Fine-Grained Fault Tolerance using Device Checkpoints

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University of Wisconsin-Madison

The (old) elephant in the room

3rd party developers

+

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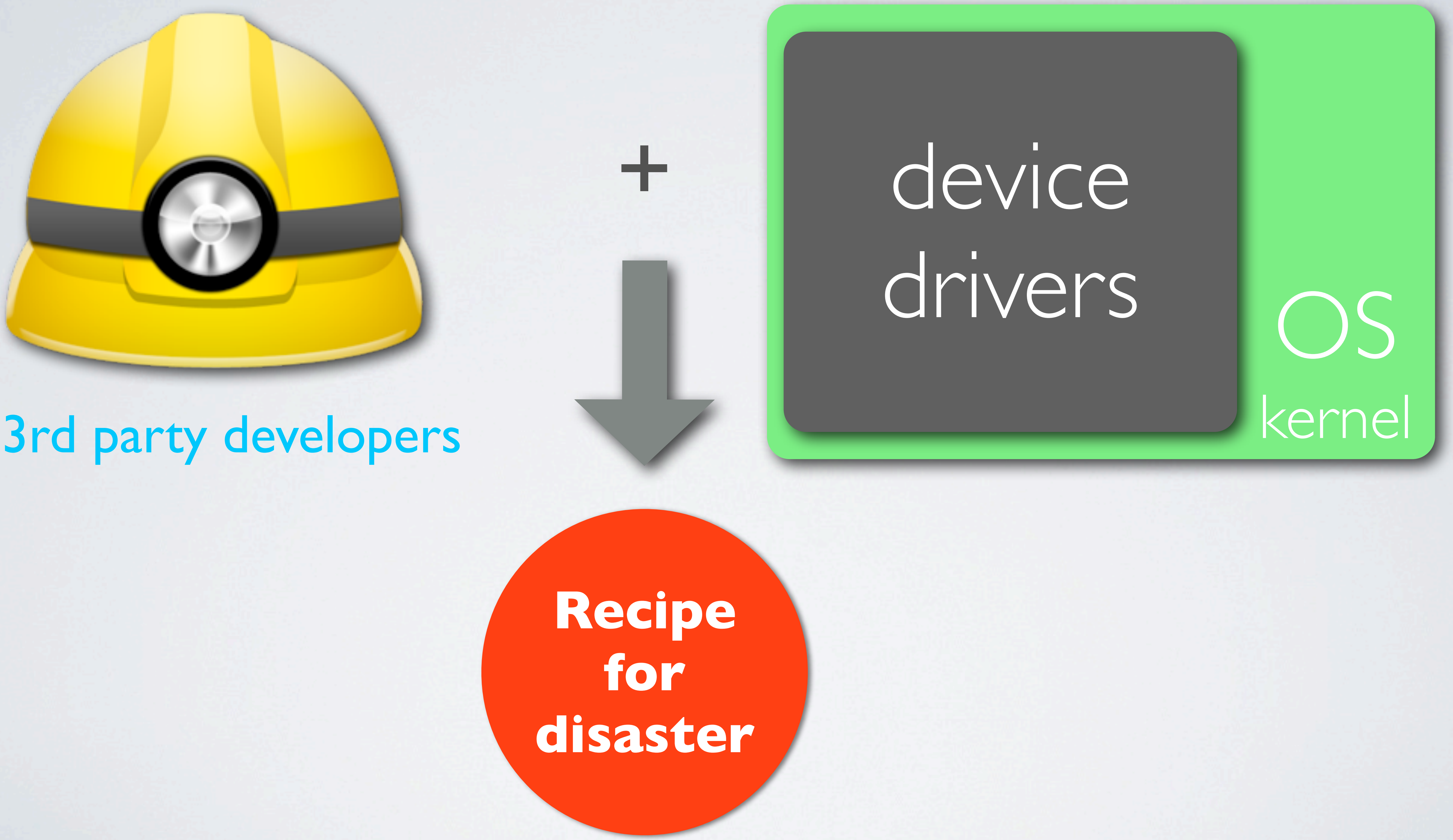

Past work mostly looks at detection and isolation

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
	Termite [SOSP 09]	2	1	2
Static analysis tools	Windows SDV [Eurosys 06]	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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Limited kernel changes + Applicable to lots of drivers => Real Impact

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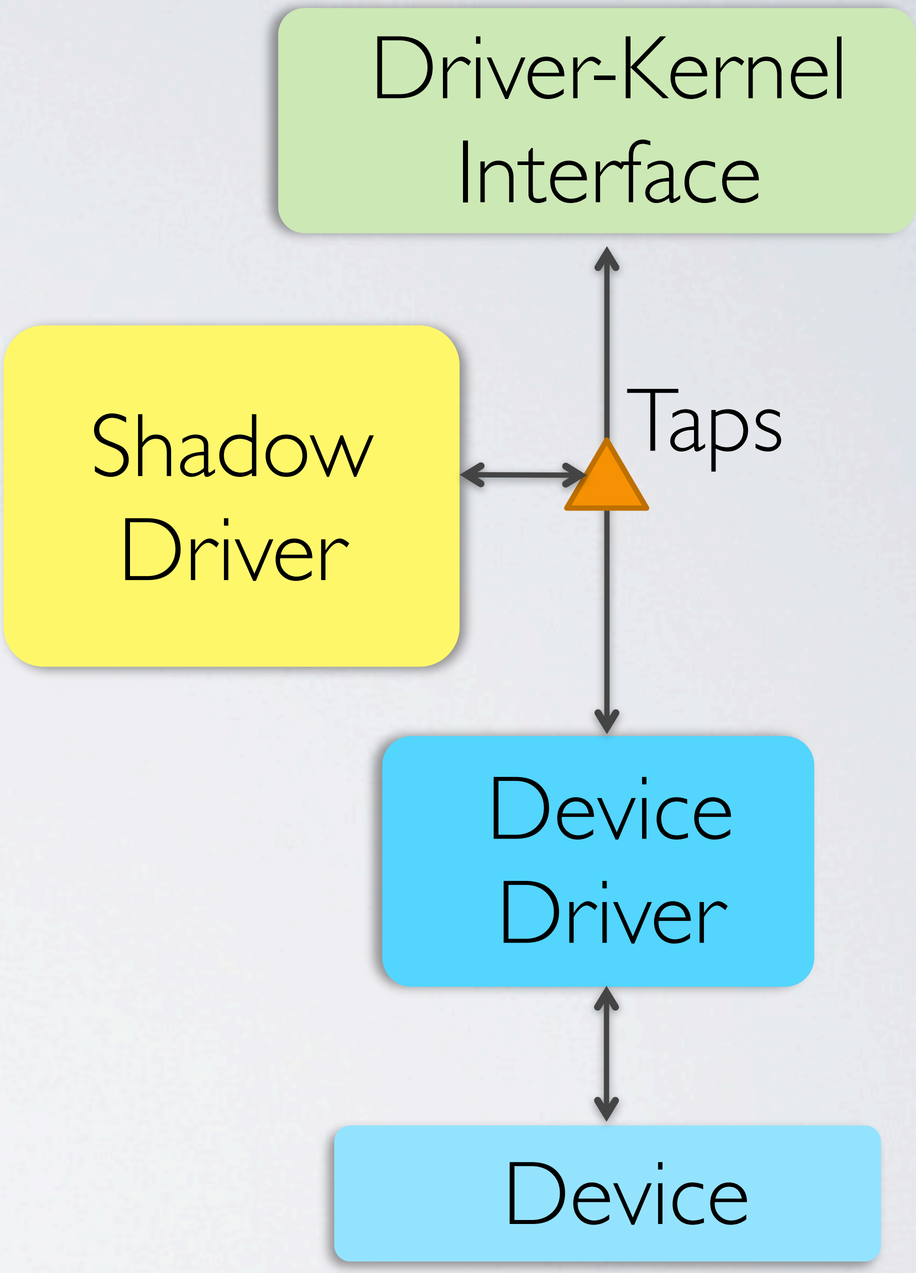
Limited kernel changes + Applicable to lots of drivers => Real Impact

Goal: Improve recovery with complete solutions that can be applied to many drivers

State of the art in recovery: Shadow drivers

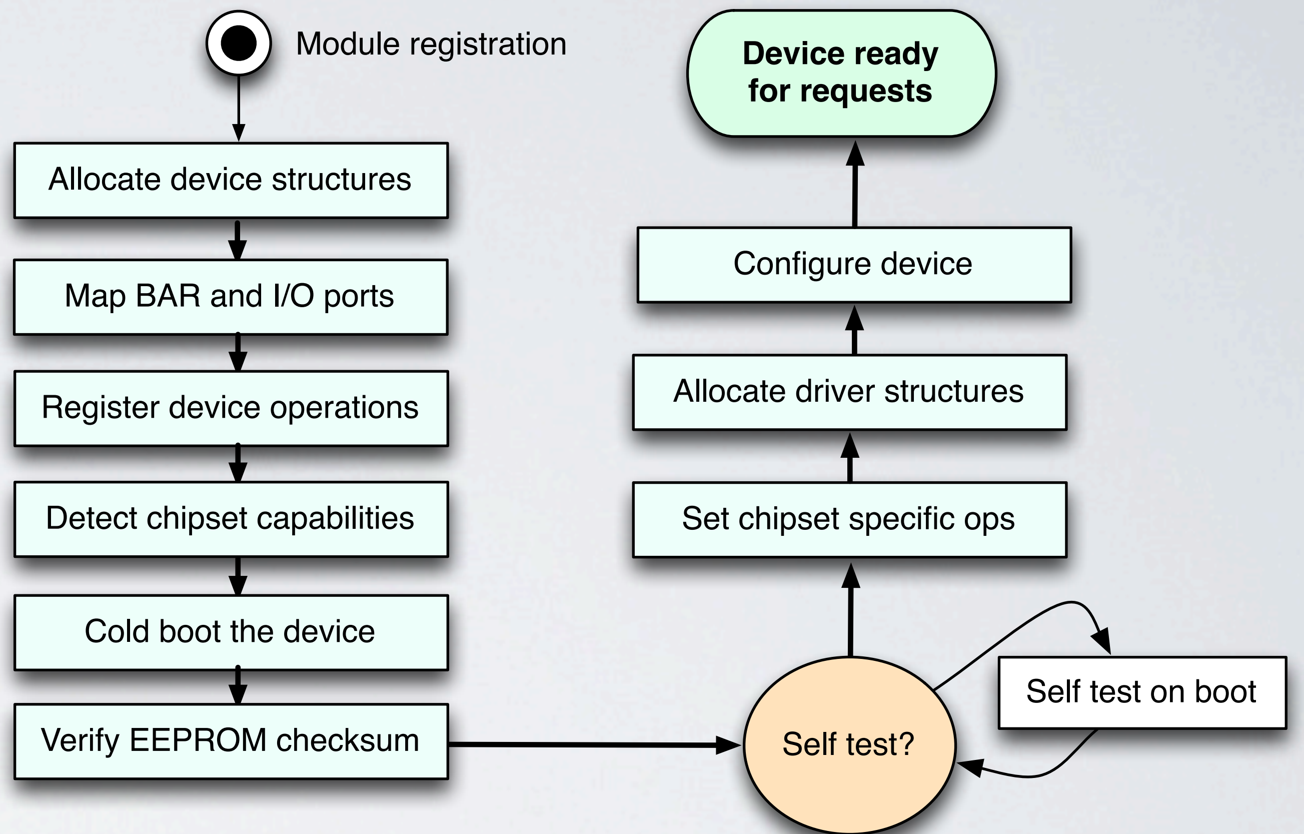
- **Carburizer calls generic recovery service if check fails**
- **Low cost transparent recovery**
  - ★ **Based on shadow drivers**
  - ★ **Records state of driver at all times**
  - ★ **Transparently restarts and replays recorded state on failure**



Swift [OSDI '04]

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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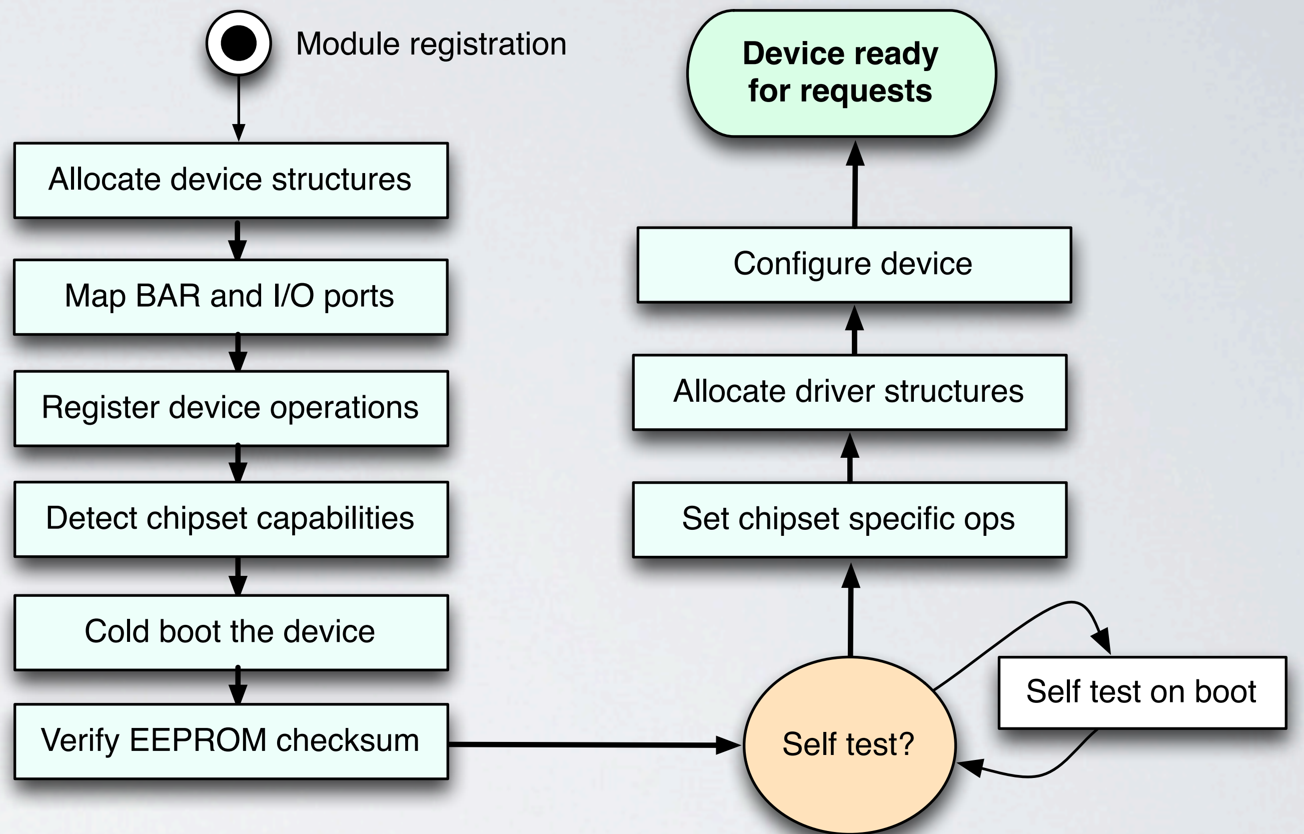
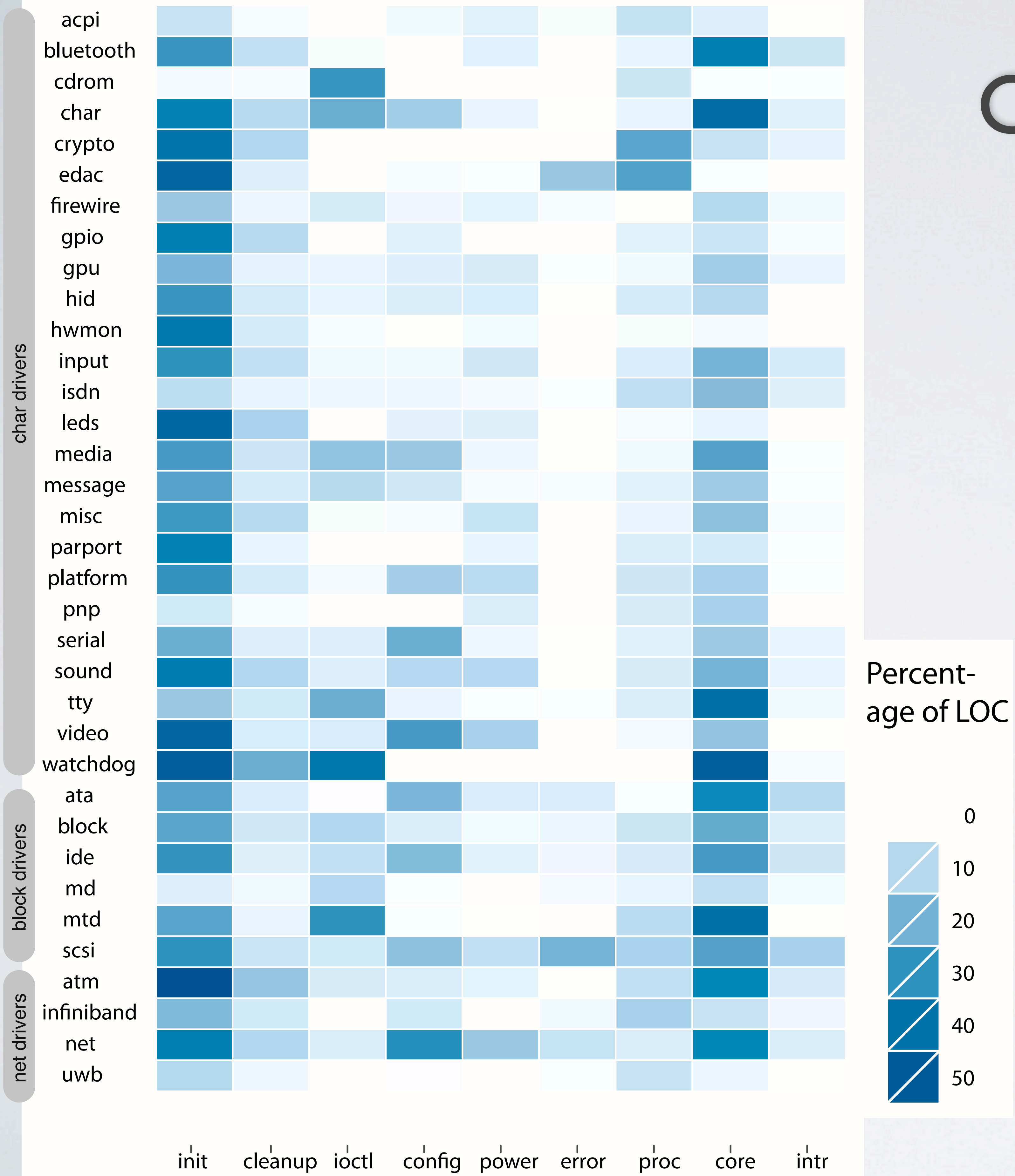


- **What does it hurt?**
  - **Fault tolerance: Driver recovery**
  - **Virtualization: Live migration, cloning, consolidation**
  - **OS functions: Boot, upgrade, NVM checkpoints**

Driver Code Characteristics

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

Driver Code Characteristics



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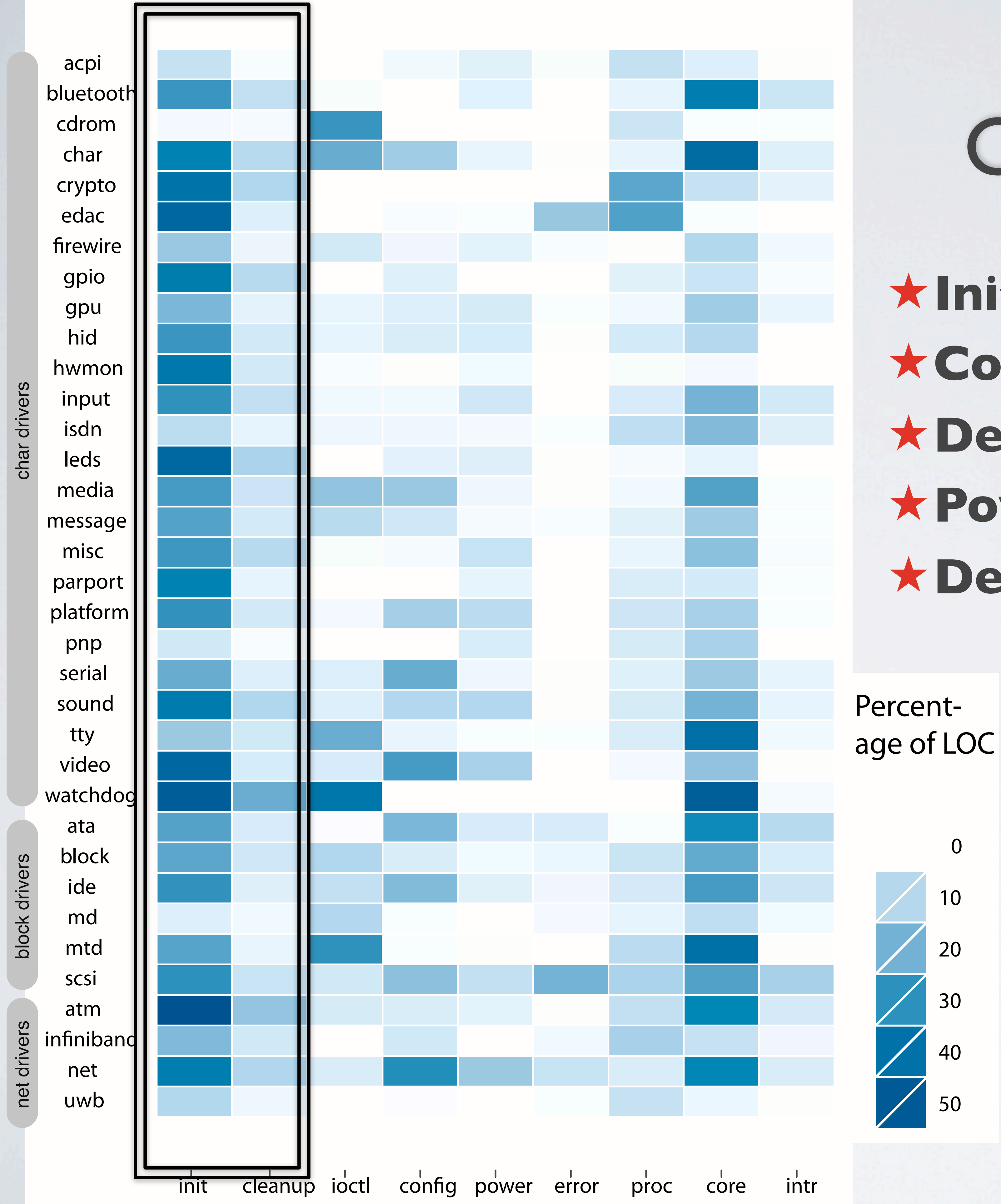

