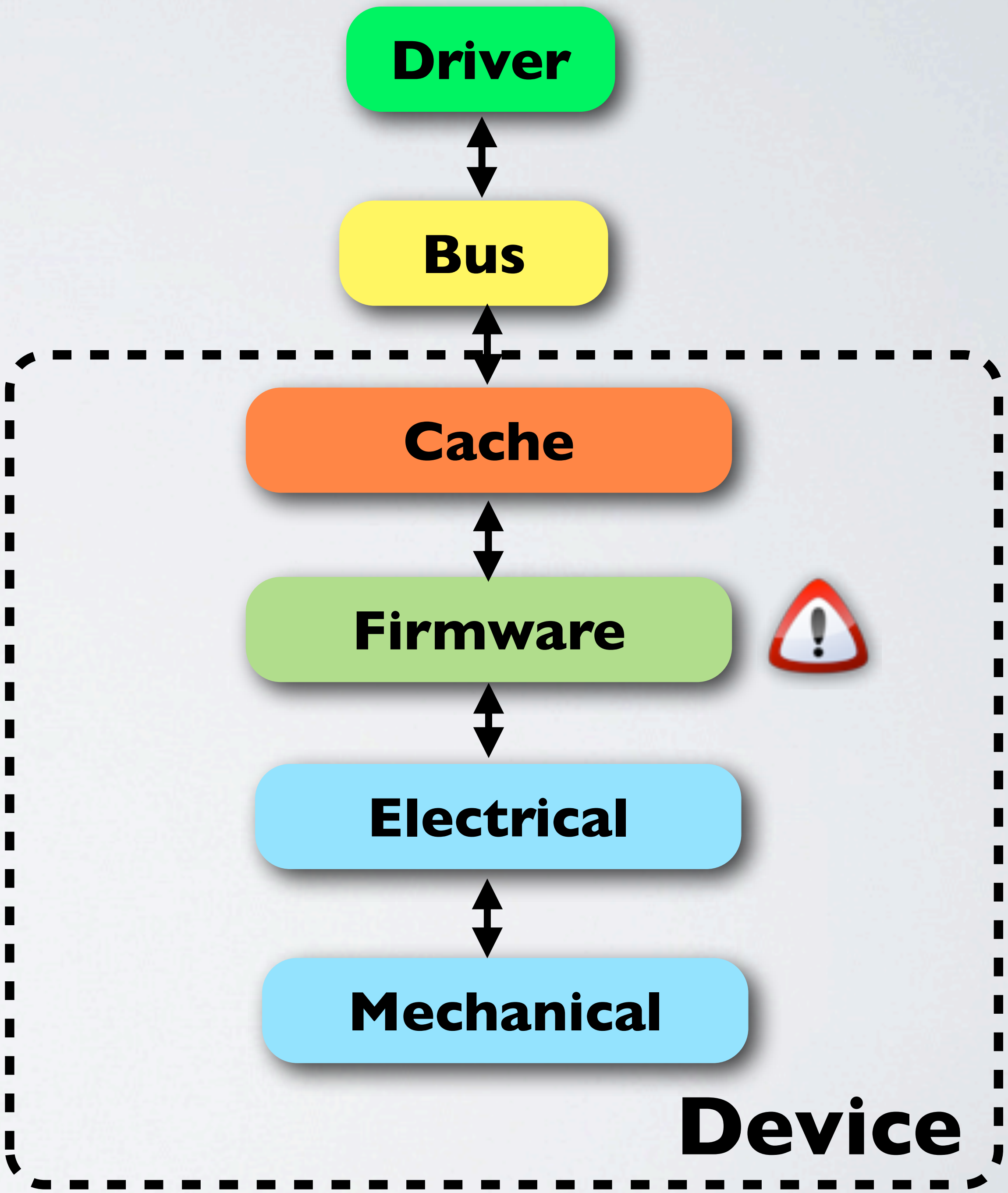

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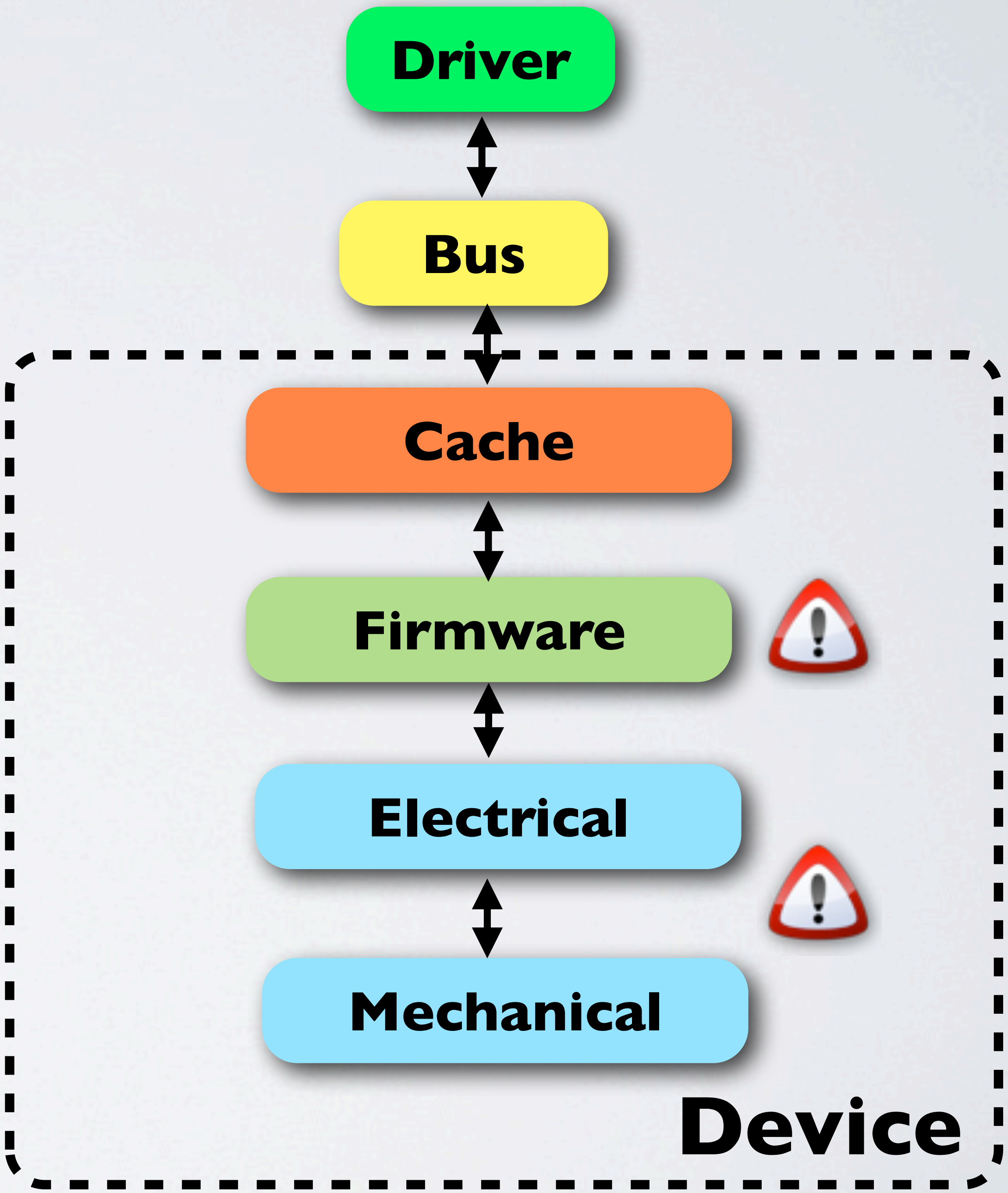

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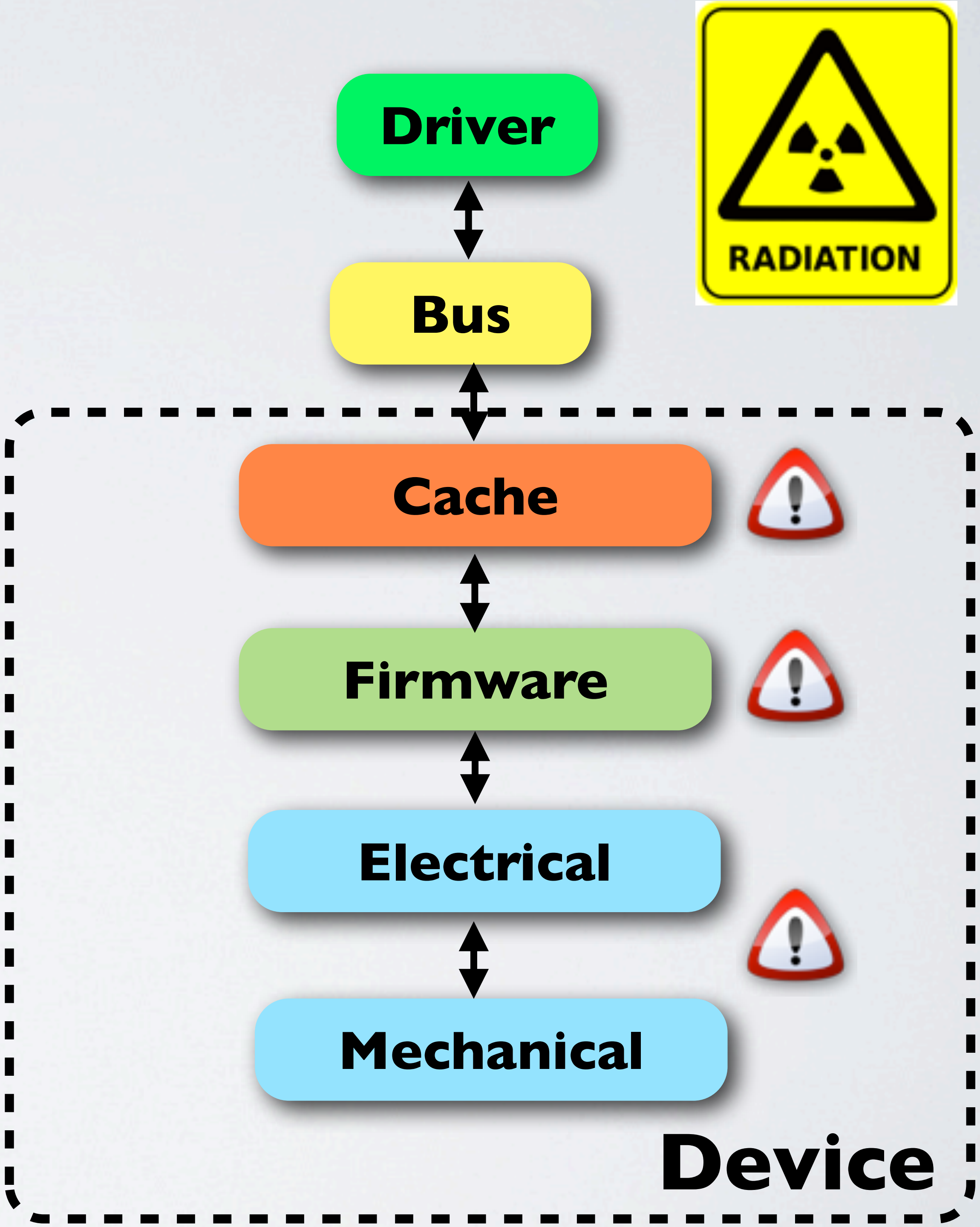

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- Results of misbehavior
  - Corrupted/stuck-at inputs
  - Timing errors
  - Interrupt storms/missing interrupts
  - Incorrect memory access

An evidence: Windows Server

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Existing solution is **hand-coded** hardened drivers

- ★ Crashes reduce from **8%** to **3%**

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Drivers use device
data in critical control and data paths

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```

3

Drivers do not detect or recover from device failures

```
if (inb(regA)!= 5) {
   panic();
}
```

Vendor recommendations for driver developers

Recommendation	Summary	Recommended by			
		Intel	Sun	MS	Linux
Validation	Input validation	●	●	●	
	Read once& CRC data	●	●		●
	DMA protection	●	●		
Timing	Infinite polling	●	●	●	
	Stuck interrupt		●		
	Lost request			●	
	Avoid excess delay in OS			●	
	Unexpected events	●		●	
Reporting	Report all failures	●	●	●	
Recovery	Handle all failures		●	●	
	Cleanup correctly	●	●		
	Do not crash on failure	●		●	●
	Wrap I/O memory access	●	●	●	●

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Goal: Automatically implement as many recommendations as possible in commodity drivers

Carburizer [SOSP '09]

Goal: Tolerate hardware device failures in software through hardware failure detection and recovery

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Static analysis component

- **Detect and fix hardware dependence bugs**
- **Detect and generate missing error reporting information**

Carburizer [SOSP '09]

Goal: Tolerate hardware device failures in software through hardware failure detection and recovery

Static analysis component

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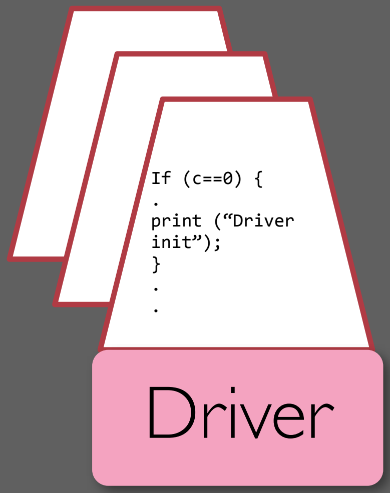
Runtime component

- **Detect interrupt failures**
- **Provide automatic recovery**

Carburizer architecture

Bug detection and automatic fix generation



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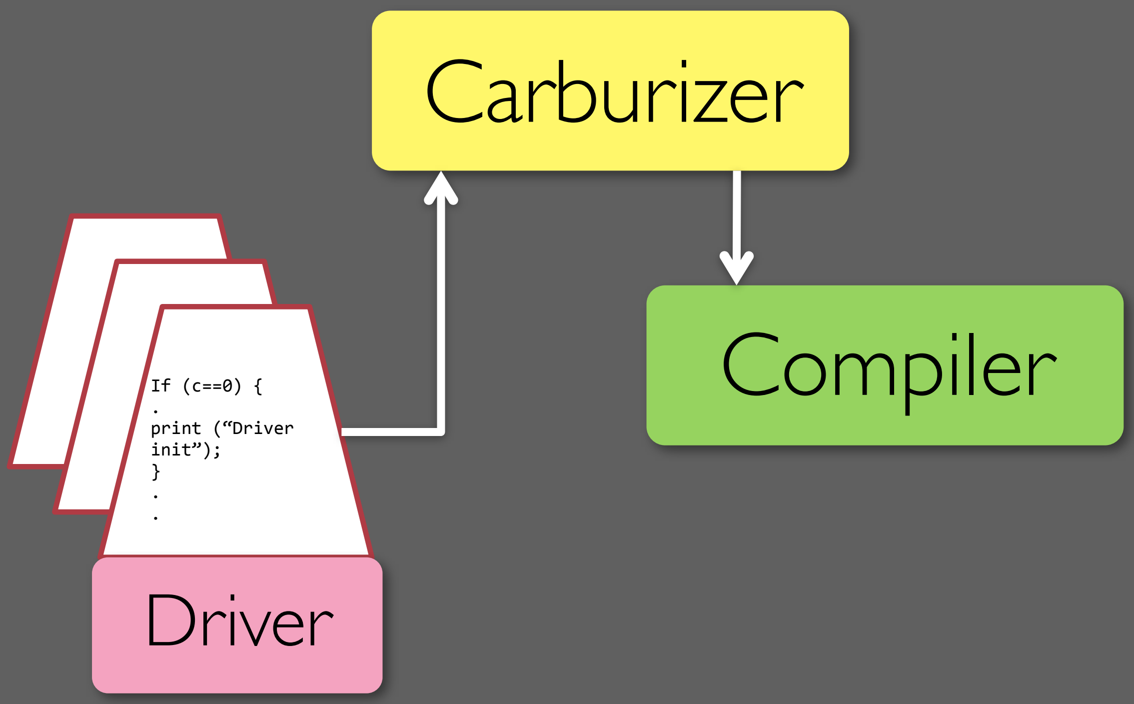

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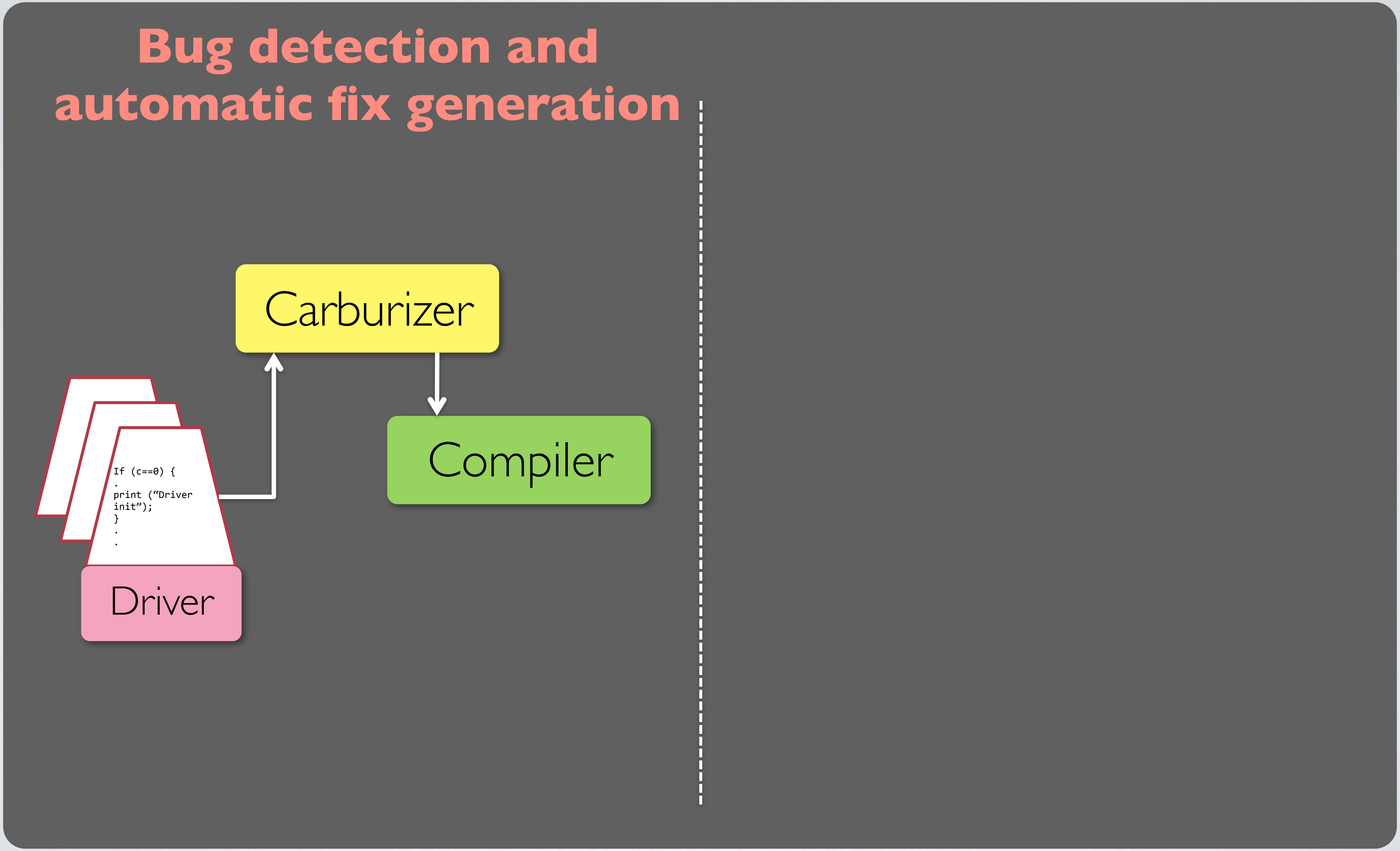

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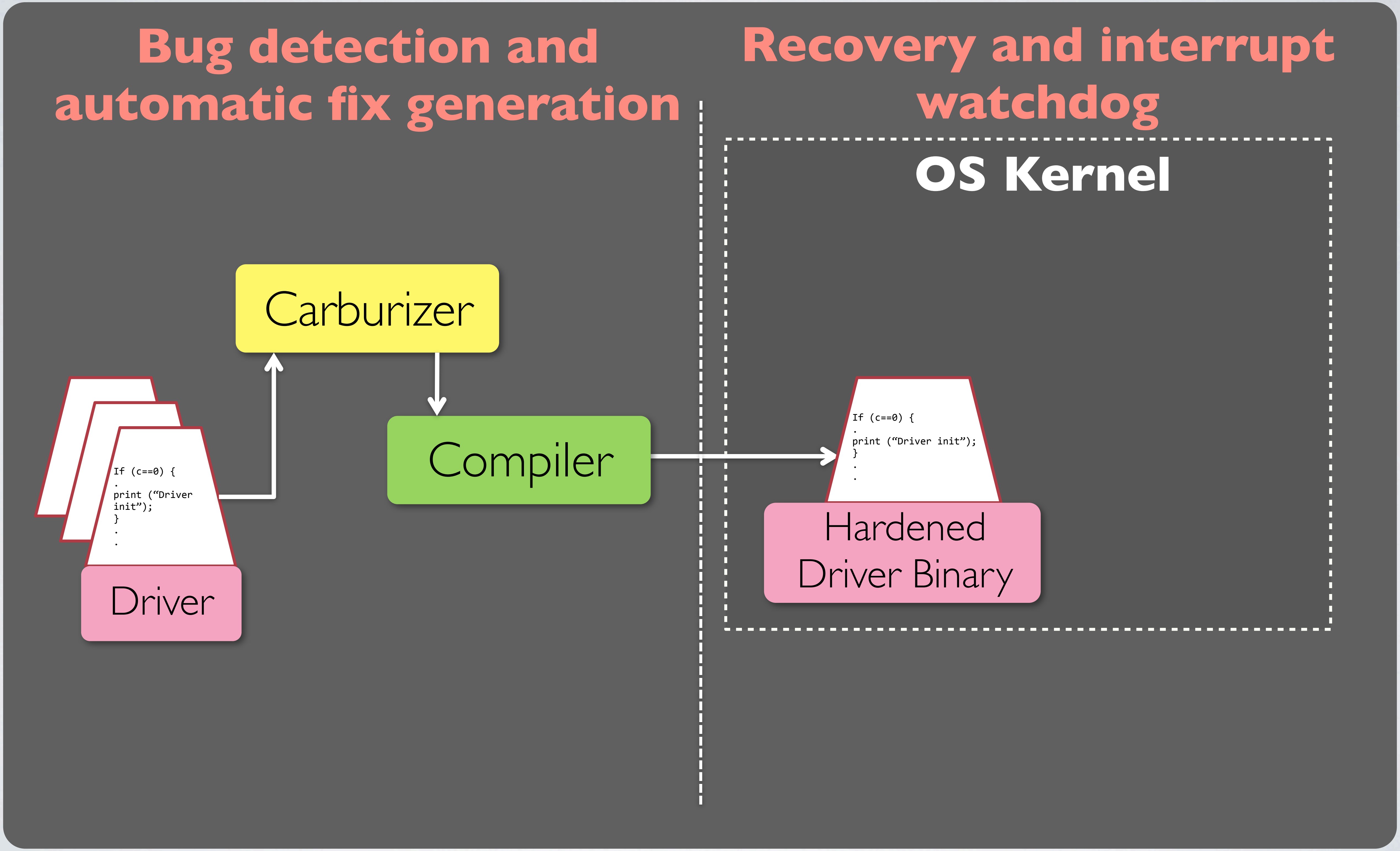

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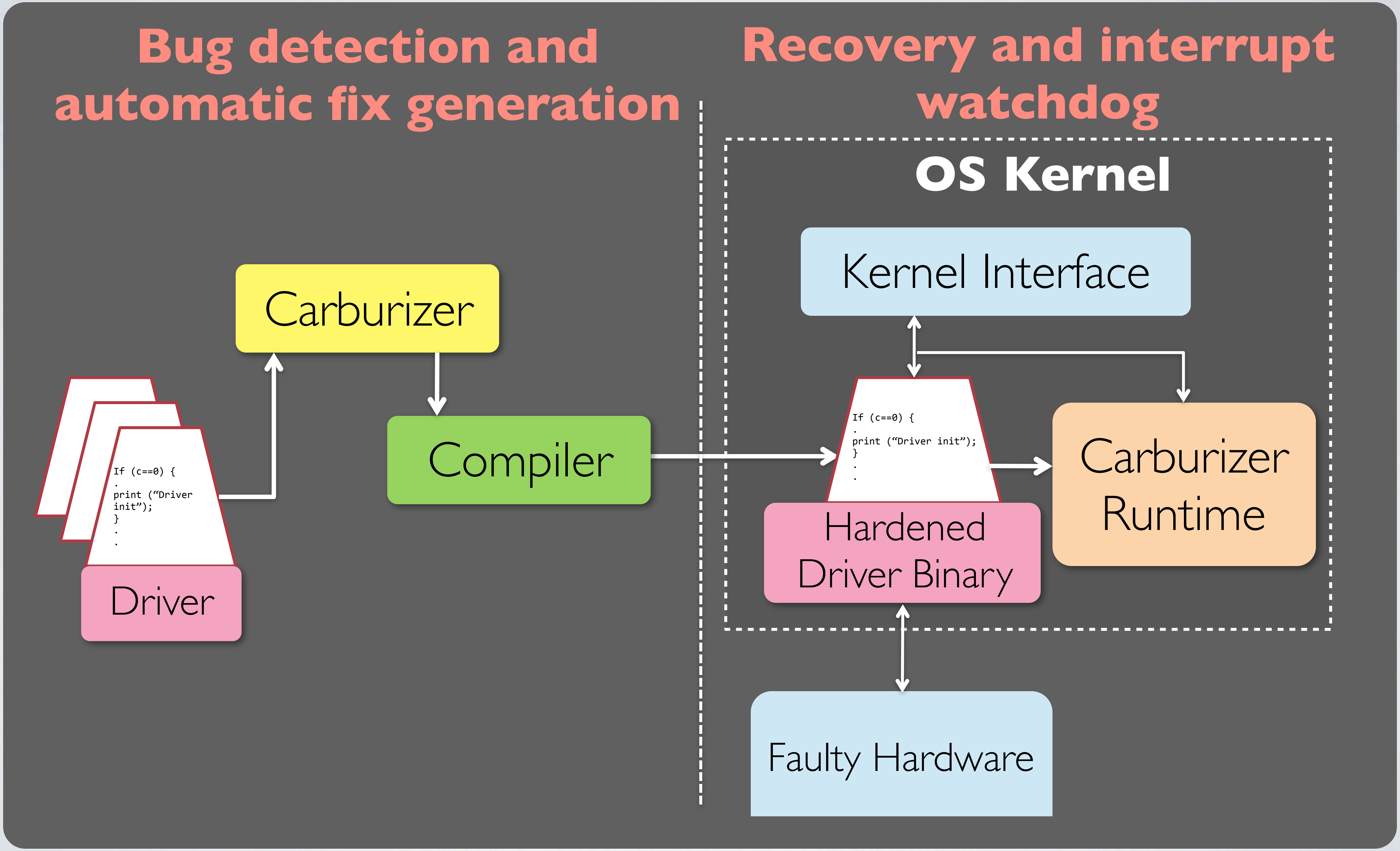

Hardening drivers

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Unsafe array reference

Unsafe pointer reference

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  - ★ **Find driver code that uses data from device**
  - ★ **Ensure driver performs validity checks**

- **Carburizer detects and fixes hardware bugs :**

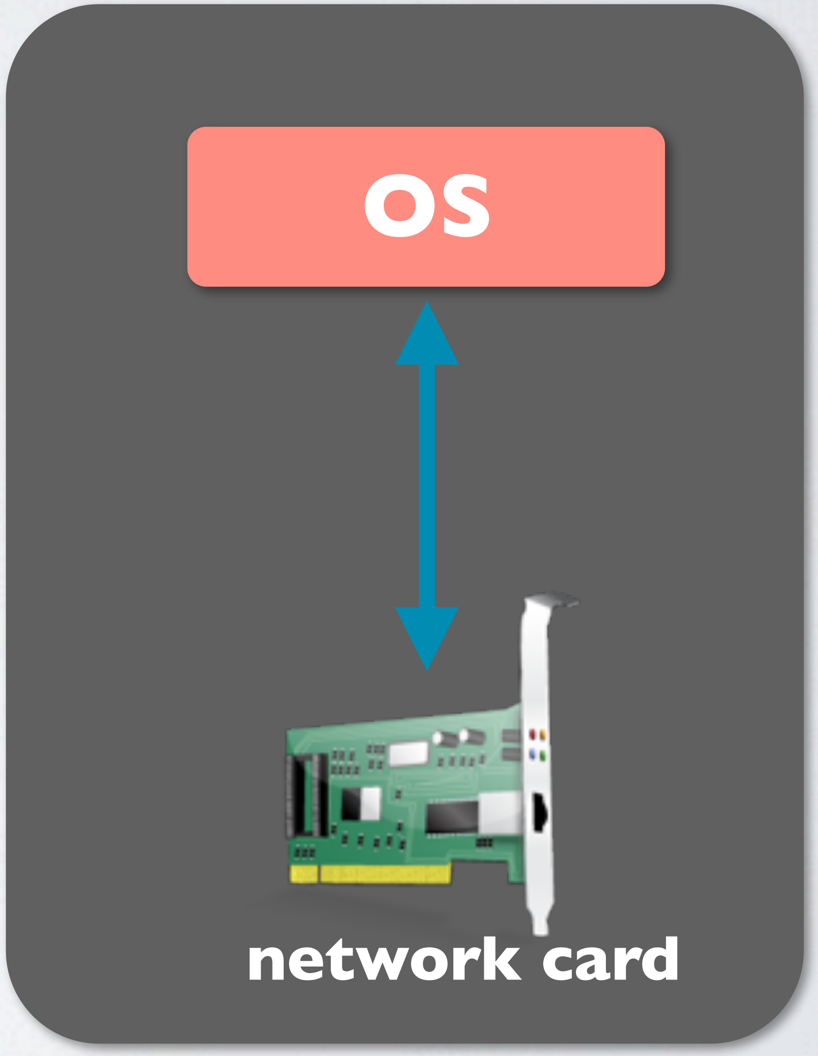
Infinite polling | **Unsafe array reference** | **Unsafe pointer reference** | **System panic calls**

Finding sensitive code

- **First pass: Identify tainted variables that contain data from device**

Types of device I/O

- **Port I/O :** `inb/inw`
- **Memory-mapped I/O :** `readl/readw`
- **DMA buffers**
- **Data from USB packets**



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int test ()  {
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int test ()  {
      a = readl();
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Tainted Variables

a

Finding sensitive code

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```
int test ()  {
        a = readl();
        b = inb();
```

Tainted Variables

a

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```

Tainted Variables

```
a
b
```

Finding sensitive code

- ★ **First pass: Identify tainted variables that contain data from device**

```
int test ()  {
        a = readl();
        b = inb();
        c = b;
```

Tainted Variables

a
b

Finding sensitive code

- **First pass: Identify tainted variables that contain data from device**

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int test ()  {
        a = readl();
        b = inb();
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```

```
Tainted Variables

        a
        b
        c
```

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```
int test ()  {
        a = readl();
        b = inb();
        c = b;
        d = c + 2;
```

Tainted Variables

a
b
c

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Tainted Variables

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b
c
d

Finding sensitive code

- **First pass: Identify tainted variables that contain data from device**

```
int test ()  {
        a = readl();
        b = inb();
        c = b;
        d = c + 2;
        return d;
```

Tainted Variables

a
b
c
d

Finding sensitive code

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}
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Tainted Variables

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c
d
test()
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Detecting risky uses of tainted variables

- Second pass: Identify risky uses of tainted variables
- Example: Infinite polling
  - Driver waiting for device to enter particular state
  - Solution: Detect loops where all terminating conditions depend on tainted variables
  - Extra analyses to existing timeouts

Infinite polling

- Infinite polling of devices can cause system lockups

```
static int amd8111e_read_phy(………)
{
 ...
  reg_val = readl(mmio + PHY_ACCESS);
  while (reg_val & PHY_CMD_ACTIVE)
        reg_val = readl(mmio + PHY_ACCESS);
  ...
}
```

AMD 8111e network driver(amd8111e.c)

Hardware data used in array reference

- ★ **Tainted variables used as array indexes**
- ★ **Detect existing range/not NULL checks**

```
static void __init attach_pas_card(...)
{
   if ((pas_model = pas_read(0xFF88)))
   {
     ...
     sprintf(temp, “%s rev %d”,
       pas_model_names[(int) pas_model], pas_read(0x2789));
     ...
}
```

Pro Audio Sound driver (pas2_card.c)

Analysis results over the Linux kernel

Driver class	Infinite polling	Static array	Dynamic array	Panic calls
net	117	2	21	2
scsi	298	31	22	121
sound	64	1	0	2
video	174	0	22	22
other	381	9	57	32
Total	860	43	89	179

- ★ **Analyzed/Built 6300 driver files (2.8 million LOC) in 37 min**
- ★ **Found 992 hardware dependence bugs in driver code**
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Lightweight and usable technique to find hardware dependence bugs

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- Carburizer automatically generates repair code
  - Inserts failure detection and recovery service callout

