Understanding and Improving Device Access

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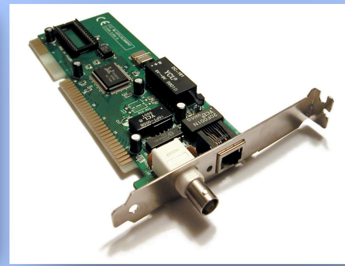
Devices enrich computers

- 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

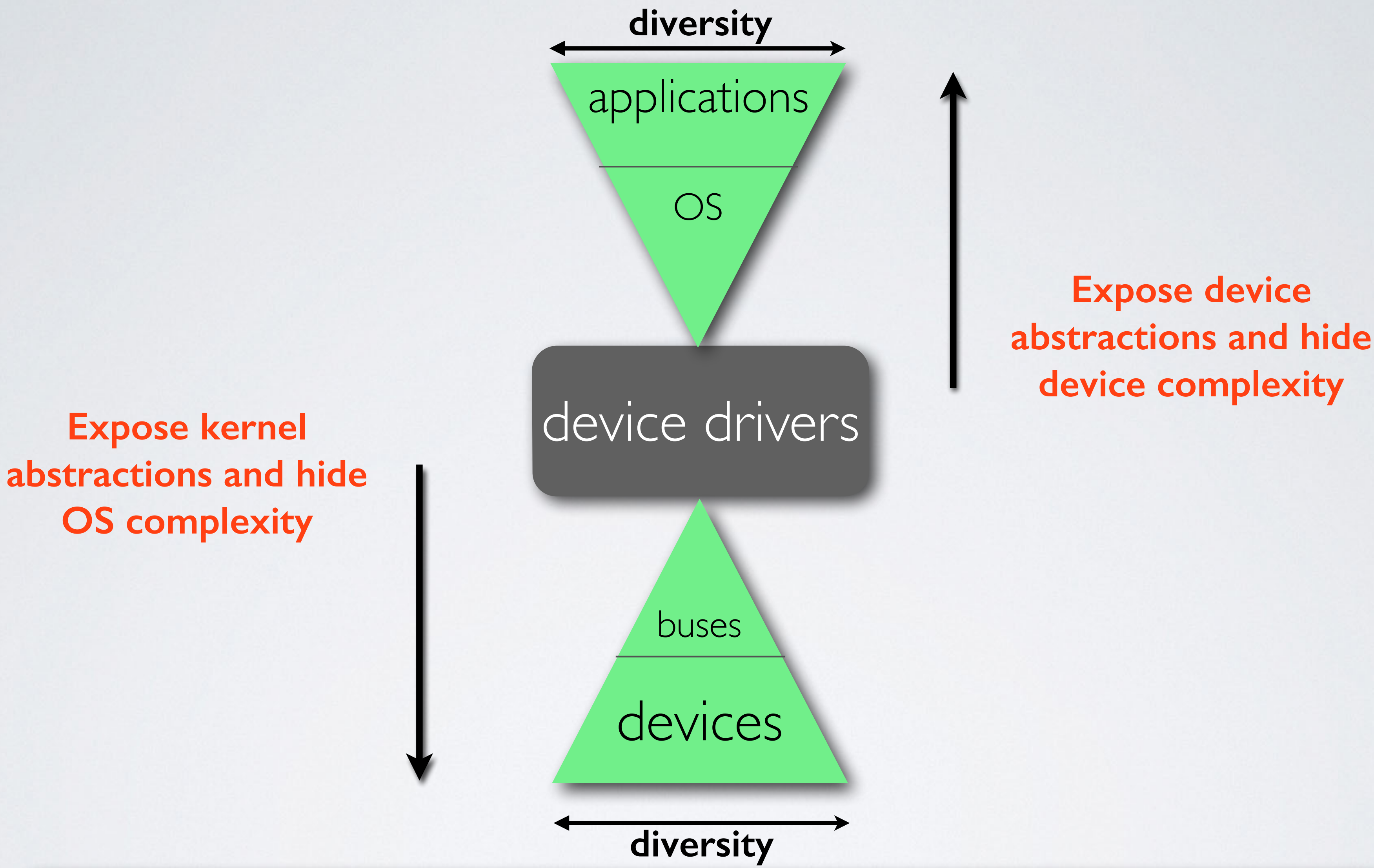
New I/O devices: accelerometers, GPUS, GPS, touch