Driver Code Characteristics

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

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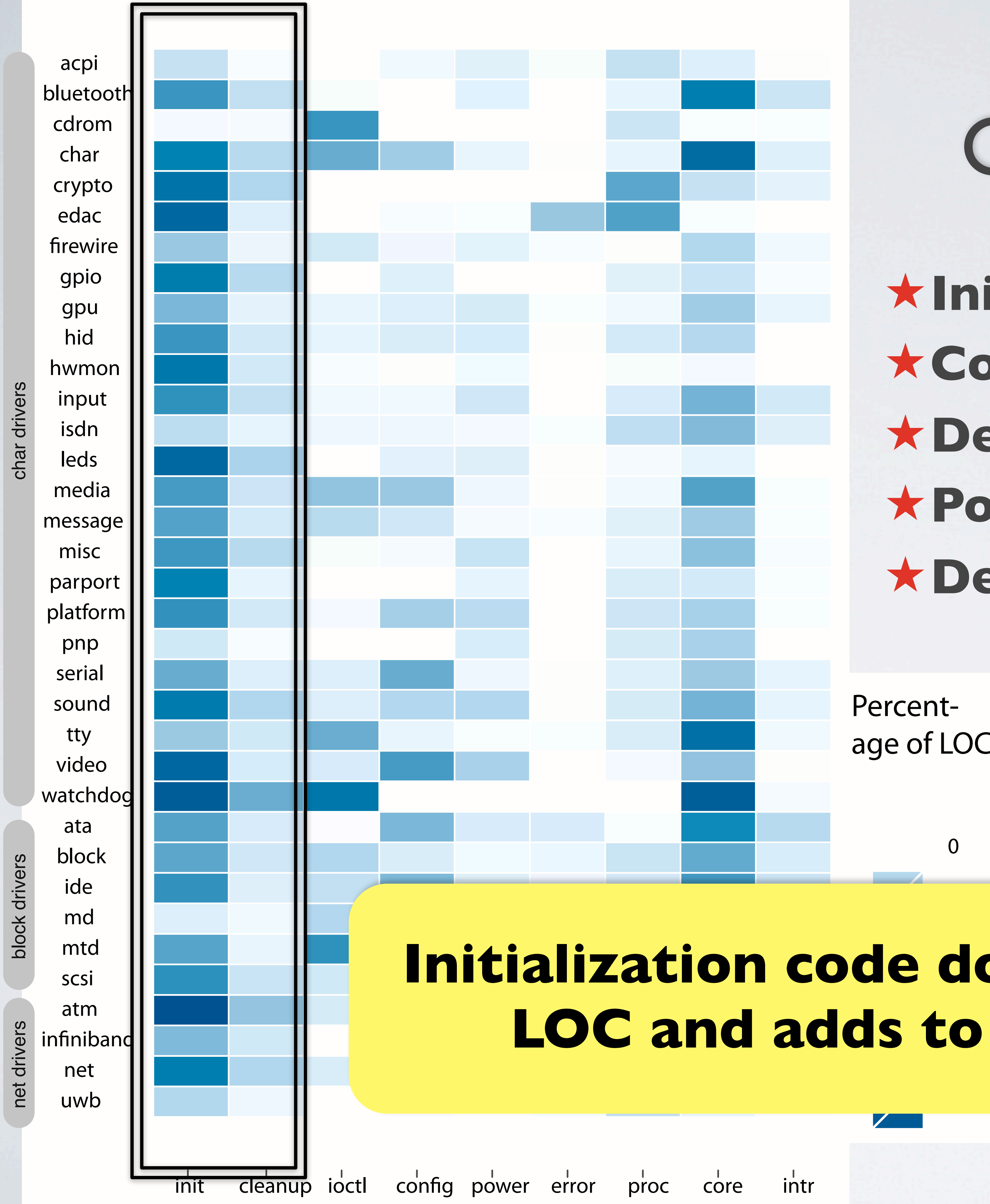

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Initialization code dominates driver LOC and adds to complexity

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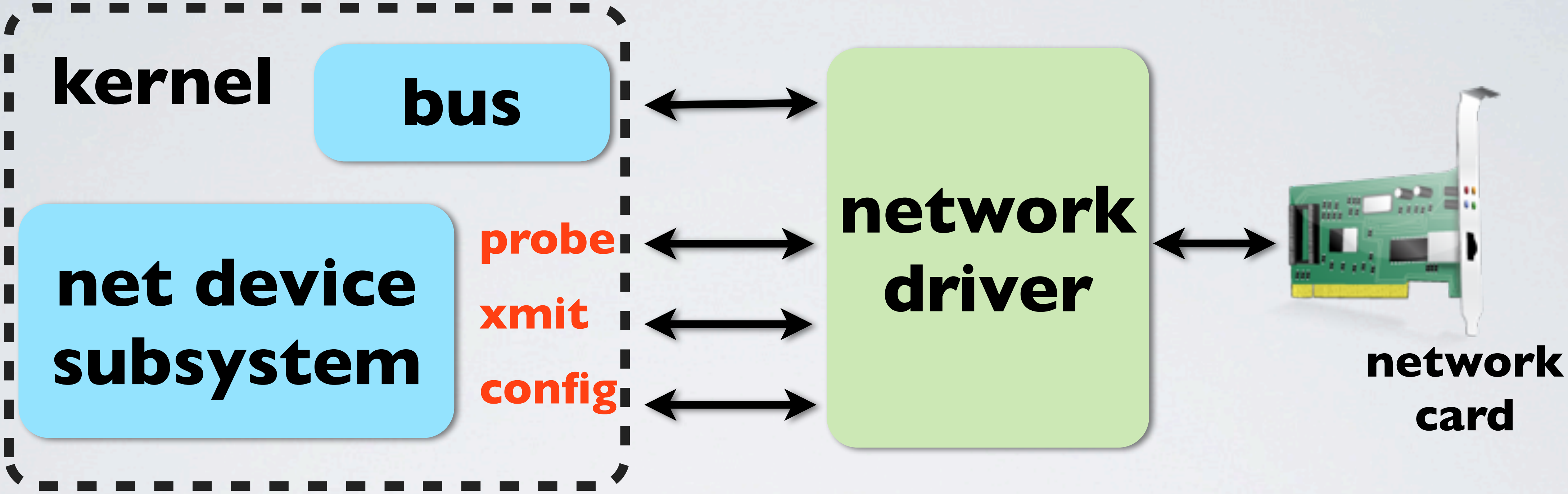
Recovery works by interposing class defined entry points



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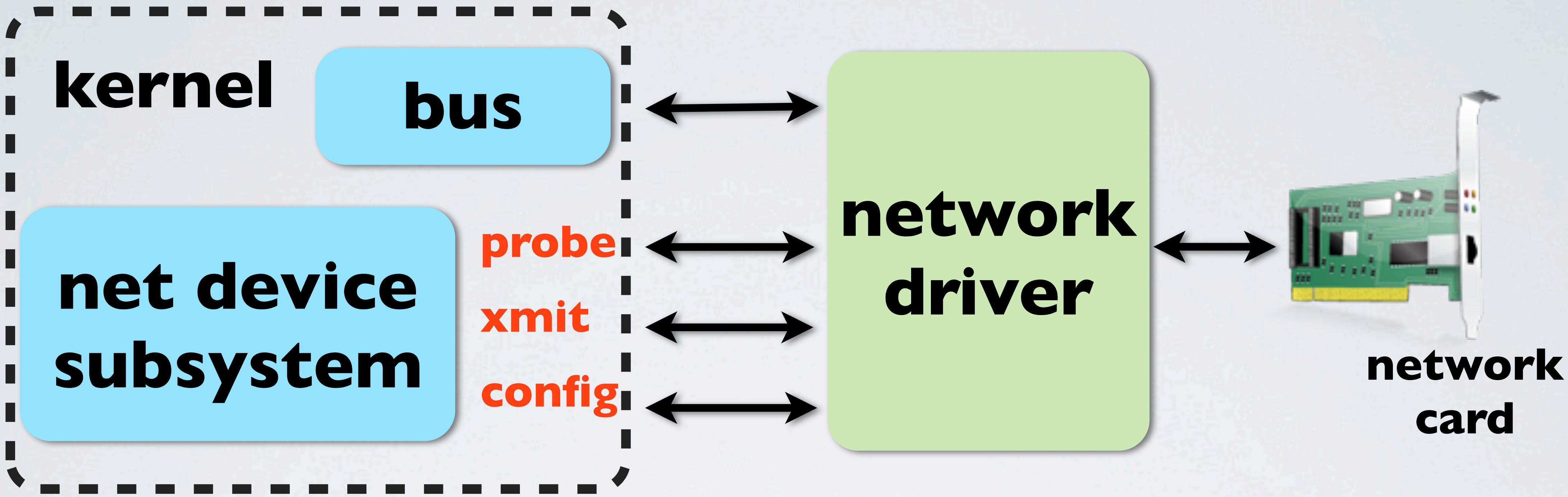

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How many drivers follow class behavior?

Restart/replay doesn't work with all drivers

- **Non-class behavior stems from:**
  - **Load time parameters, procfs and sysfs interactions, unique ioctls**

```
... qlcnic_sysfs_write_esw_config (...)       {
  ...
      switch (esw_cfg[i].op_mode) {
      case QLCNIC_PORT_DEFAULTS:
           qlcnic_set_eswitch_...(...,&esw_cfg[i]);
          ...
      case QLCNIC_ADD_VLAN:
          qlcnic_set_vlan_config(...,&esw_cfg[i]);
          ...
      case QLCNIC_DEL_VLAN:
          esw_cfg[i].vlan_id = 0;
          qlcnic_set_vlan_config(...,&esw_cfg[i]);
          ...
```

Drivers/net/qlcnic/qlcnic_main.c: Qlogic driver(network class)

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Restart/replay doesn't work with all drivers

- **Non-class behavior stems from:**
  - **Load time parameters, procfs and sysfs interactions, unique ioctls**

- **Results as measured by our analyses:**
  - **36% of drivers use load time parameters**
  - **16% of drivers use proc /sysfs support**

- **Overall, 44% of drivers do not conform to class behavior and recovery will not work correctly for these drivers**

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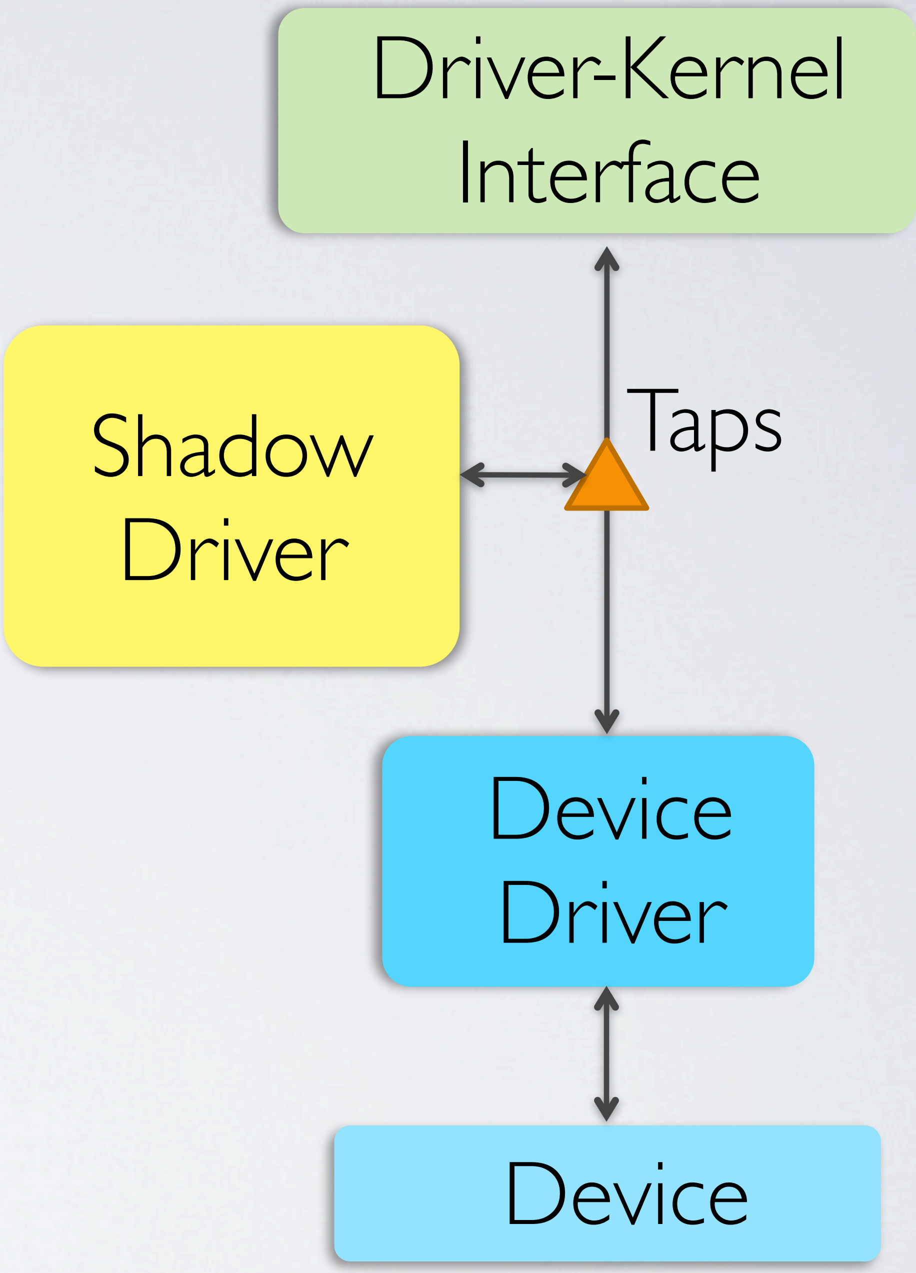
Limitations of restart/replay recovery

- **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 subsystems**



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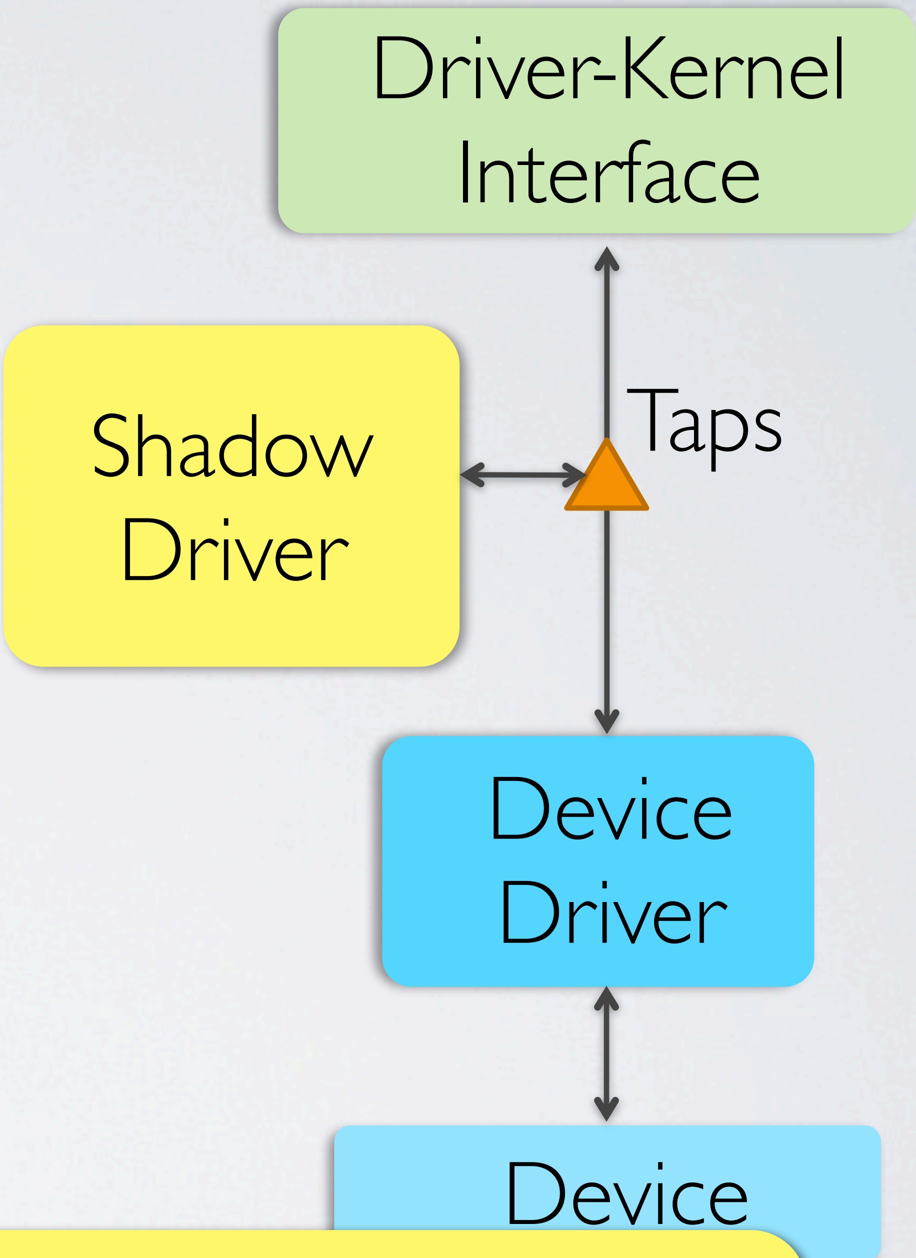

Checkpoint/restore of device and driver state removes the need to reboot device and replay state

Fine-Grained Fault Tolerance (FGFT)

Goal: Fault isolation and recovery system based on "pay as you go" failure model

Fine-Grained Isolation

- **Ability to run select entry points as transactions**

Checkpoint based recovery

- **Provides fast and correct recovery semantics**

- **Requires incremental changes to drivers and has low overhead**

Outline

Introduction

Fine-grained isolation

Checkpoint based recovery

Conclusion

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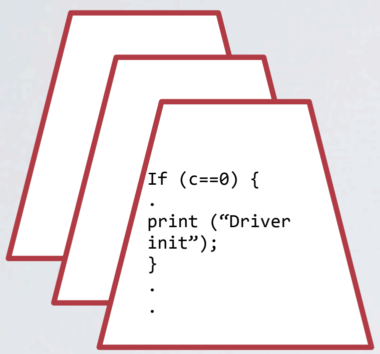
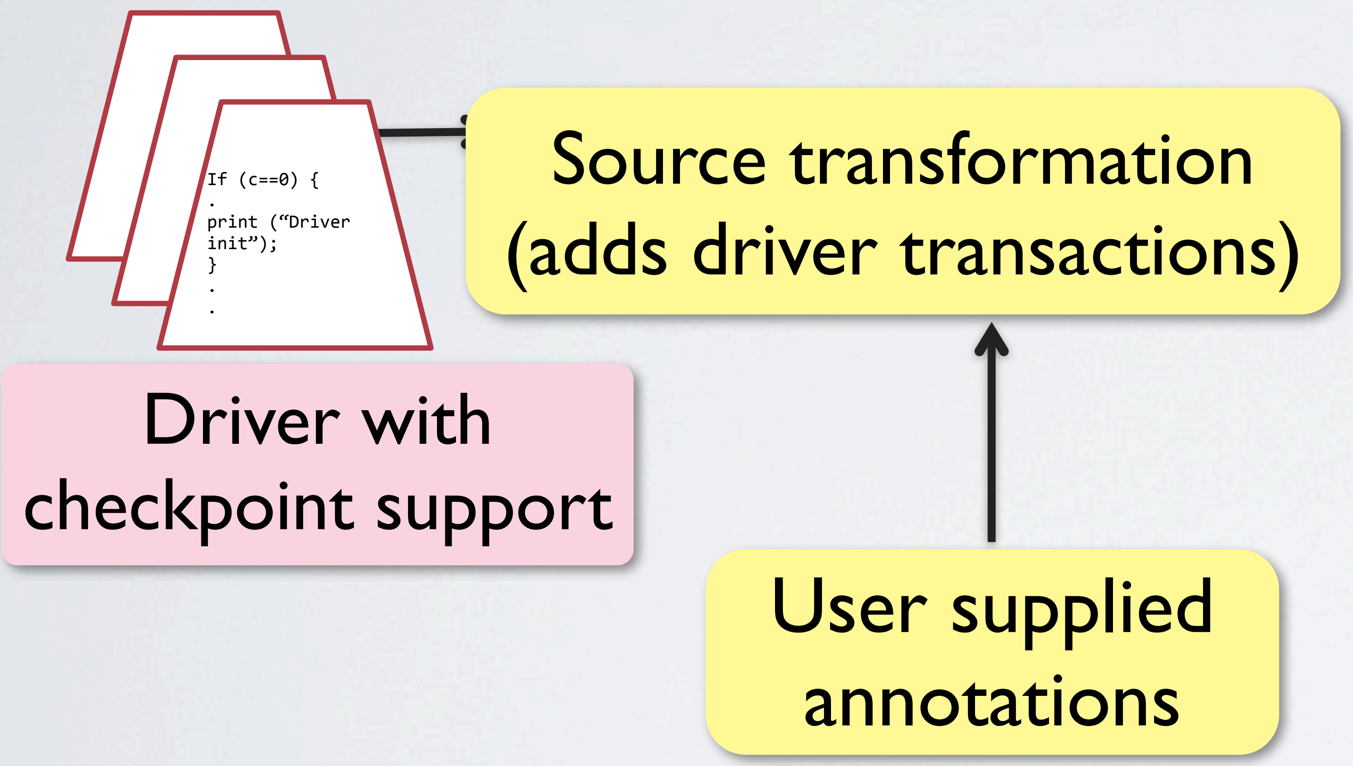
FGFT overview



Driver with checkpoint support

Static modifications

FGFT overview



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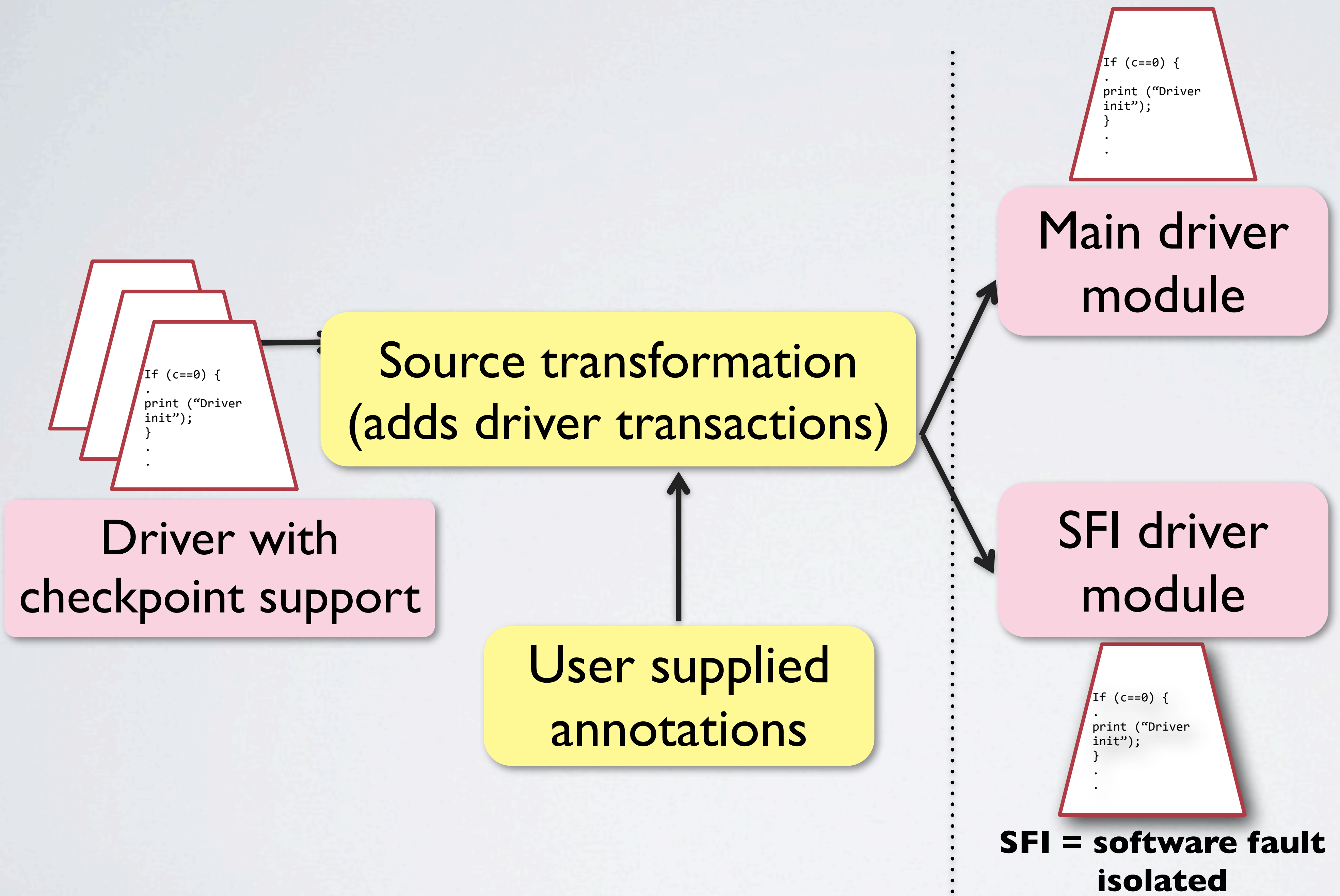