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Unsafe array reference

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System panic calls

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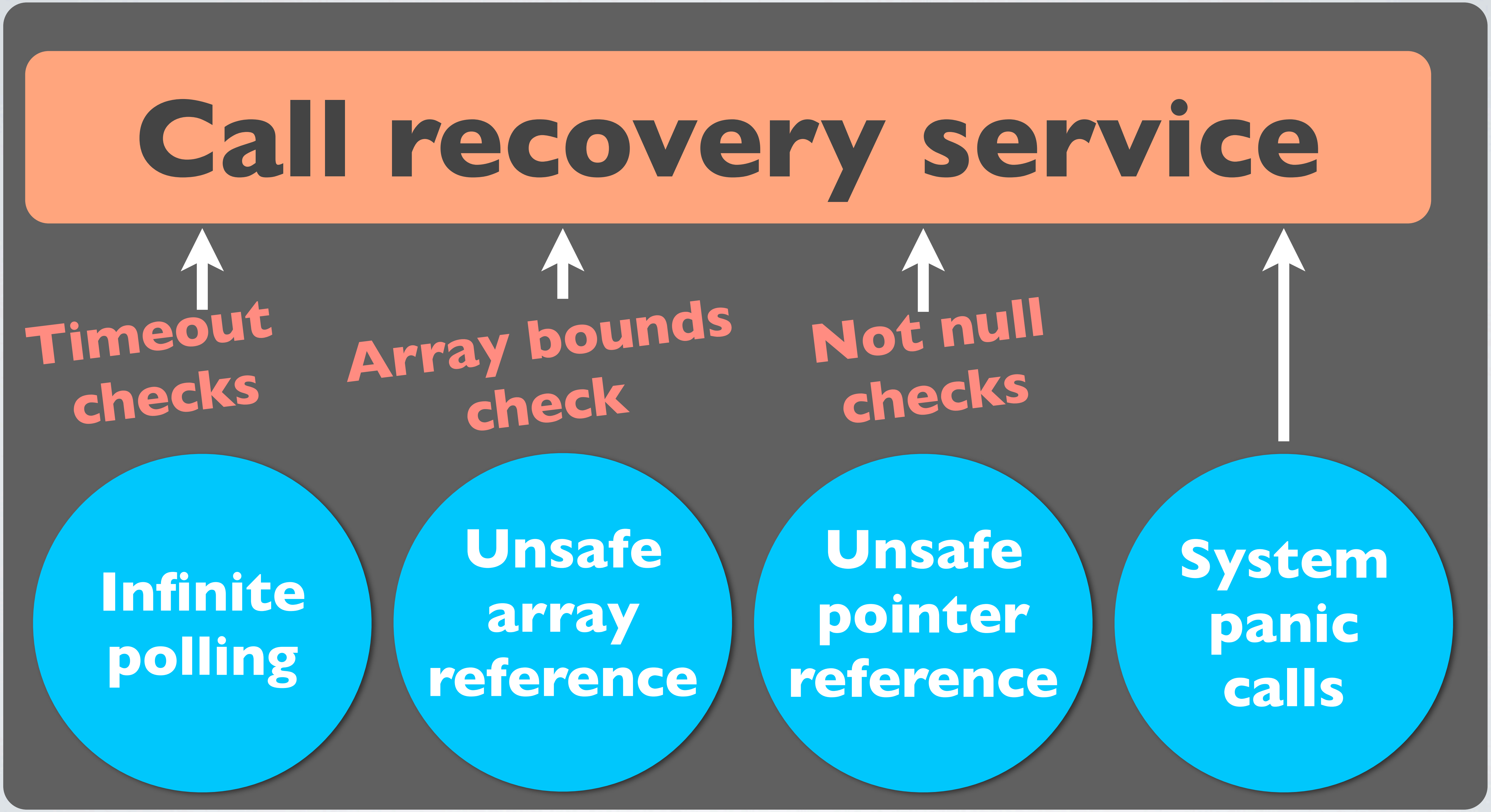
Timeout checks — **Infinite polling**

Array bounds check — **Unsafe array reference**

Not null checks — **Unsafe pointer reference**

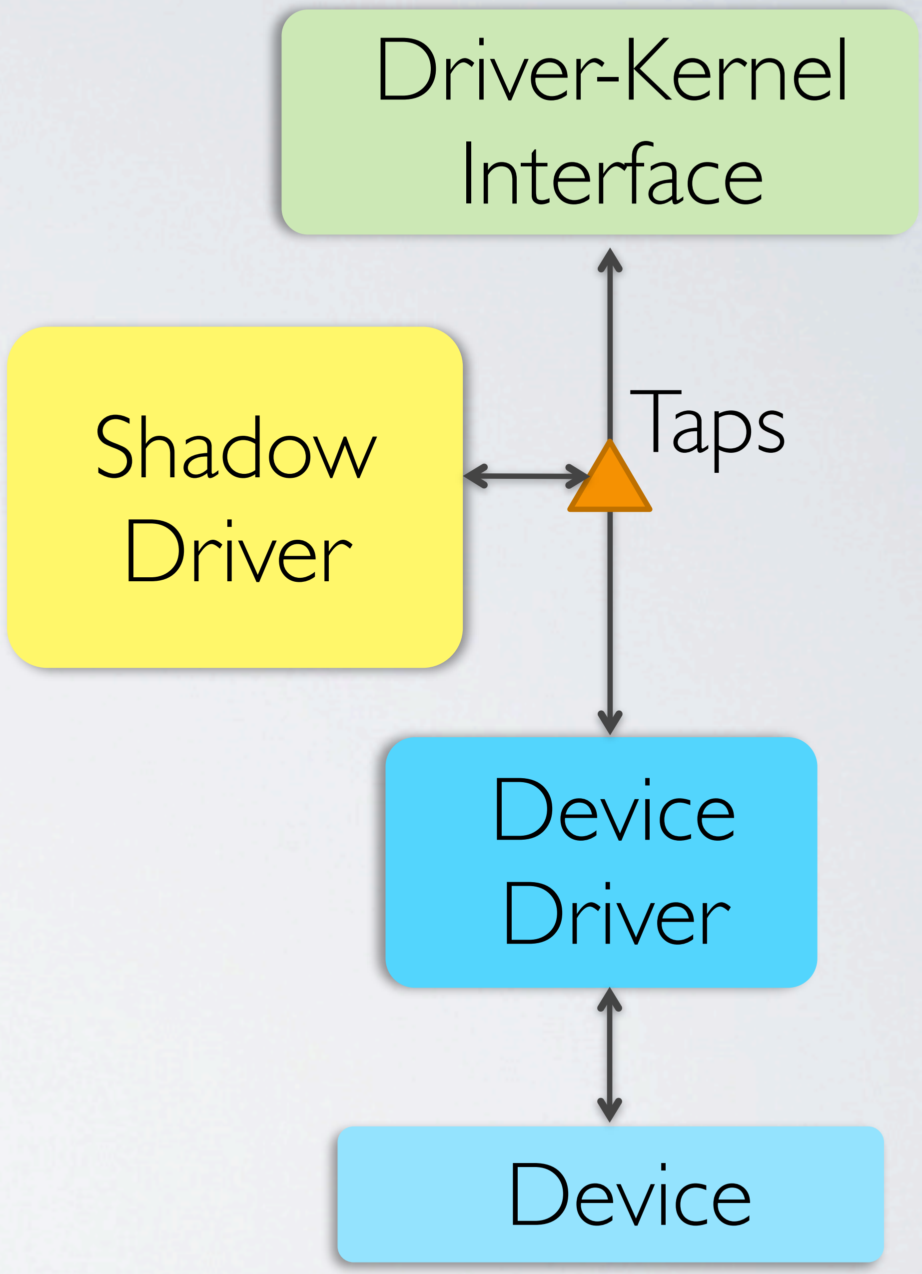
System panic calls

Repairing drivers



Runtime fault recovery : Shadow drivers

- **Carburizer calls generic recovery service if check fails**
- **Low cost transparent recovery**
  - ⋆ **Based on shadow drivers**
  - ⋆ **Records state of driver at all times**
  - ⋆ **Transparently restarts and replays recorded state on failure**
- **No isolation required (like Nooks)**



Swift [OSDI '04]

Carburizer automatically fixes infinite loops

```
timeout = rdtscll(start) + (cpu/khz/HZ)*2;
reg_val = readl(mmio + PHY_ACCESS);
while (reg_val & PHY_CMD_ACTIVE)      {
        reg_val = readl(mmio + PHY_ACCESS);

        if (_cur < timeout)
            rdtscll(_cur);
        else
            __recover_driver();


}
```

Timeout code added

AMD 8111e network driver(amd8111e.c)

*Code simplified for presentation purposes

Carburizer automatically adds bounds checks

```
static void __init attach_pas_card(...)
{

  if ((pas_model = pas_read(0xFF88)))
  {
    ...
    if ((pas_model< 0)) || (pas_model>= 5))
        __recover_driver();
    ...
    sprintf(temp, “%s rev %d”,
      pas_model_names[(int) pas_model], pas_read(0x2789));

}
```

Array bounds detected and check added

Pro Audio Sound driver (pas2_card.c)

*Code simplified for presentation purposes

Fault injection and performance

- **Synthetic fault injection on network drivers**

Fault injection and performance

- **Synthetic fault injection on network drivers**

Device/ Driver	Original Driver		Carburizer		
	Behavior	Detection	Behavior	Detection	Recovery
3COM 3C905	CRASH	None	RUNNING	Yes	Yes
DEC DC 21x4x	CRASH	None	RUNNING	Yes	Yes

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- **< 0.5% throughput overhead and no CPU overhead with network drivers**

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Carburizer failure detection and transparent recovery works and has very low overhead

Summary

Recommendation	Summary	Recommended by				**Carburizer Ensures**
		Intel	Sun	MS	Linux	
Validation	Input validation	●	●	●		●
	Read once& CRC data	●	●		●	
	DMA protection	●	●			
Timing	Infinite polling	●	●	●		●
	Stuck interrupt		●			●
	Lost request			●		●
	Avoid excess delay in OS			●		
	Unexpected events	●		●		
Reporting	Report all failures	●	●	●		●
Recovery	Handle all failures		●	●		●
	Cleanup correctly	●	●			●
	Do not crash on failure	●		●	●	●
	Wrap I/O memory access	●	●	●	●	

Summary

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	Lost request			●		●
	Avoid excess delay in OS			●		
	Unexpected events	●		●		
Reporting	Report all failures	●	●	●		●
	Wrap I/O memory access	●	●	●	●	

Carburizer improves system reliability by automatically ensuring that hardware failures are tolerated in software

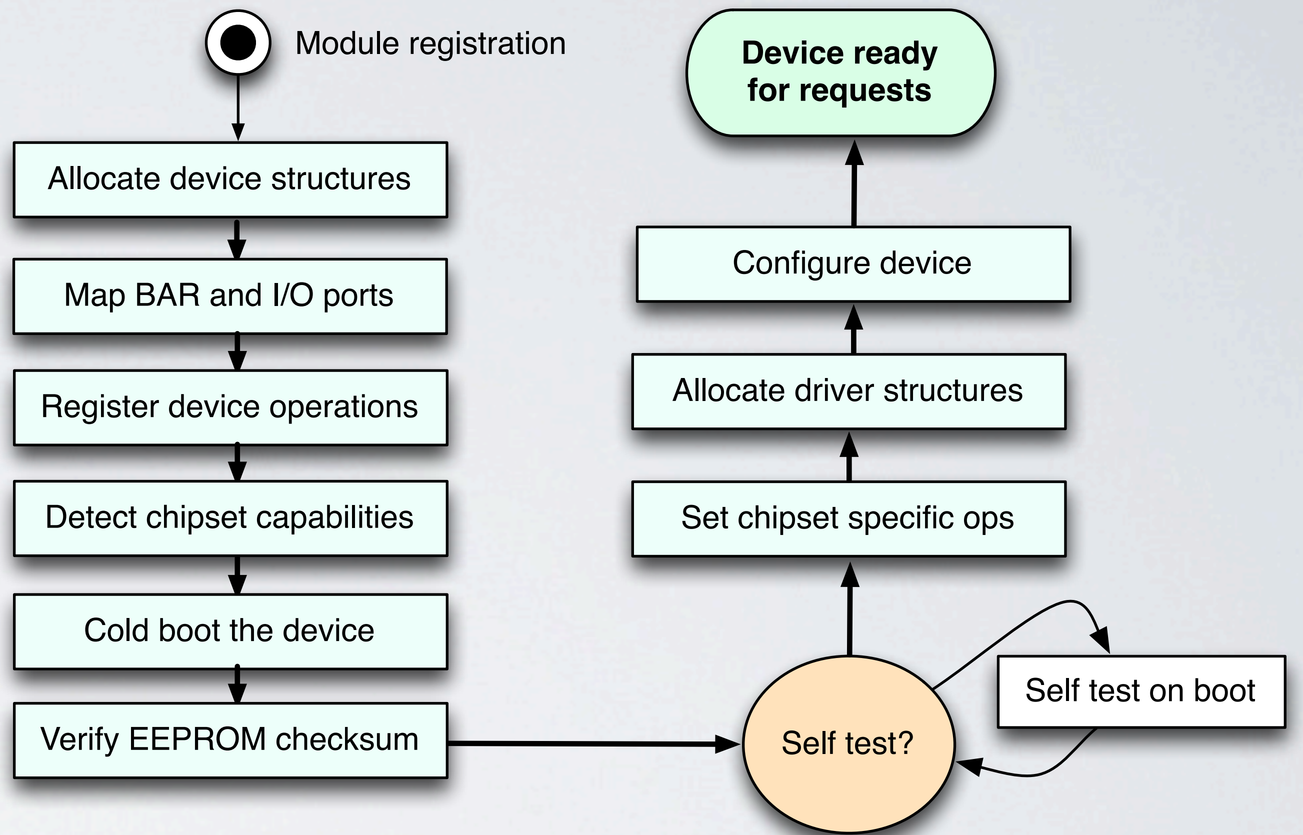
Contributions beyond research

- ★ **Linux Plumbers Conference [Sep '11]**
- ★ **LWN Article with paper & list of bugs [Feb '12]**
- ★ **Released patches to the Linux kernel**
- ★ **Tool + source available for download at:**

`http://bit.ly/carburizer`

Recovery performance: device initialization is slow

- **Multi-second device probe**
  - **Identify device**
  - **Cold boot device**
  - **Setup device/driver structures**
  - **Configuration/Self-test**



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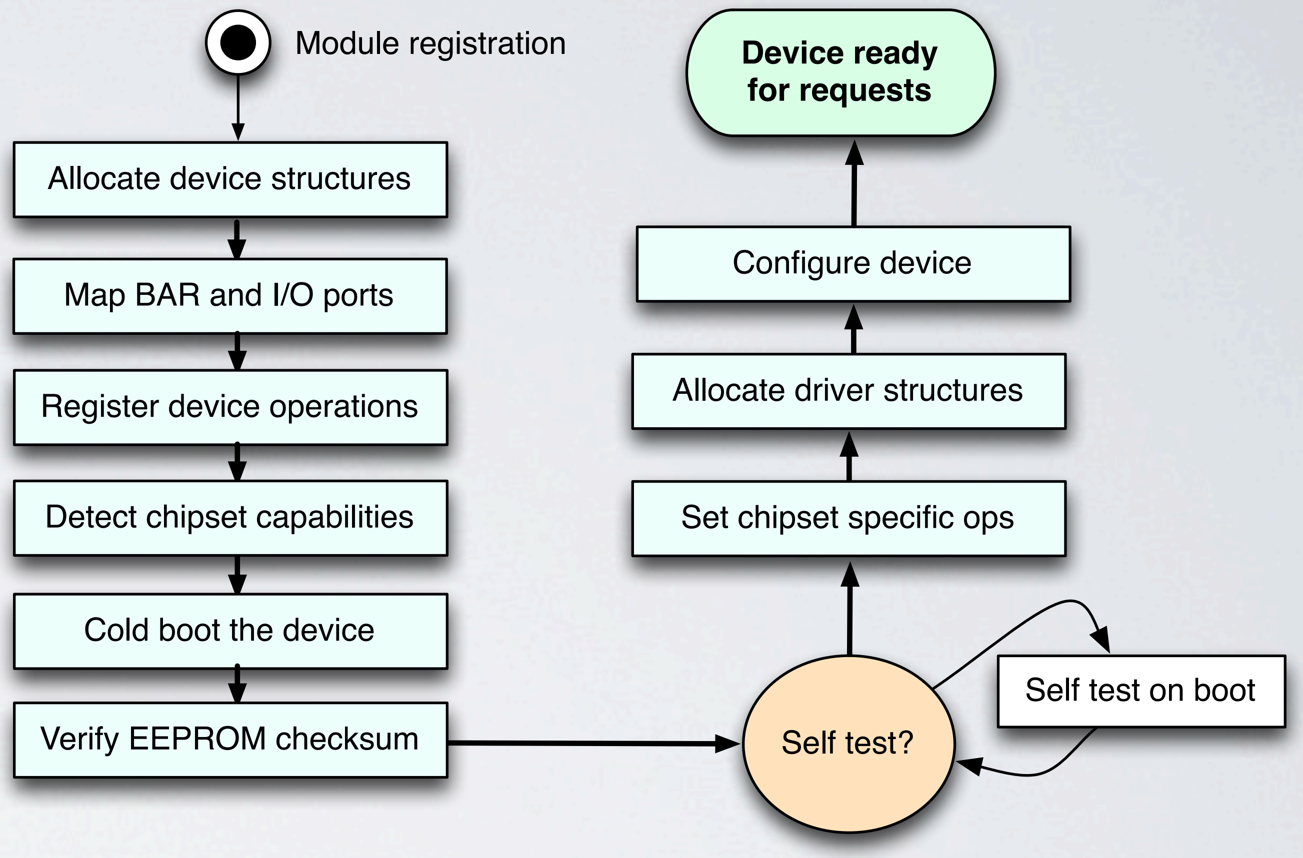
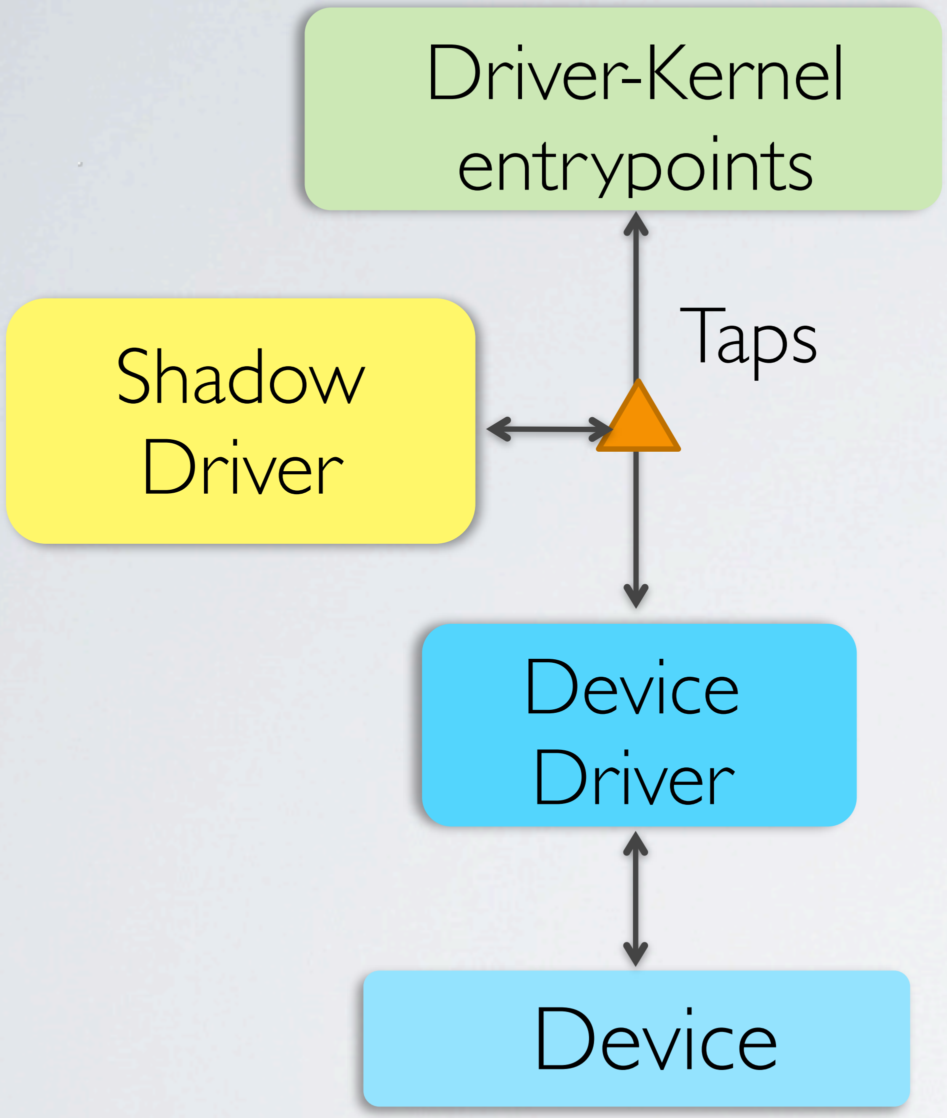


- **What does slow device re-initialization hurt?**
  - **Fault tolerance: Driver recovery**
  - **Virtualization: Live migration, cloning**
  - **OS functions: Boot, upgrade**

Recovery functionality: assumes drivers follow class behavior



- ★ **Kernel exports standard entry points for every class (like "packet send" for network class)**
- ★ **Shadow drivers records state by interposing class defined entry points**
- ★ **Recovery = Restart and replay of captured state**
- ★ **Do drivers have additional state?**

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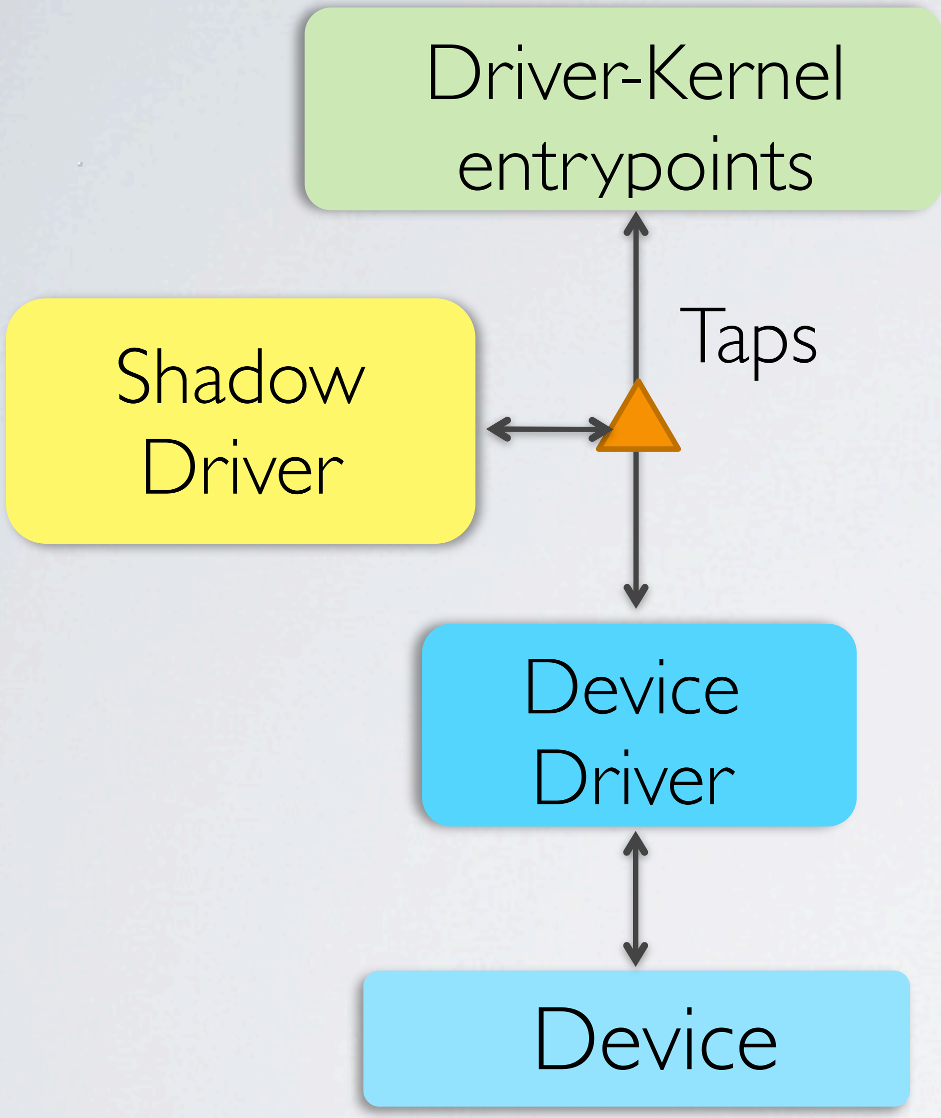

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How many drivers obey class behavior?

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Tolerate device failures

Understand drivers and potential opportunities

Overview
Recovery specific results

Transactional approach for cheap recovery

Our view of drivers is narrow

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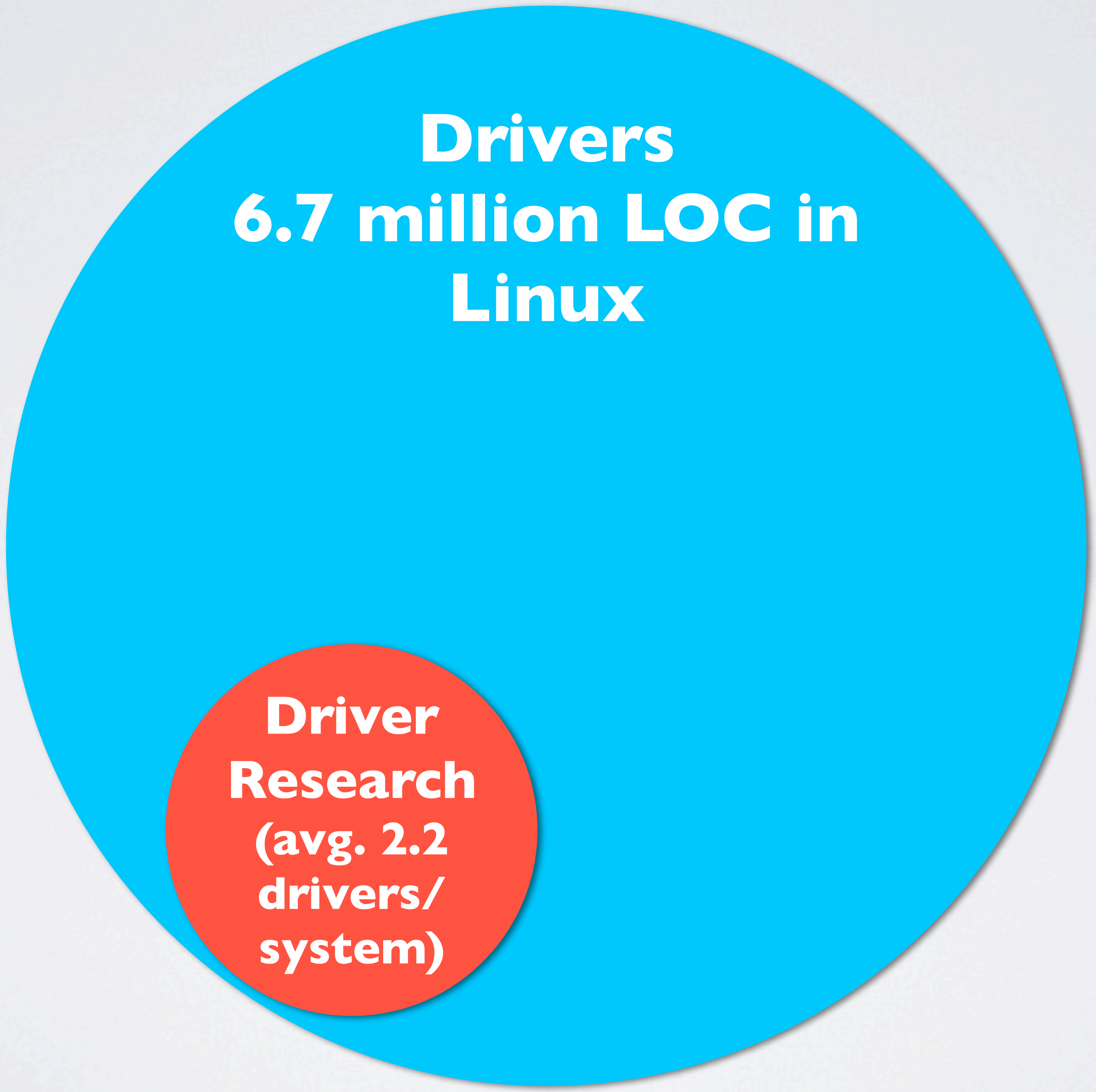

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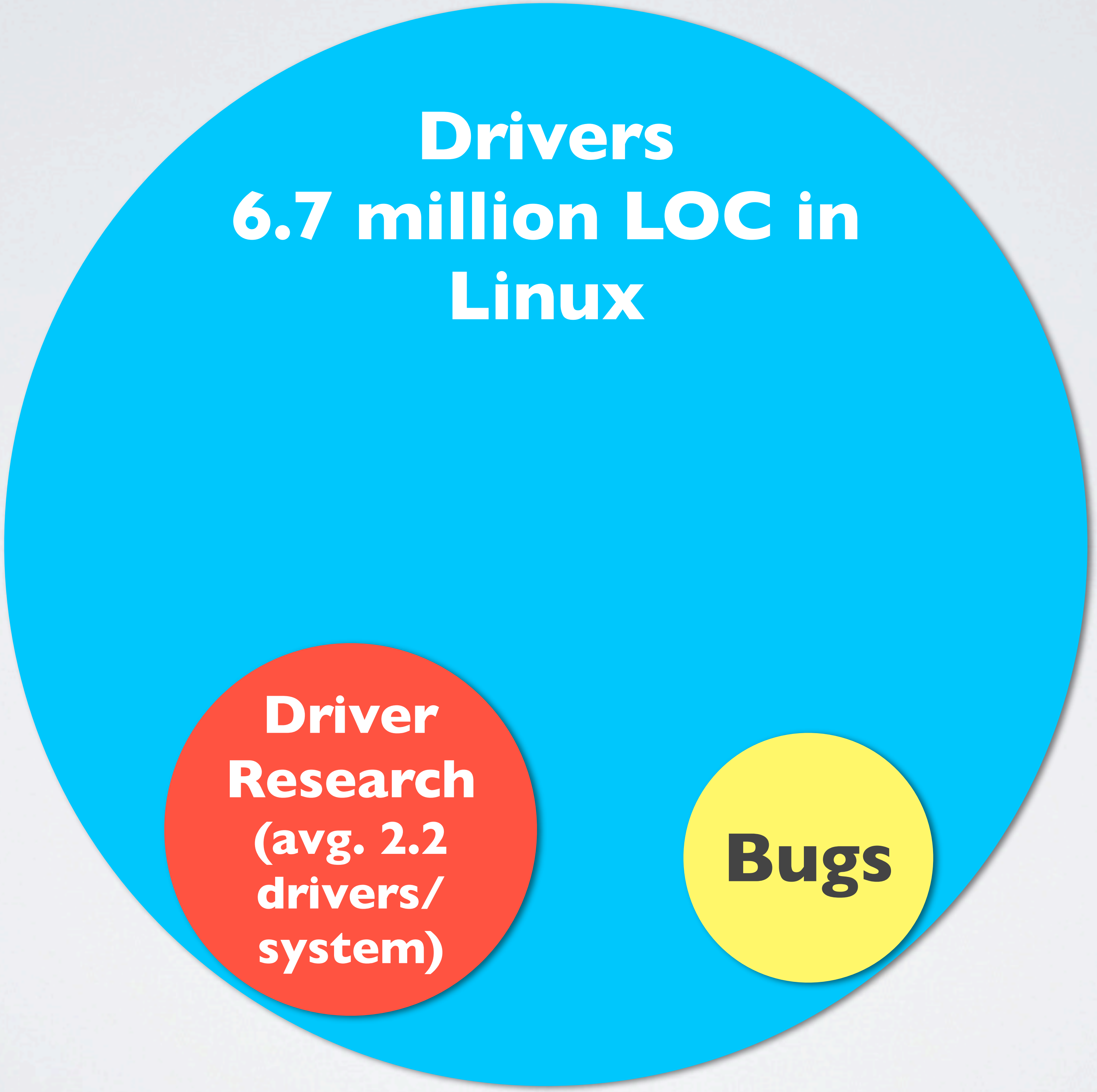

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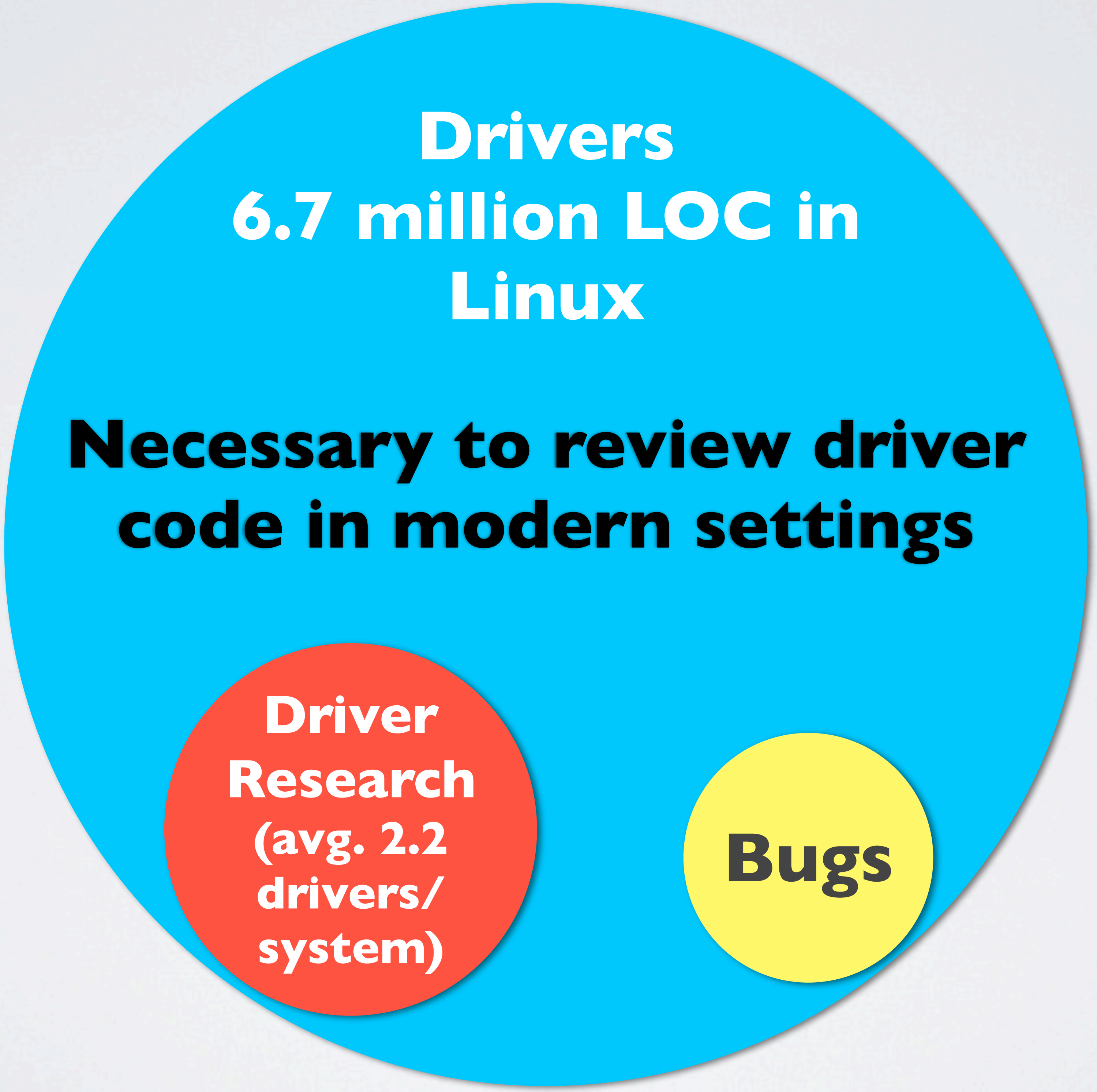

Understanding Modern Device Drivers[ASPLOS 2012]

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Study source of all Linux drivers for x86 (~3200 drivers)

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Driver properties

- ★ **Code properties**
- ★ **Verify research assumptions**

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Driver interaction

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- ★ **Driver kernel & device interaction**
- ★ **Driver architecture**

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- Code properties
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Driver interaction

- Driver kernel & device interaction
- Driver architecture

Driver similarity

- 7 million lines of code needed?