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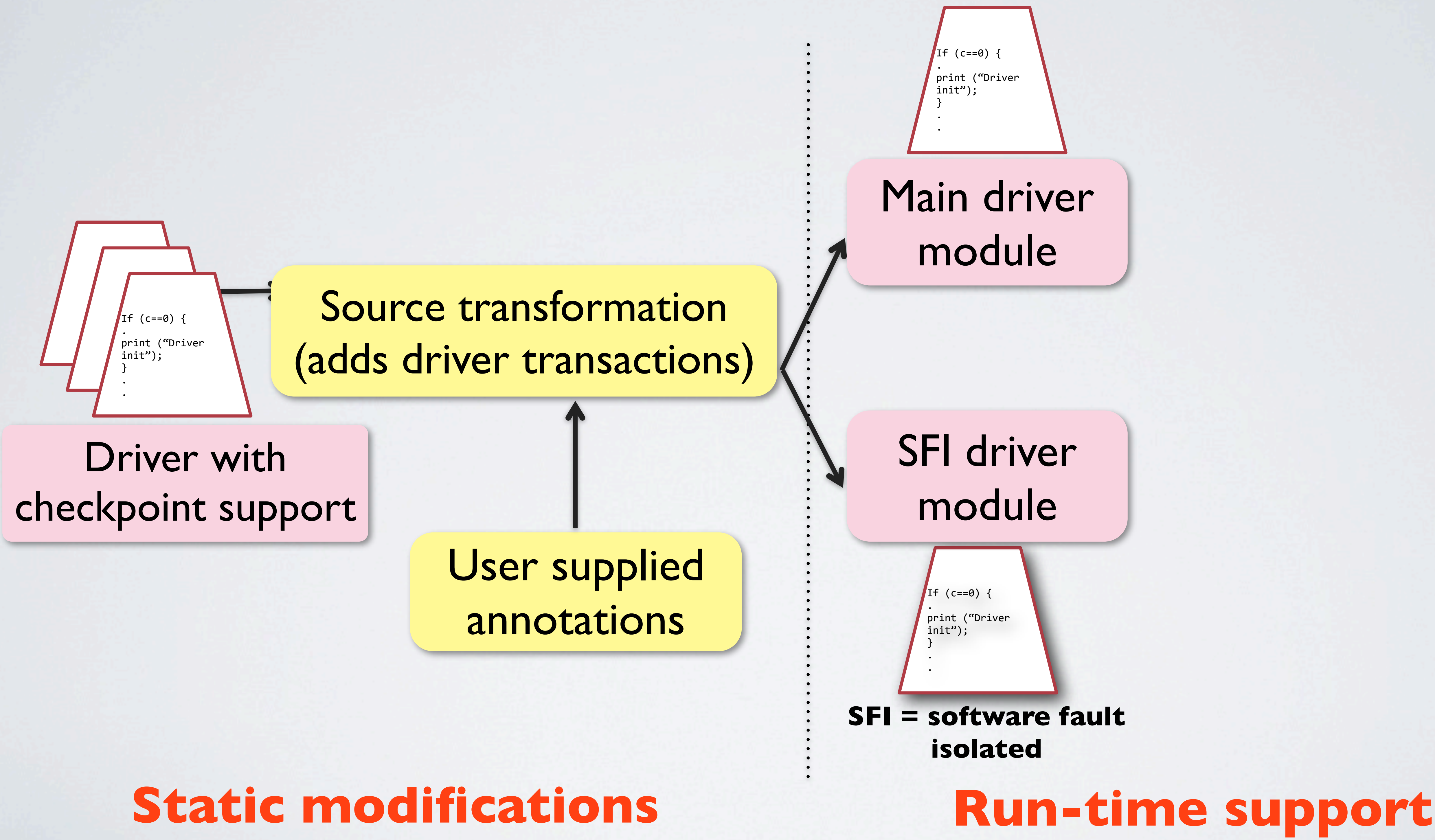

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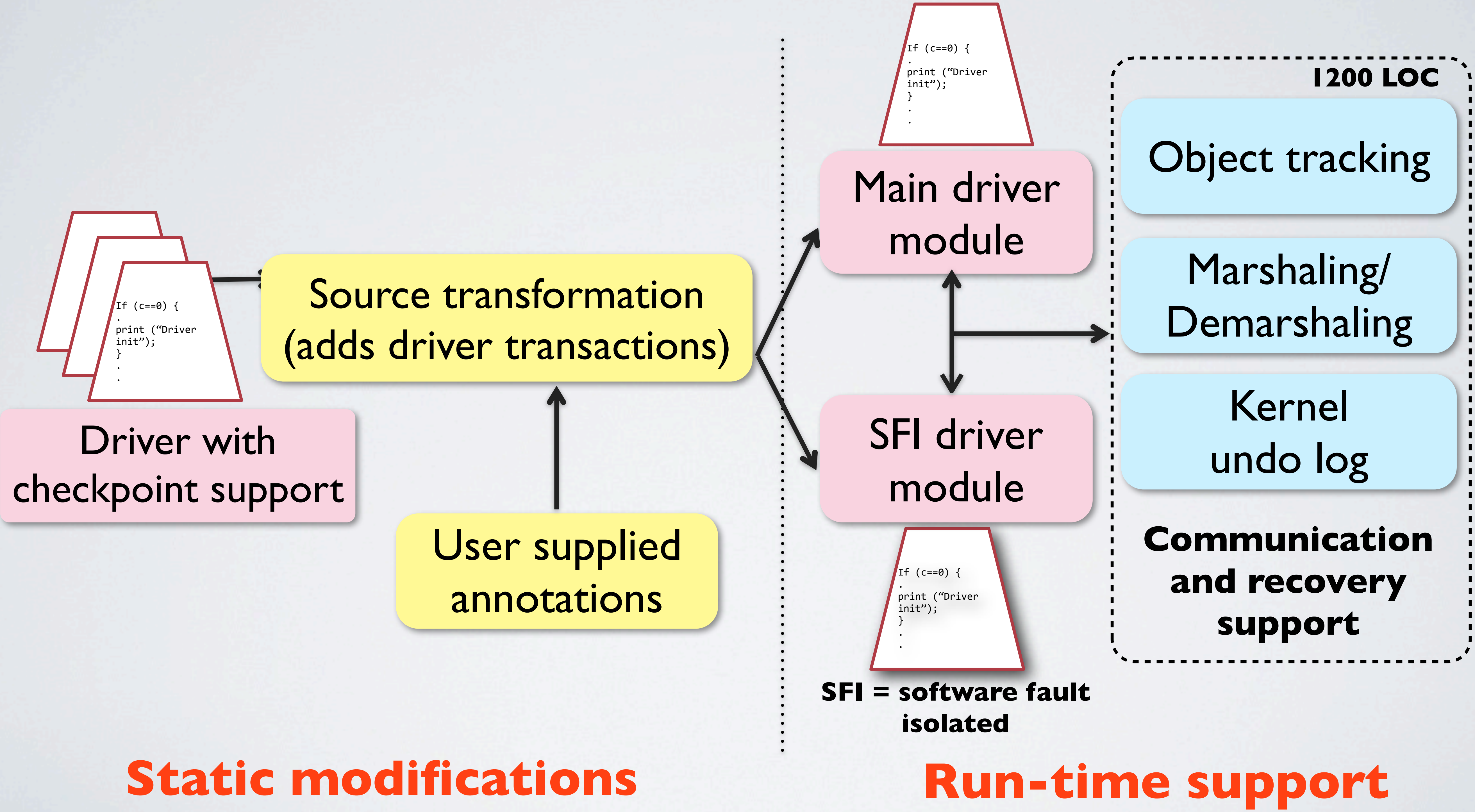
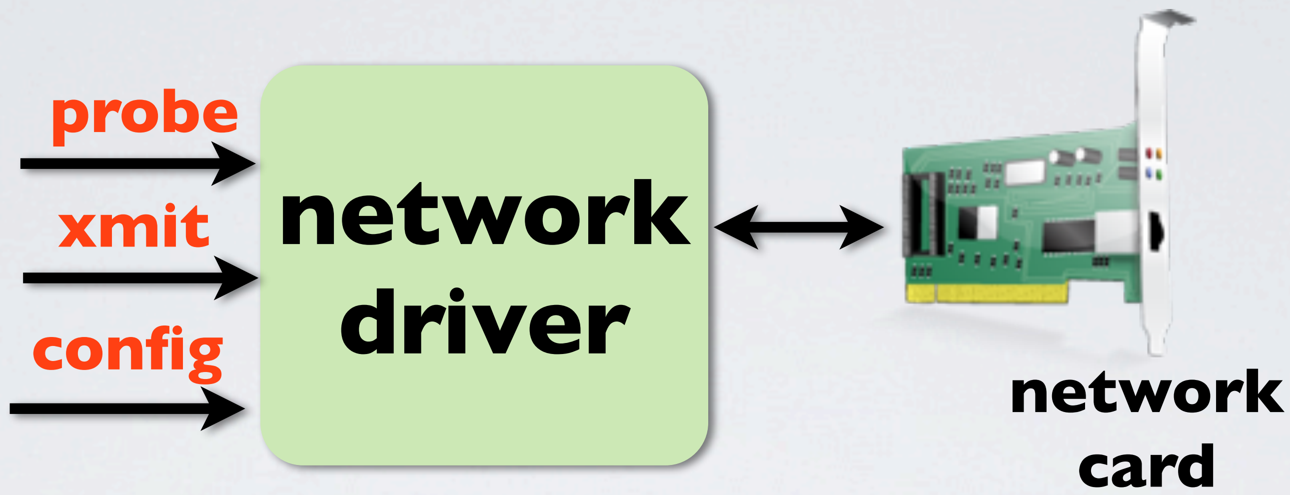


Fault model in FGFT



- Can be applied to untested code, statically and dynamically detected suspicious entry points
- Detect and recover from:
  - Memory errors like NULL pointer accesses
  - Structural errors like malformed structures
  - Processor exceptions like divide by zero, stack corruption

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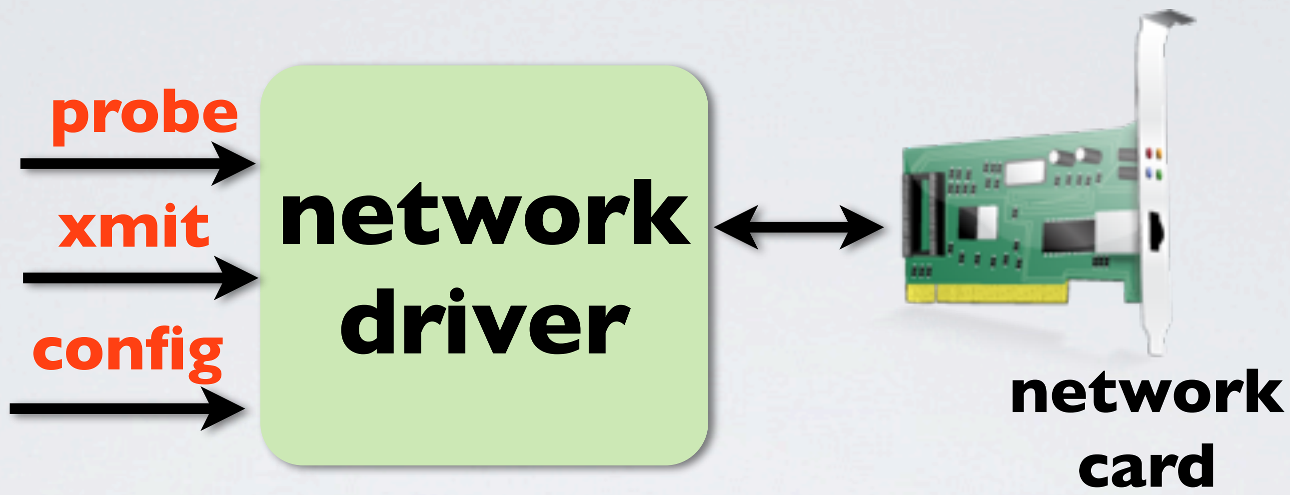

- ★ **Provide fault tolerance to specific driver entry points**
- ★ **Can be applied to untested code, statically and dynamically detected suspicious entry points**
- ★ **Detect and recover from:**
  - ★ **Memory errors like NULL pointer accesses**
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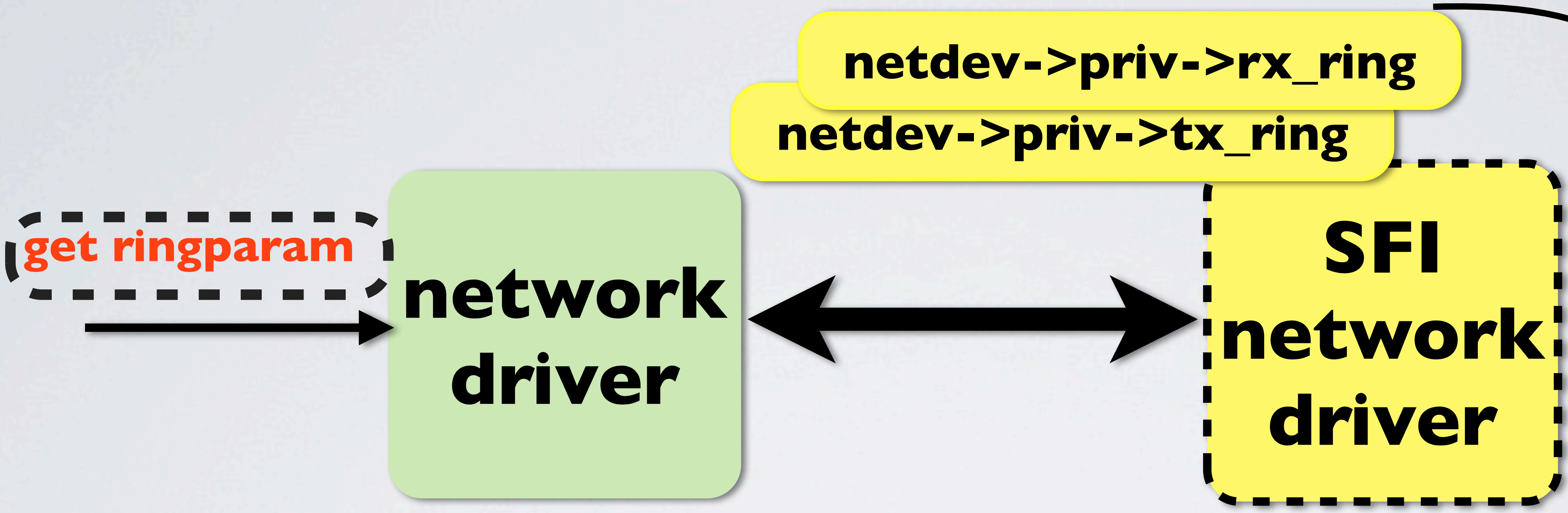
Transactional support through code generation



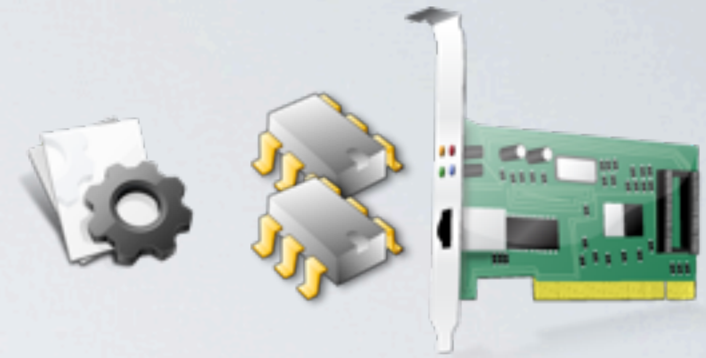
Range Table

Address	Access rights
oxffffaooo	Read
oxffffaoo8	Write
oxffffaooa	Read

- ★ **Generate code to run driver invocations on a separate stack with a copy of parameters**
- ★ **Reduce copy overhead by copying only referenced fields in driver and kernel structures to a range table**
- ★ **Instrument all memory references in SFI module to compare accesses against copied fields in range table**

Resource access during isolated execution

- Device registers and I/O memory
  - Grant drivers full access to devices
  - Restore device checkpoint in case of failure



- Locks: Spinlocks and semaphores
  - Grants read access to locks
  - Maintain kernel log of locks acquired
  - Release locks at the end of entry point/failures

- Kernel resources like memory
  - All allocations generate range table entry
  - Maintain kernel log of all acquired resources
  - Free resources on failures

`malloc ()` →

Range Table

Address	Access rights
0xffffa000	Read
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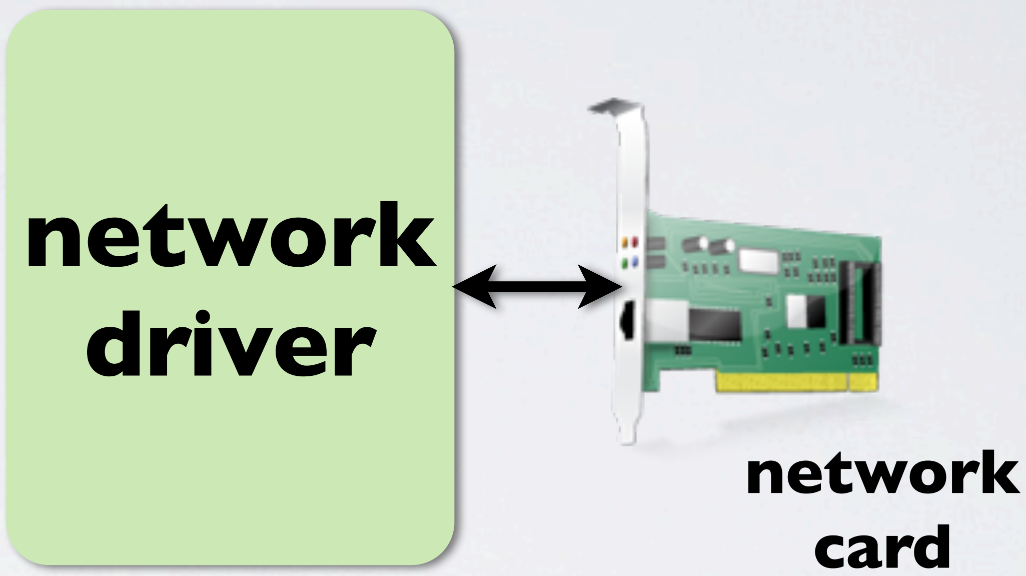
Checkpointing drivers is hard

★ **Existing mechanisms limited to capturing memory state**



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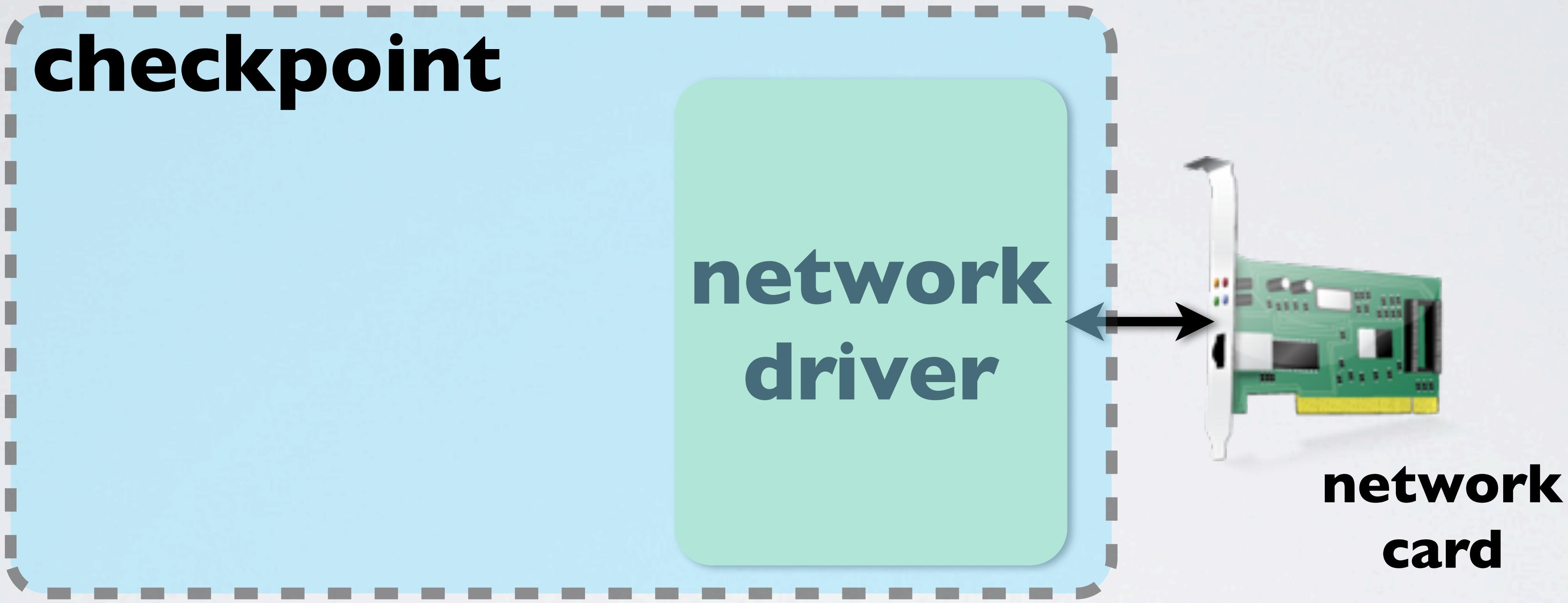

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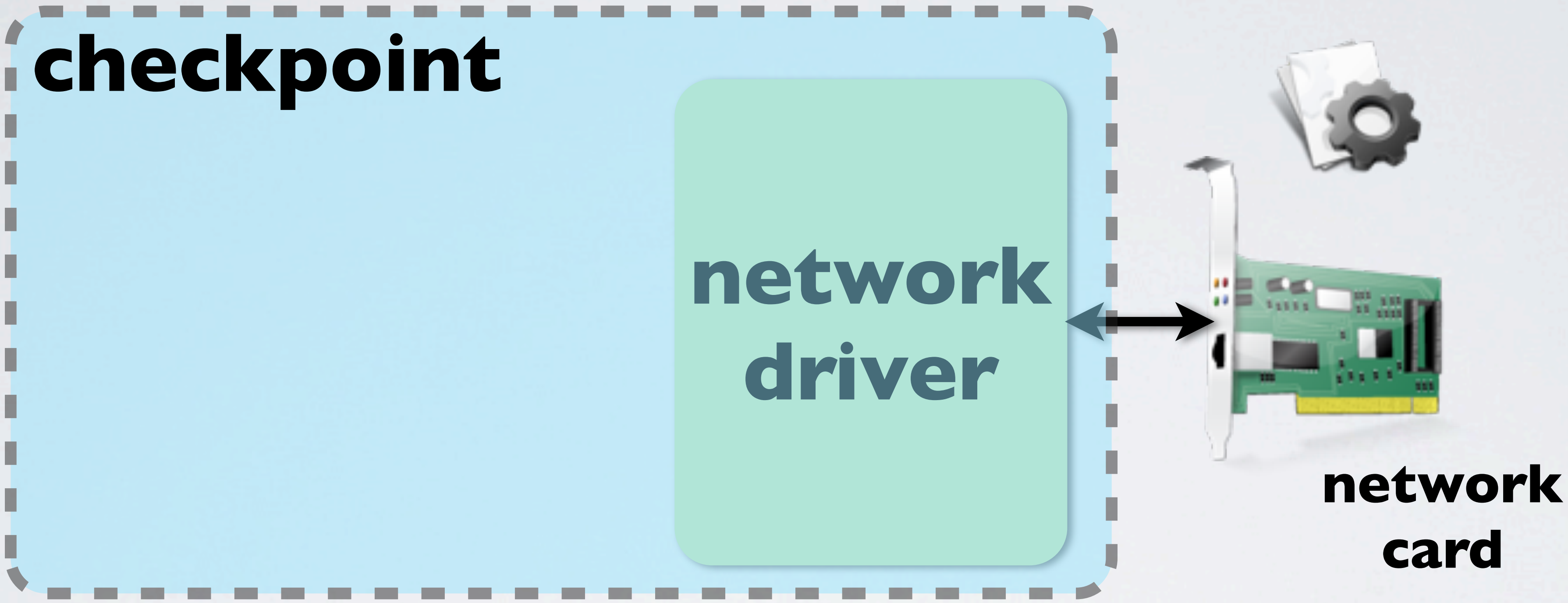

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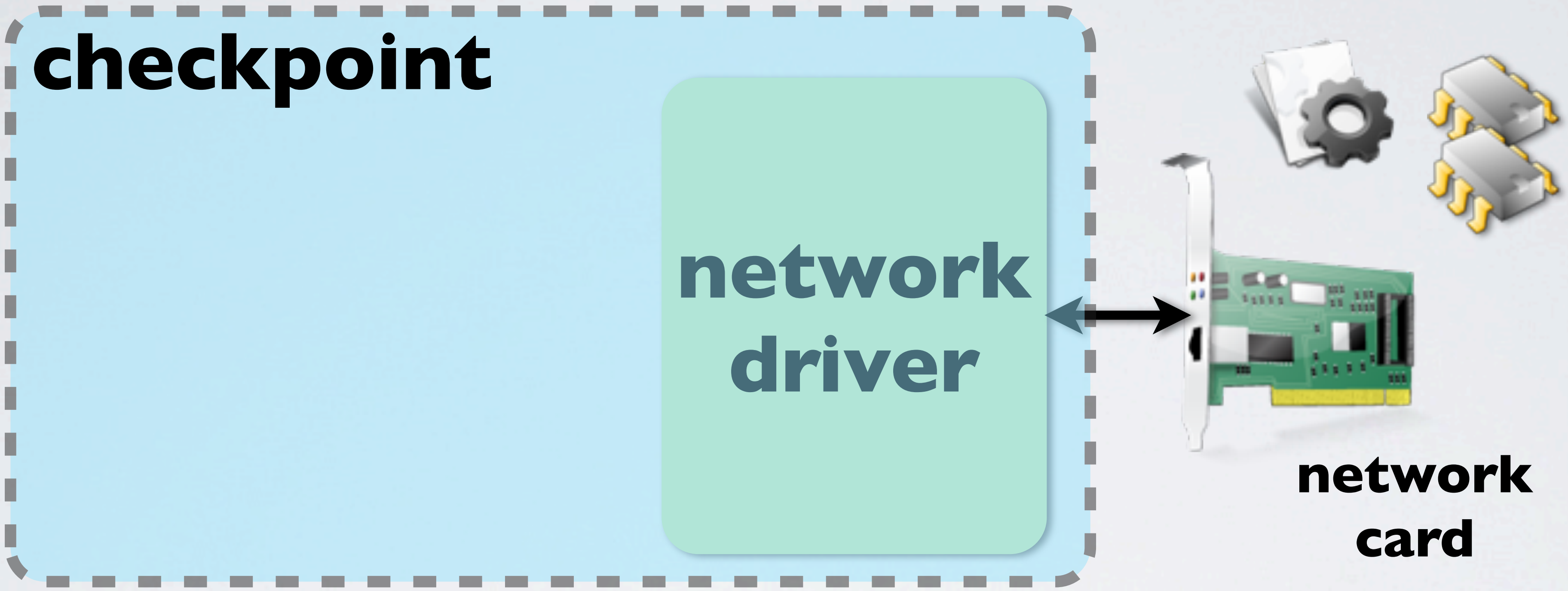

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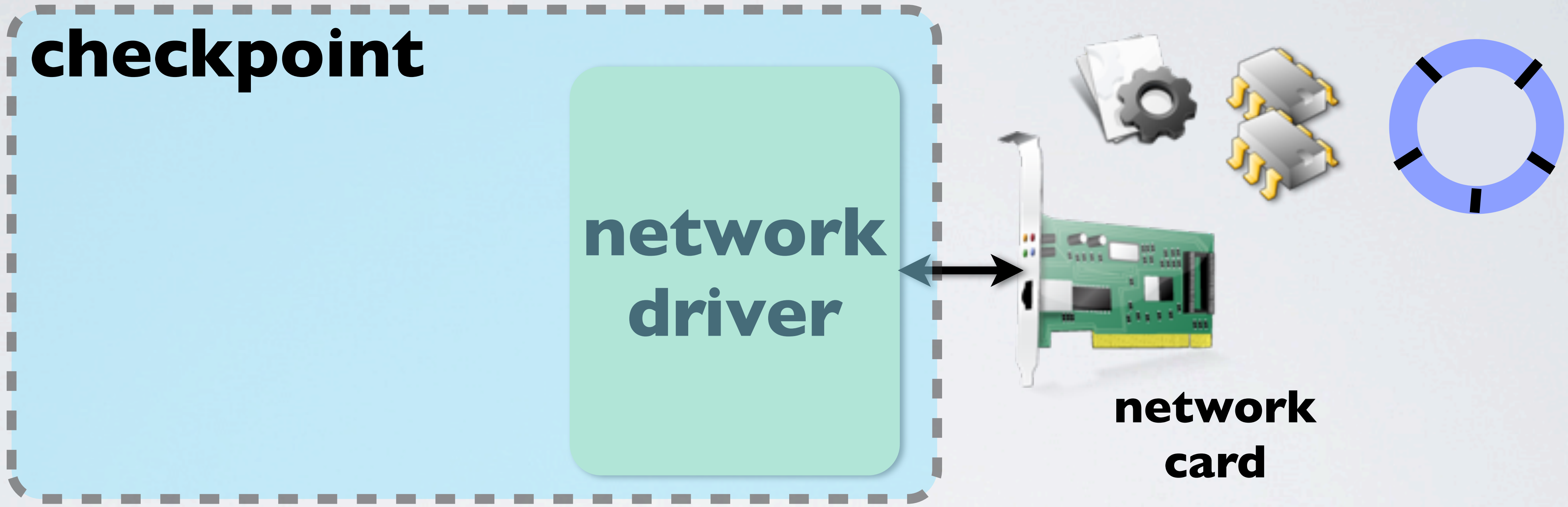

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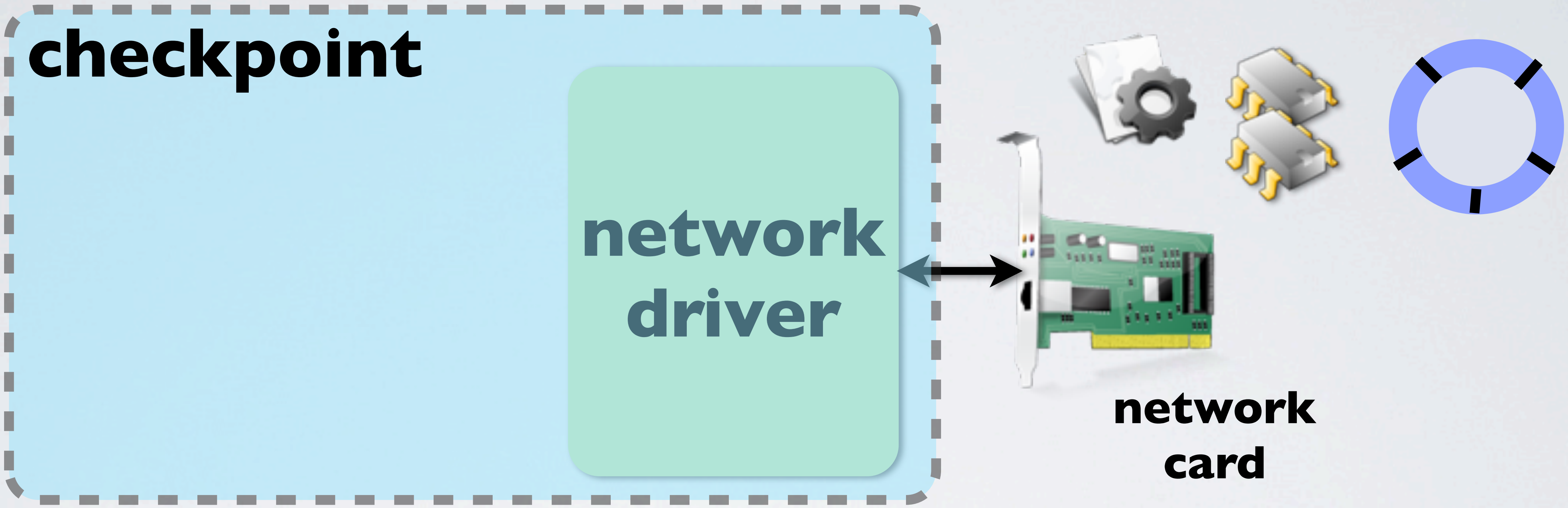

★ Device state is not captured

- ★ Device configuration space
- ★ Internal device registers and counters
- ★ Memory buffer addresses used for DMA
- ★ Unique for every class, bus and vendor

Device checkpoint/restore from PM code

Suspend	Resume
Save config state	Restore config state
Save register state	Restore register state
Disable device	Restore s/w state & reset
Copy-out s/w state	Re-attach/Enable device
Suspend device	Device Ready

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Suspend/resume code provides device checkpoint functionality

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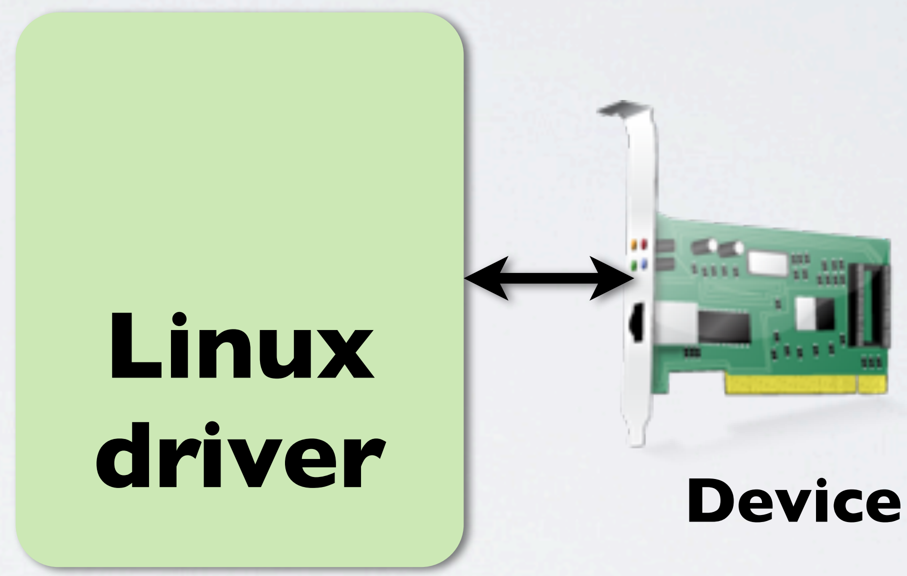

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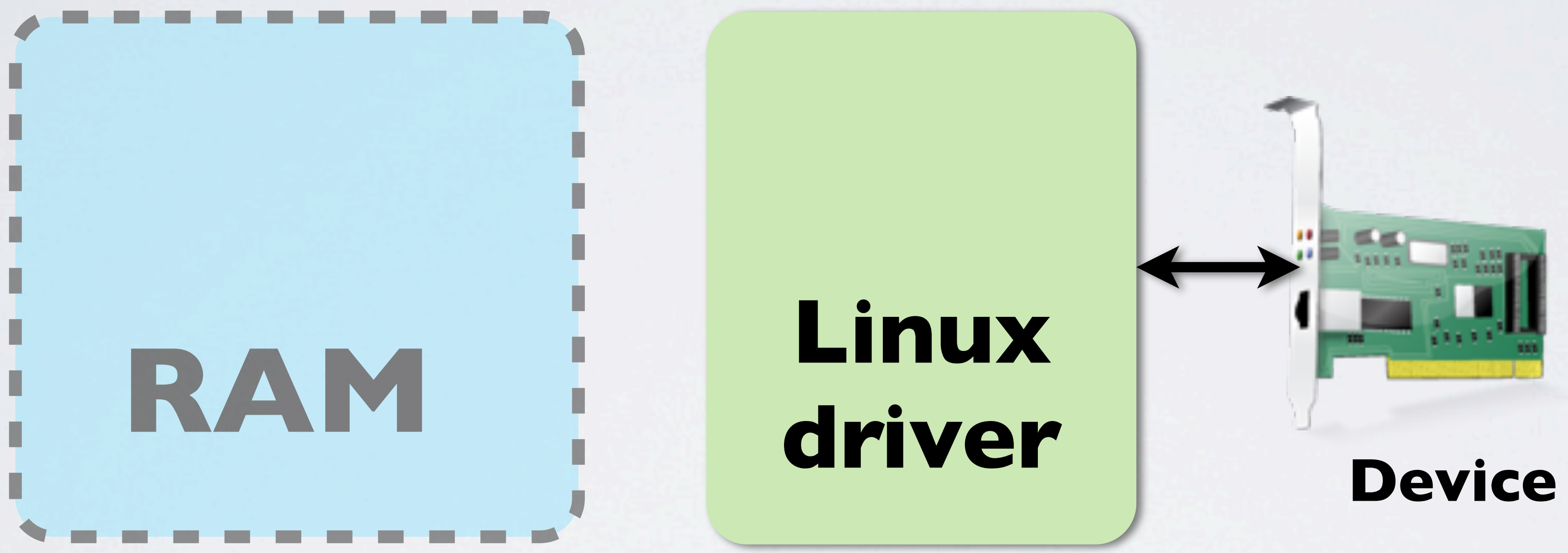

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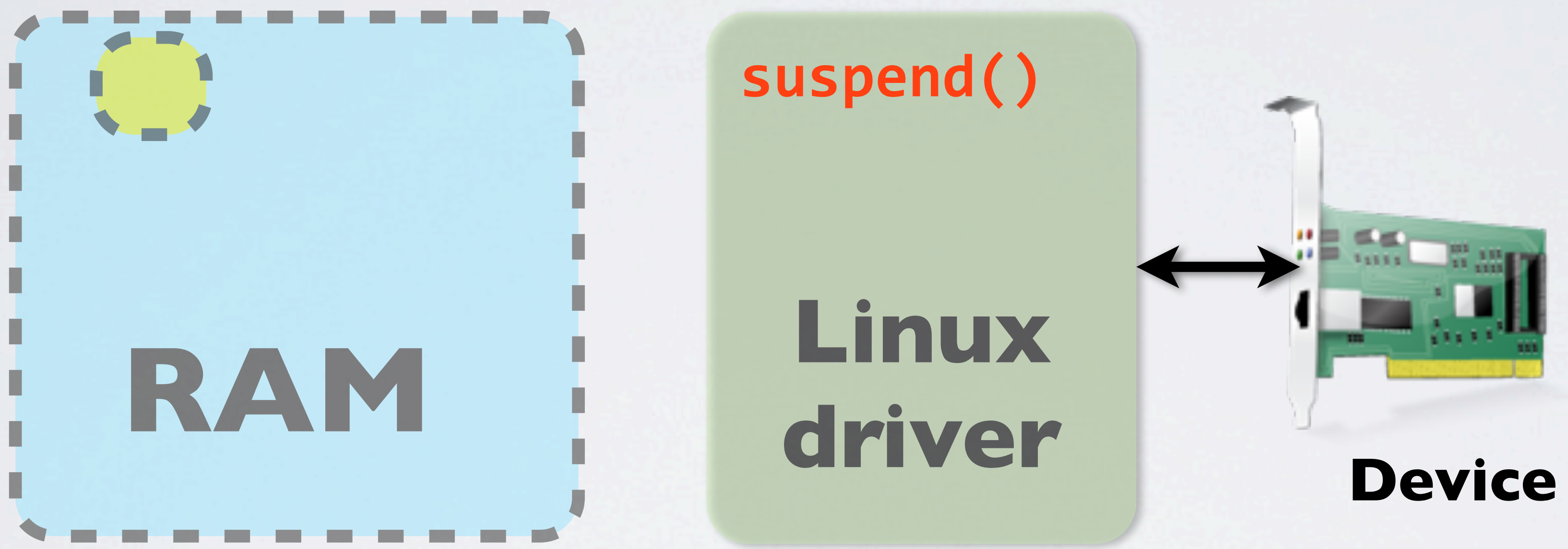

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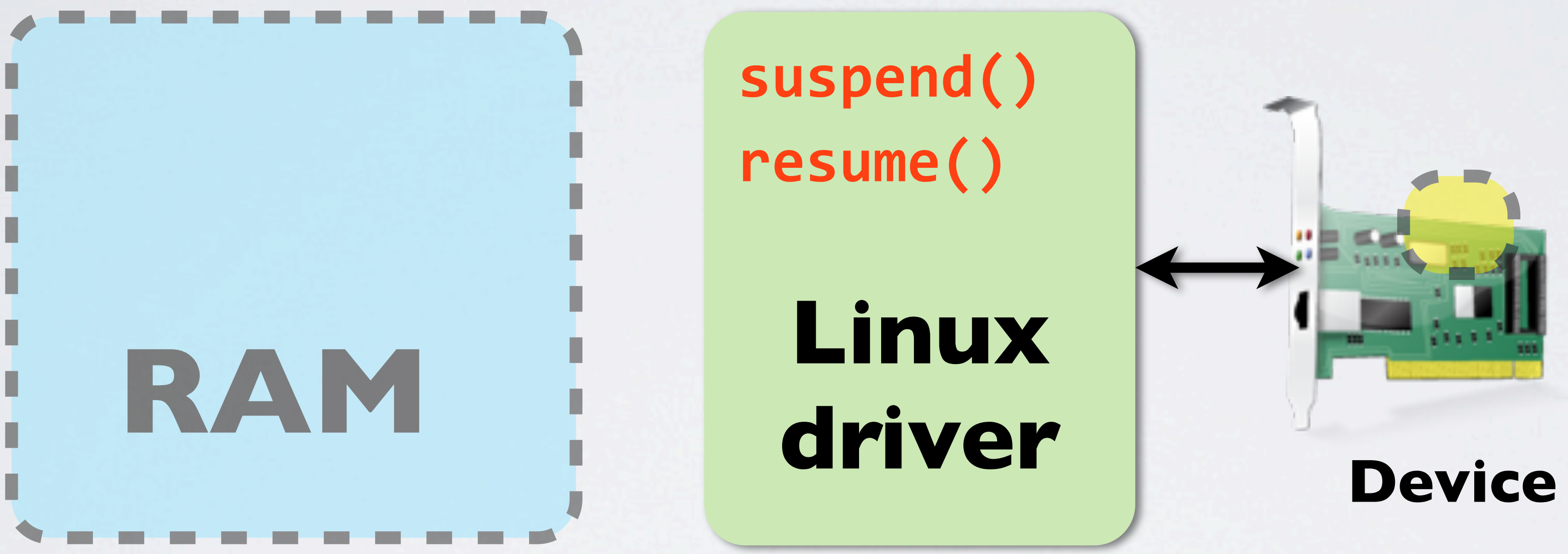

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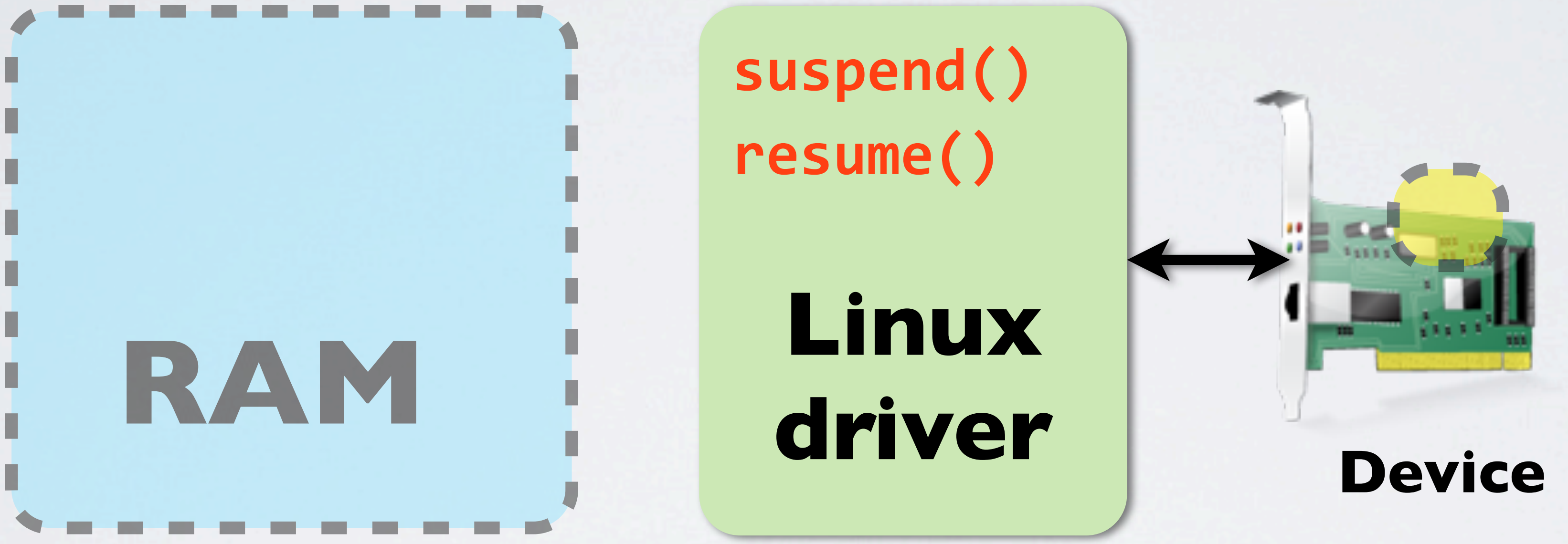

- **Refactor power management code for device checkpoints**
  - **Correct: Developer captures unique device semantics**
  - **Fast: Avoids probe and latency critical for applications**

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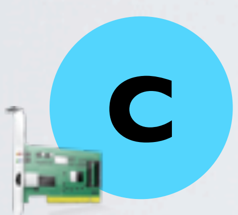

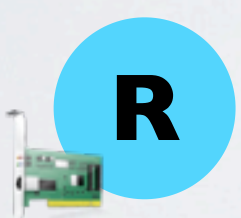

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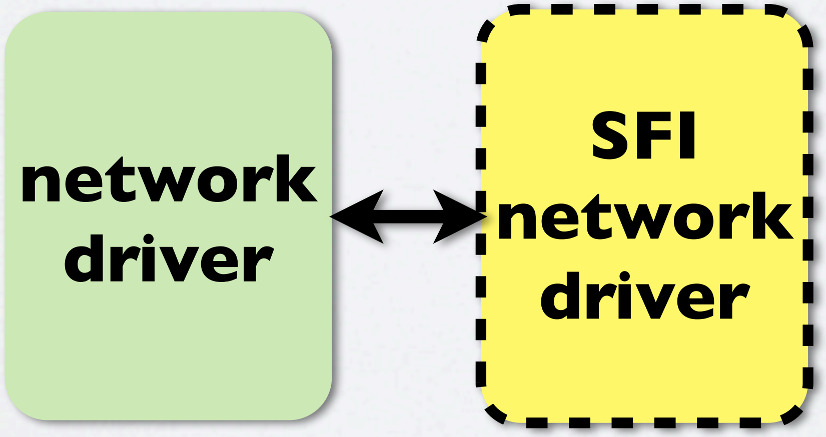