Study methodology

- ★ **Static source analysis of 3200 drivers in Linux 2.6.37.6 (May 2011)**

Study methodology

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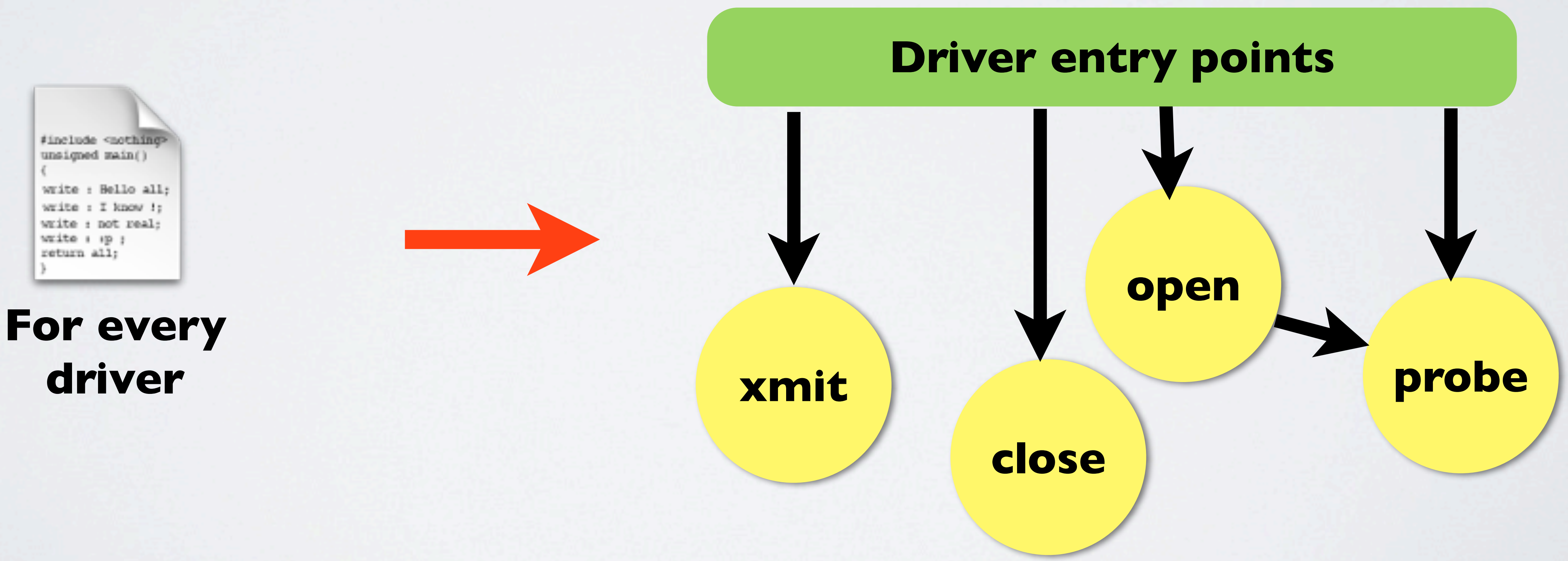

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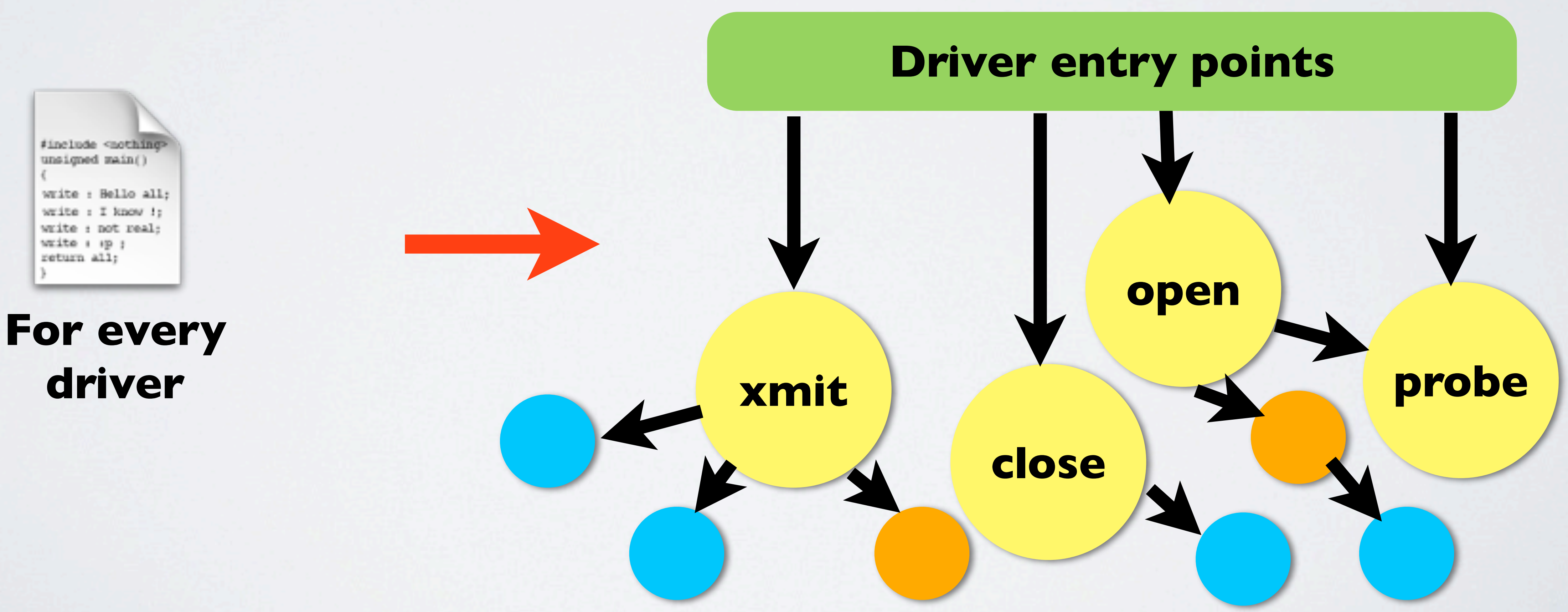

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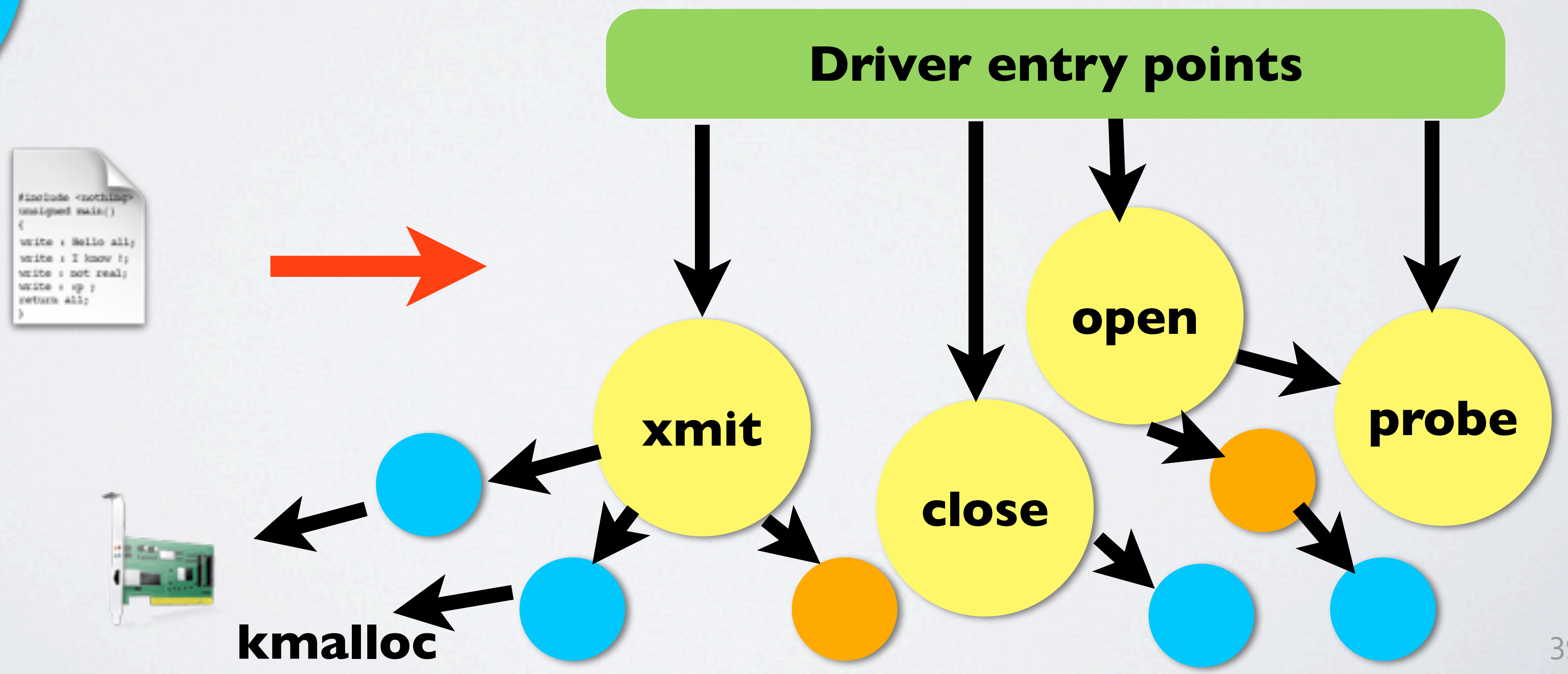
Driver interactions

★ **Reverse propagate information to aggregate bus, device and kernel behavior**



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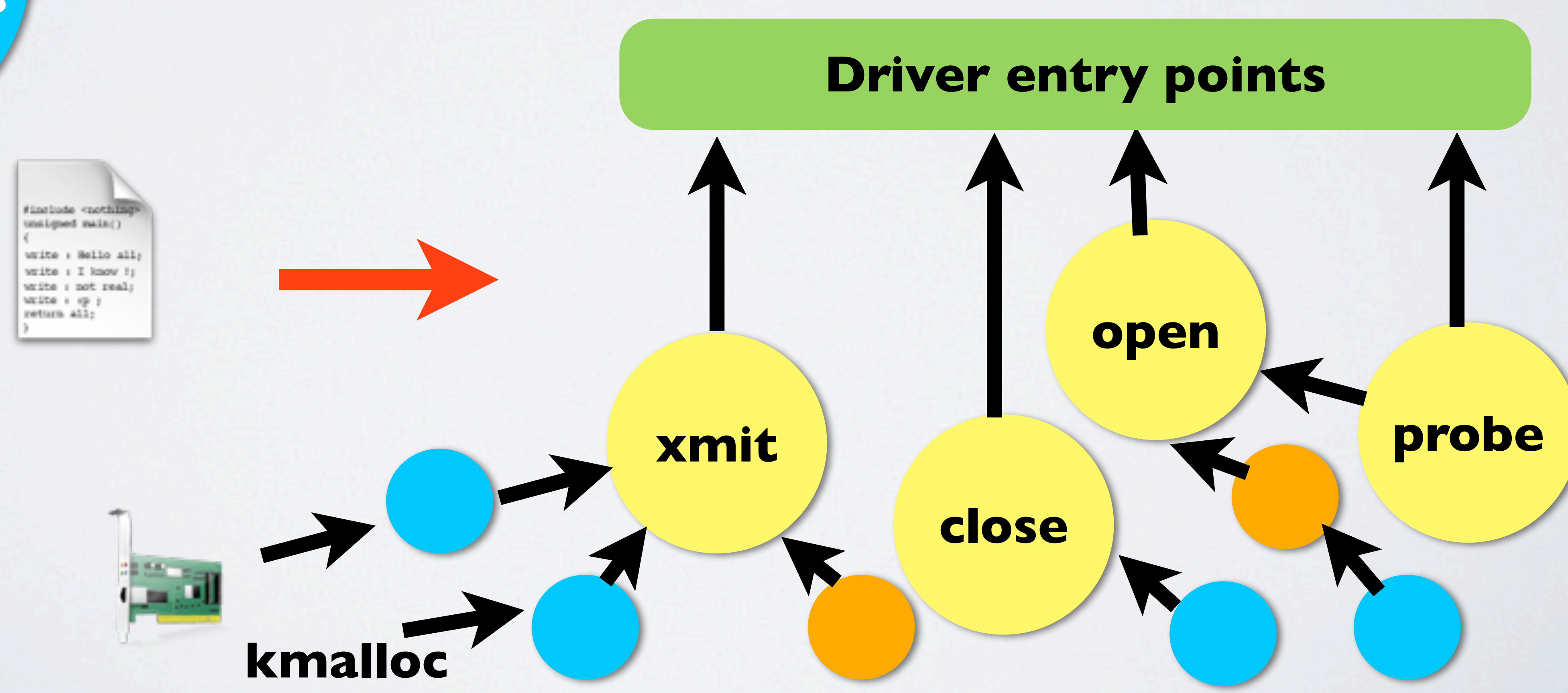

Study methodology

★ **Static source analysis of 3200 drivers in Linux 2.6.37.6 (May 2011)**

Driver properties

★ **Identify driver wide and function specific properties of all drivers**

Driver interactions

★ **Reverse propagate information to aggregate bus, device and kernel behavior**

Driver similarity

★ **Use statistical clustering techniques and static analysis to identify similar code**

Contributions/Outline

Tolerate device failures

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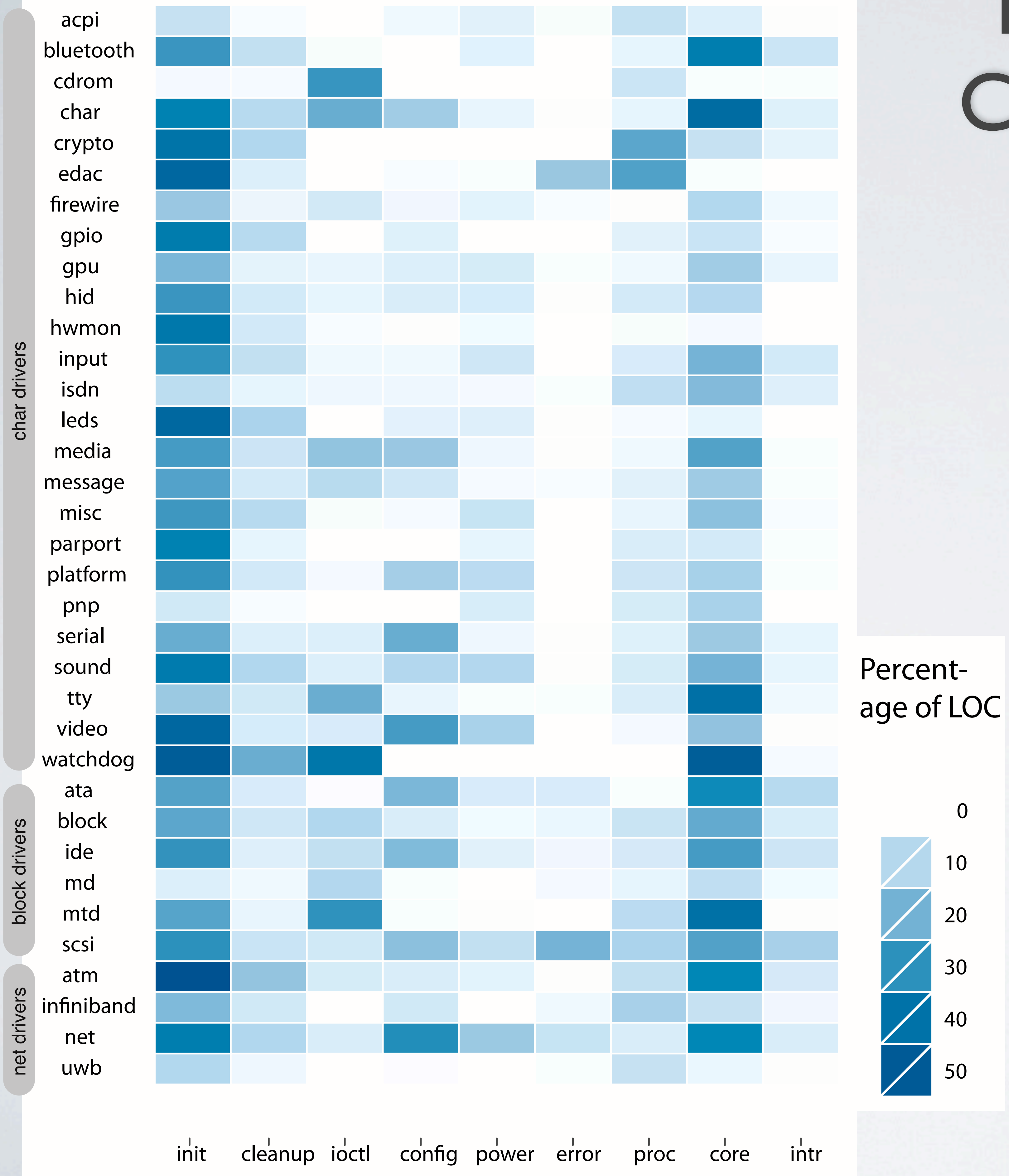
Driver Code Characteristics

Driver Code Characteristics



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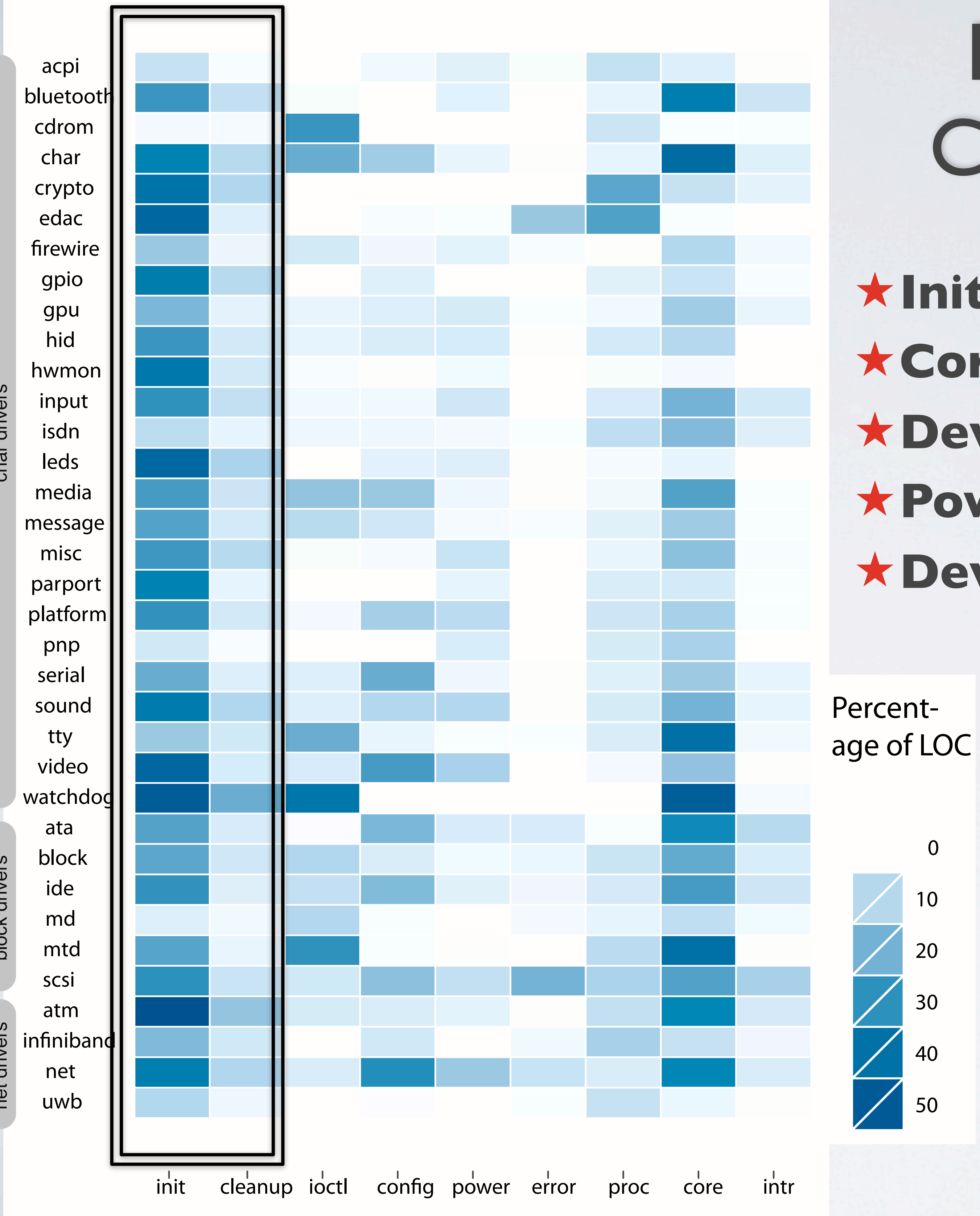
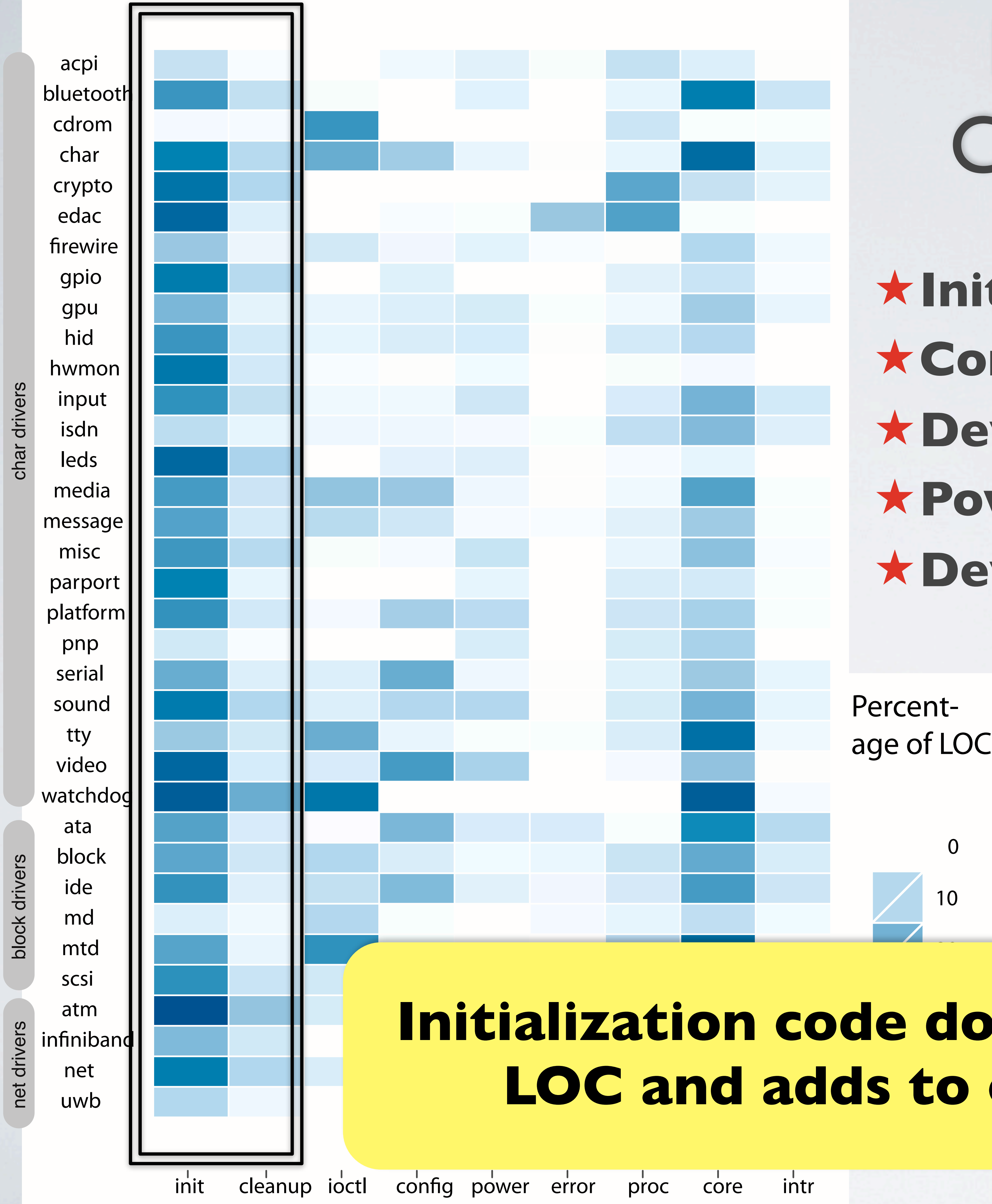


- ★ **Initialization/cleanup – 36%**
- ★ **Core I/O & interrupts – 23%**
- ★ **Device configuration – 15%**
- ★ **Power management – 7.4%**
- ★ **Device ioctl – 6.2%**

Driver Code Characteristics



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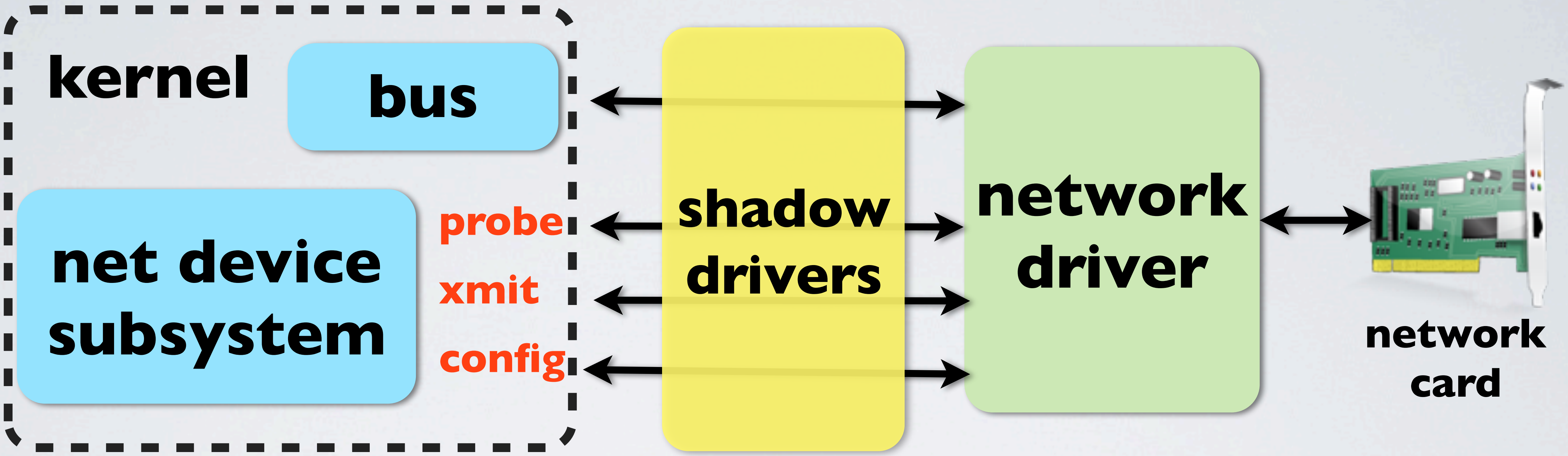
Initialization code dominates driver LOC and adds to complexity

Problem 2: Shadow drivers assume drivers follow class behavior



- Class definition includes:
  - Callbacks registered with the bus, device and kernel subsystem

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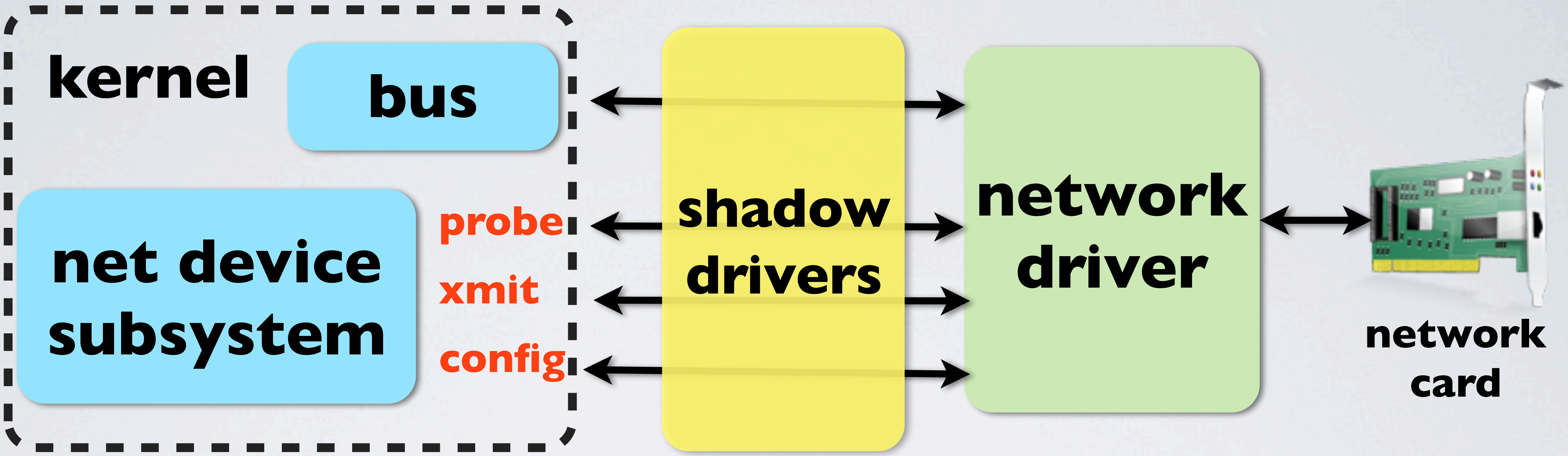
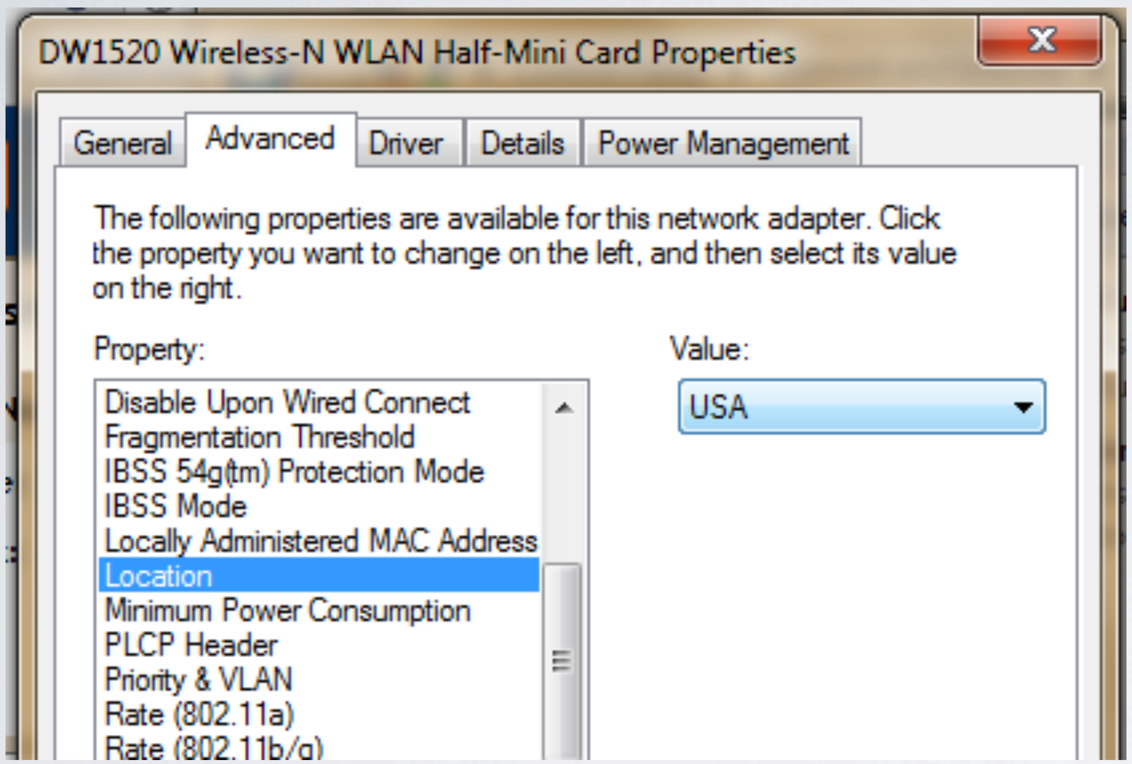


- Class definition includes:
  - Callbacks registered with the bus, device and kernel subsystem

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

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

- **Non-class behavior in device drivers:**
  - **module parameters, unique ioctls, procfs/sysfs interactions**



Windows WLAN card config via private ioctls

```
$ echo 1 > /sys/class/sound/mixer/
device/enable
```

Linux sound card config via sysfs

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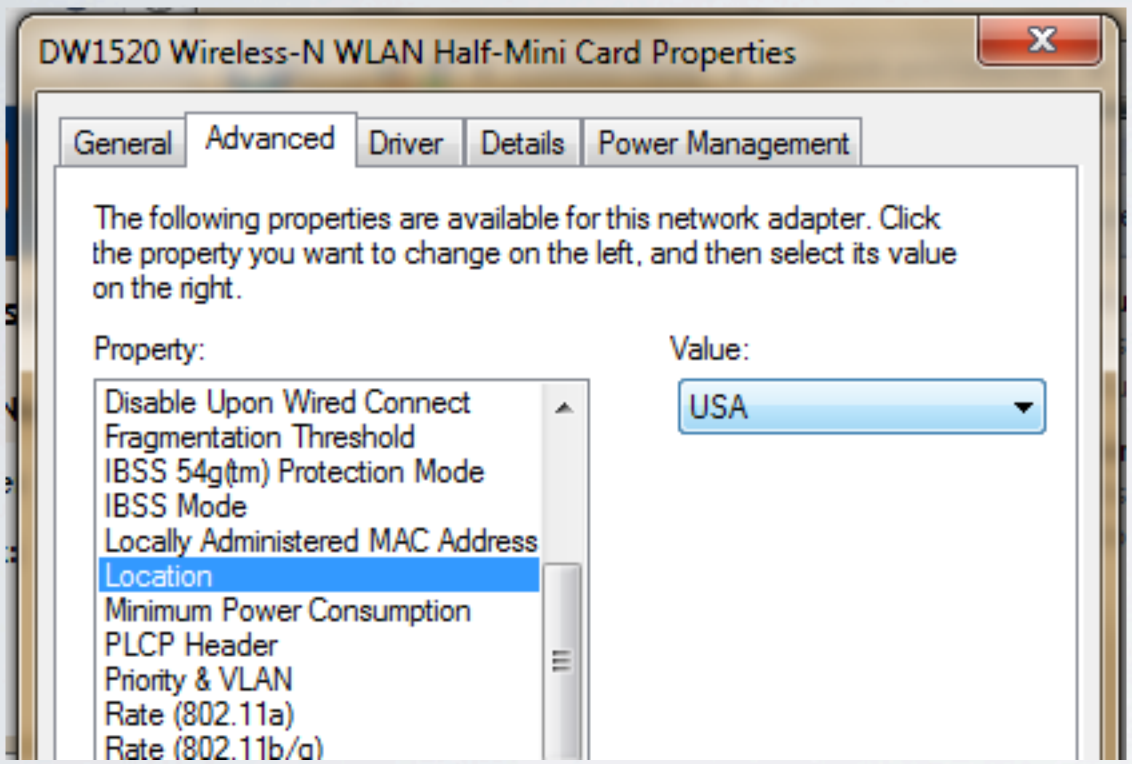

Windows WLAN card config via private ioctls

```
$ echo 1 > /sys/class/sound/mixer/
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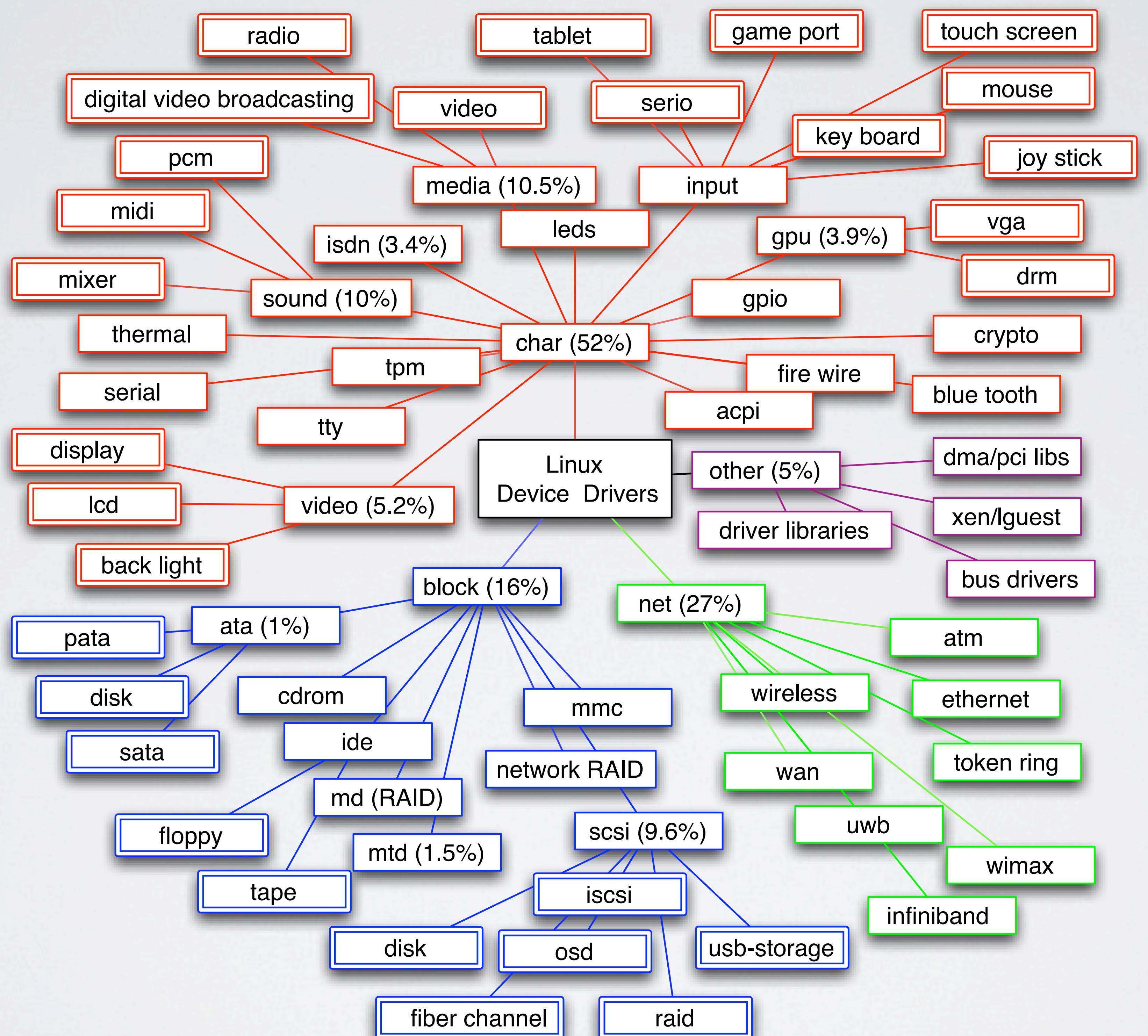
```

Linux sound card config via sysfs

Overall 44% of drivers have non-class behavior and research making this assumption will not apply

Problem 2(b): Too many classes



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

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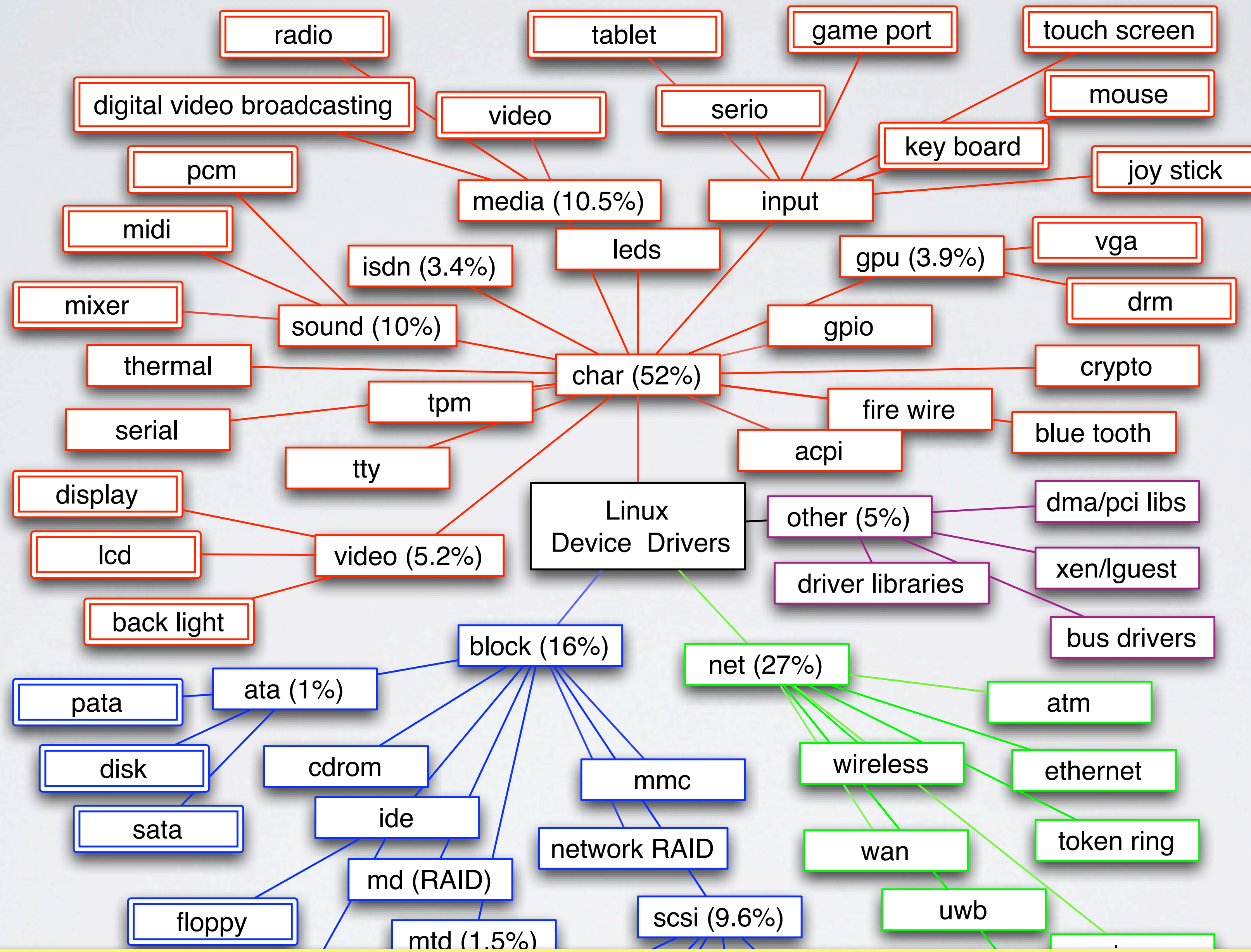


Class-specific driver recovery leads to a large kernel recovery subsystem

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

Few other results

Driver properties

- ★ Many assumptions made by driver research does not hold:
  - ★ 44% of drivers do not obey class behavior
  - ★ 15% drivers perform significant processing
  - ★ 28% drivers support multiple chipsets

Driver interactions

- ★ USB bus offers efficient access (as compared to PCI, Xen)
  - ★ Supports high # devices/driver (standardized code)
  - ★ Coarse-grained access

Driver similarity

- ★ 400, 000 lines of code similar to code elsewhere and ripe for improvement via:
  - ★ Procedural abstractions
  - ★ Better multiple chipset support
  - ★ Table driver programming

★ More results in "Understanding Modern Device Drivers" ASPLOS 2012

Outline

Tolerate device failures

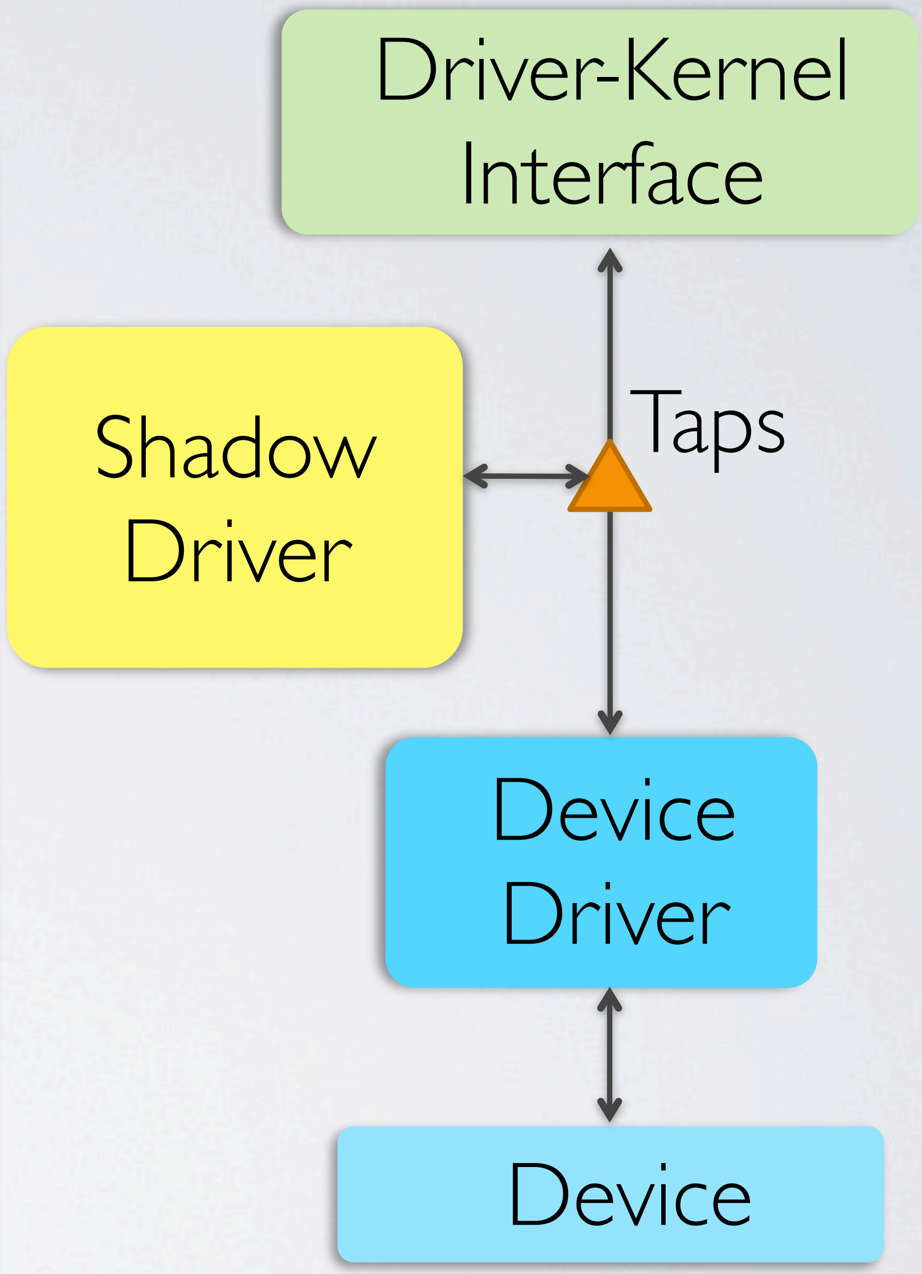
Understand drivers and potential opportunities

Transactional approach for cheap recovery

Checkpoint/restore
FGFT
Future work and conclude

Limitations of restart/replay recovery

- **Device save/restore limited to restart/replay**
  - **Slow: Device initialization is complex (multiple seconds)**
  - **Incomplete: Unique device semantics not captured**
  - **Hard: Need to be written for every class of drivers**
  - **Large changes: Introduces new, large kernel subsystem**



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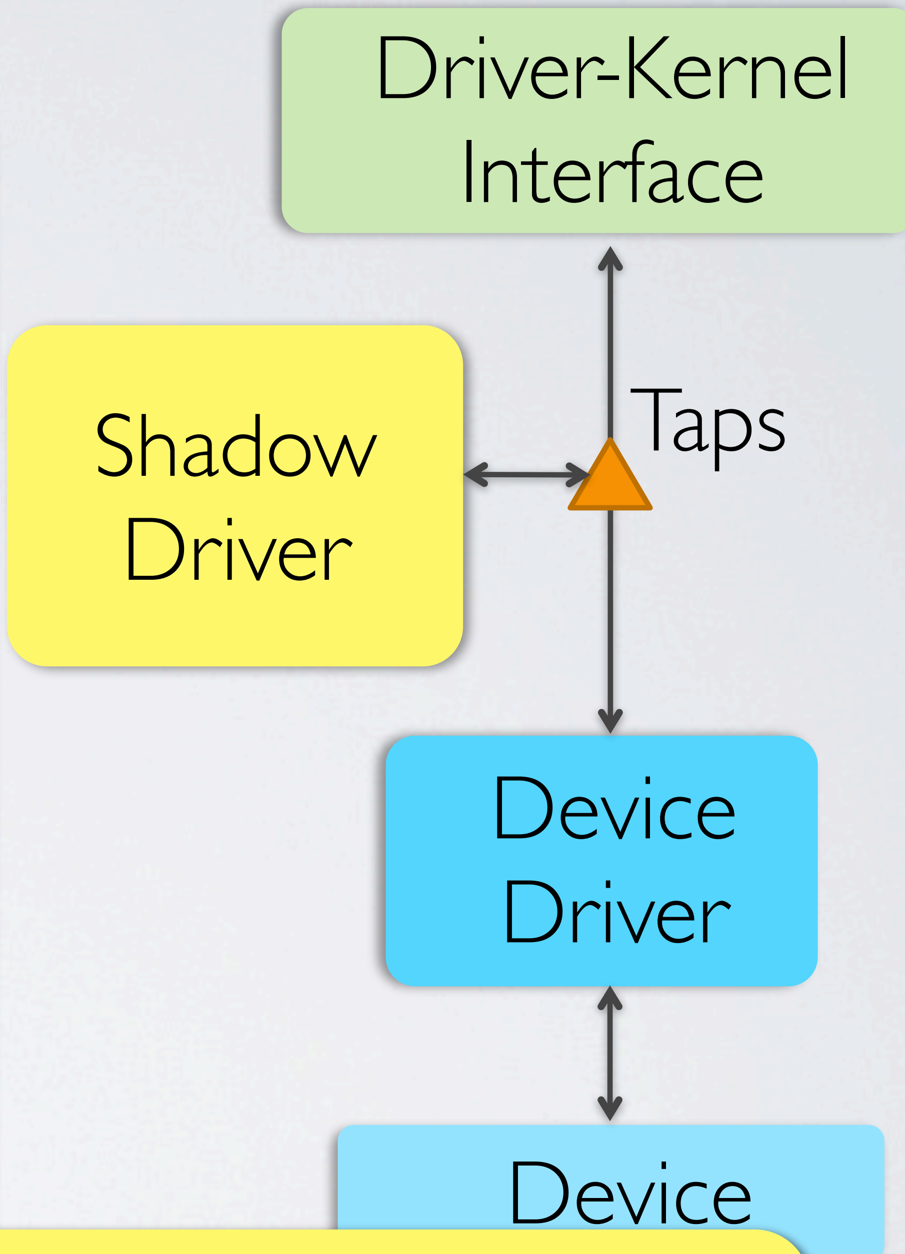
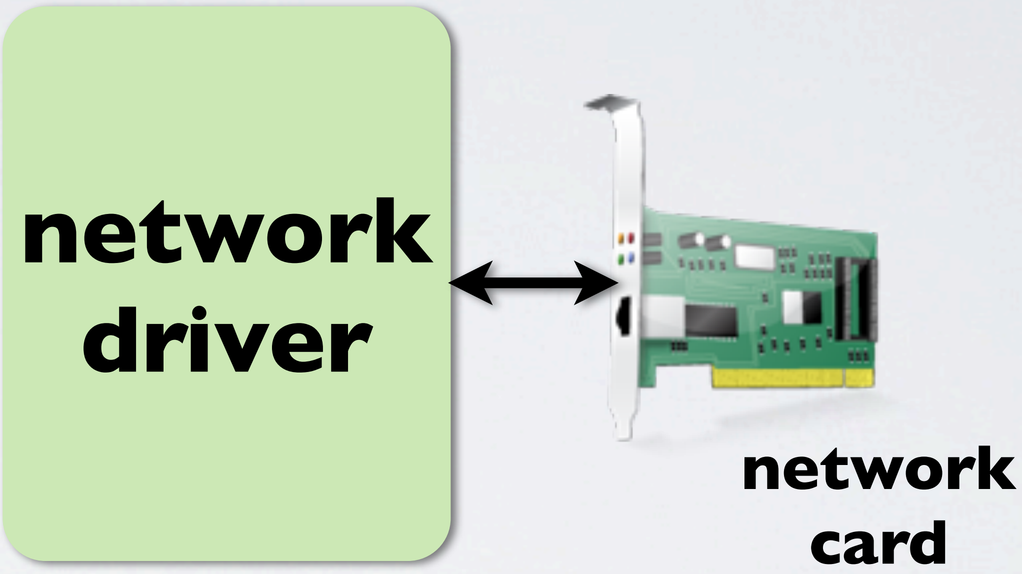


Checkpoint/restore of device and driver state removes the need to reboot device and replay state

Checkpointing drivers is hard

★ **Easy to capture memory state**



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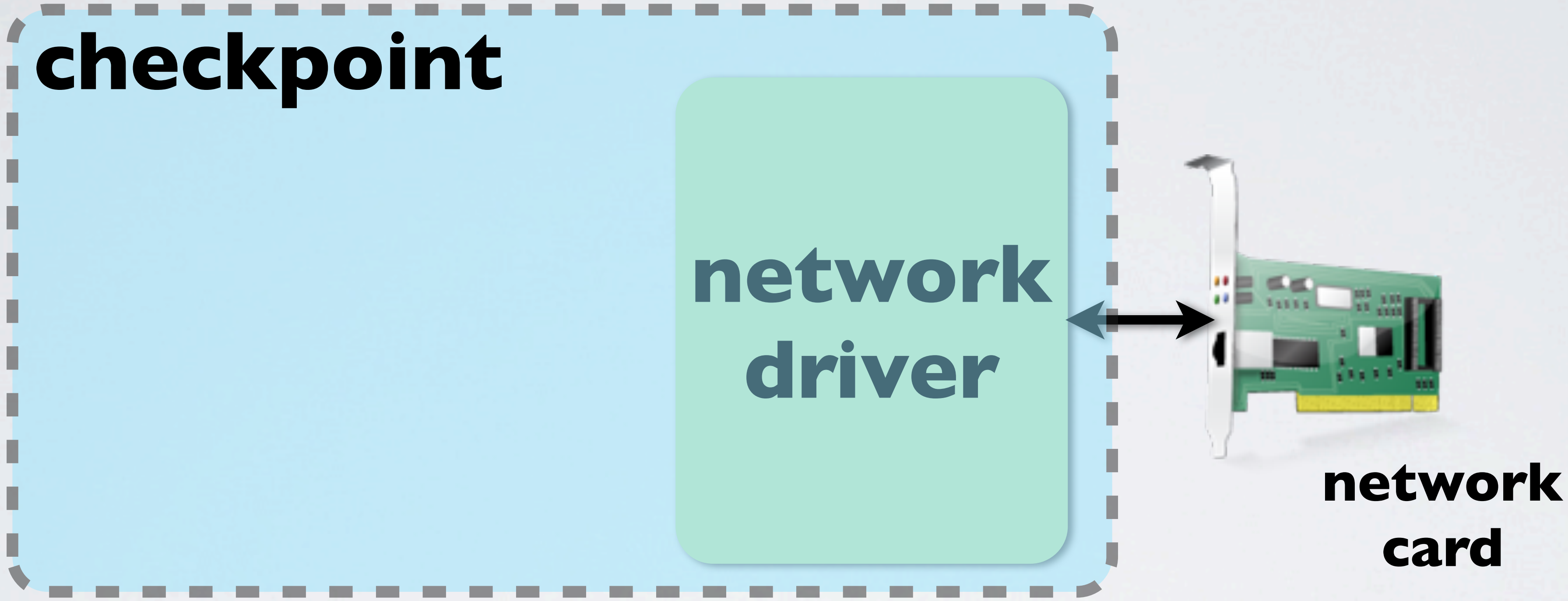

Checkpointing drivers is hard

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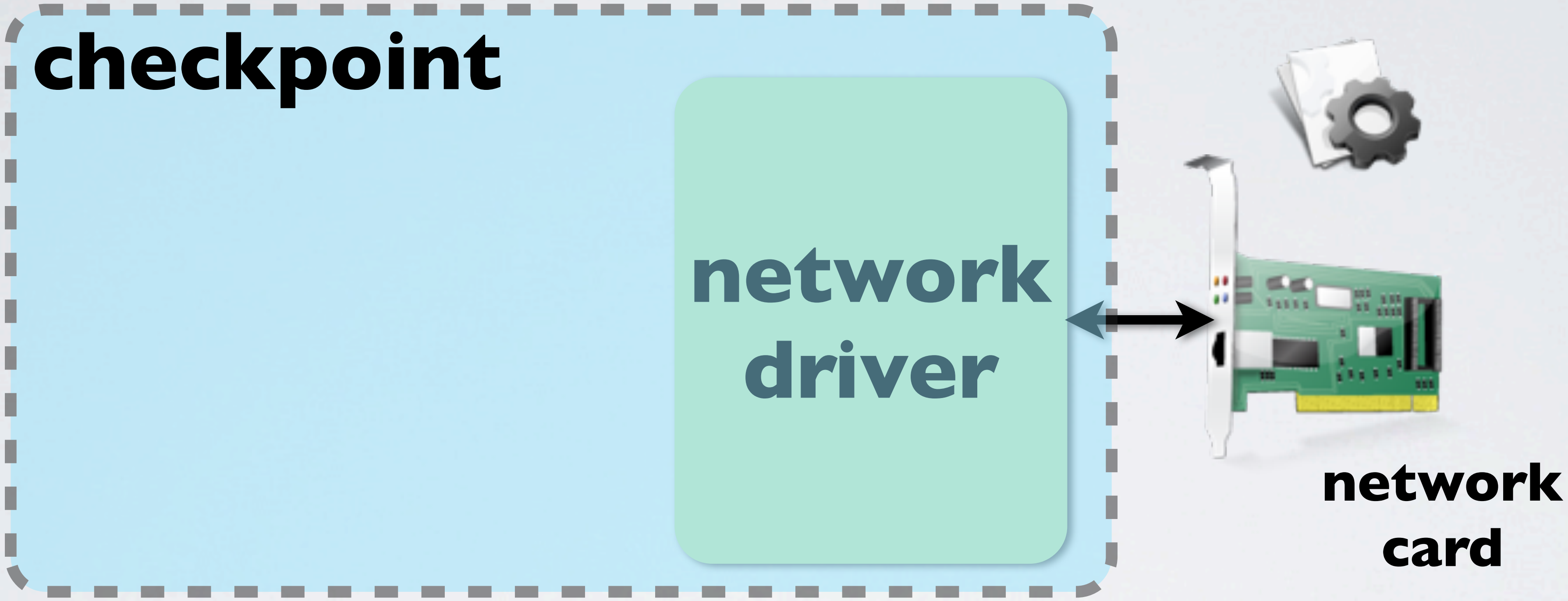

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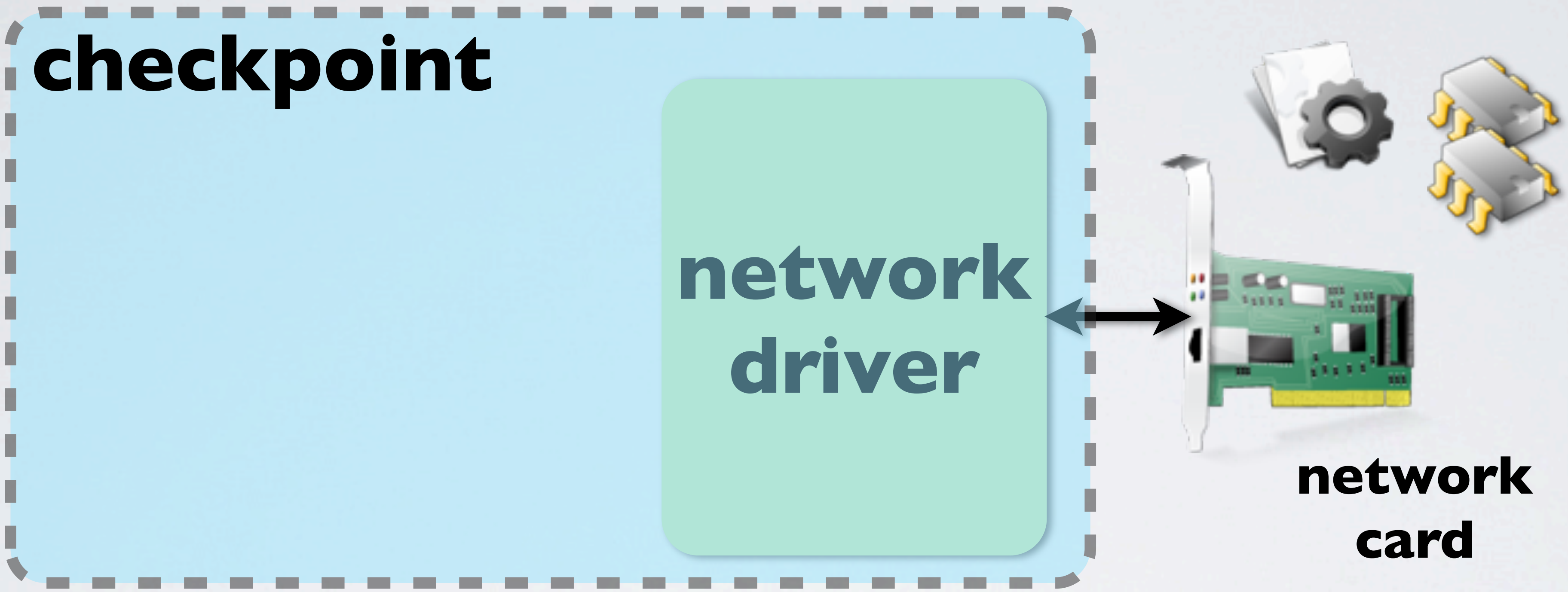

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Checkpointing drivers is hard

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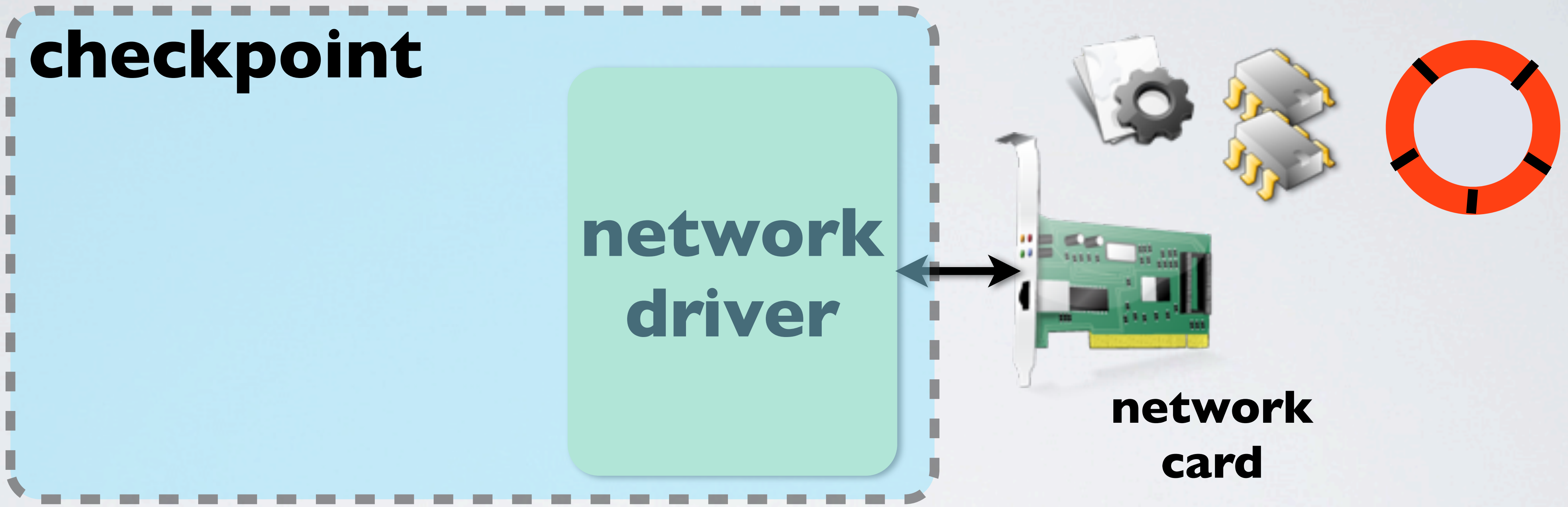