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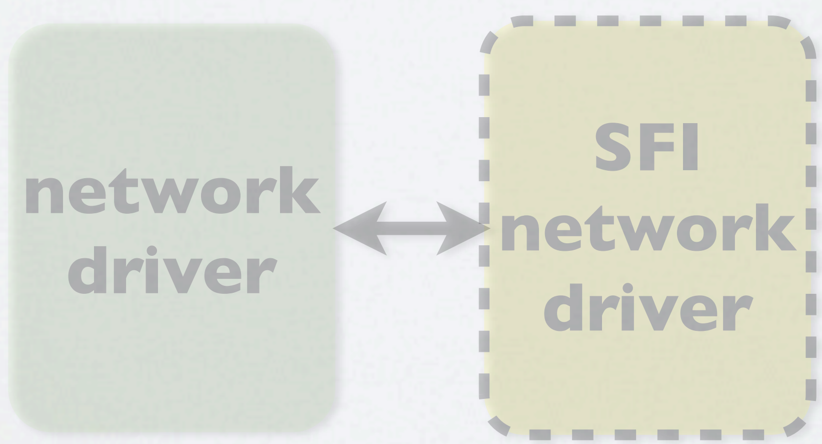
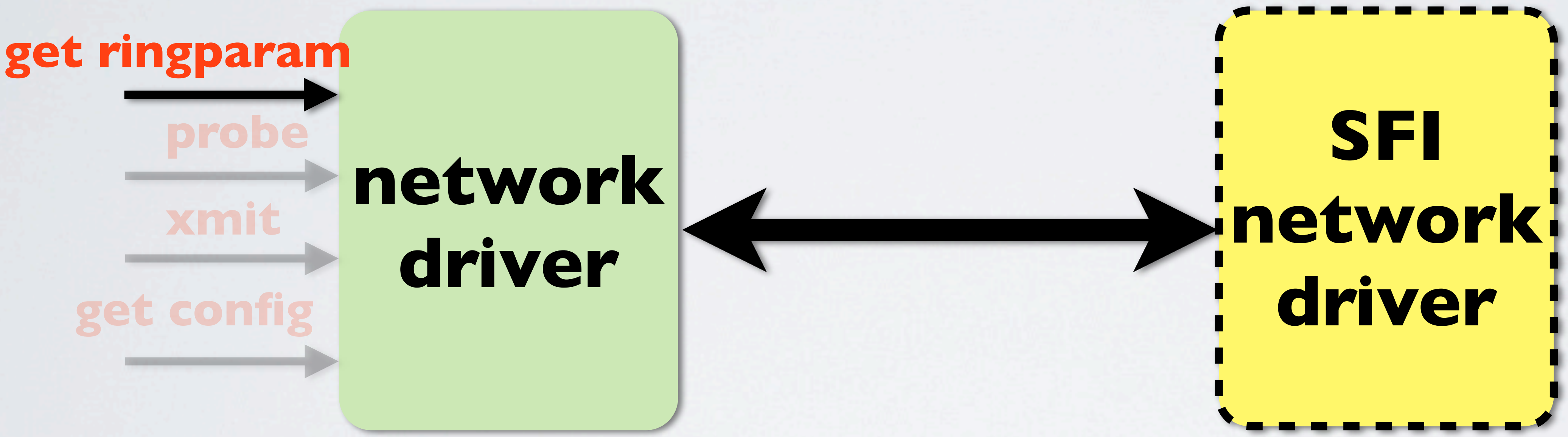


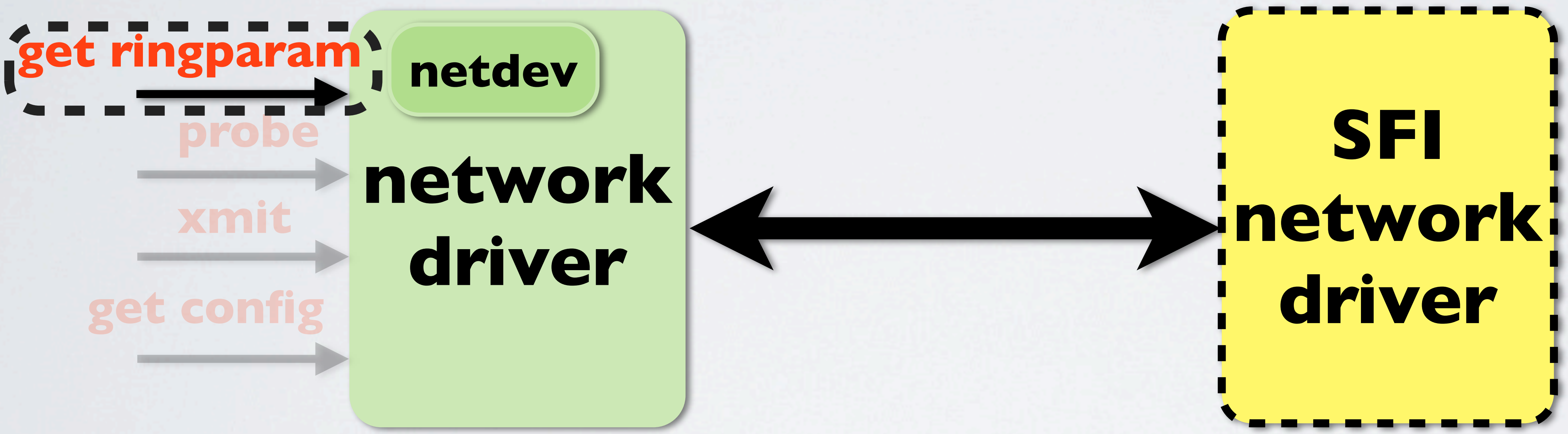
Execution model

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

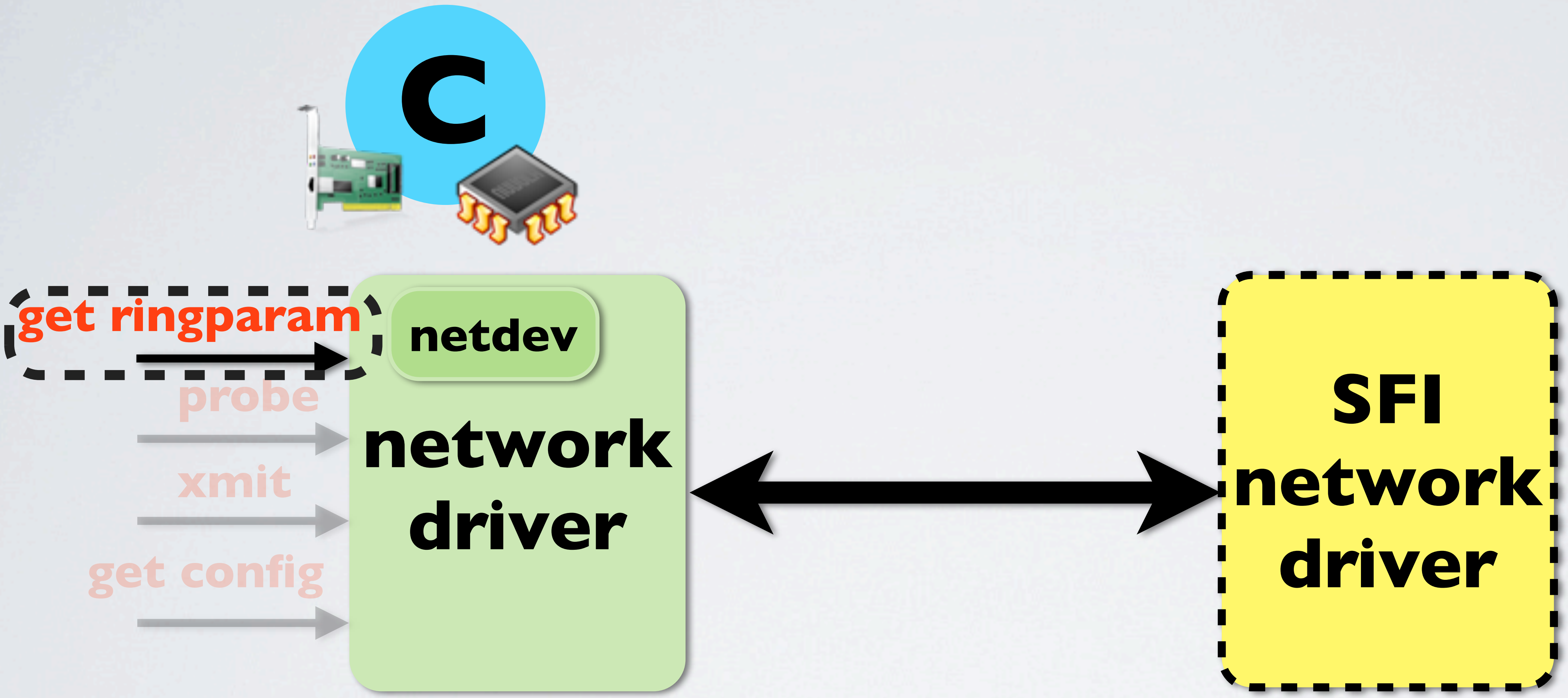
Example transactional execution



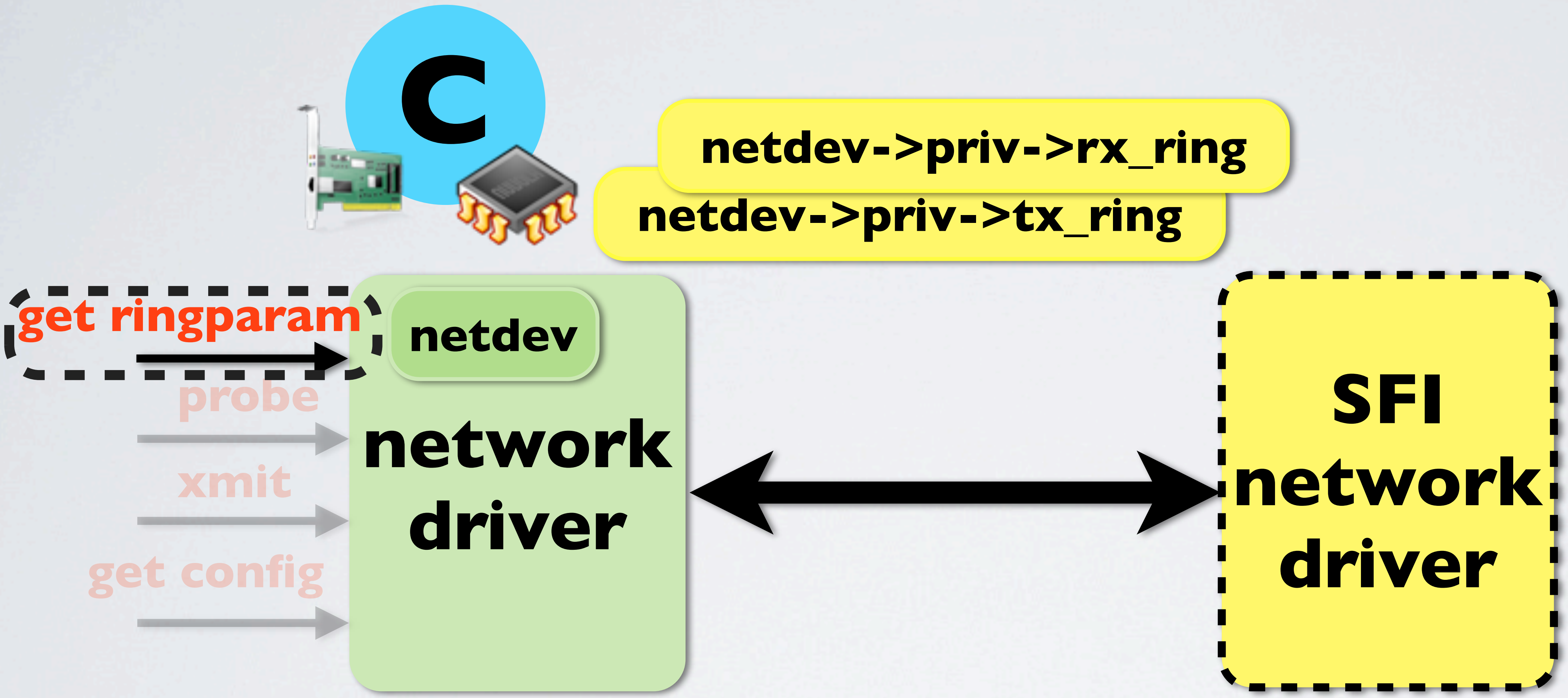
Example transactional execution



Example transactional execution



Example transactional execution



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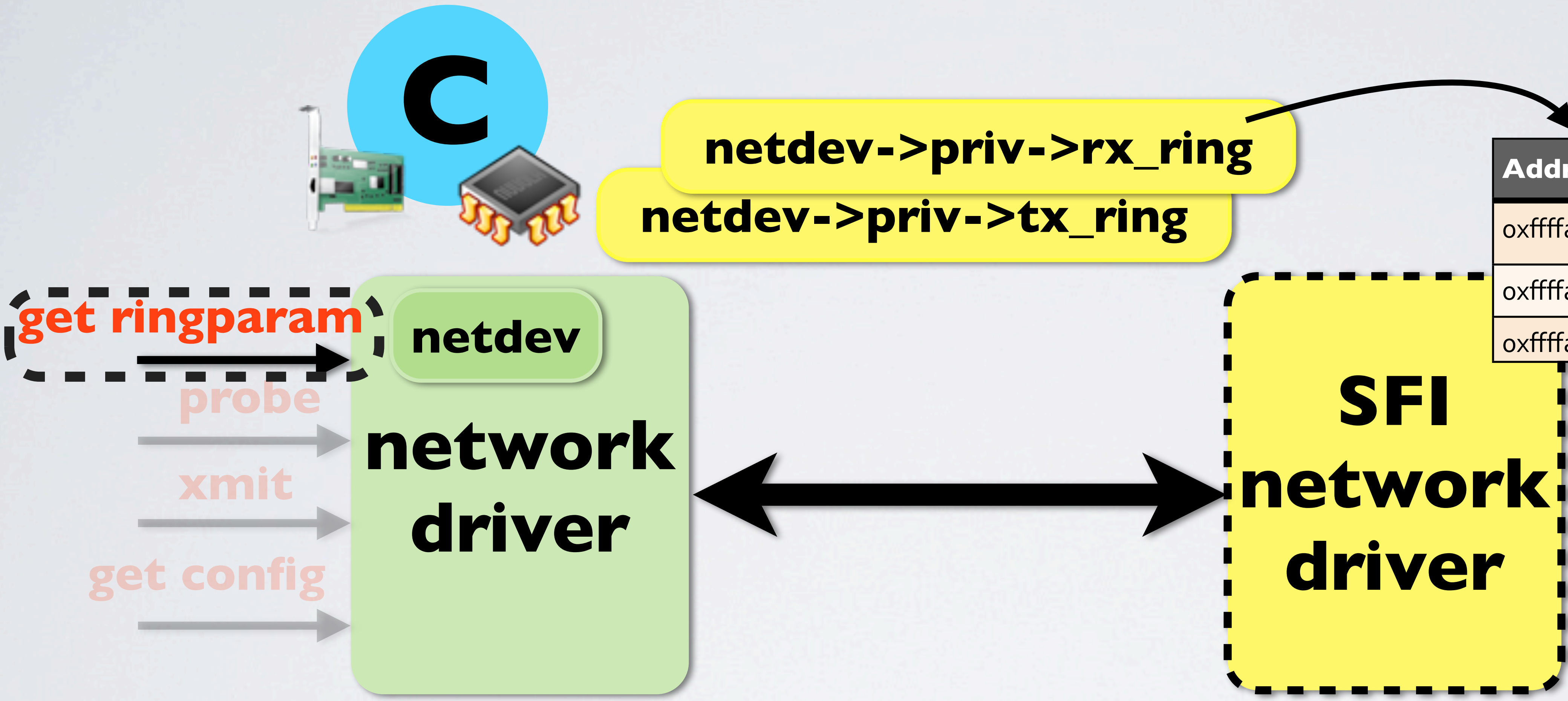
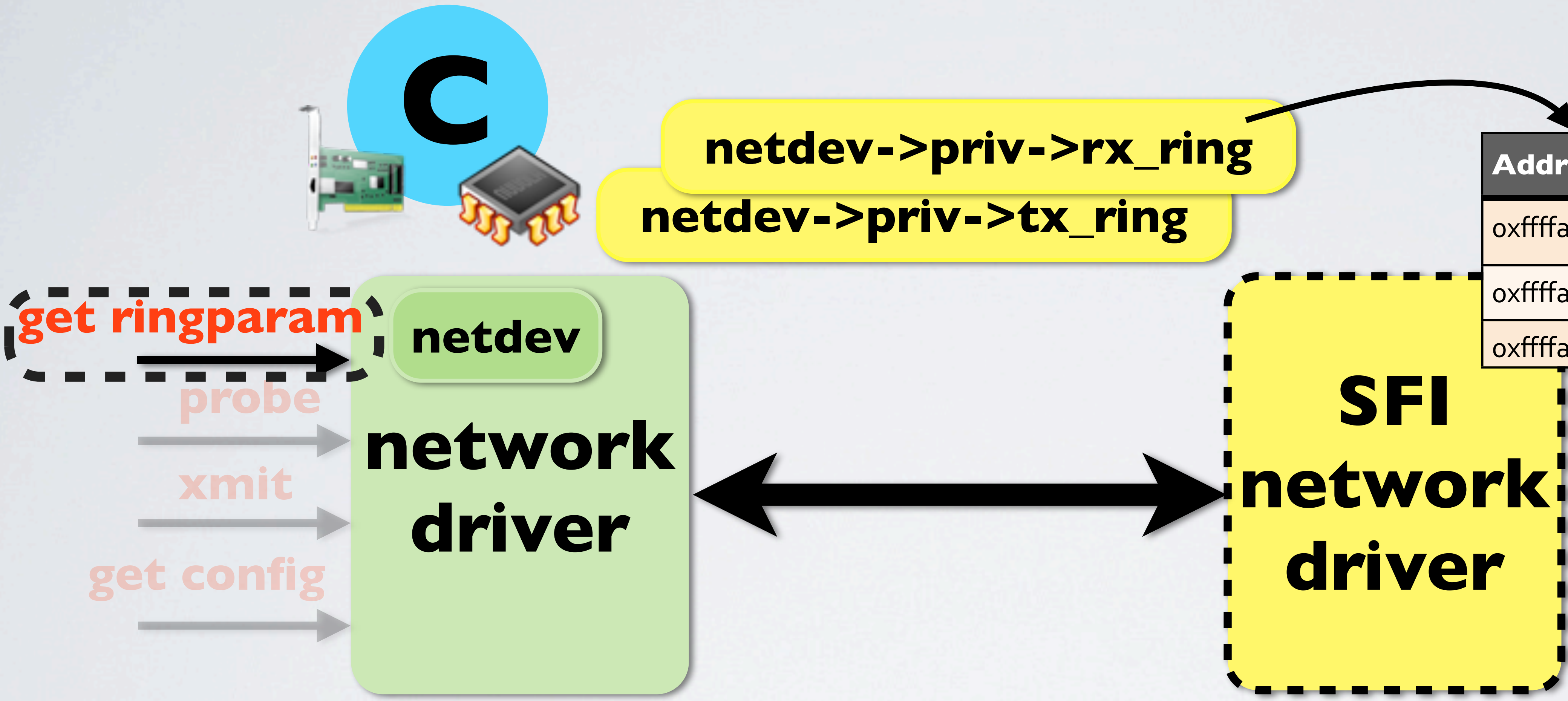


Range Table

Address	Access rights
oxffffaooo	Read
oxffffaoo8	Write
oxffffaooa	Read

Example transactional execution



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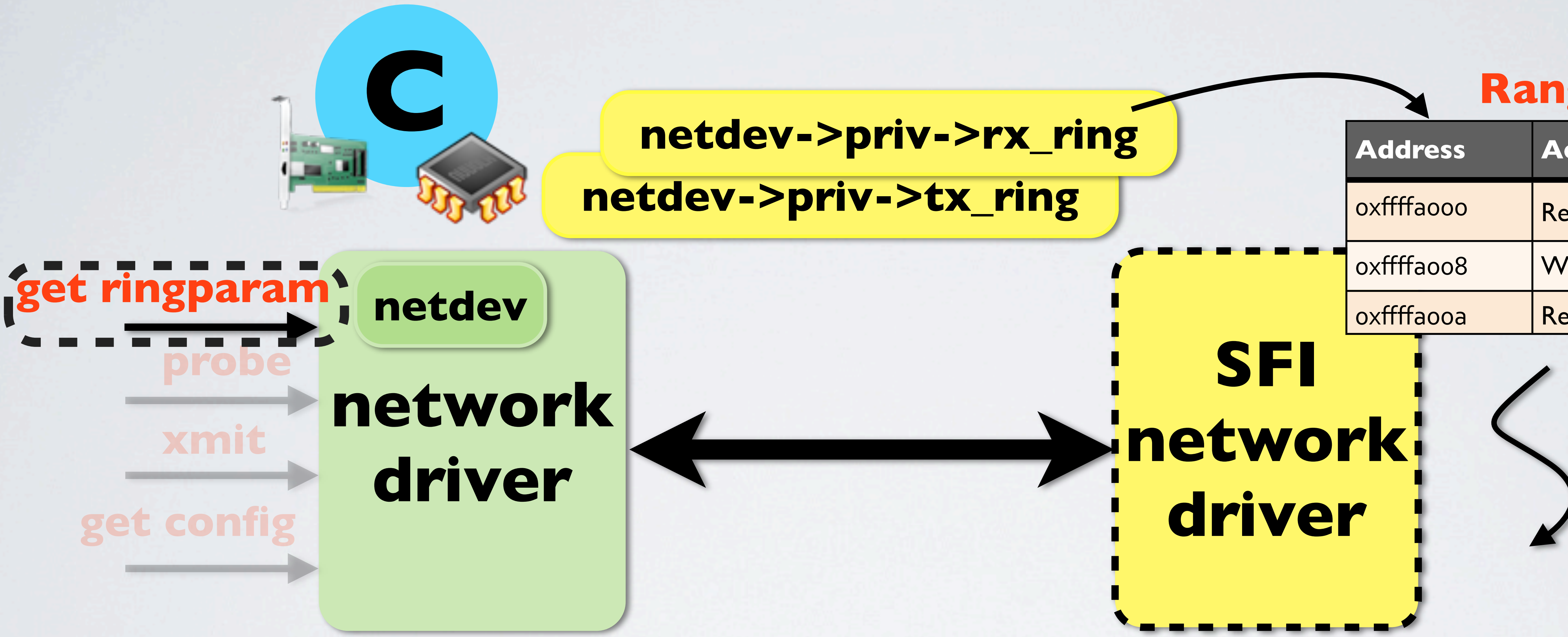