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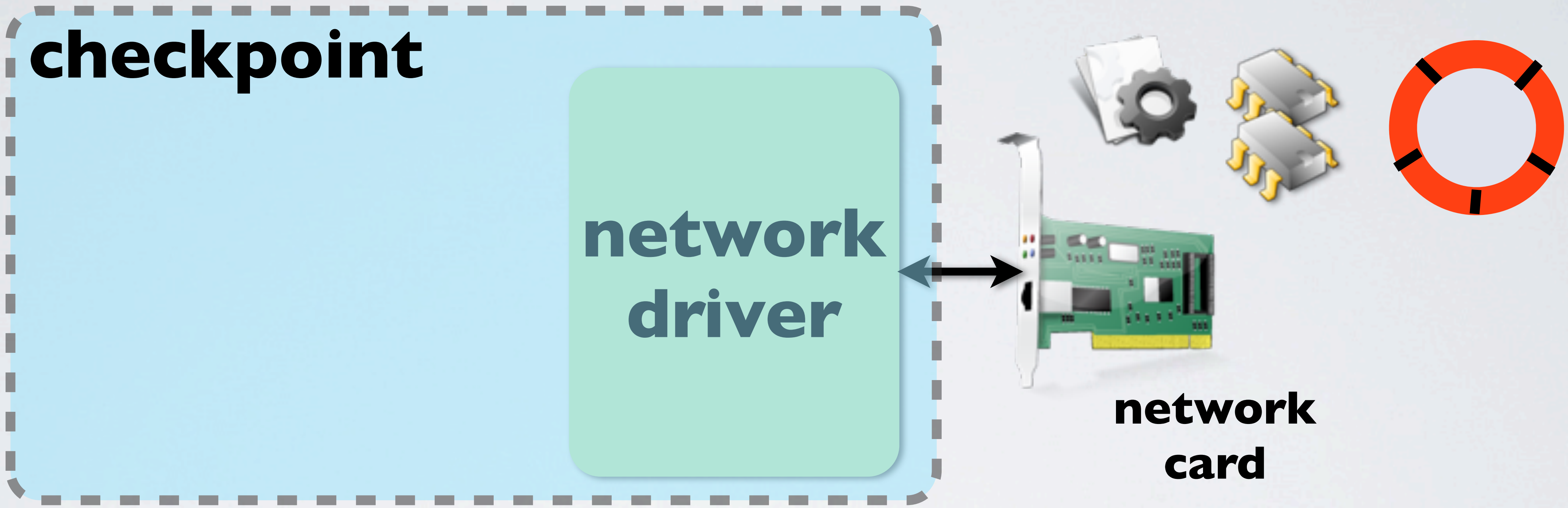

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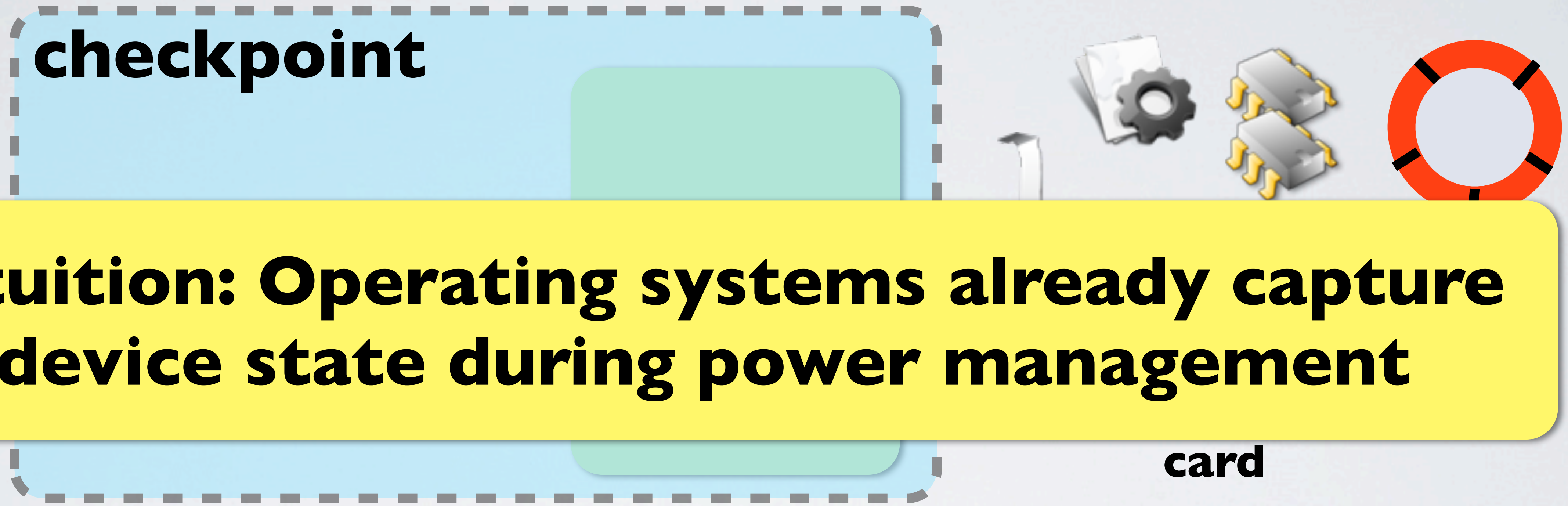

Intuition: Operating systems already capture device state during power management

- Device state is not captured
  - Device configuration space
  - Internal device registers and counters
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- 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

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

Resume

- Restore config state
- Restore register state
- Restore or reset DMA state
- Re-attach/Enable device
- Device Ready

Device checkpoint/restore from PM code

Suspend

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

Resume

- Restore config state
- Restore register state
- Restore or reset DMA state
- Re-attach/Enable device
- Device Ready

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- Restore config state
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Device checkpoint/restore from PM code

Checkpoint	Restore
Save config state	Restore config state
Save register state	Restore register state
Save DMA state	Restore or reset DMA state

Device checkpoint/restore from PM code

Checkpoint

- Save config state
- Save register state
- Save DMA state

Restore

- Restore config state
- Restore register state
- Restore or reset DMA state

Suspend/resume code provides device checkpoint functionality

Fine-Grained Fault Tolerance[ASPLOS 2013]

- **Goal: Improve driver recovery with minor changes to drivers**
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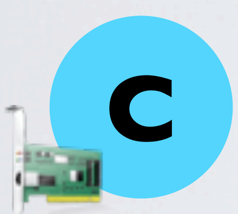

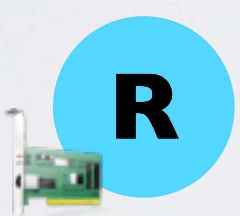

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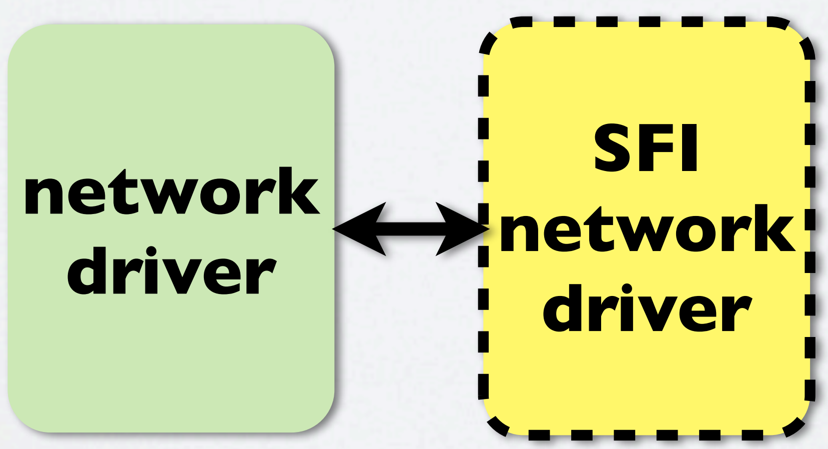
- ★ **Use source transformation to copy parameters and run on separate stack**



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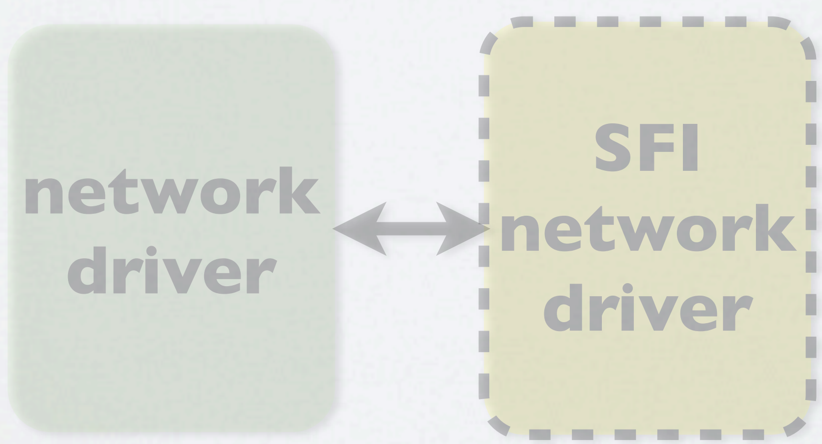
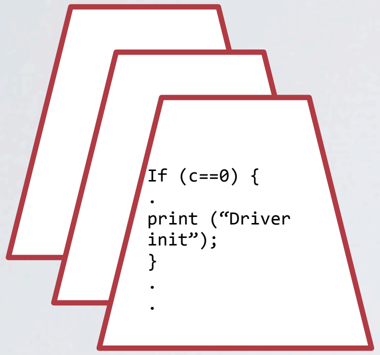


Execution model

- ★ Checkpoint device
- ★ Execute driver code as memory transactions
- ★ On failure, rollback and restore device
- ★ Re-use existing device locks in the driver

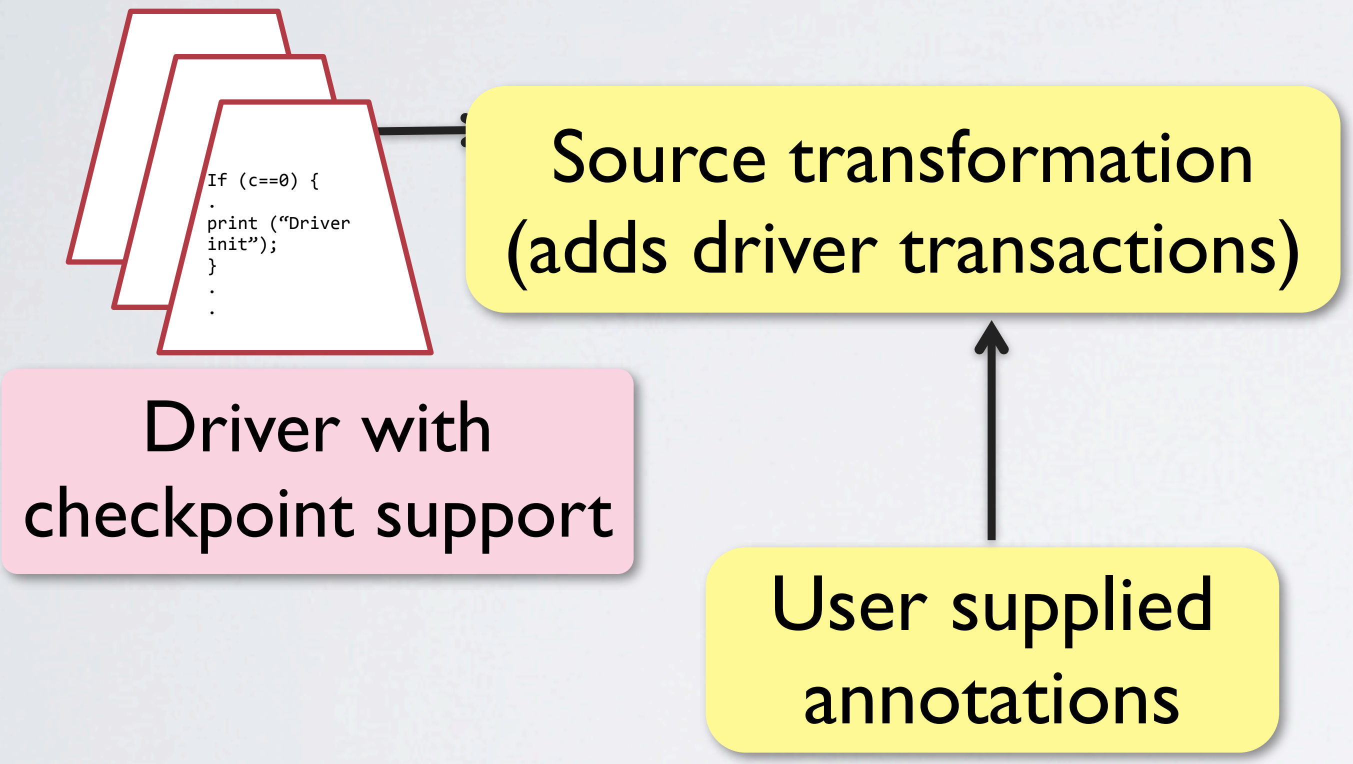
Adding transactional support to drivers



Driver with
checkpoint support

Static modifications

Adding transactional support to drivers



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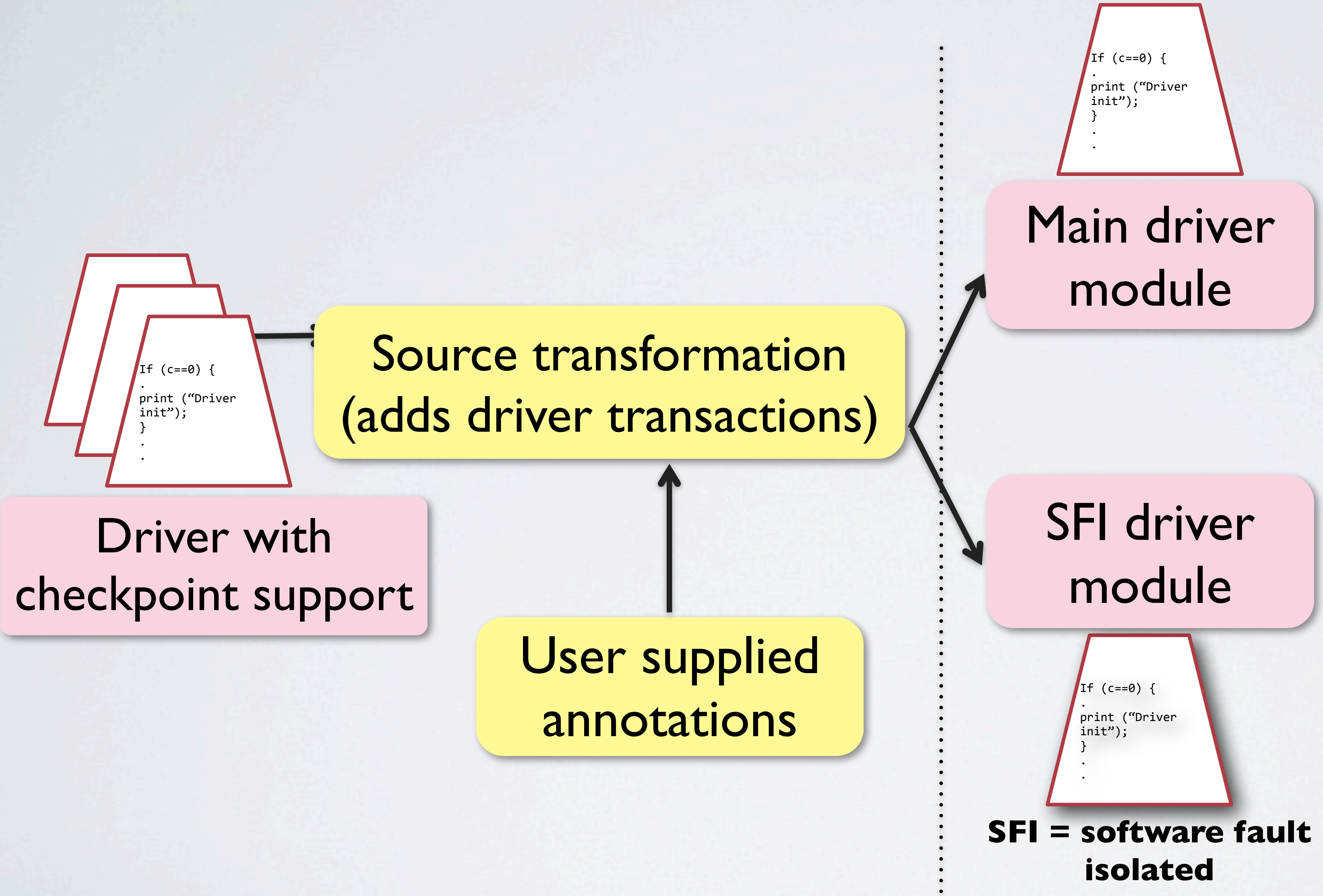

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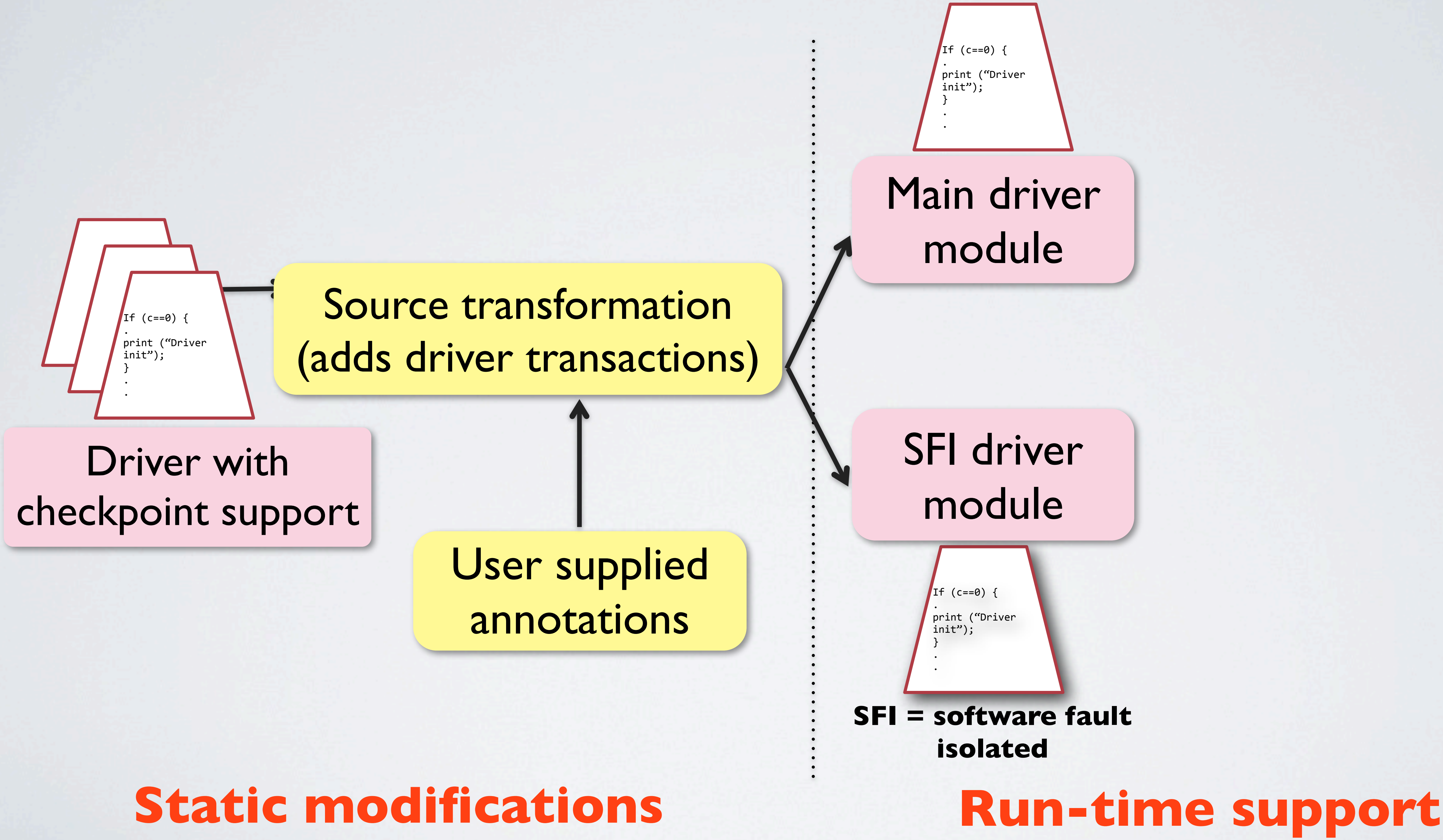

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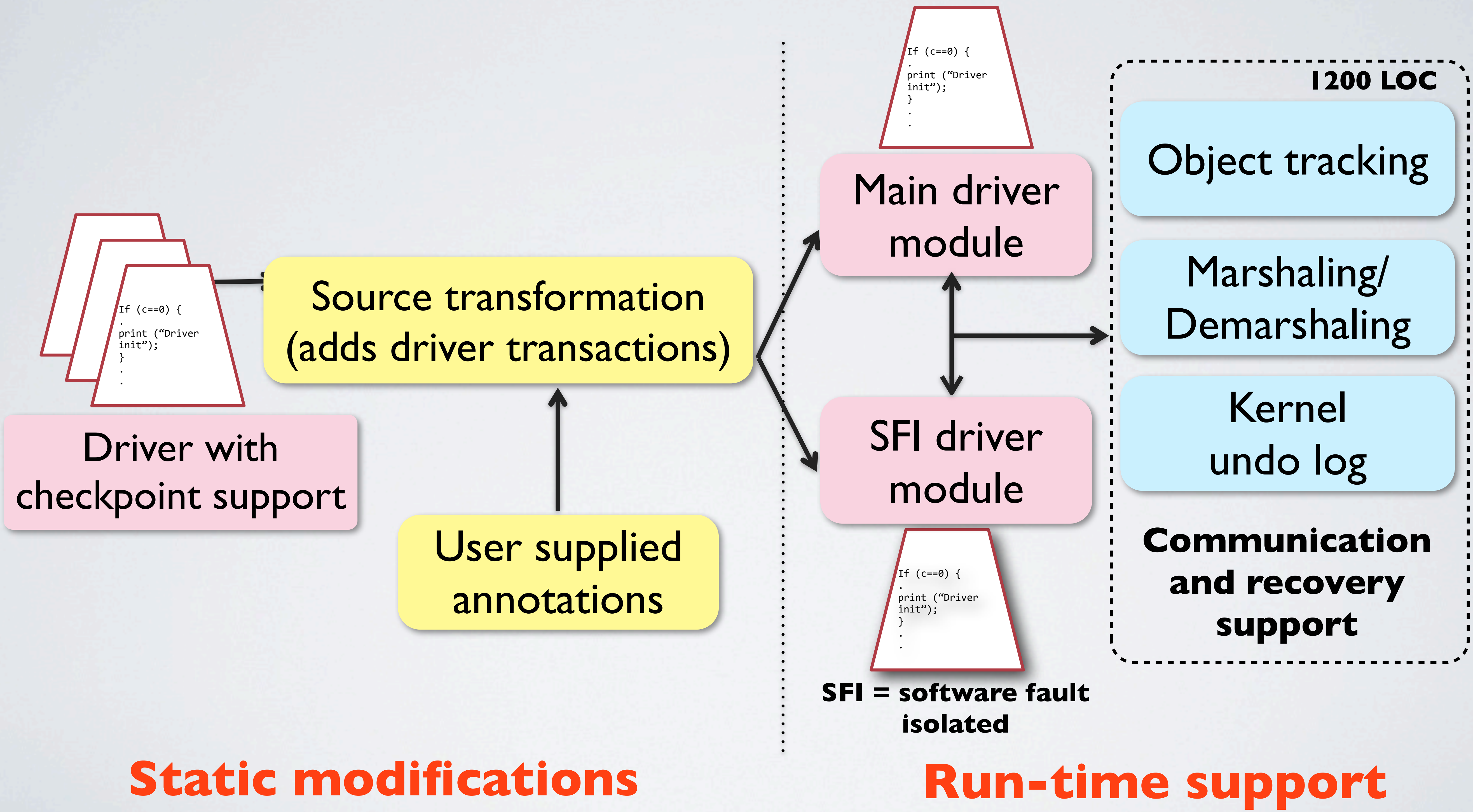
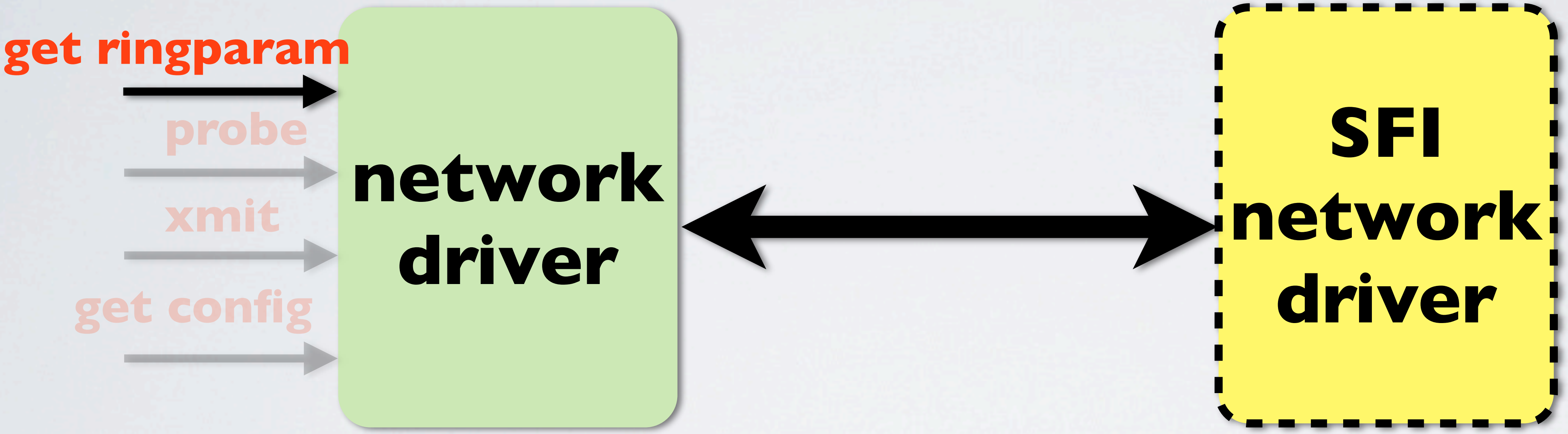


Transactional execution of drivers



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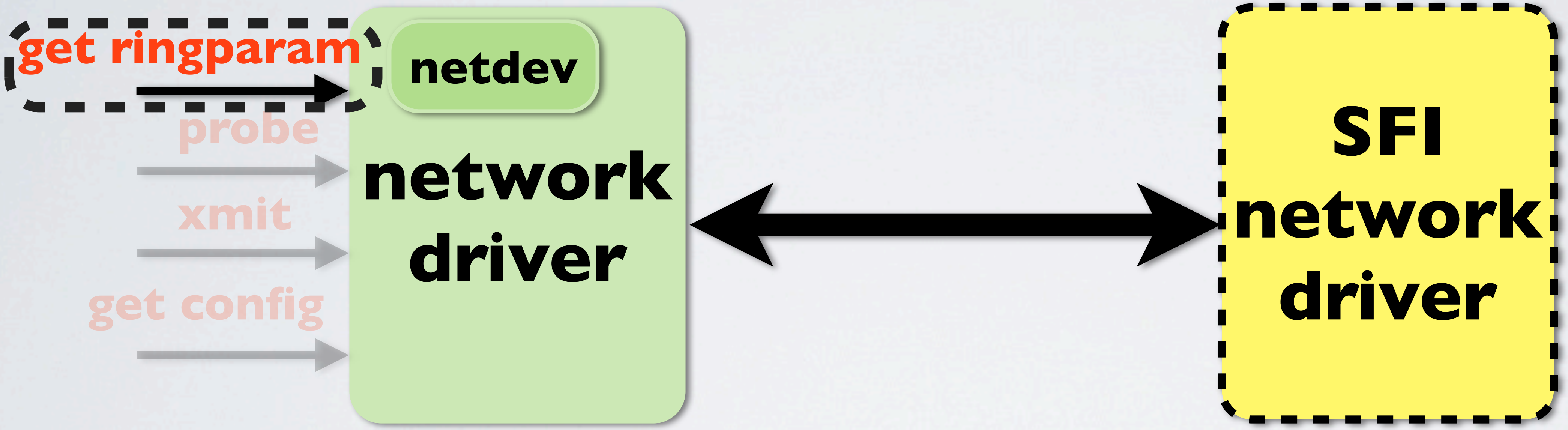

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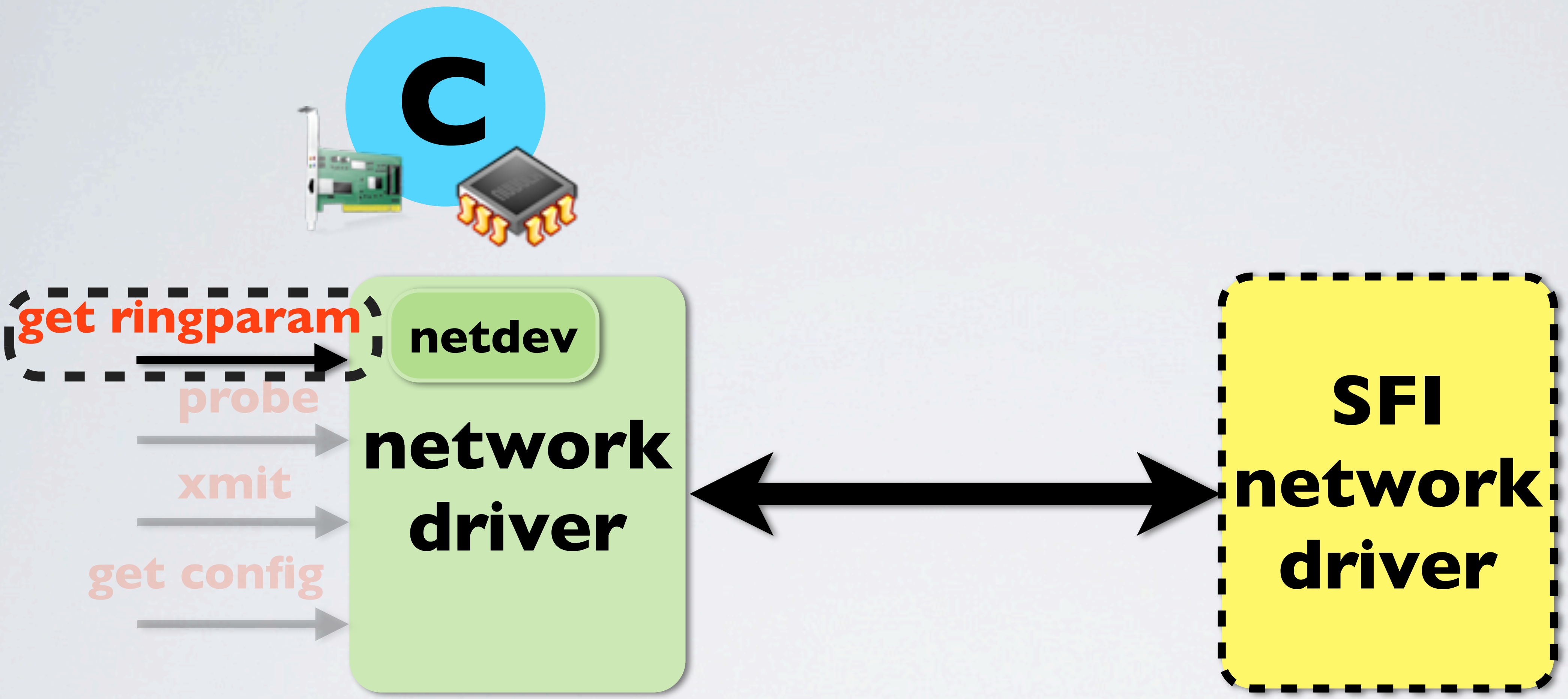

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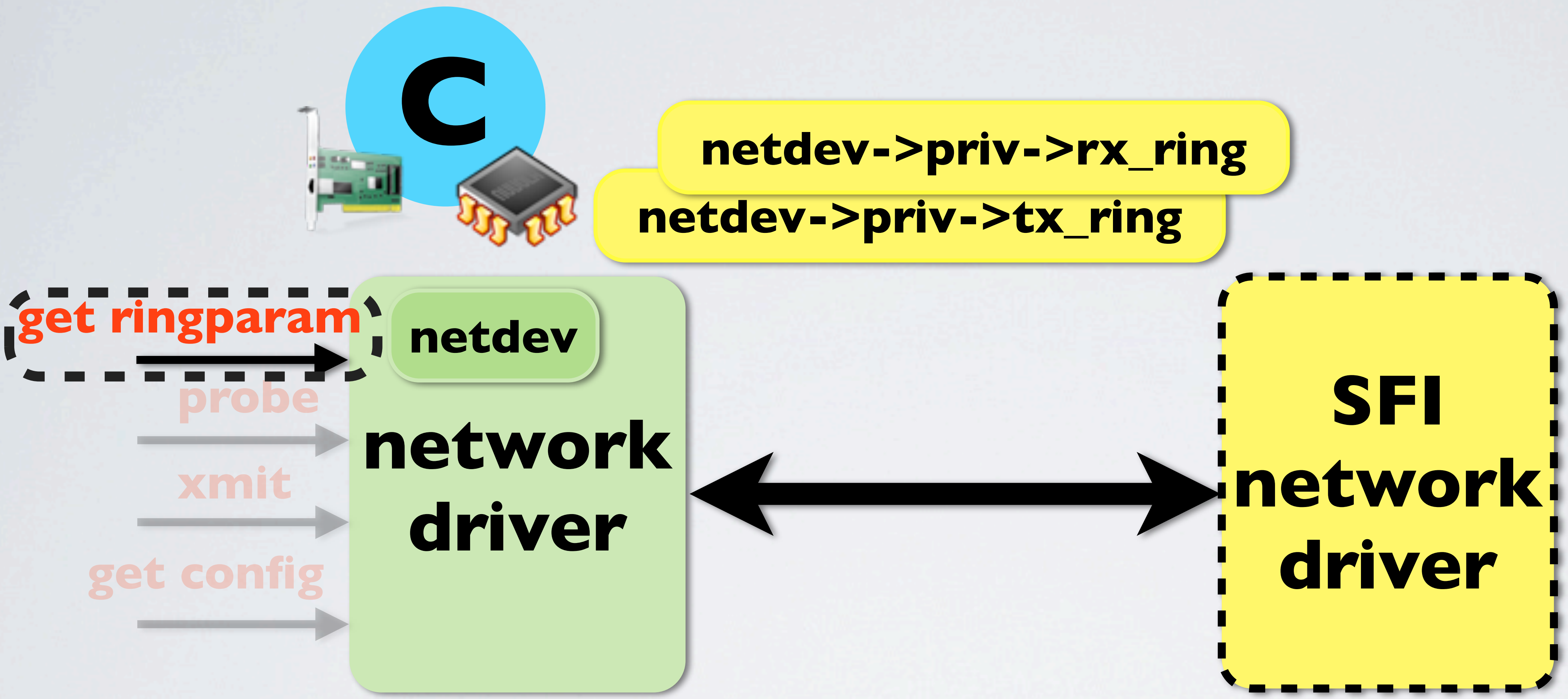

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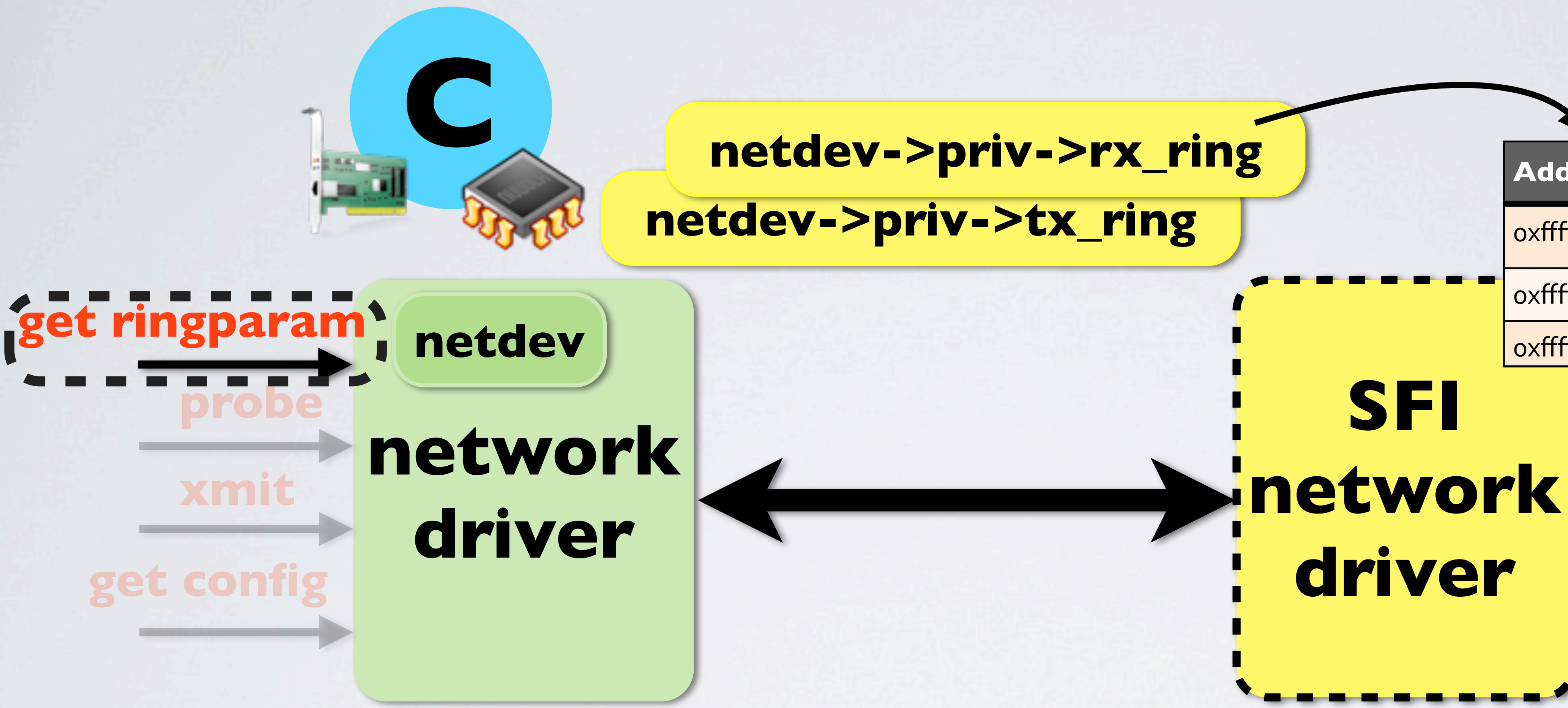
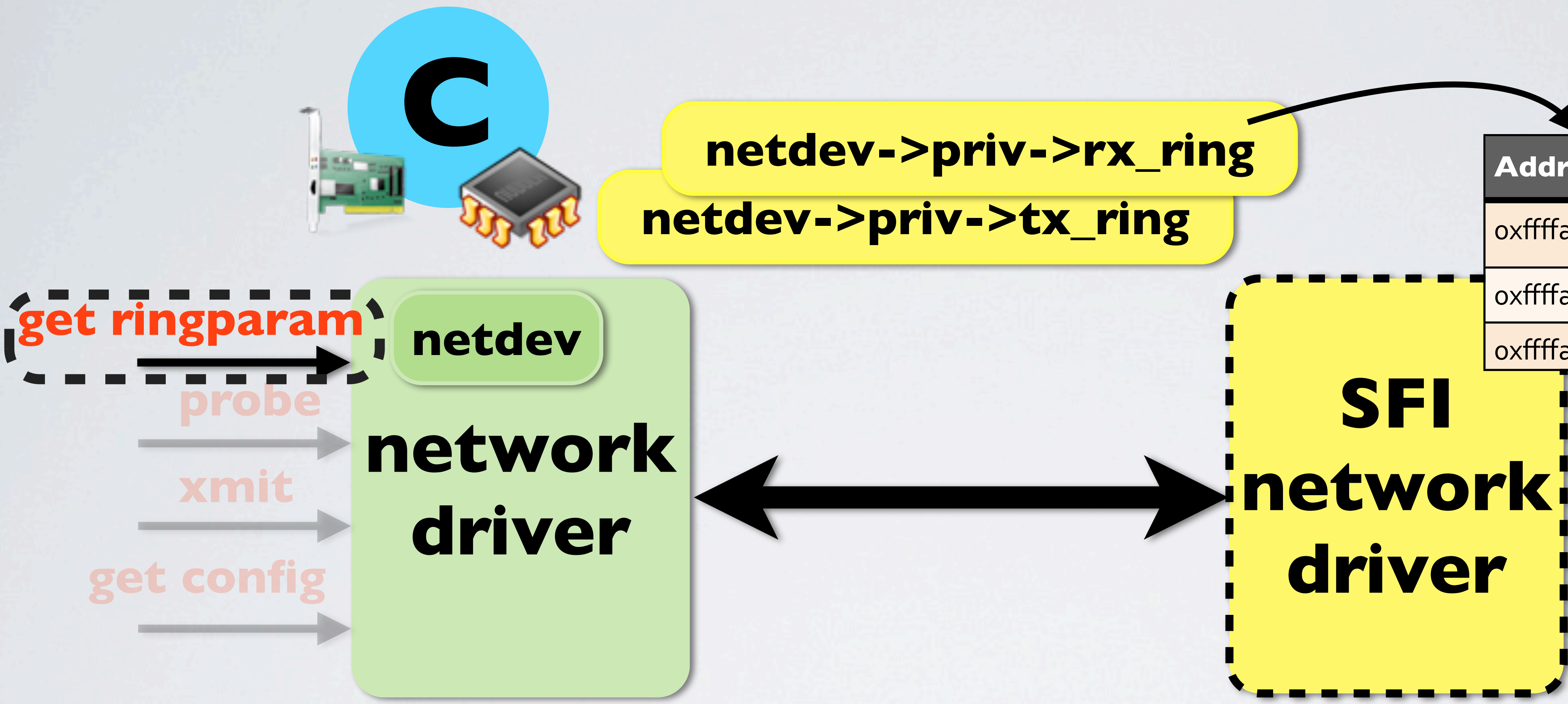


Address	Access rights
0xffffa000	Read
0xffffa008	Write
0xffffa00a	Read

Transactional execution of drivers



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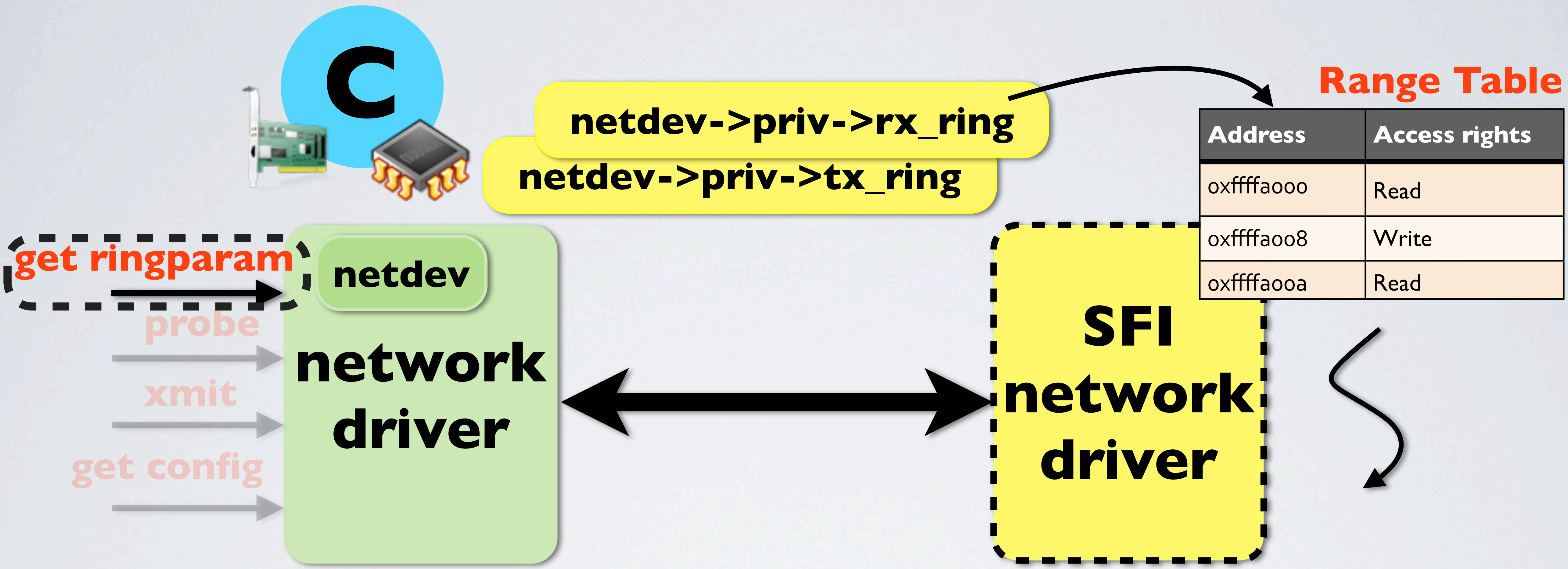

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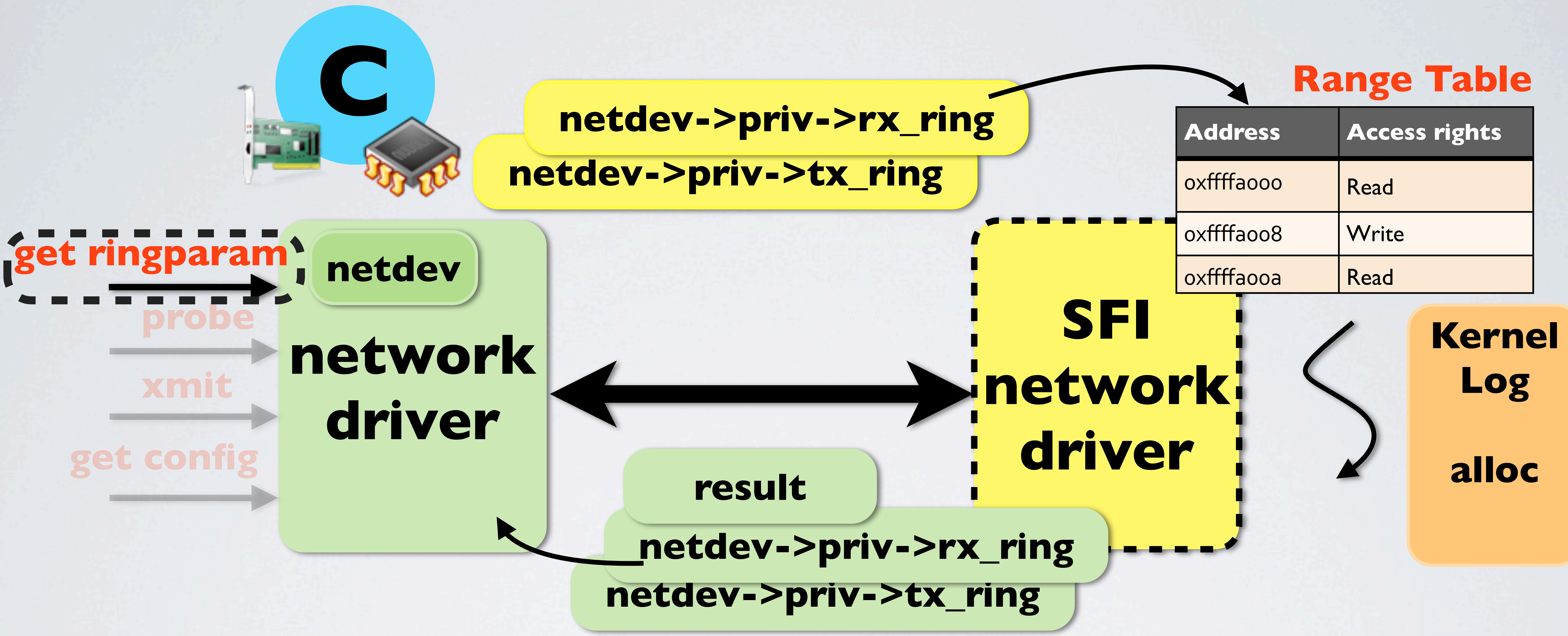

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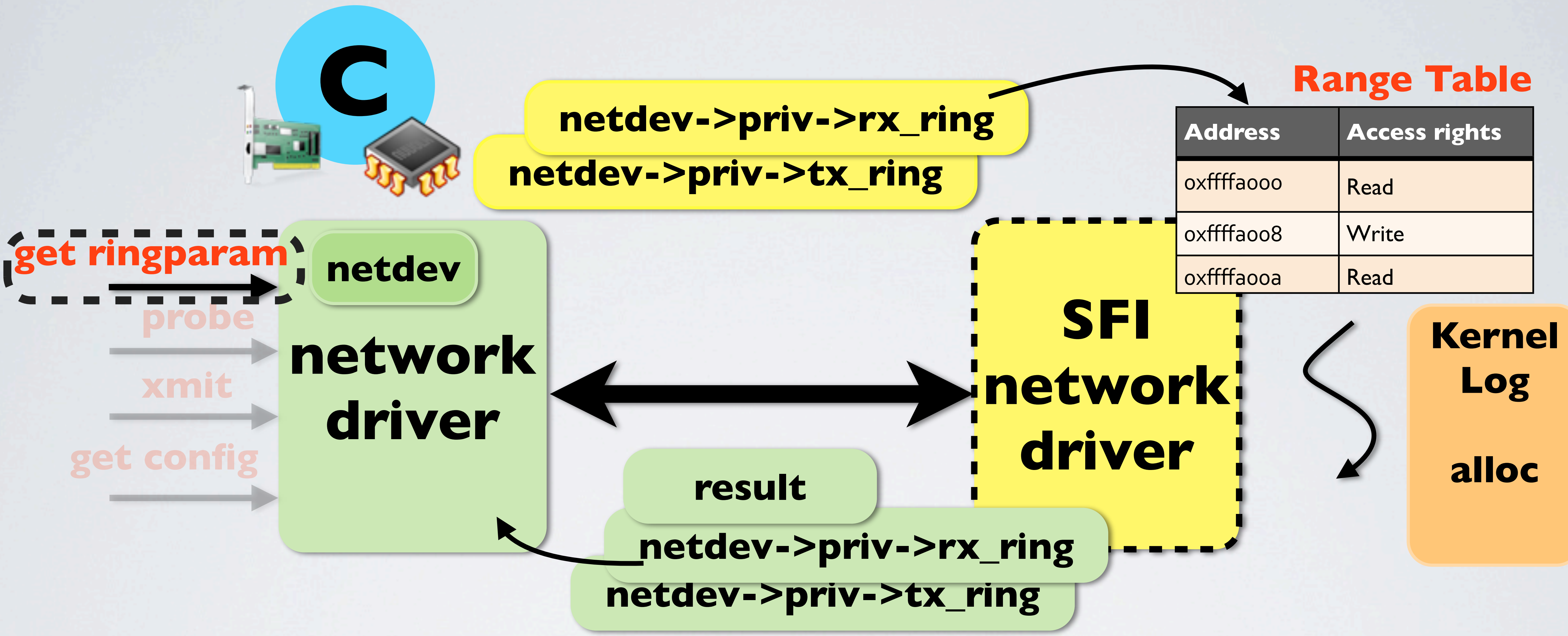

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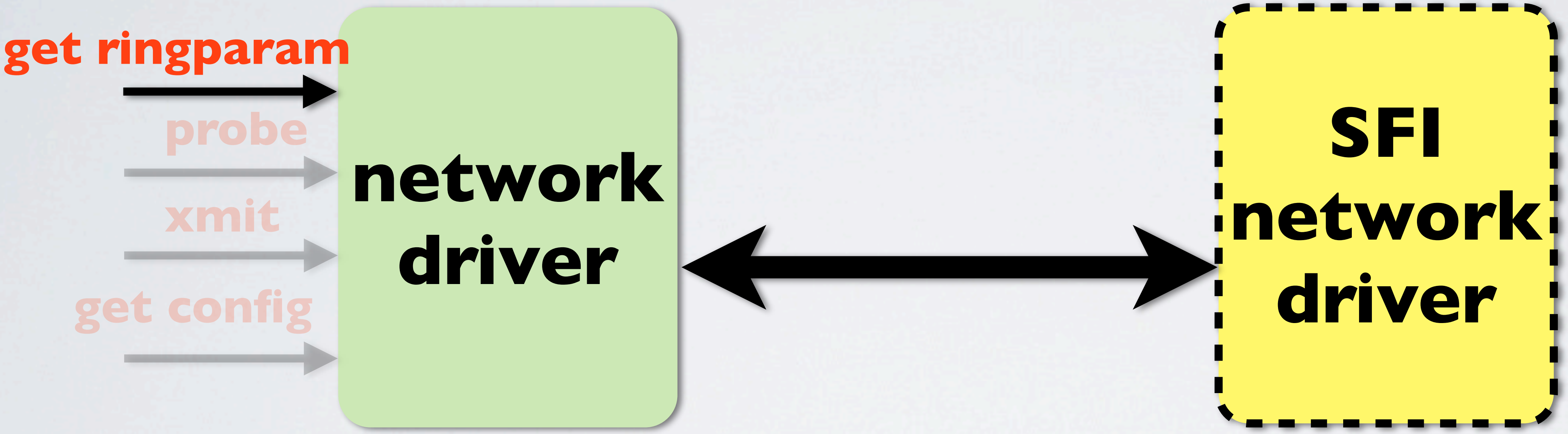
- Detects and recovers from:
  - Memory errors like invalid pointer accesses
  - Structural errors like malformed structures
  - Processor exceptions like divide by zero, stack corruption

FGFT: Failed transactions



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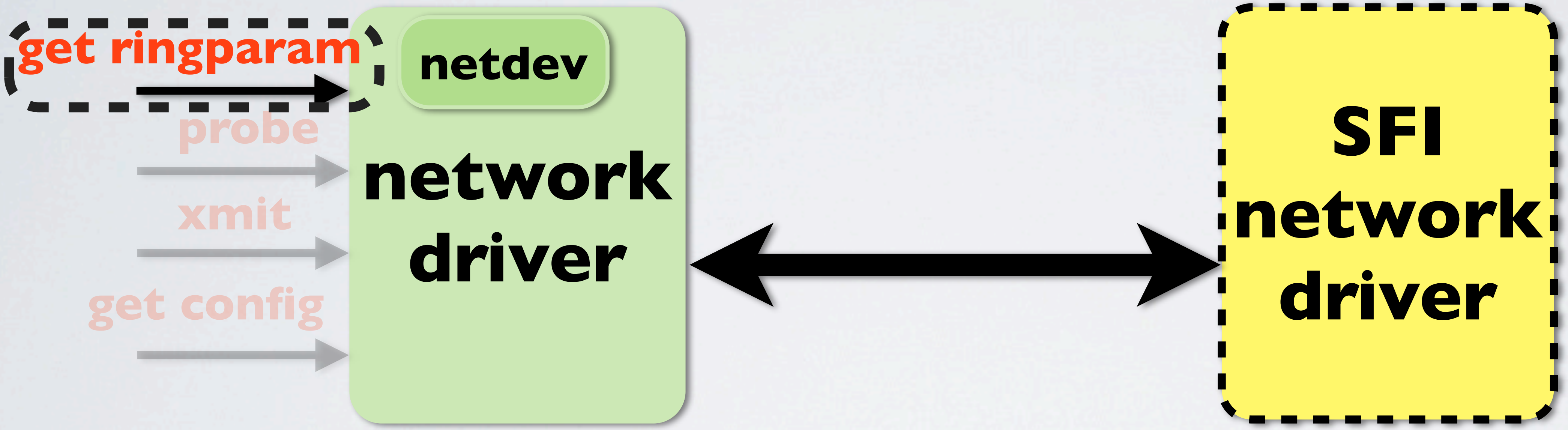

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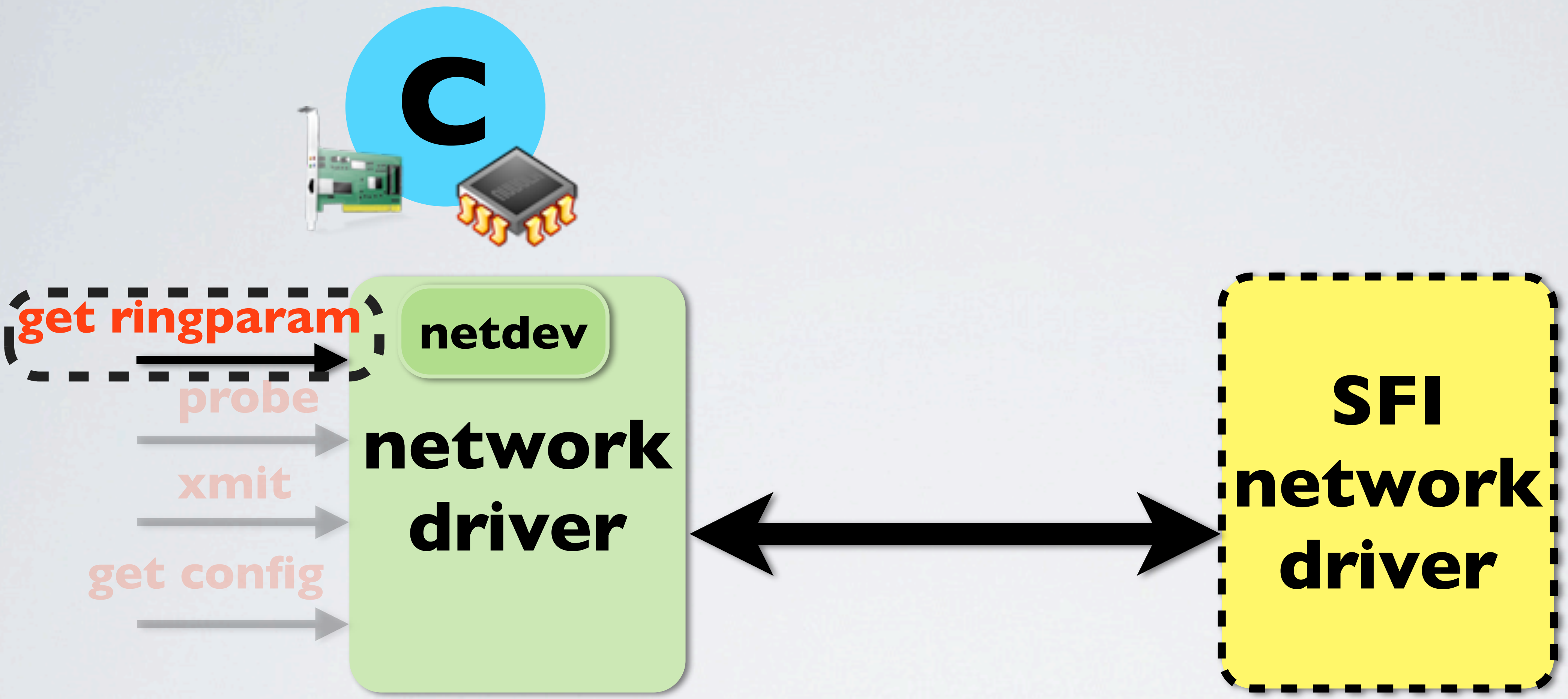

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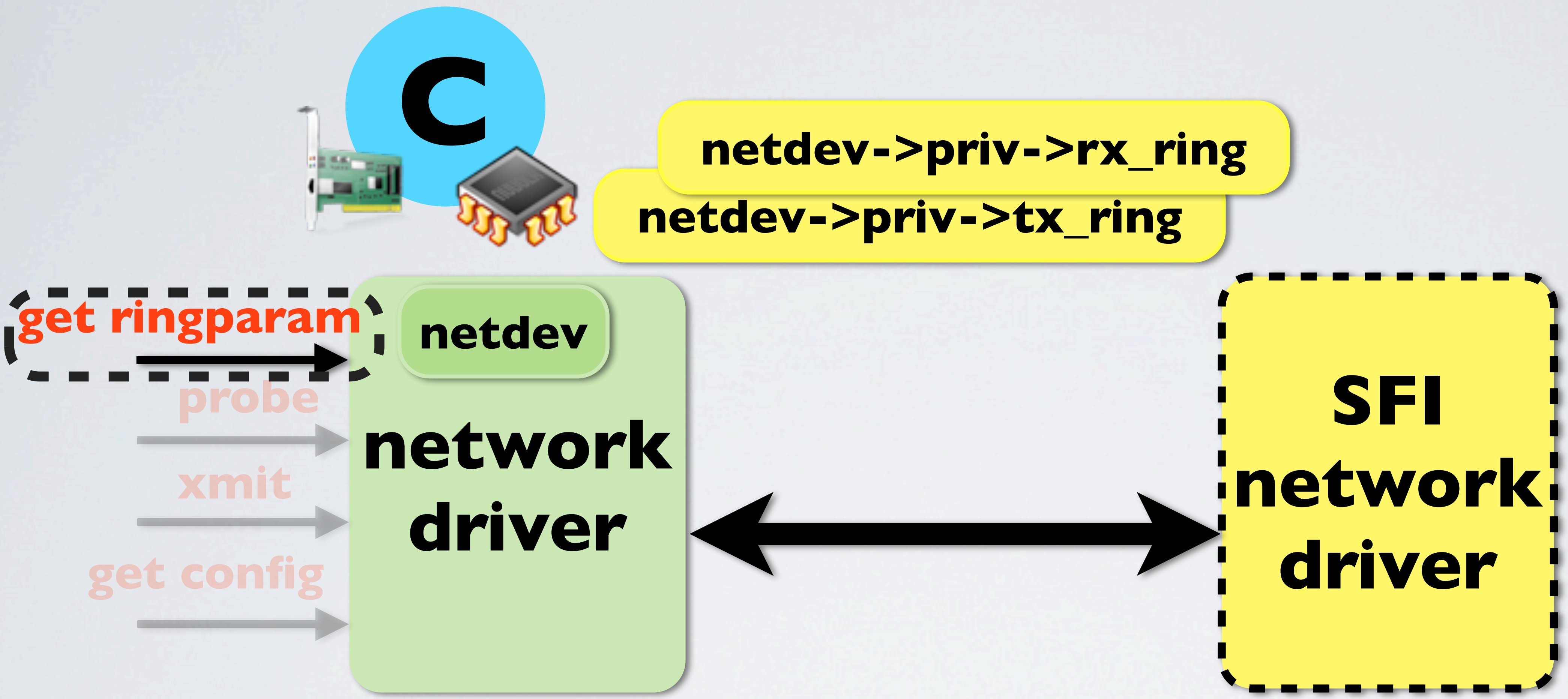

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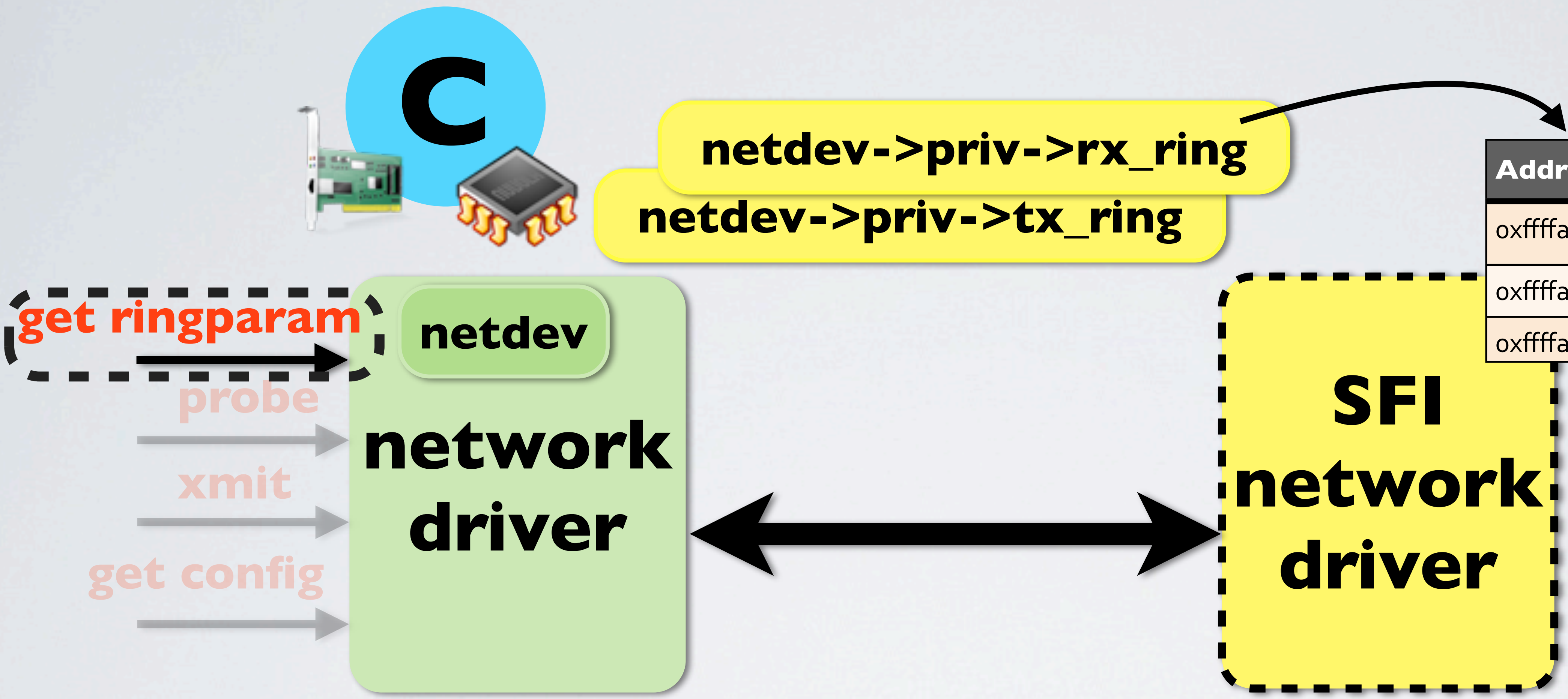