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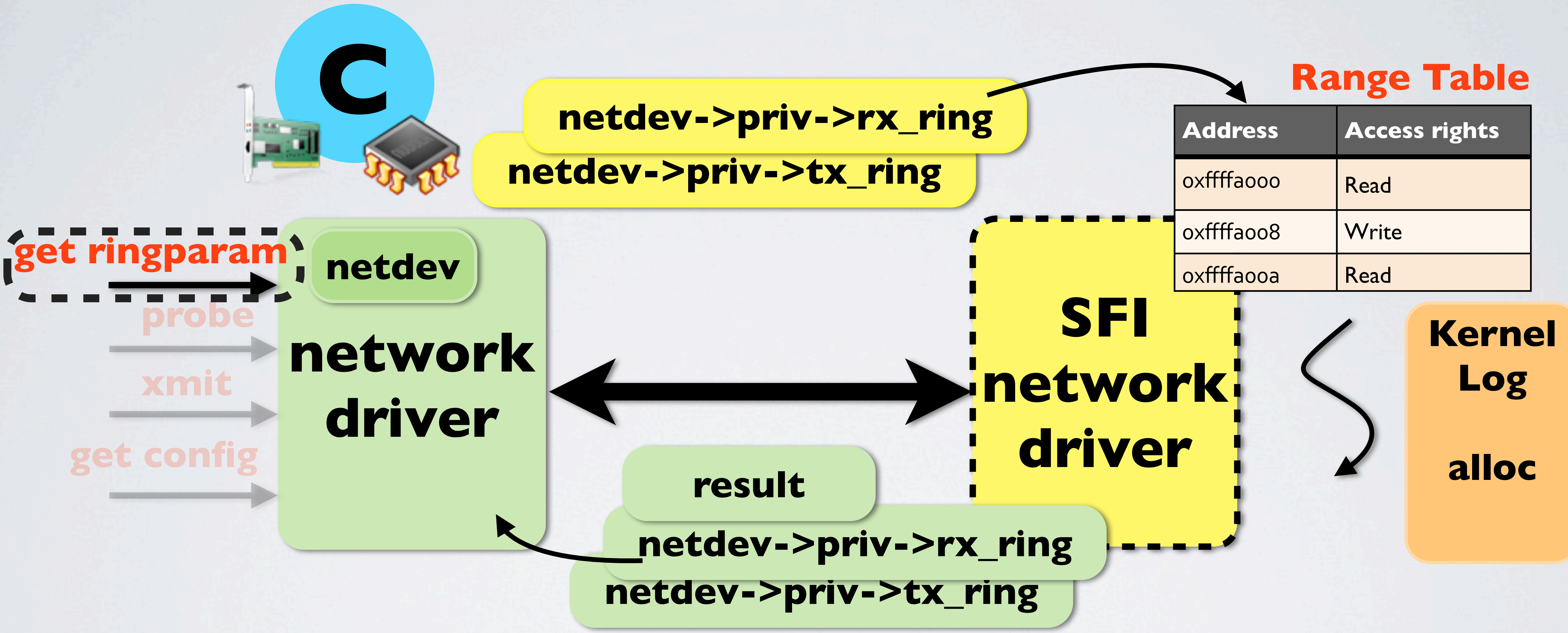

Address	Access rights
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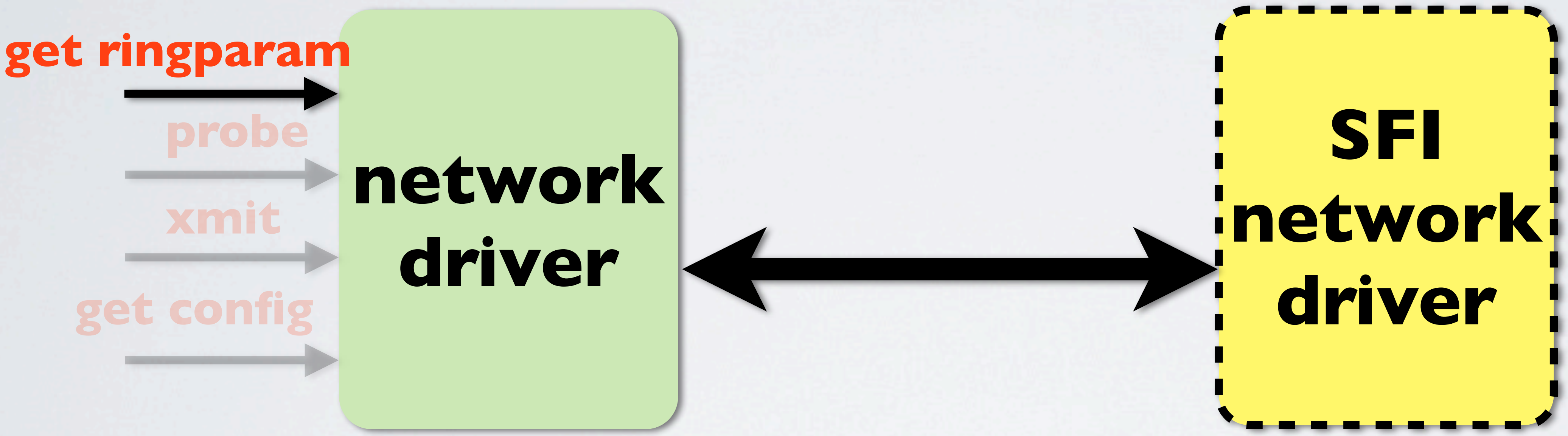
Example failed transaction



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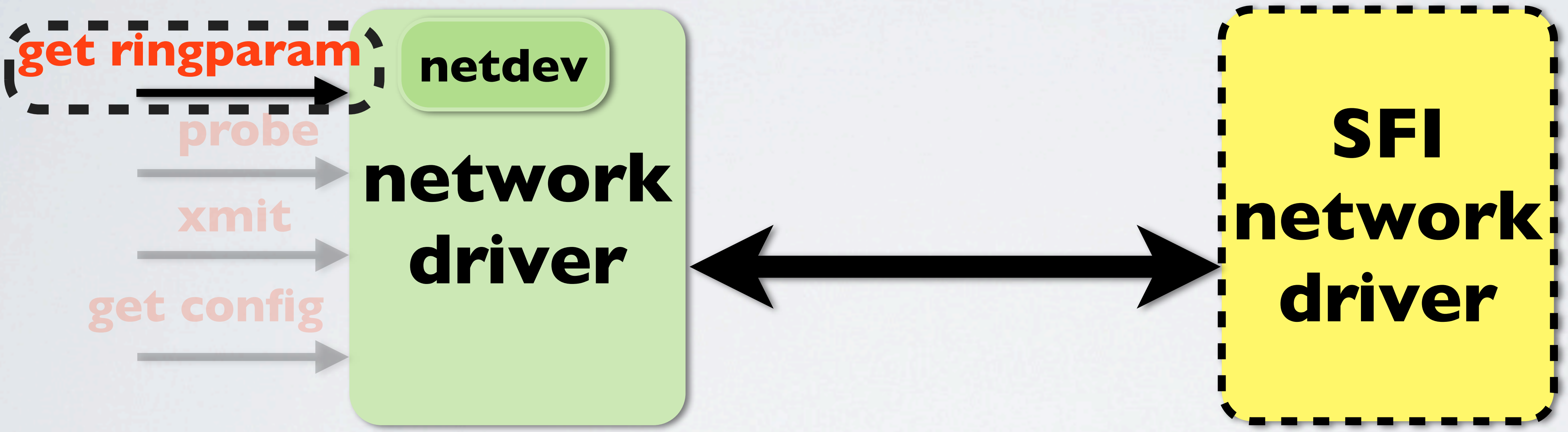

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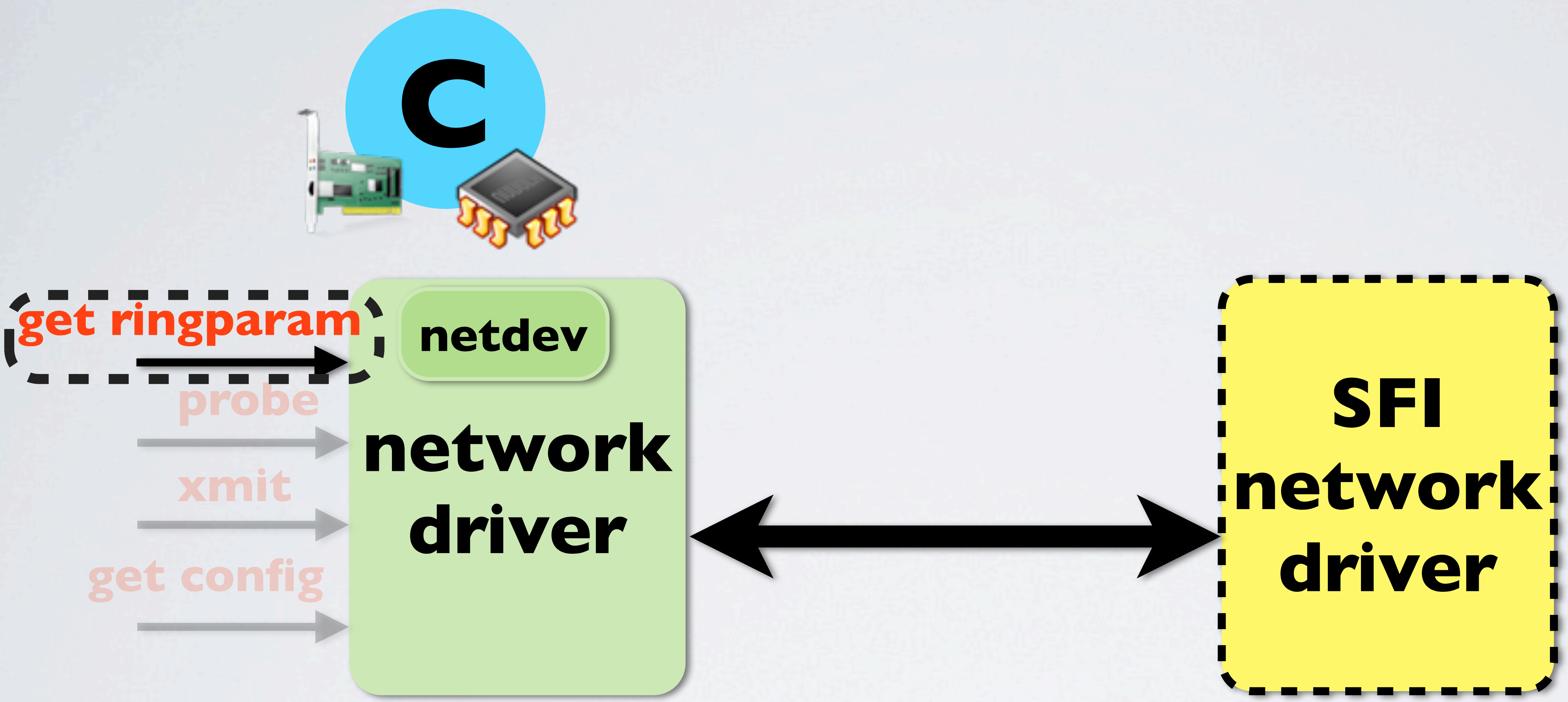

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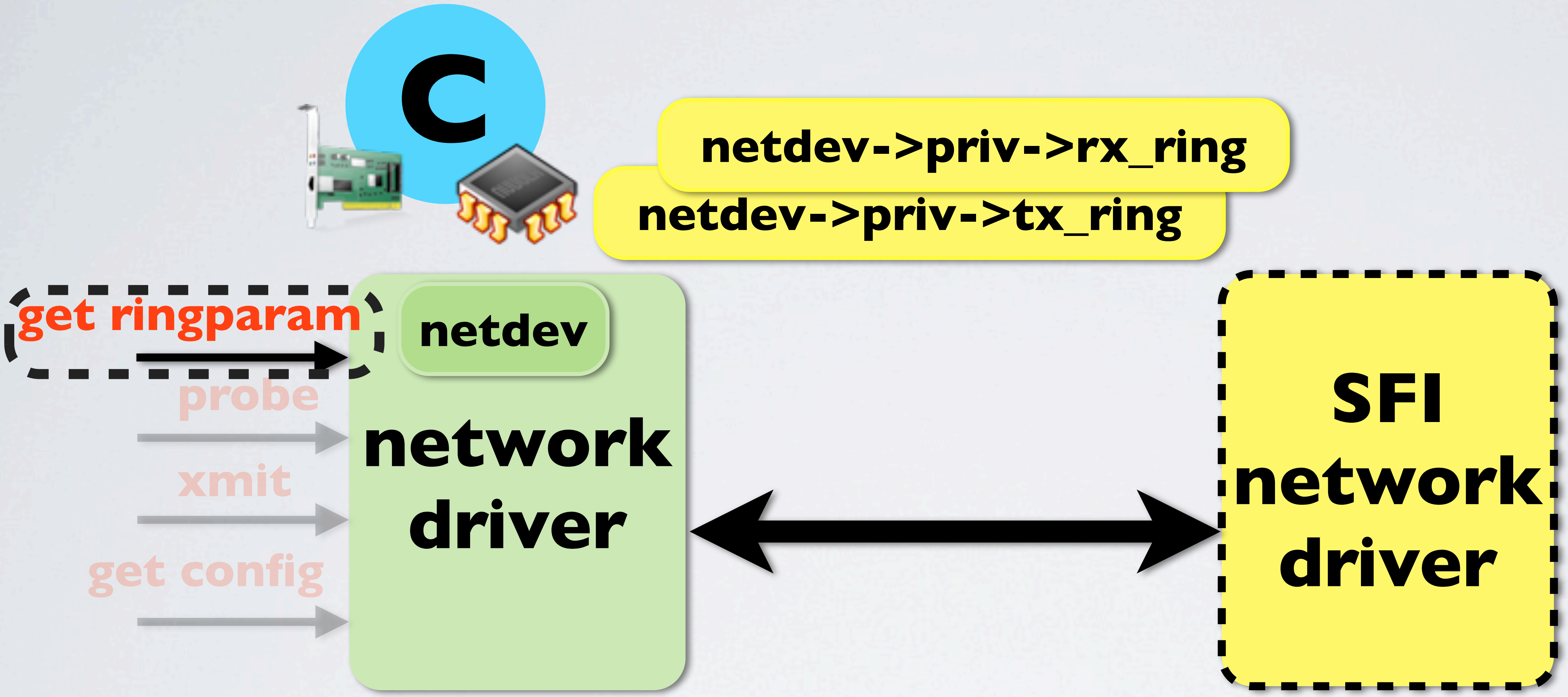

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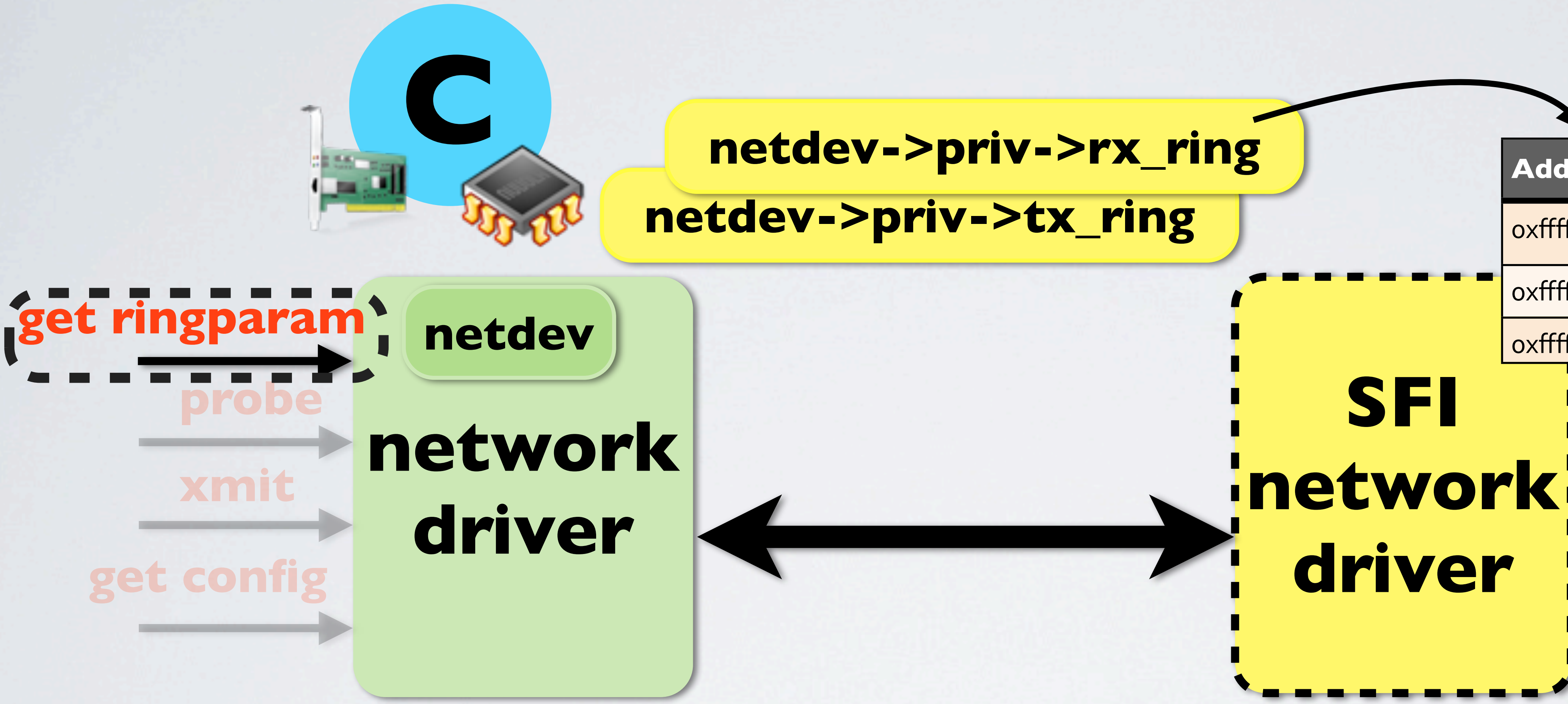

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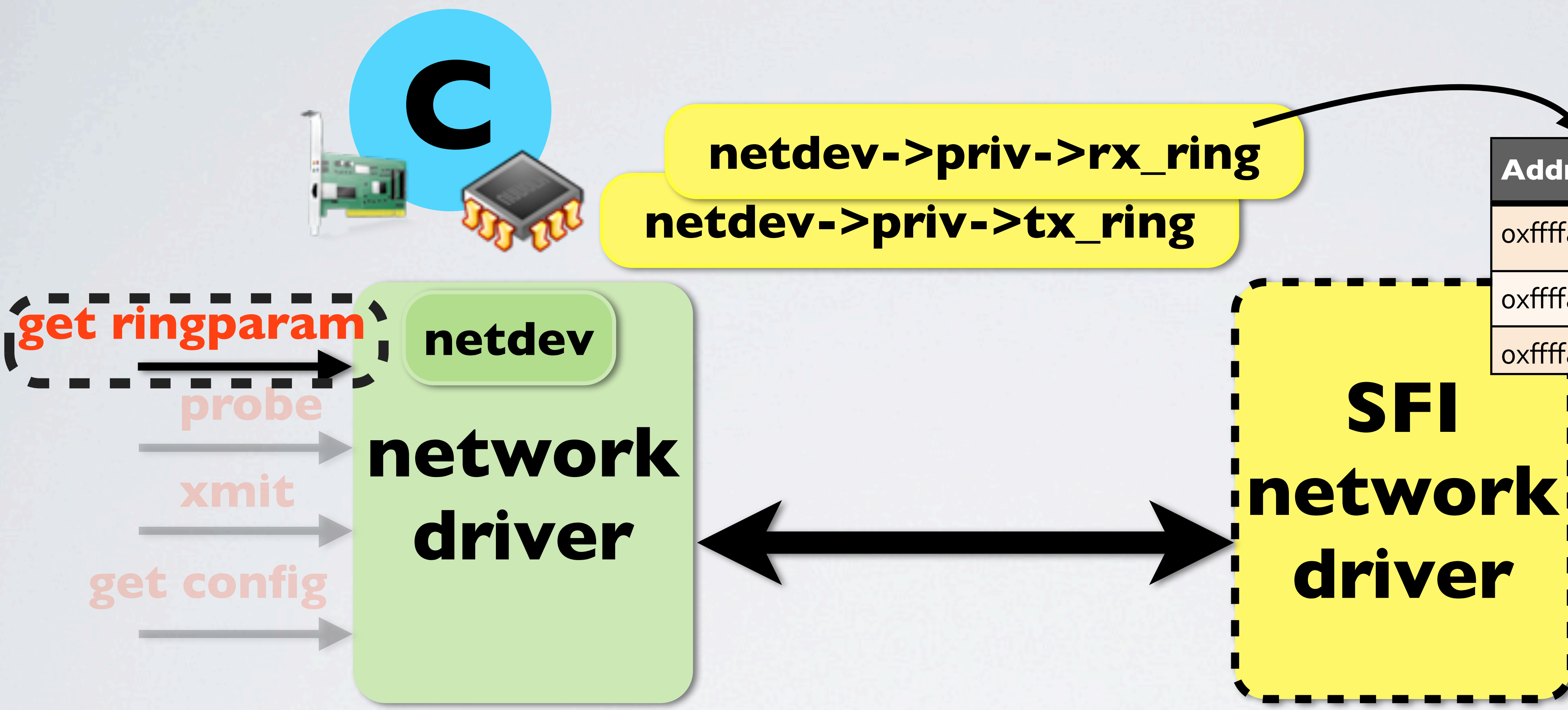

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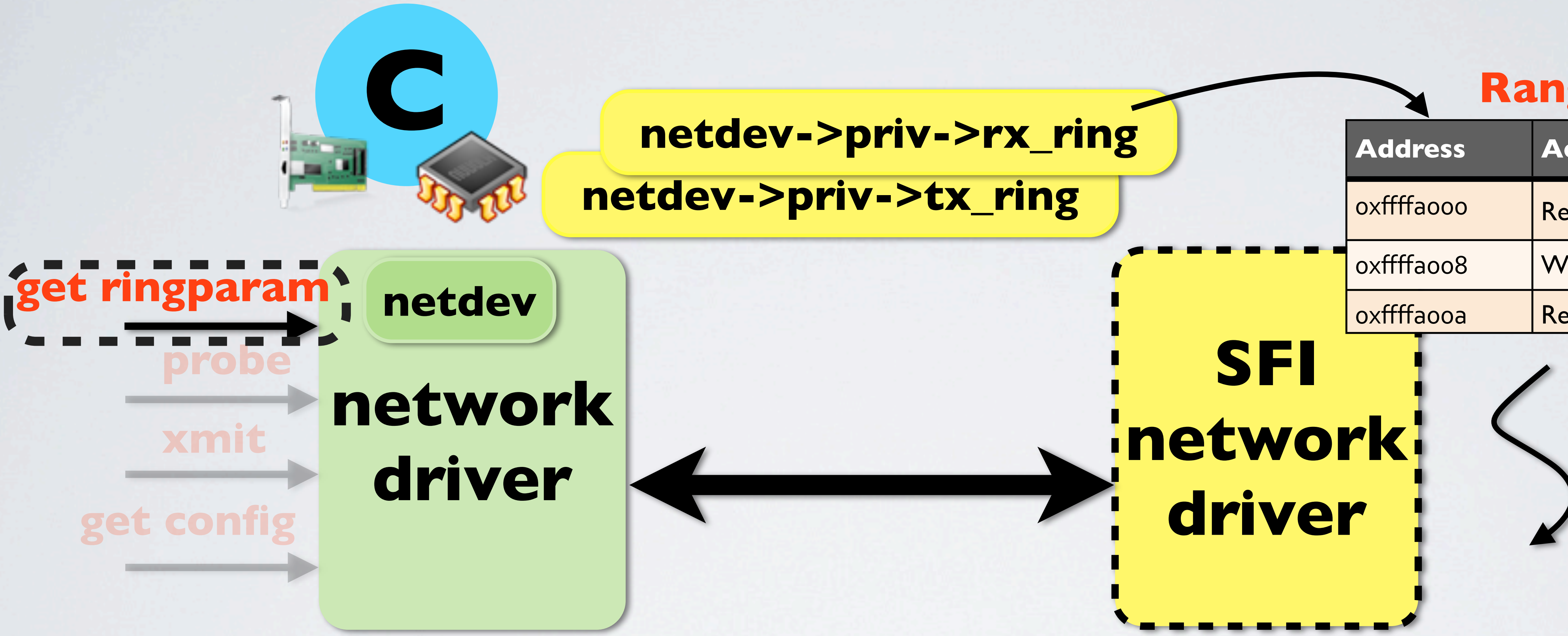