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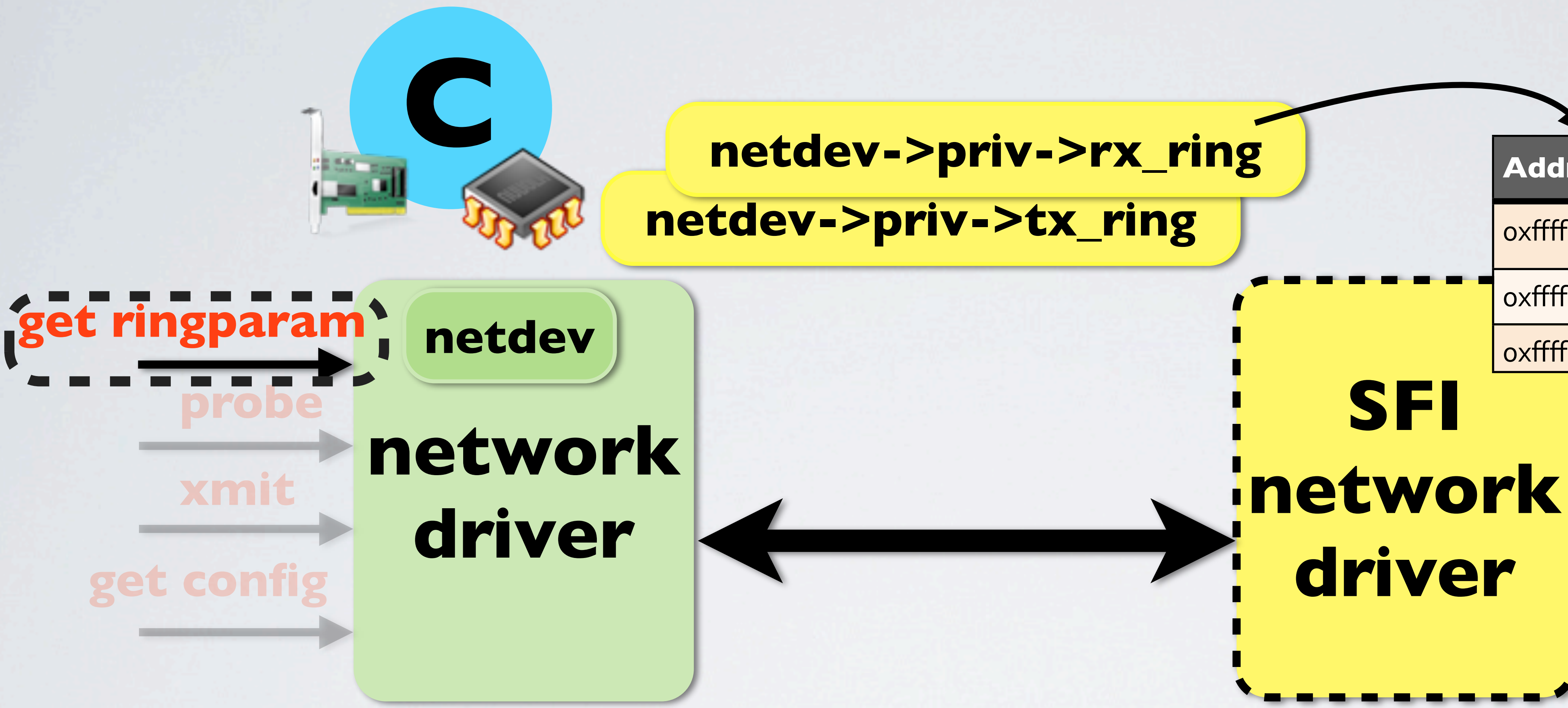

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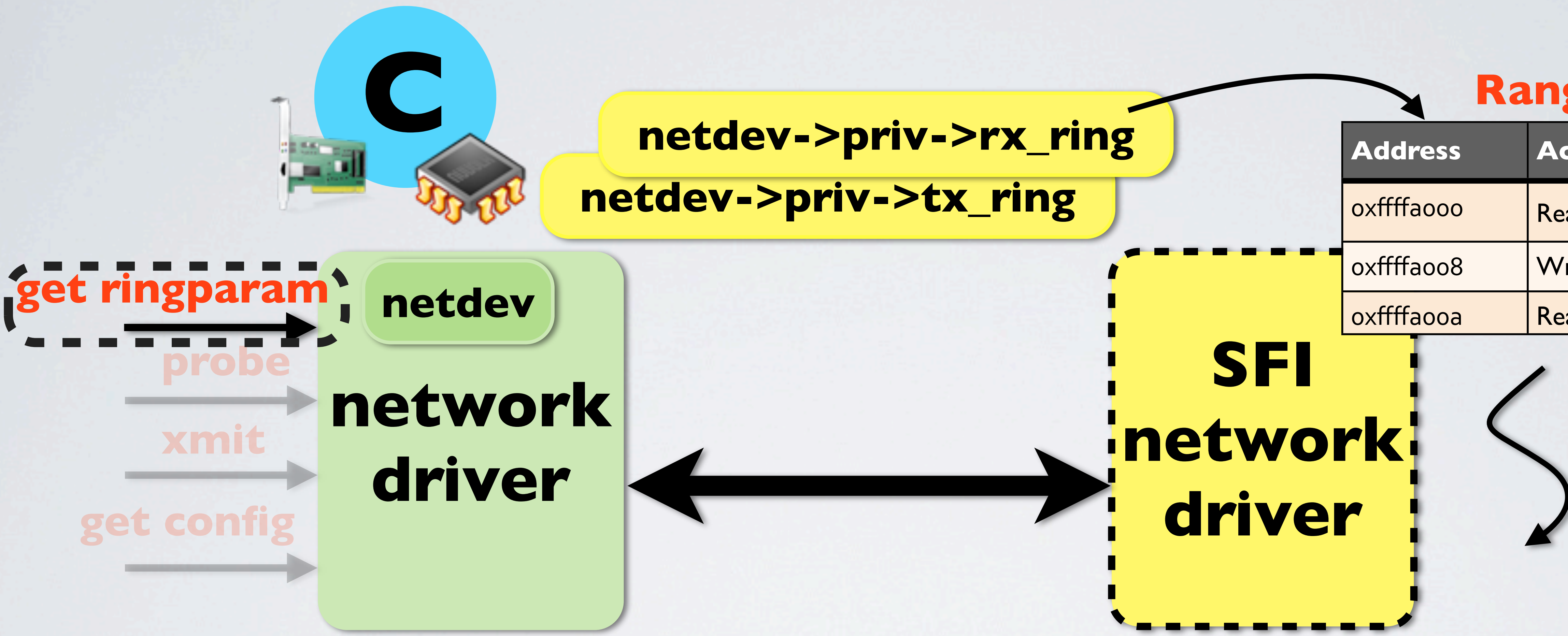

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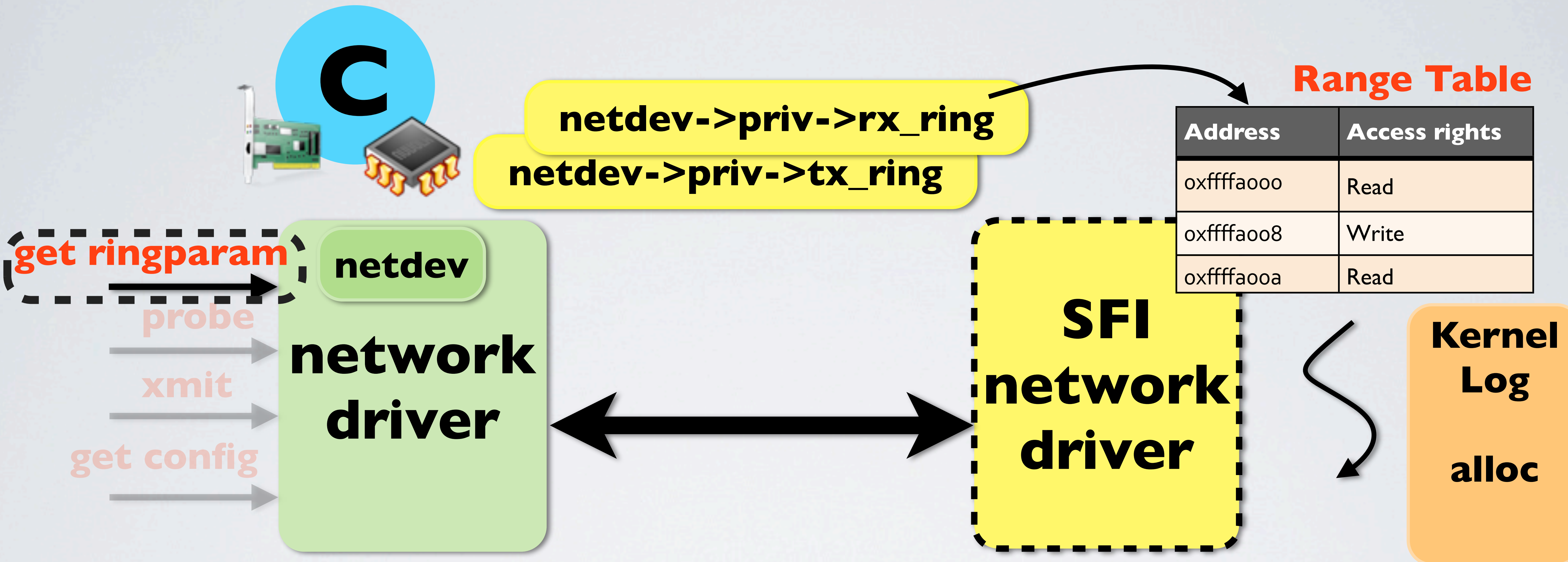

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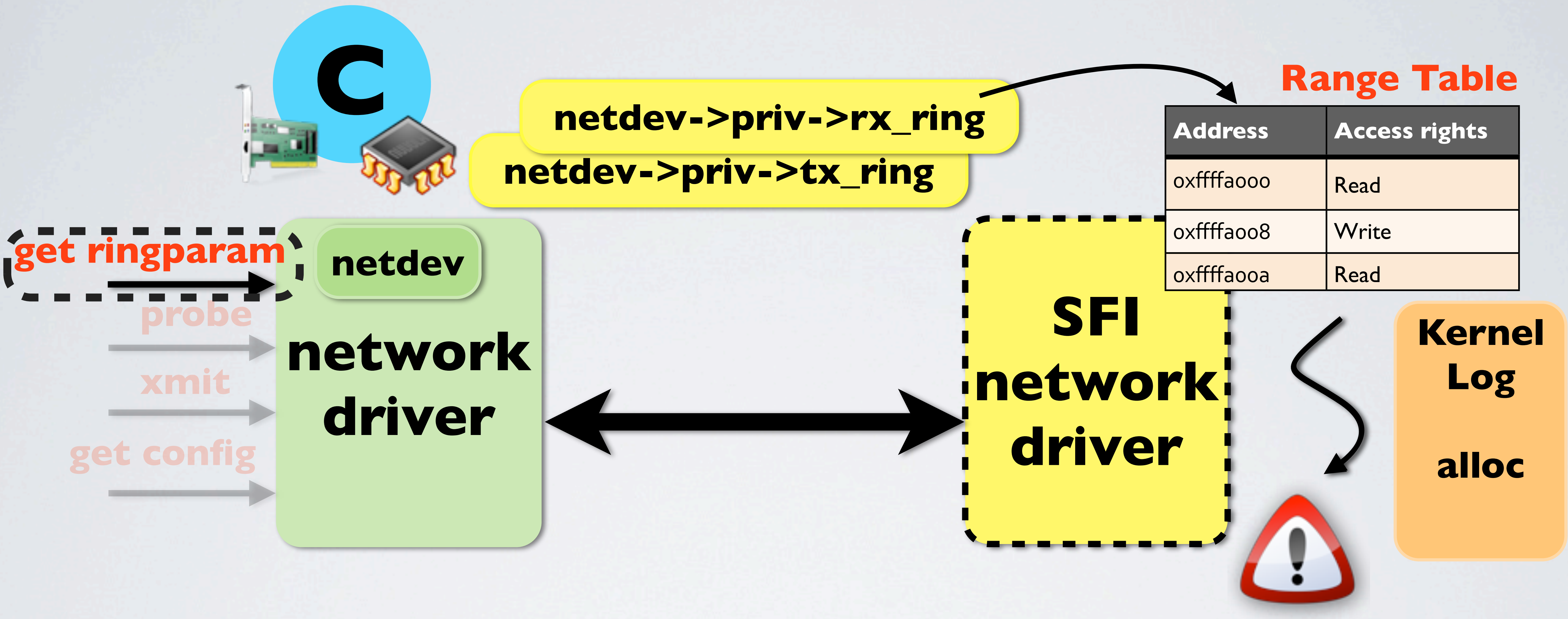

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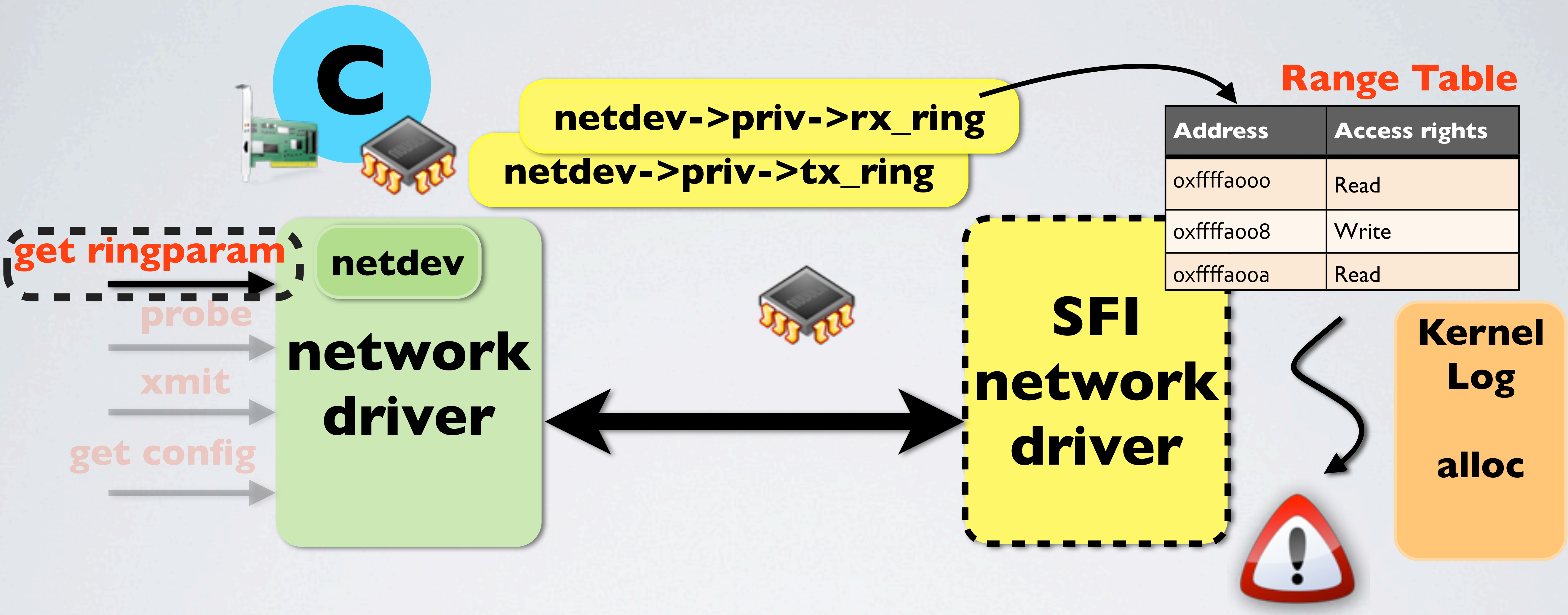

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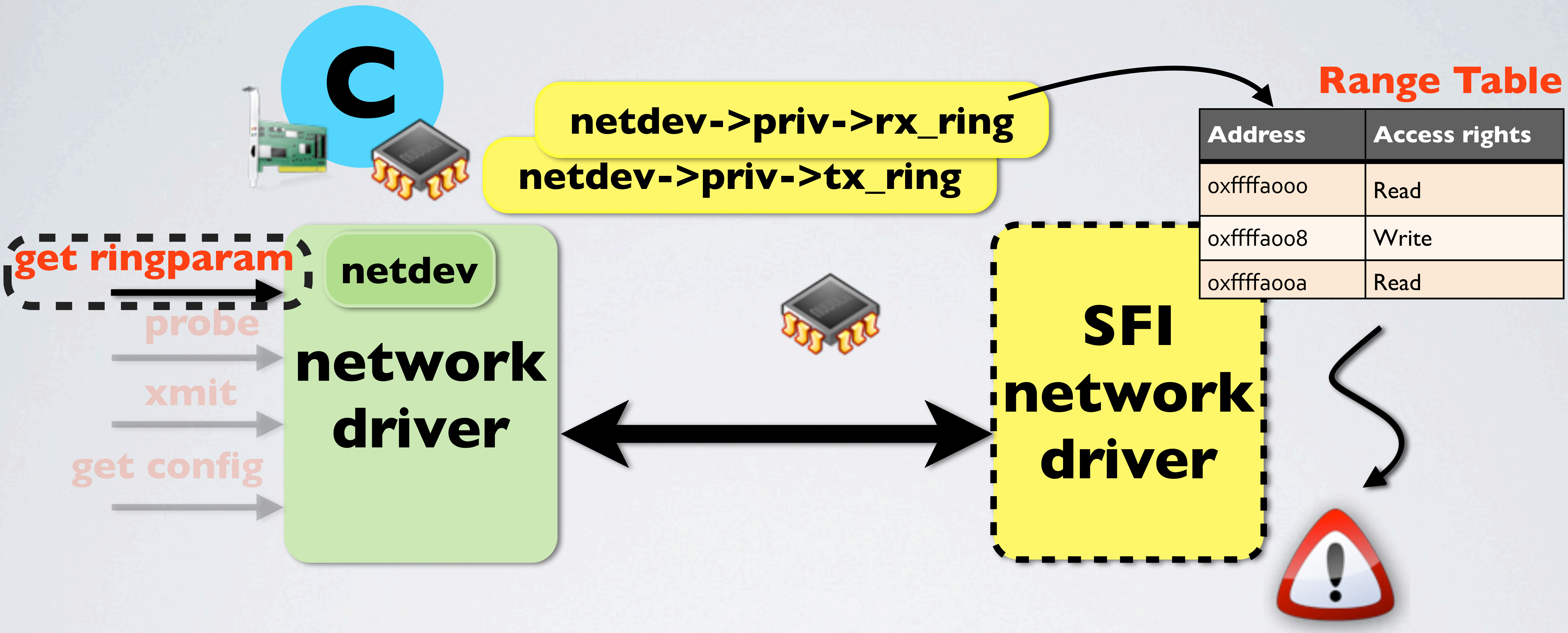

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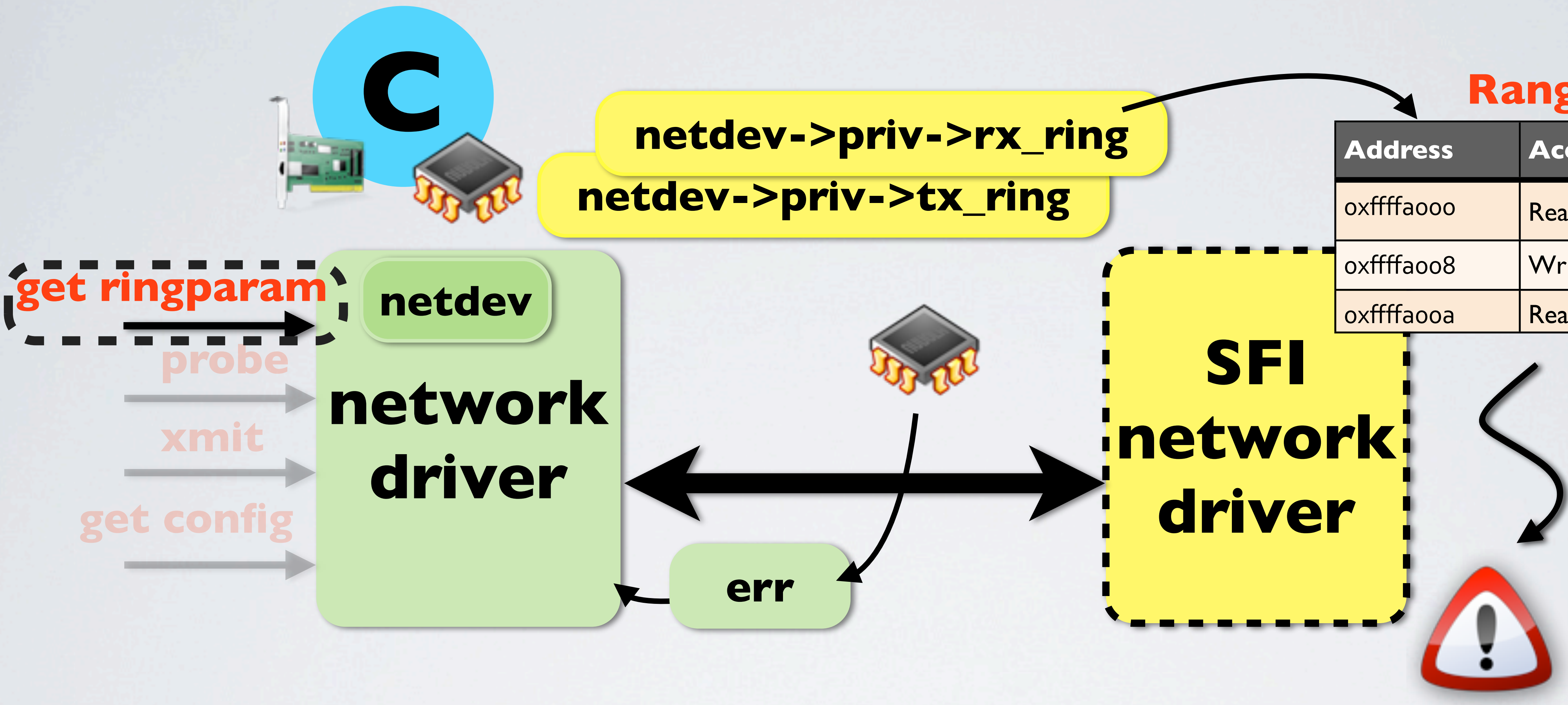

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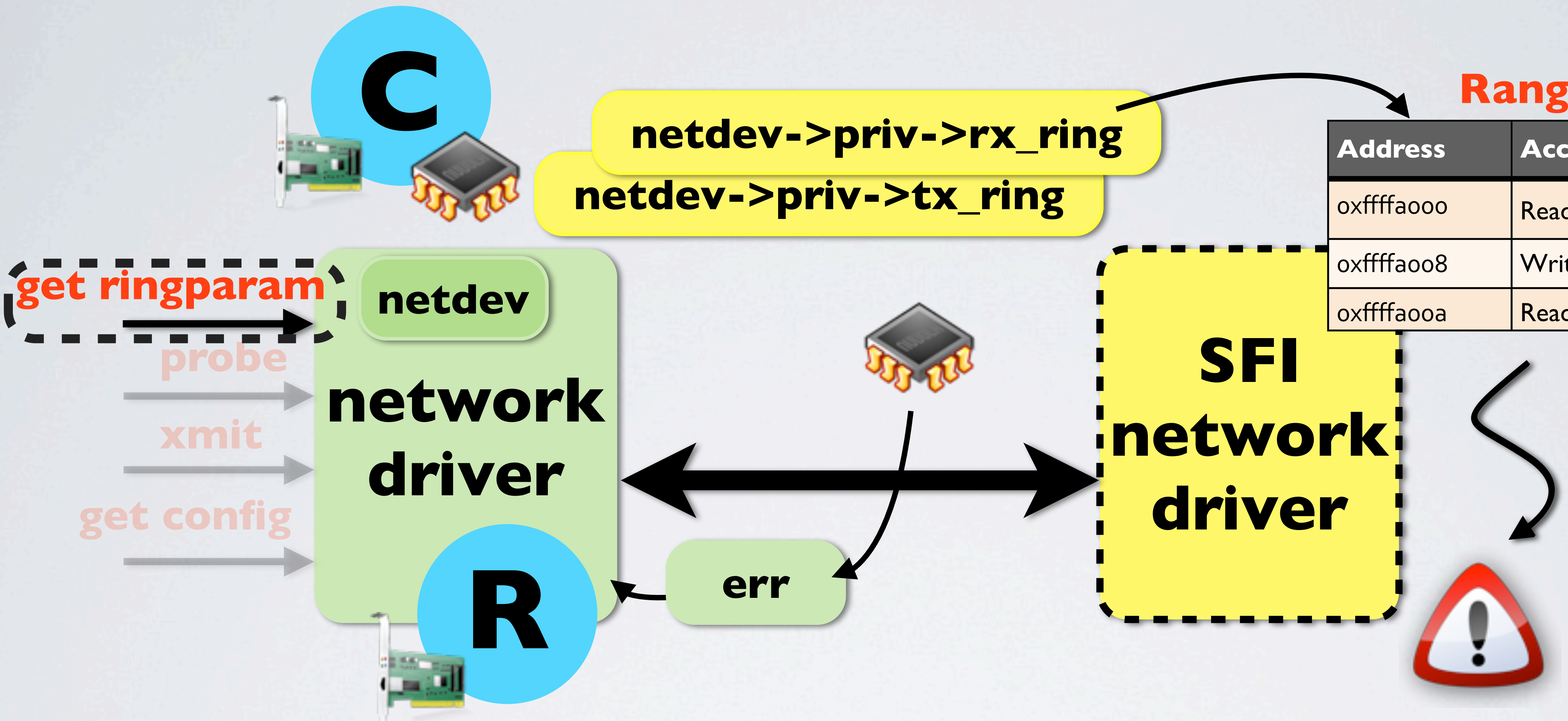

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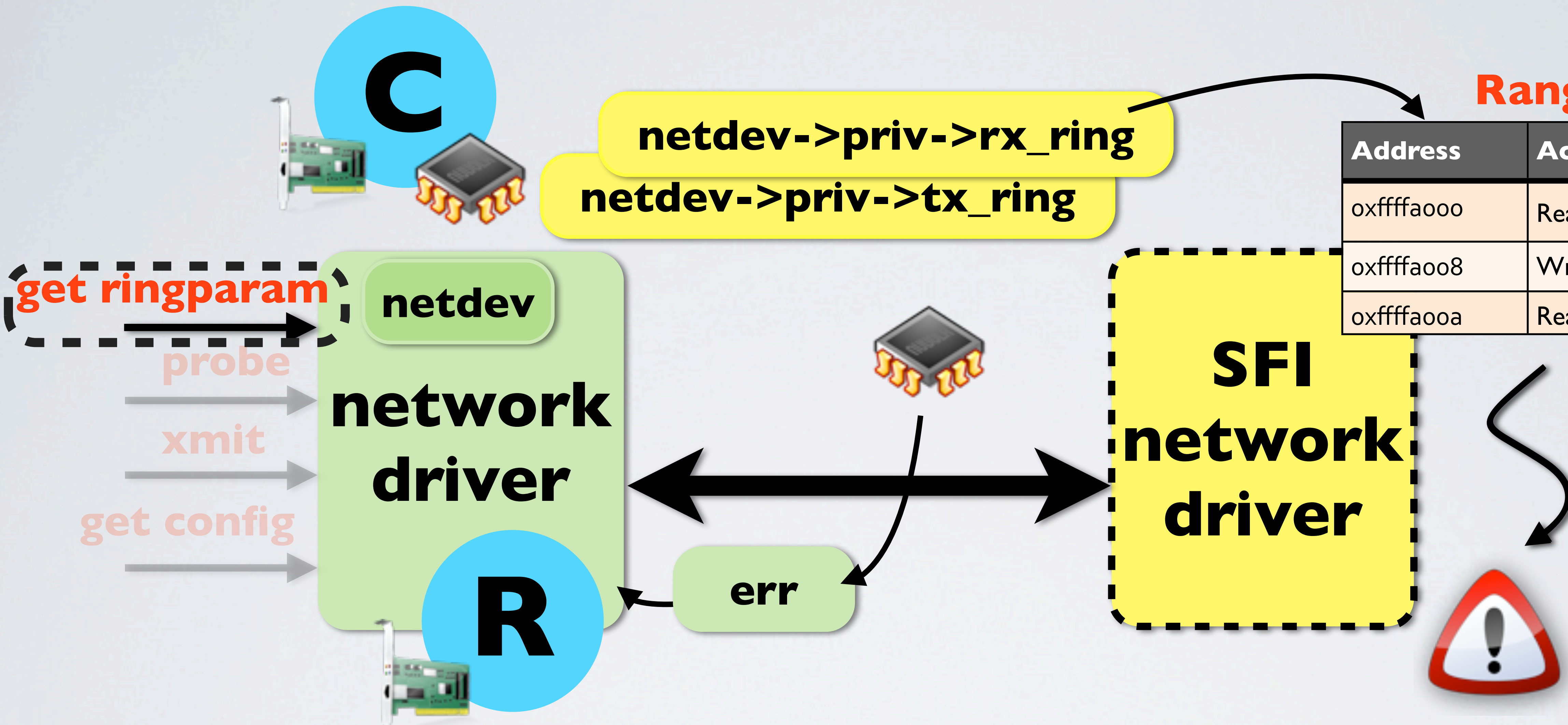

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FGFT provides transactional execution of driver entry points

How does this give us transactional execution?

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- **Atomicity: All or nothing execution**
  - **Driver state: Run code in SFI module**
  - **Device state: Explicitly checkpoint/restore state**

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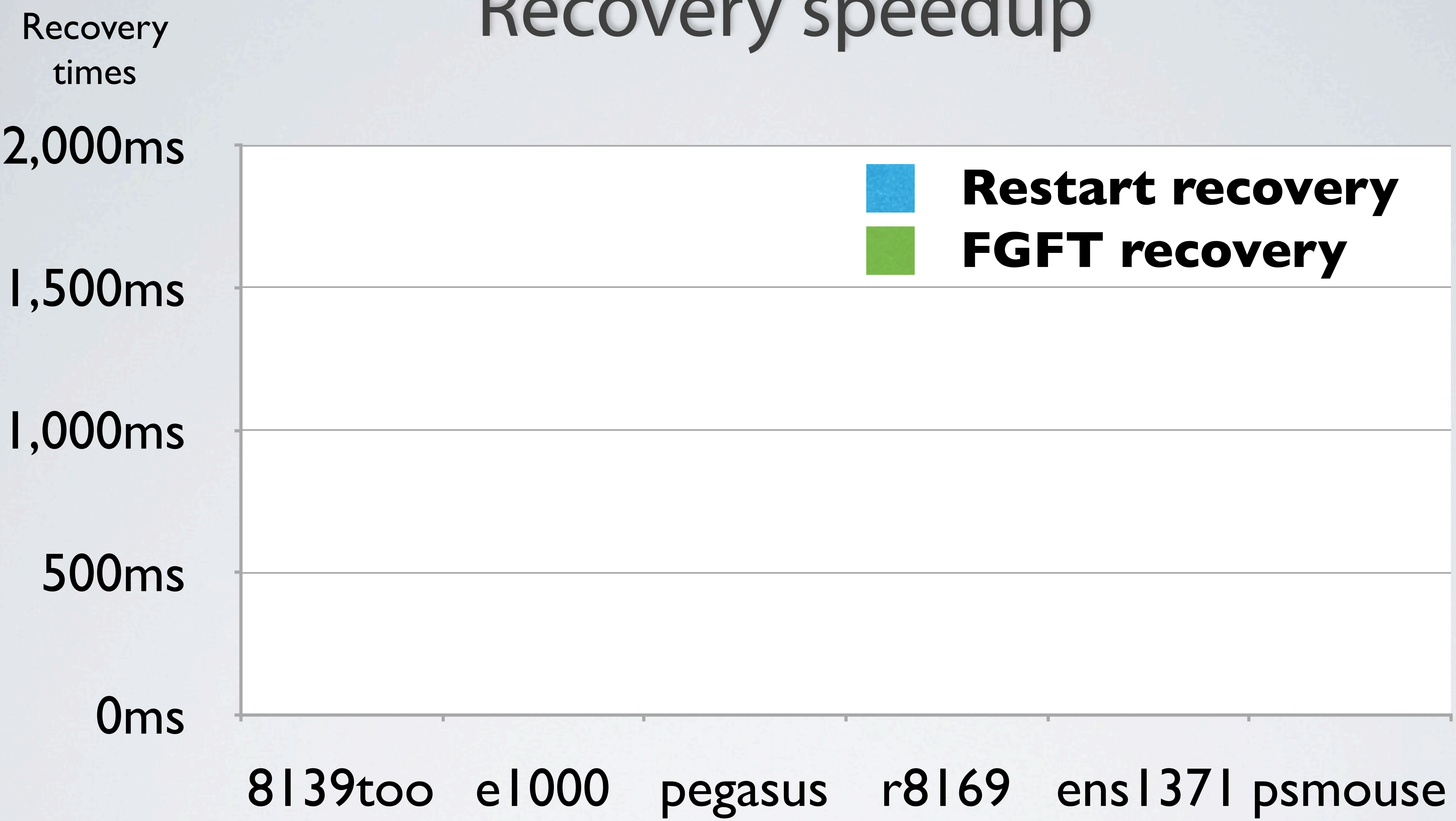
- **Isolation: Serialization to hide incomplete transactions**
  - **Re-use existing device locks to lock driver**
  - **Two phase locking**

- **Consistency: Only valid (kernel, driver and device) states**
  - **Higher level mechanisms to rollback external actions**
  - **At most once device action guarantee to applications**