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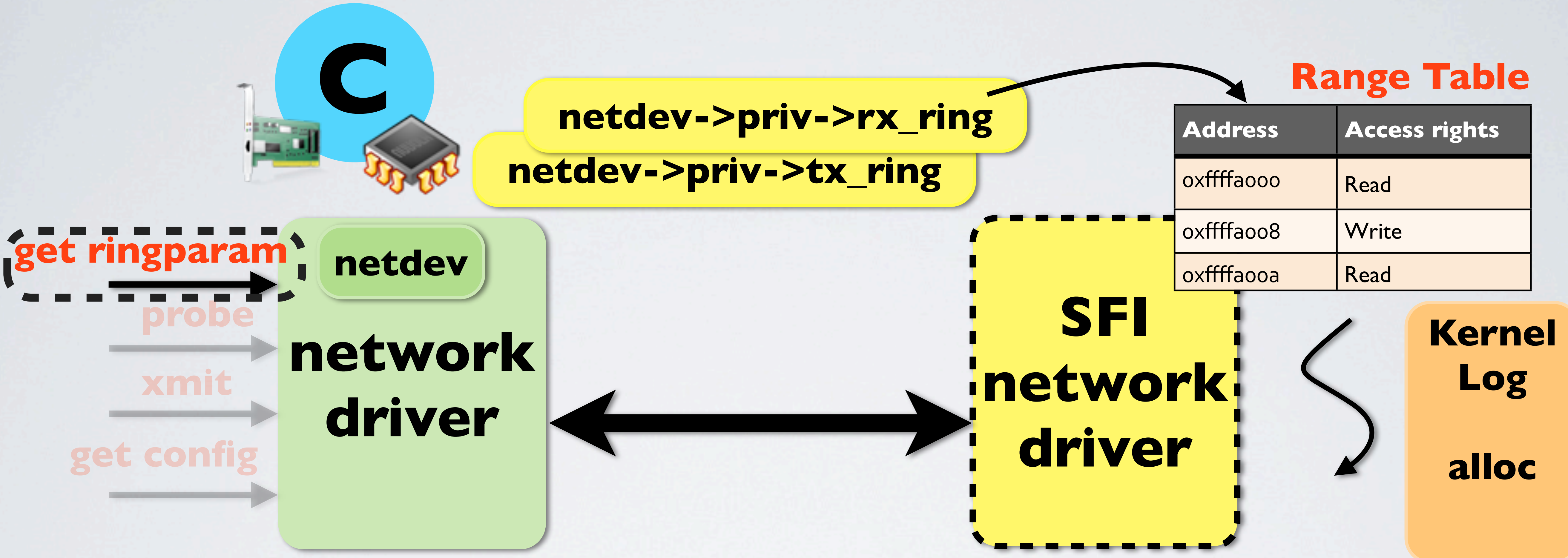
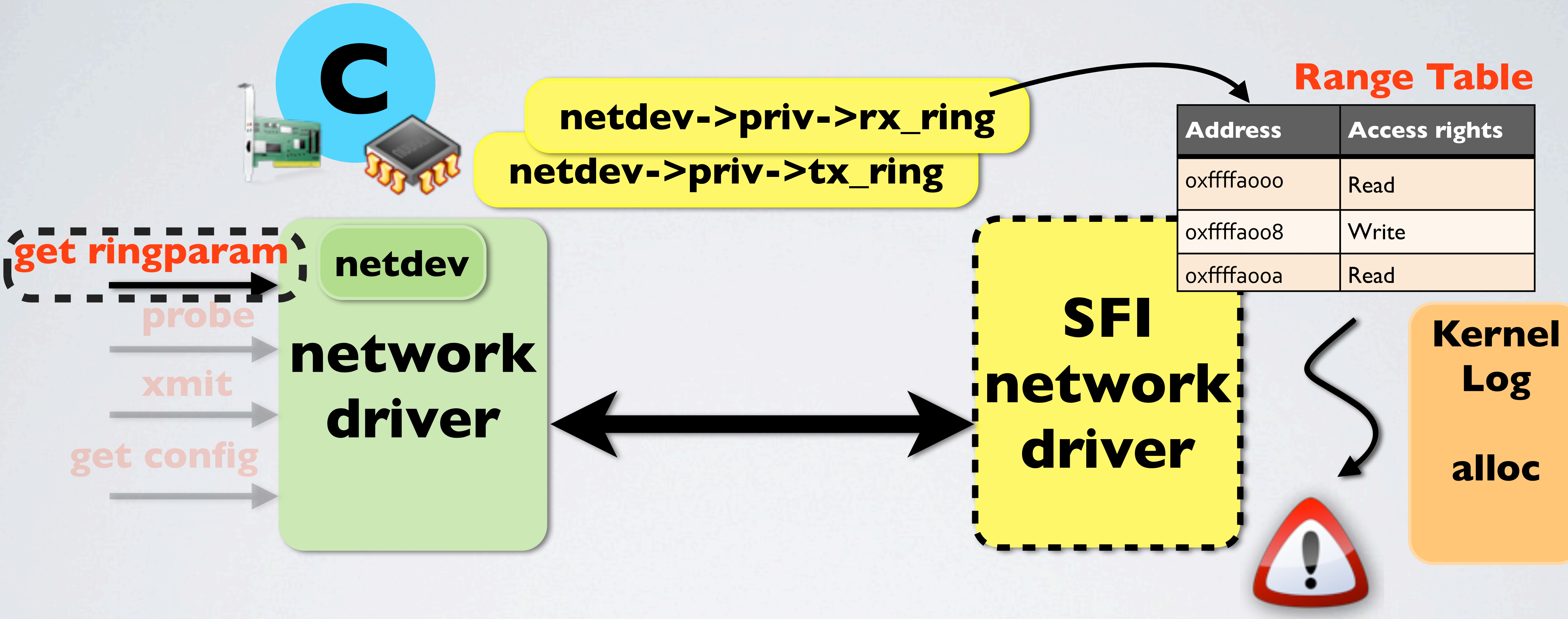


Address	Access rights
0xffffa000	Read
0xffffa008	Write
0xffffa00a	Read

Example failed transaction



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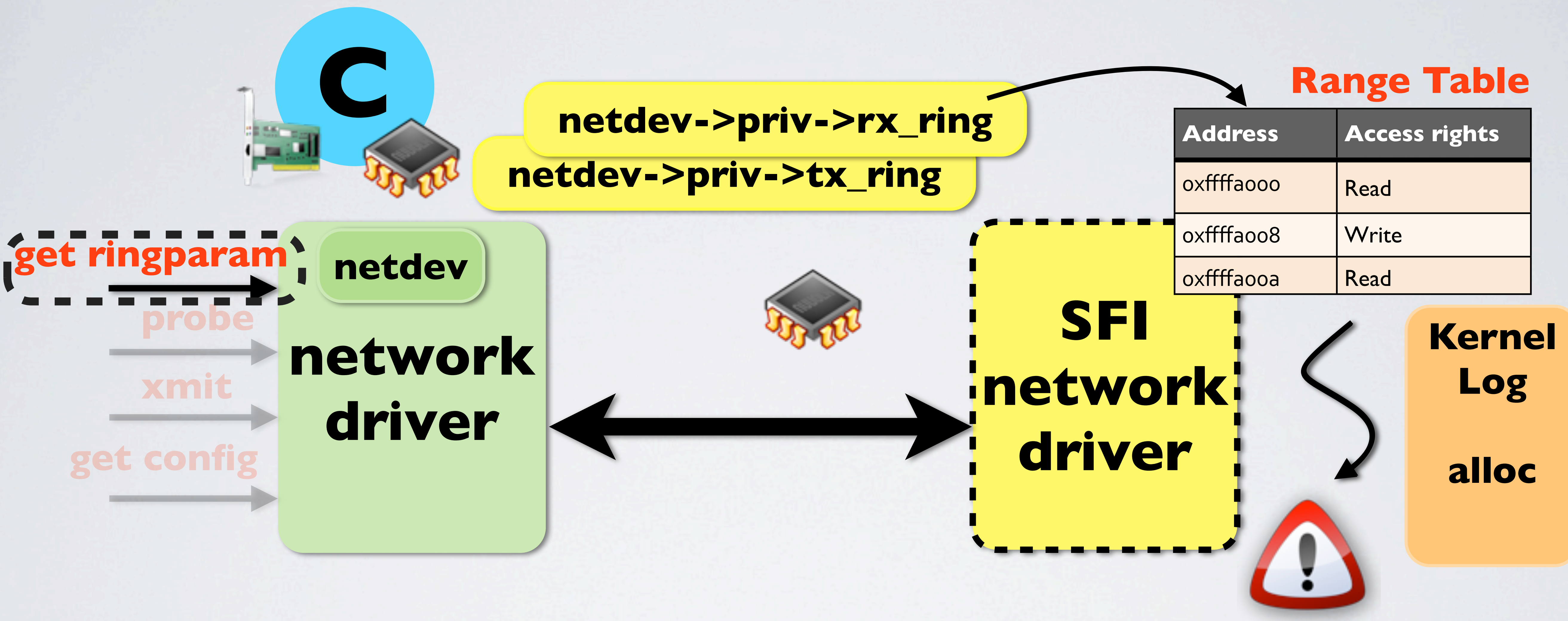

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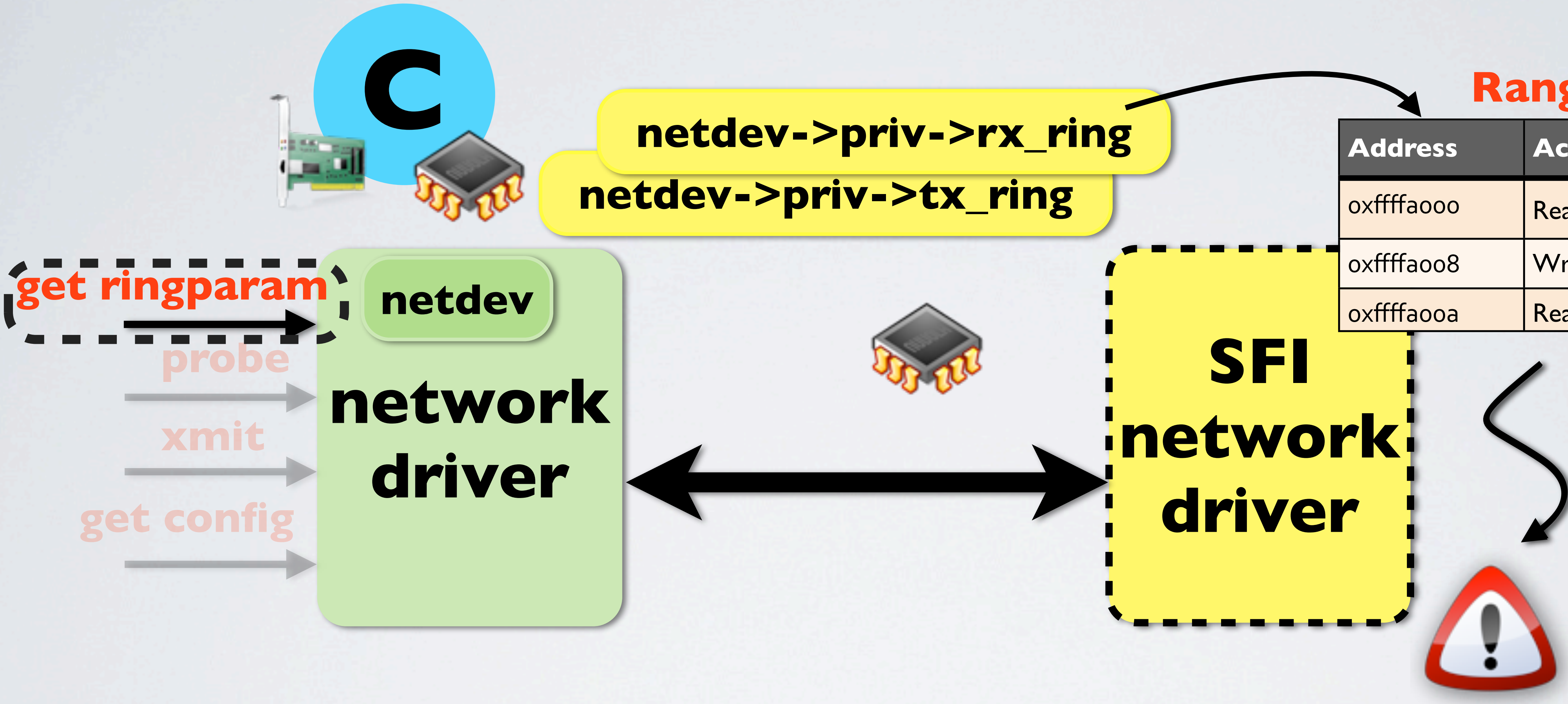

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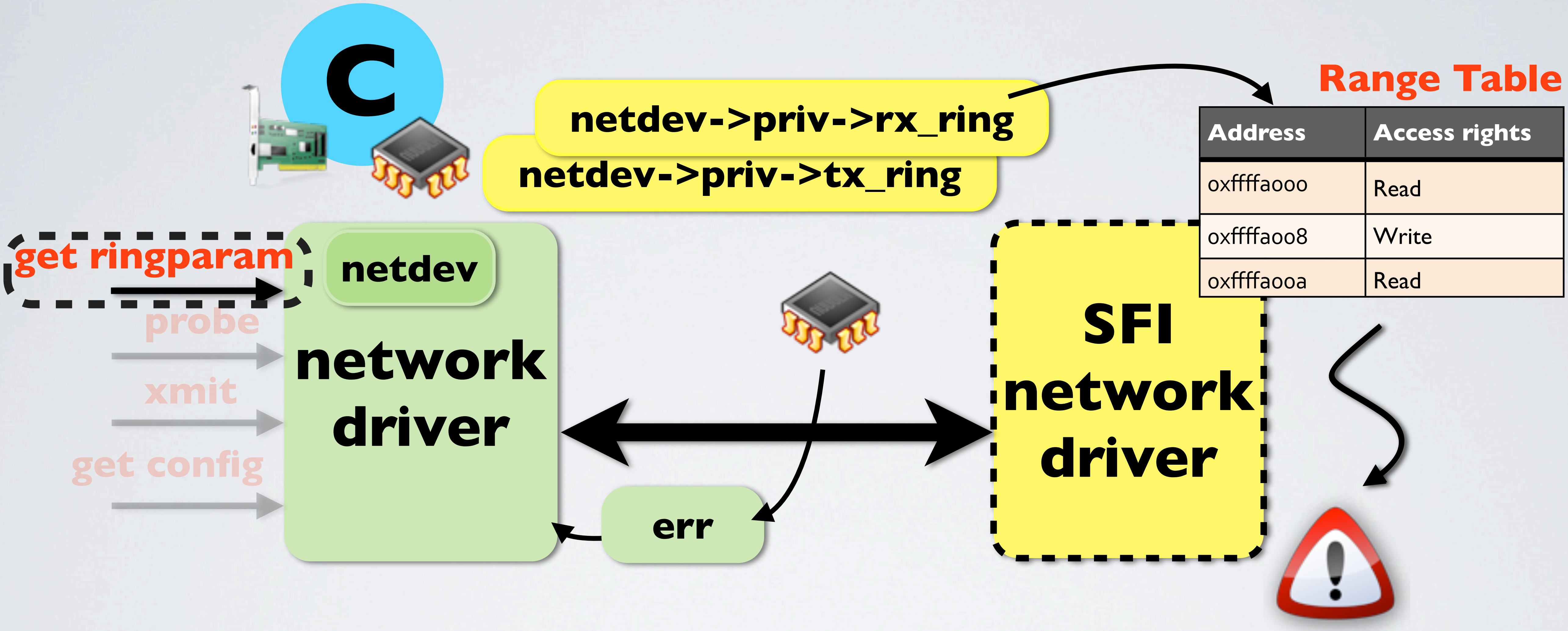

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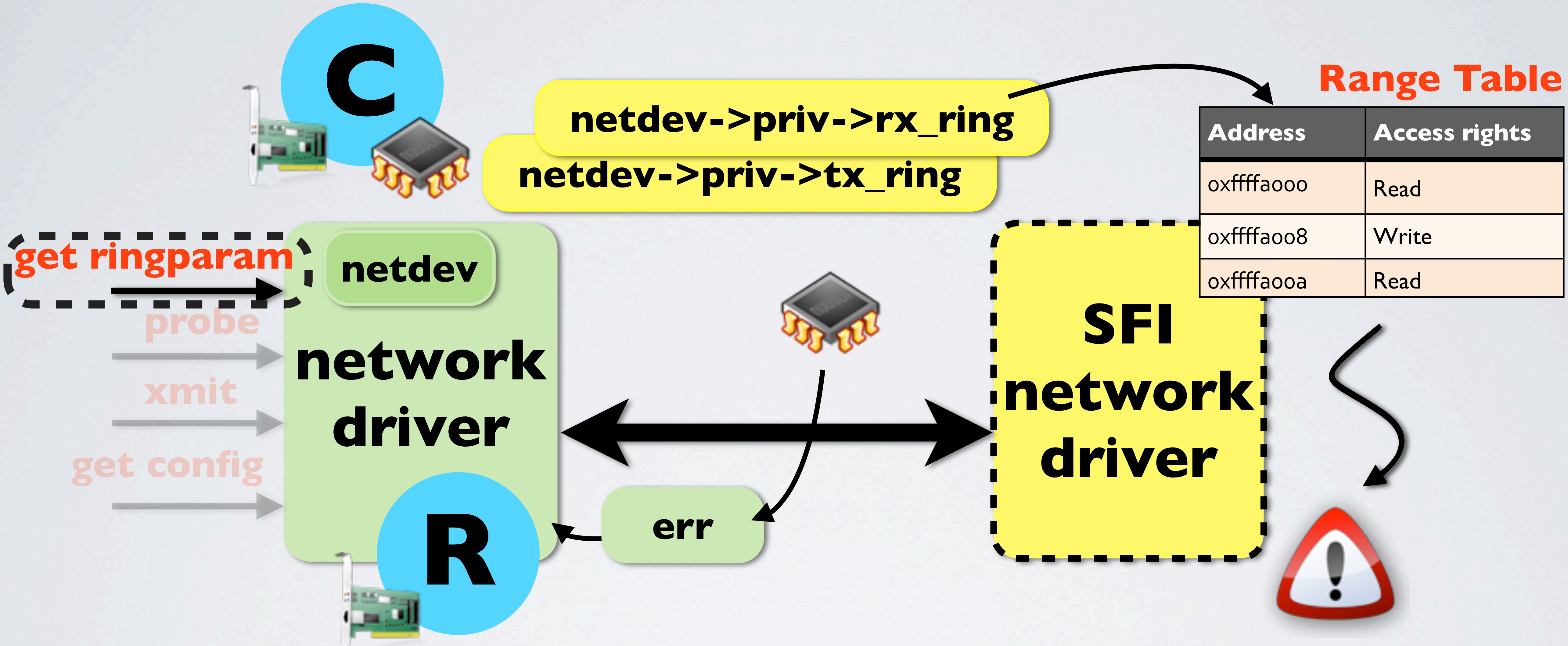

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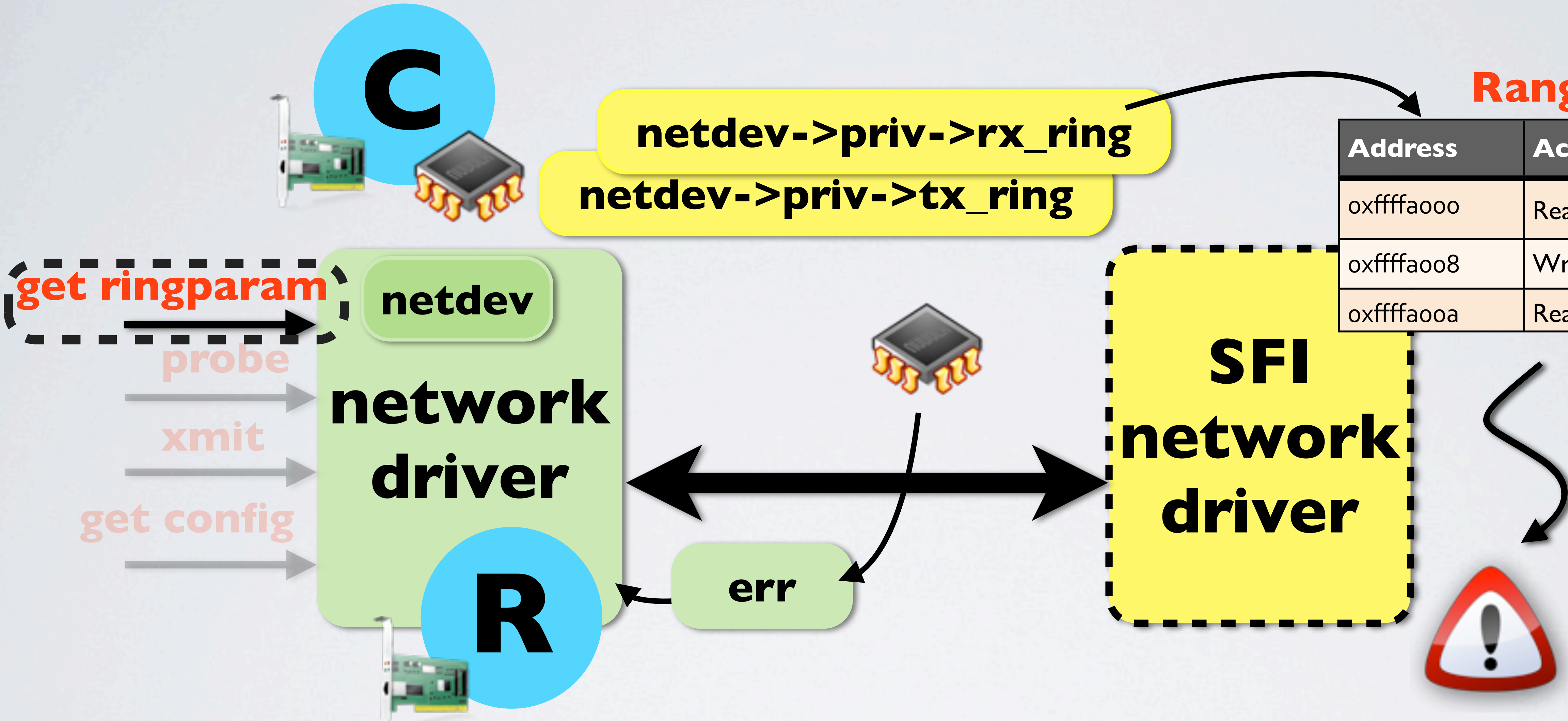

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FGFT provides transactional execution of driver entry points

Outline

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Fine-grained isolation

Checkpoint based recovery

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Recovery speedup

Driver	Class	Bus	Restart recovery	FGFT recovery	Speedup
8139too	net	PCI	0.31s	70µs	4400
e1000	net	PCI	1.80s	295ms	6
r8169	net	PCI	0.12s	40µs	3000
pegasus	net	USB	0.15s	5ms	30
ens1371	sound	PCI	1.03s	115ms	9
psmouse	input	serio	0.68s	410ms	1.65