Recovery speedup



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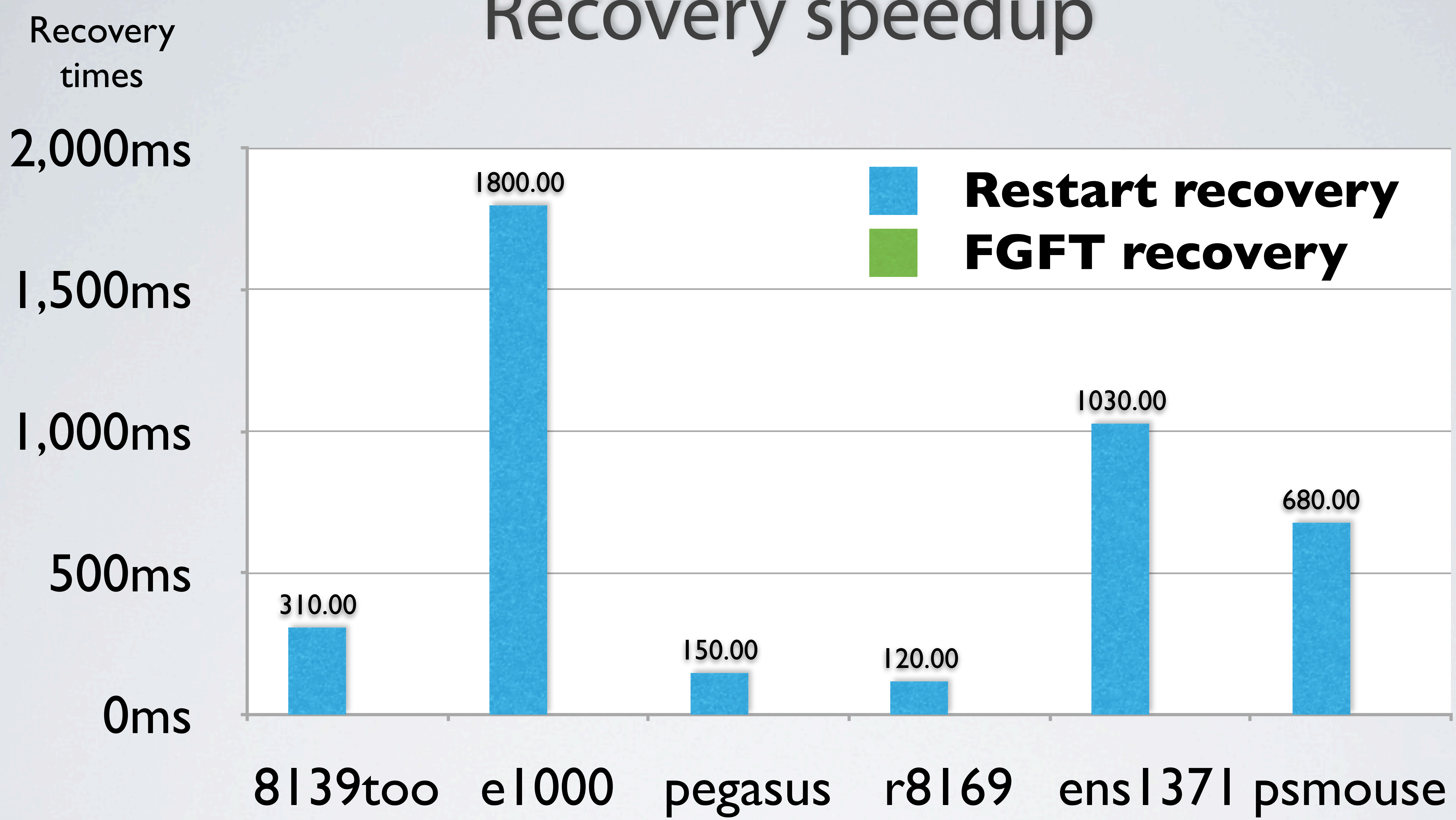

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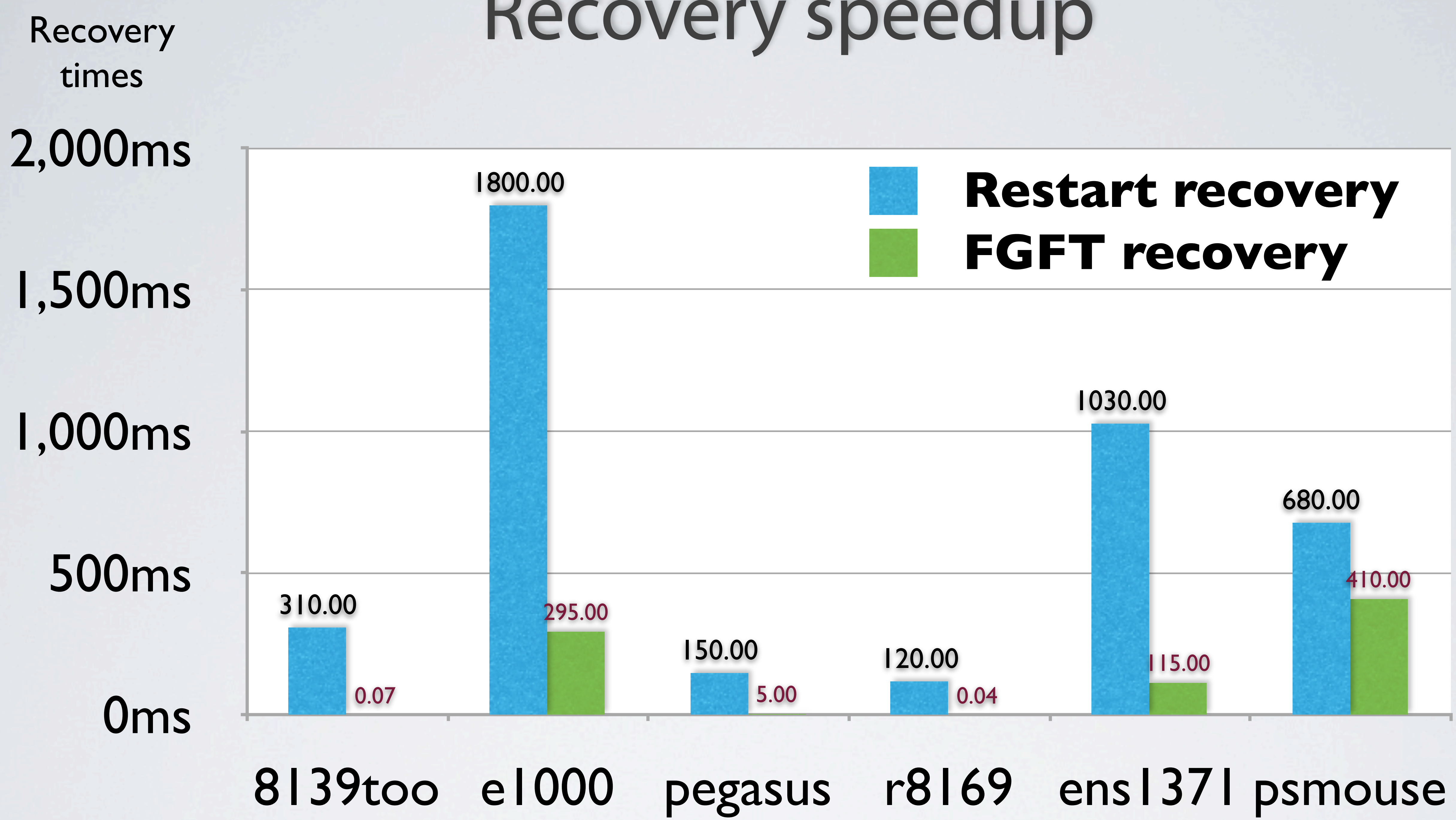

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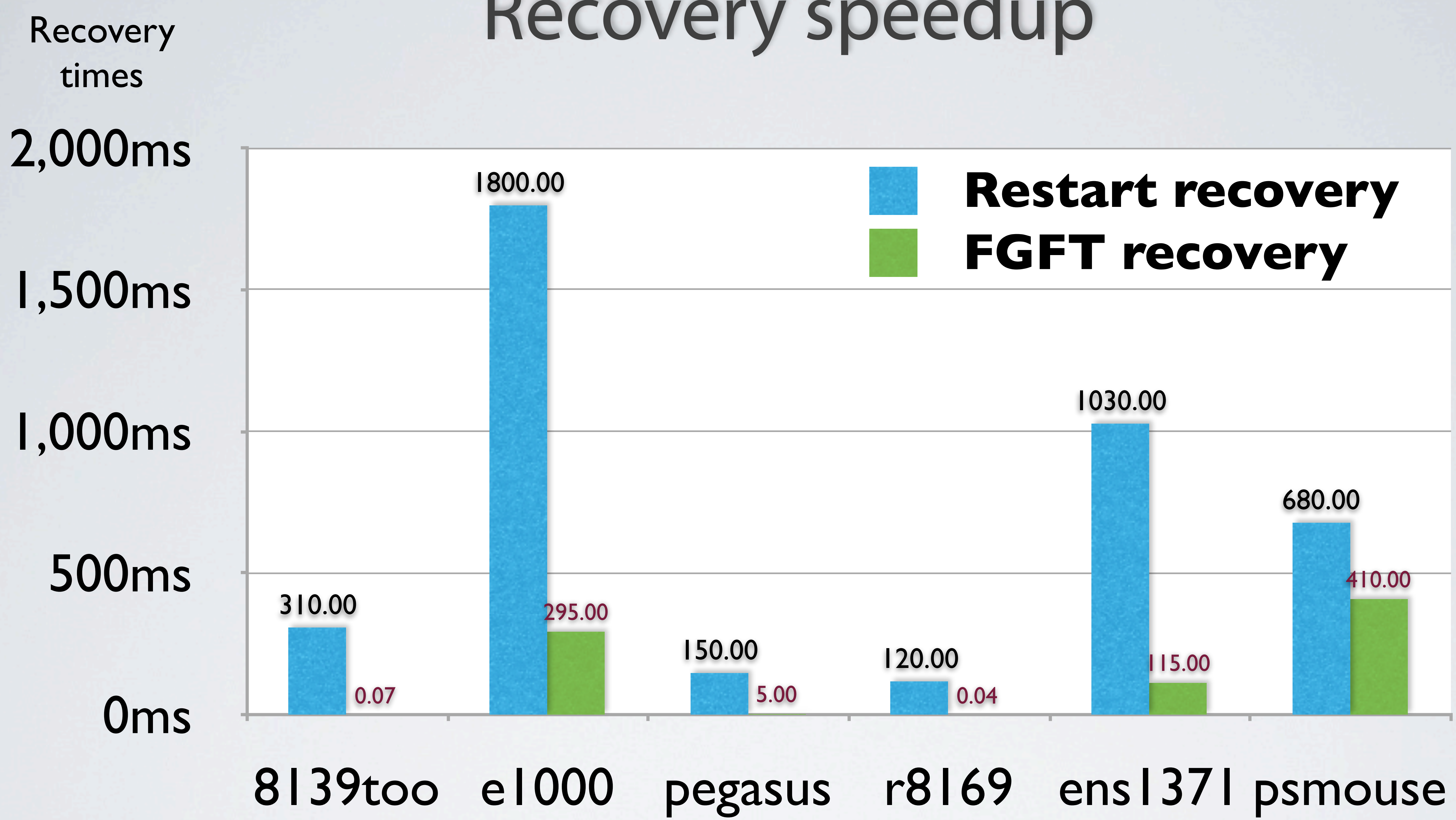


FGFT provides significant speedup in driver recovery and improves system availability

Programming effort

Driver	LOC	Checkpoint/restore effort	
		LOC Moved	LOC Added
8139too	1, 904	26	4
e1000	13, 973	32	10
r8169	2, 993	17	5
pegasus	1, 541	22	5
ens1371	2, 110	16	6
psmouse	2, 448	19	6

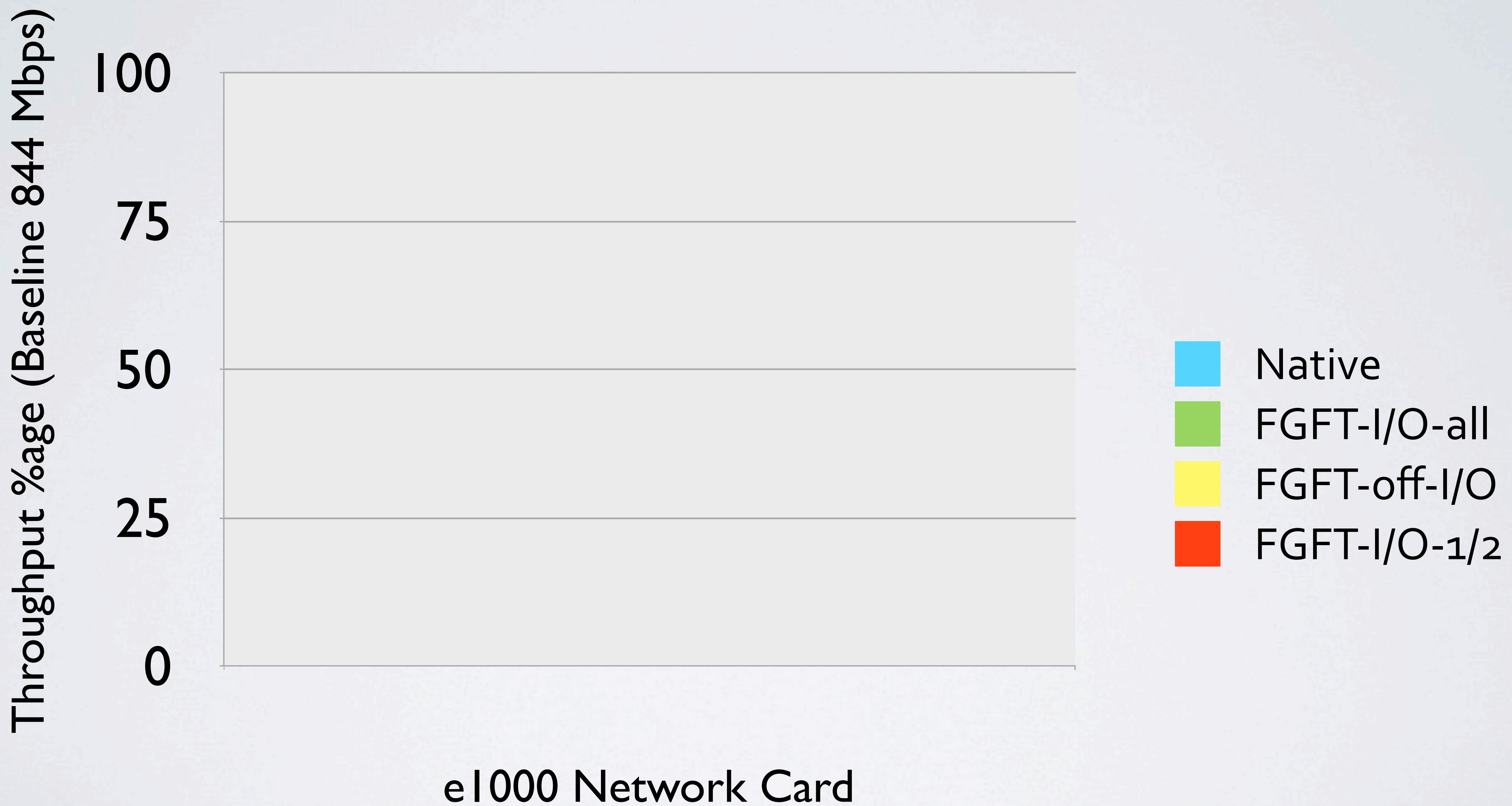
FGFT requires limited programmer effort and needs only 38 lines of new kernel code

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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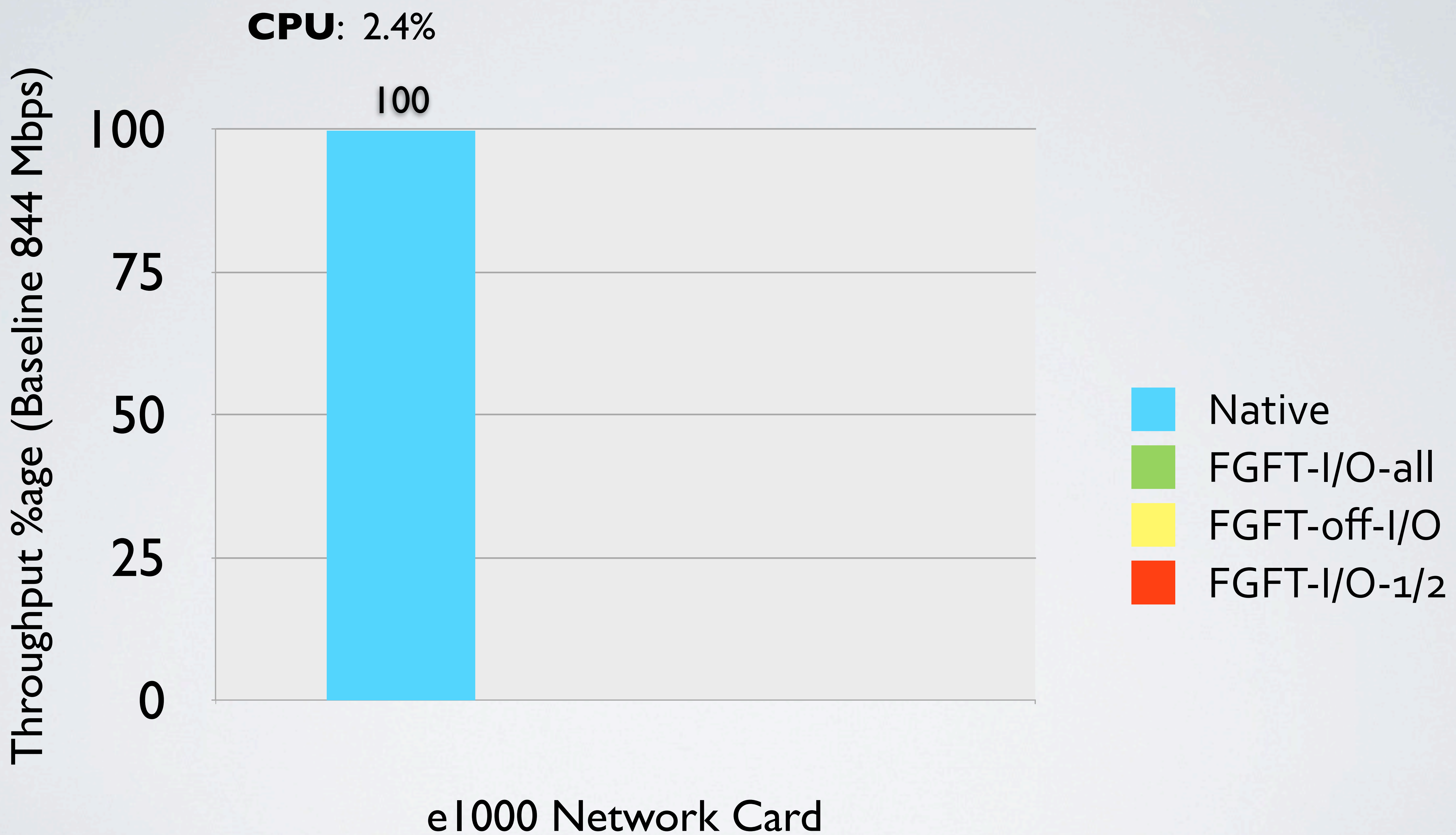

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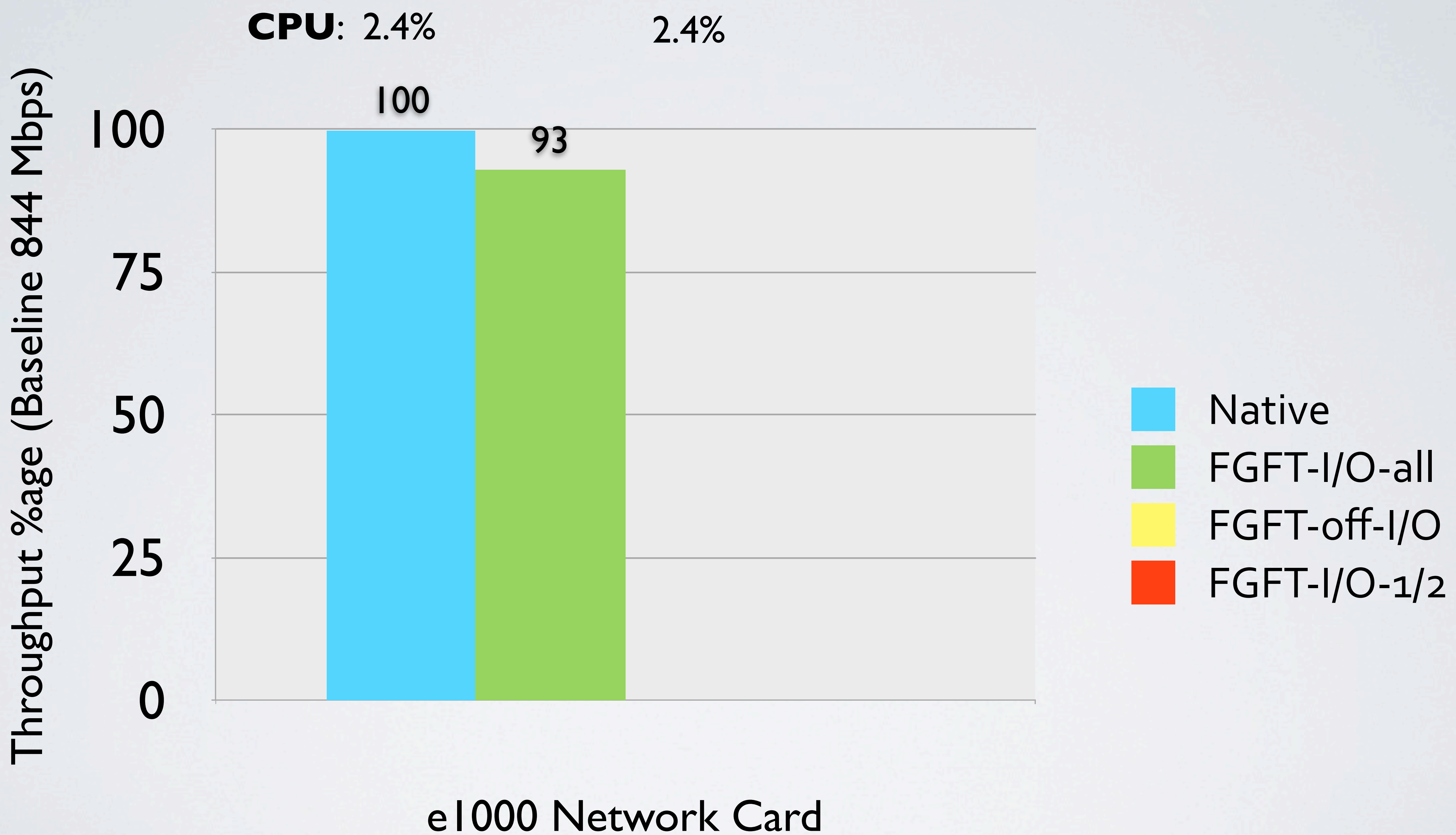

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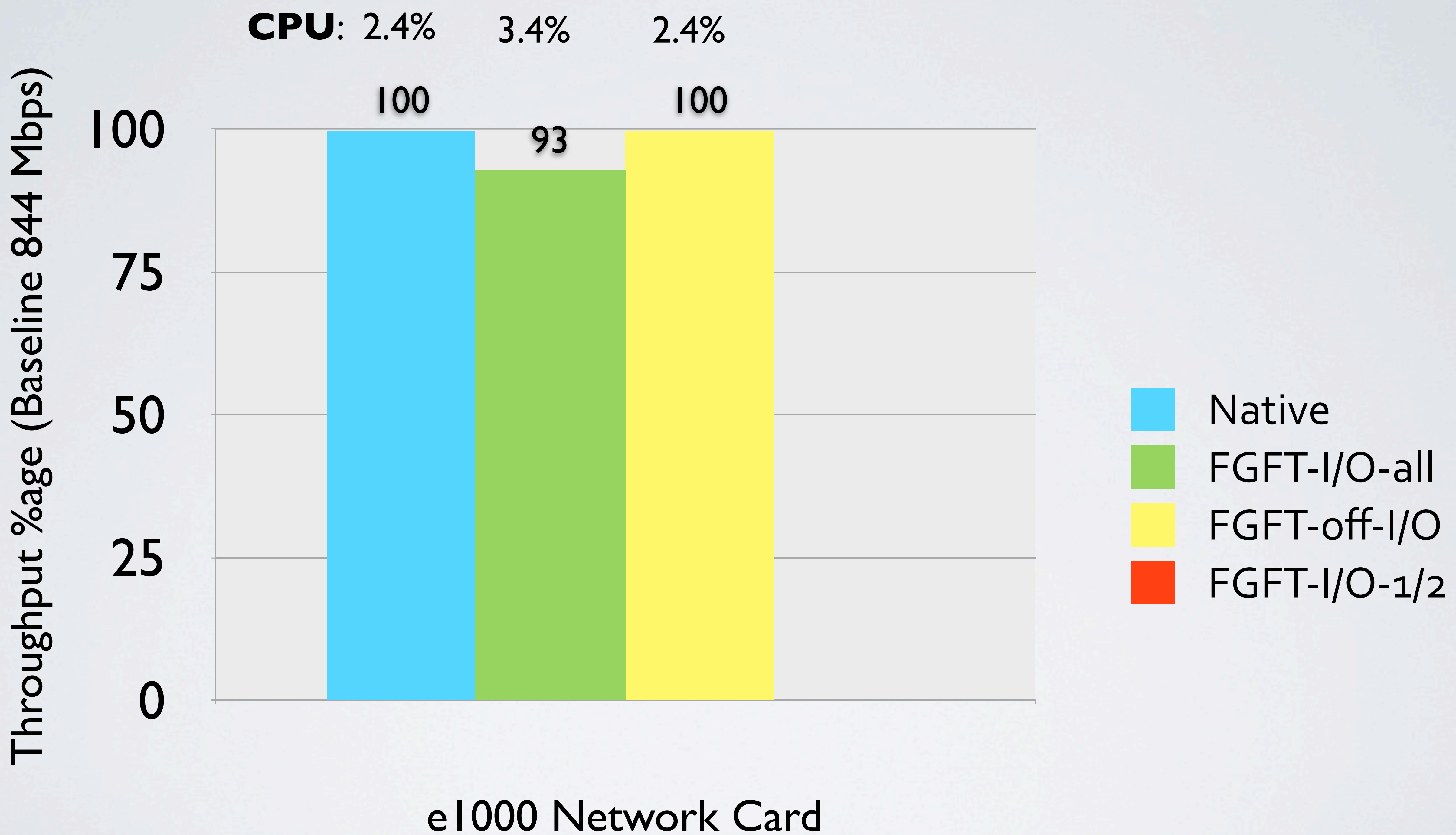

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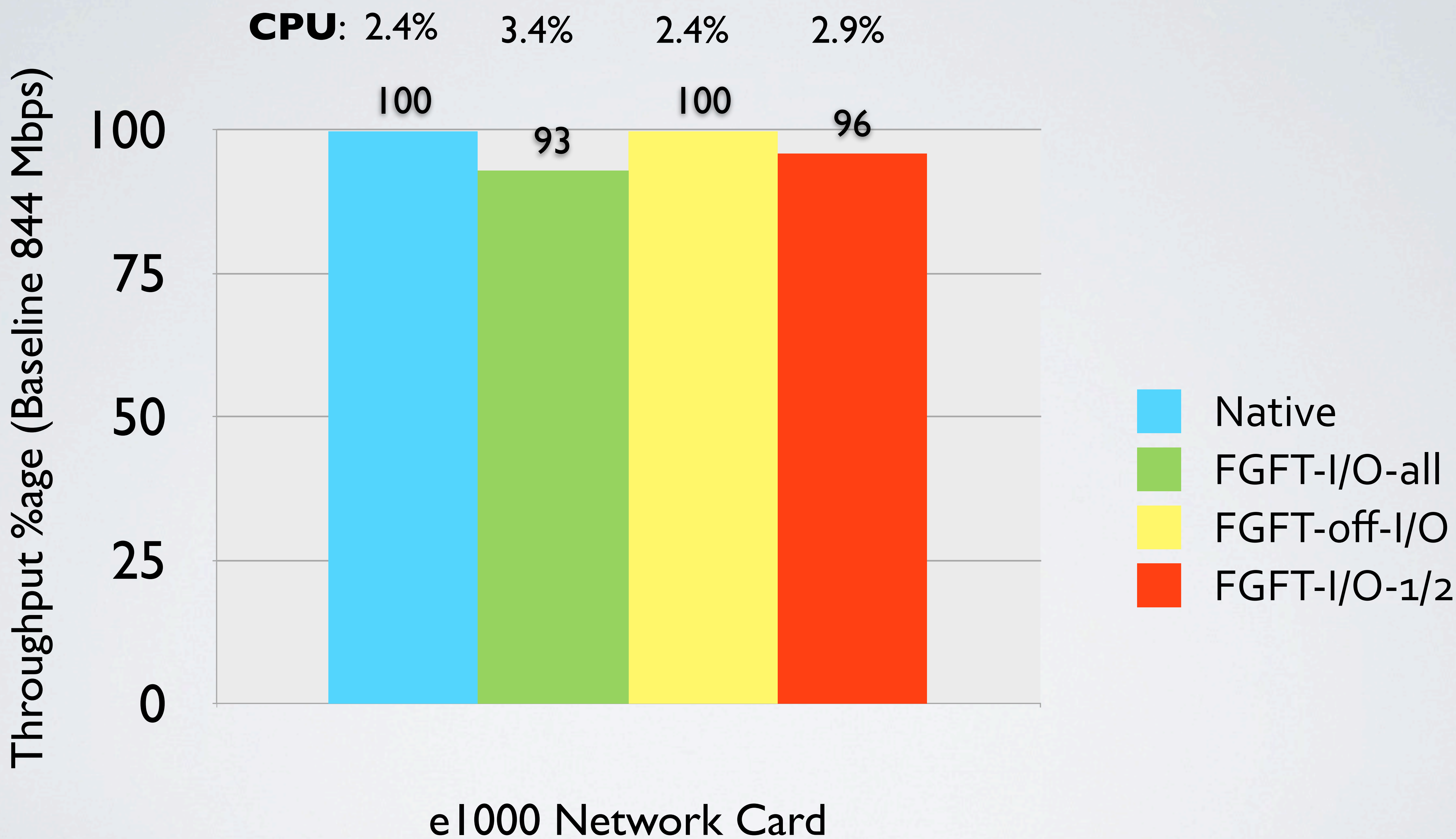

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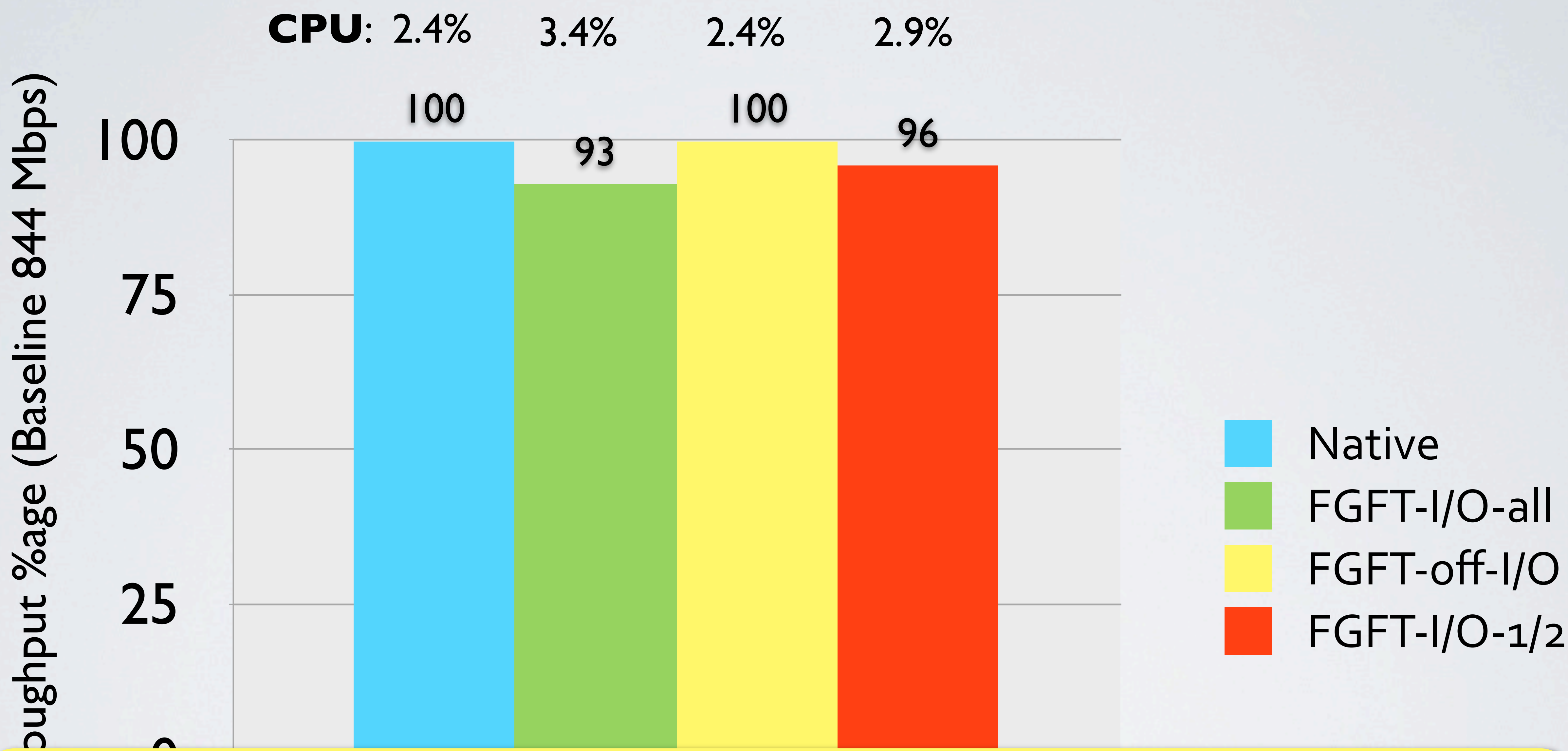

FGFT can isolate and recover high bandwidth devices at low overhead without adding kernel subsystems

netperf on Intel quad-core machines

Talk summary

First research consideration of hardware failures in drivers

SOSP '09

Released tool, patches & informed developers

Largest study of drivers to understand their behavior and verify research assumptions

ASPLOS '12

Measured driver behavior & identified new directions

Introduced checkpoint/restore in drivers for low latency fault tolerance

ASPLOS '13

Fast & correct recovery with incremental changes to drivers

Questions

Asim Kadav

- **http://cs.wisc.edu/~kadav**
- **kadav@cs.wisc.edu**