FGFT provides significant speedup in driver recovery

Static and dynamic fault injection

Driver	Injected Faults	Benign Faults	Native Crashes	FGFT Crashes
8139too	43	0	43	NONE
e1000	47	0	47	NONE
r8169	36	0	36	NONE
pegasus	34	1	33	NONE
ens1371	22	1	21	NONE
psmouse	46	0	46	NONE
TOTAL	258	2	256	NONE

FGFT survives multiple static and dynamic faults

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

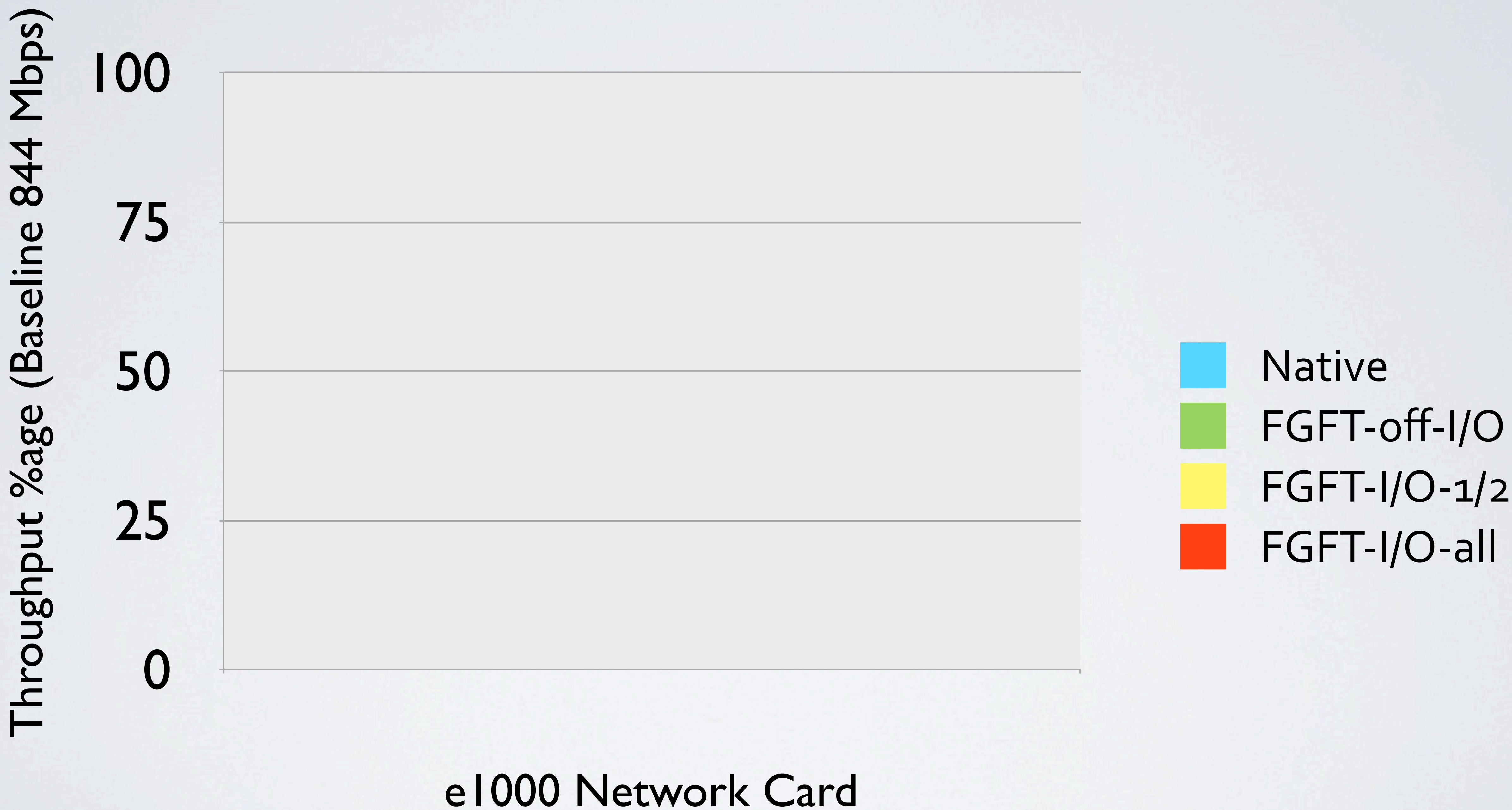
FGFT requires limited programmer effort and needs only 38 lines of new kernel code

Throughput with isolation and recovery

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

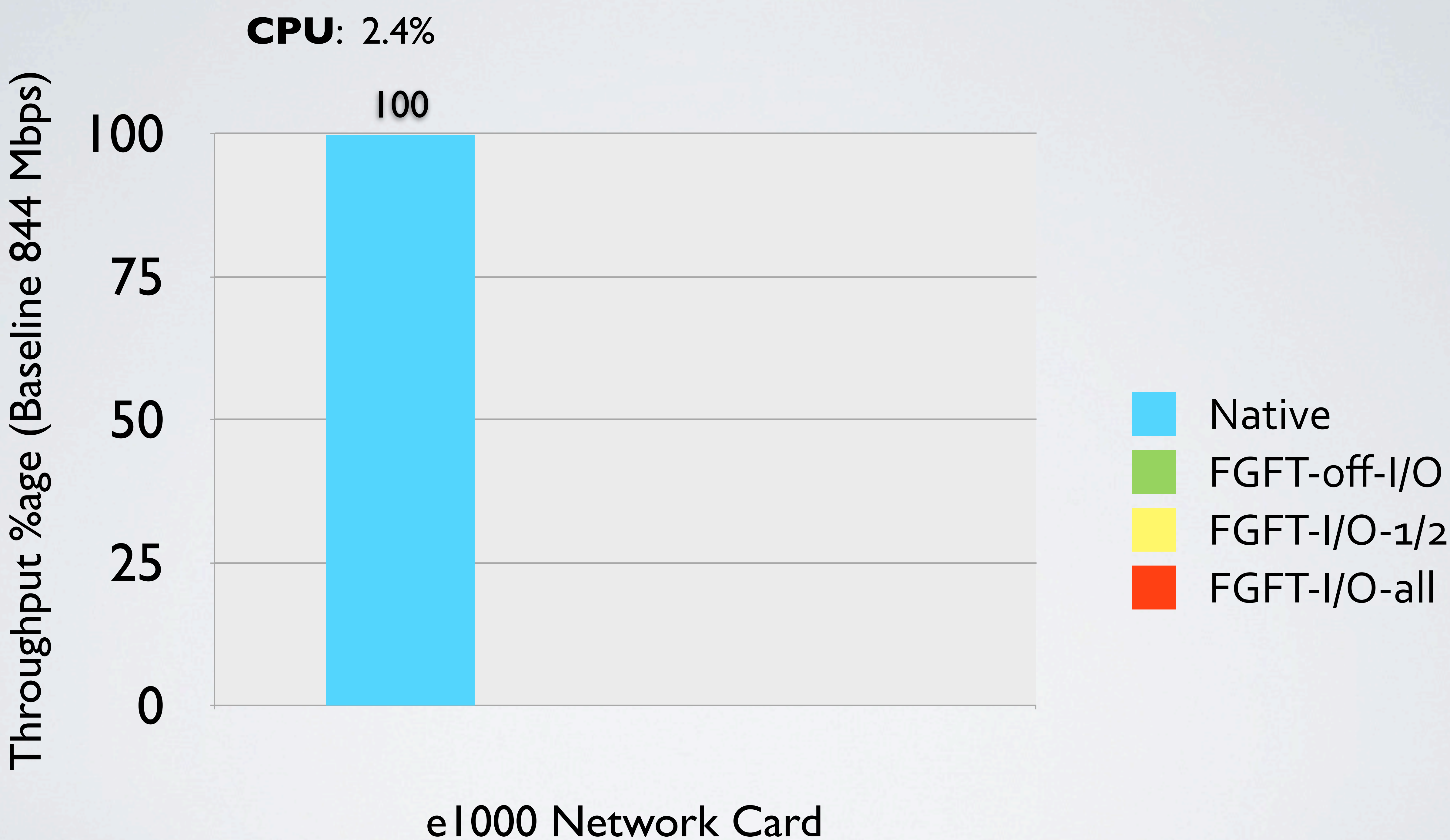
netperf on Intel quad-core machines

Throughput with isolation and recovery



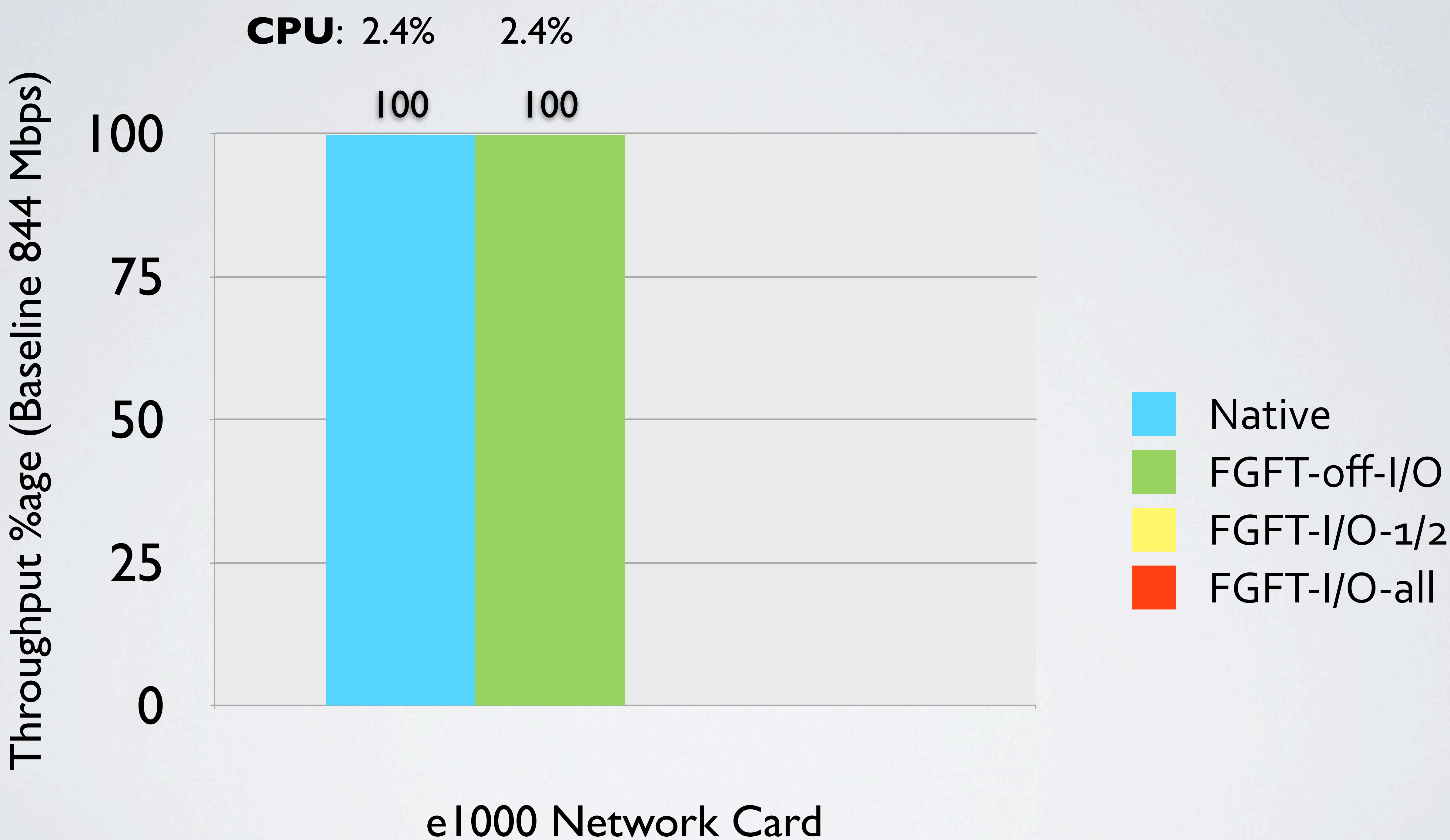
netperf on Intel quad-core machines

Throughput with isolation and recovery



netperf on Intel quad-core machines

Throughput with isolation and recovery



netperf on Intel quad-core machines

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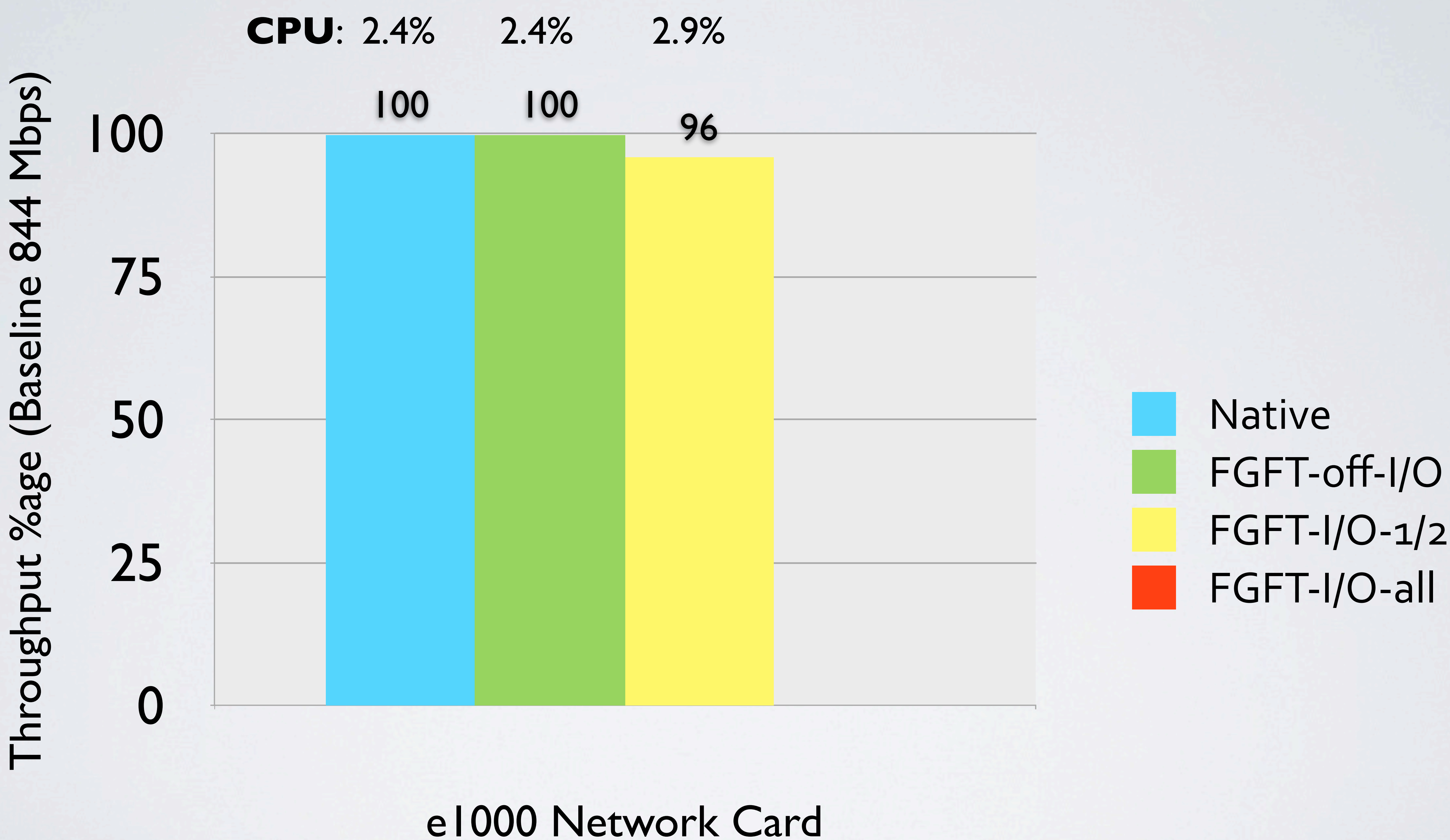
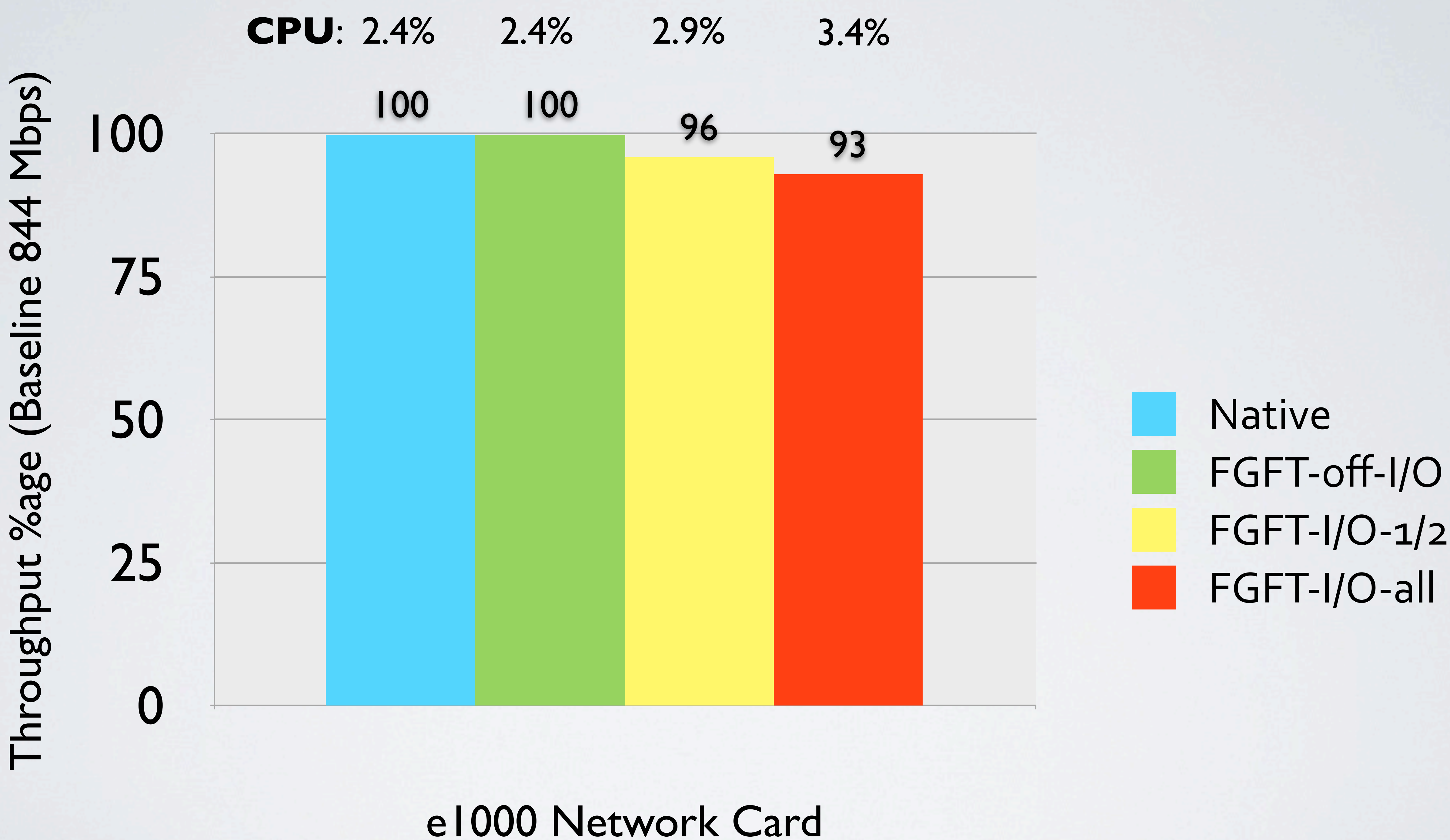


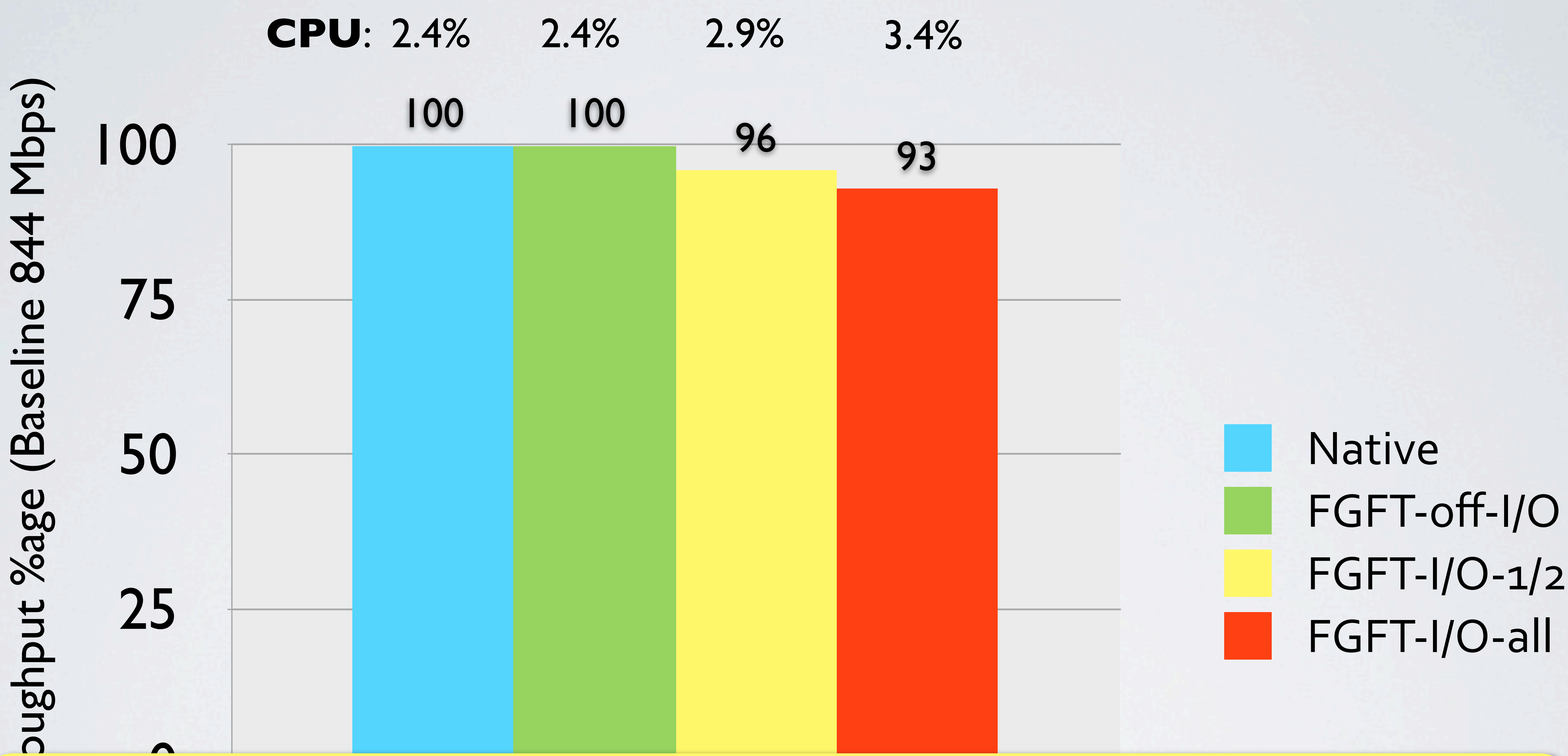
netperf on Intel quad-core machines

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

- **Fine-Grained Fault tolerance based on a *pay-as-you go* model**
  - **Provides fault tolerance at incremental performance costs and programmer efforts**
- **Introduces fast checkpointing for drivers**
  - **Device checkpoints average ~20micros**
  - **Reduces recovery time significantly**
  - **Should be explored in other domains apart from fault tolerance like fast reboot, upgrade etc.**

Questions

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