Many buses: USB, PCI-e, thunderbolt

Heterogeneous OS support: 10G ethernet vs card readers

Device drivers: OS interface to devices



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

Evolution of devices hurts device access

Simplicity

Low latency

Reliability

Cost effective

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

Goal: Address software and hardware complexity

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

Increasing hardware complexity

Reliability against hardware failures

1

Increasing hardware complexity

Low latency device availability

2

Increasing software complexity

Better understanding of driver code

3

Outline

SOSP '09

First research consideration of hardware failures in drivers

Tolerate device failures

ASPLOS '12

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

Understand drivers and potential opportunities

ASPLOS '13

Introduce checkpoint/restore in drivers for low latency fault tolerance

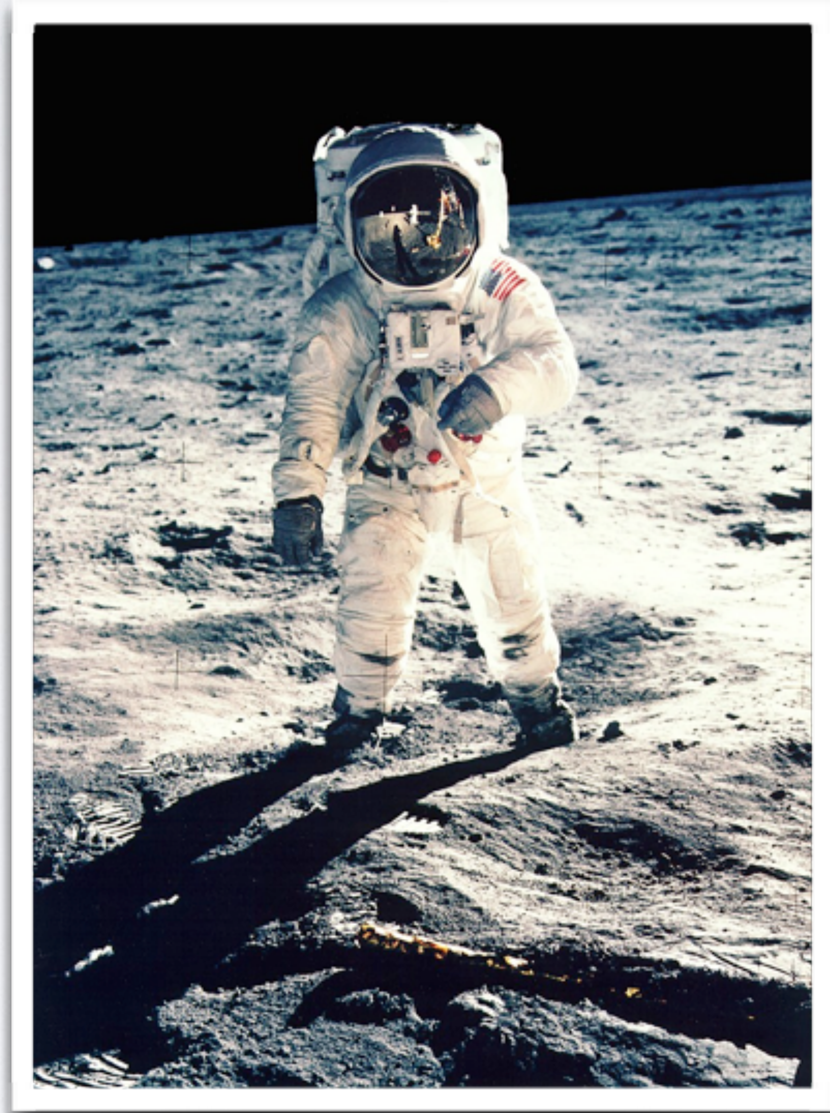
Transactional approach for low latency recovery

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

- ★ **Many device drivers often assume device perfection**
  - **- Common Linux network driver: 3c59x.c**

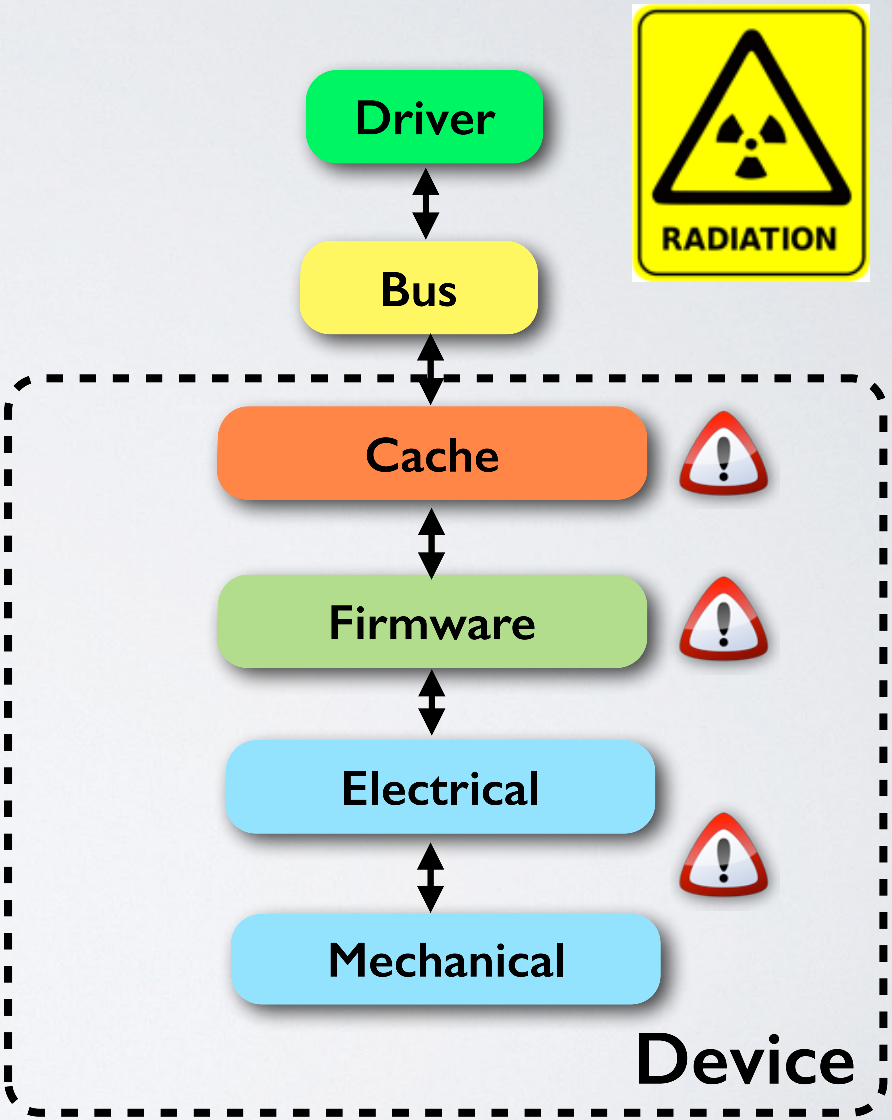
```
while (ioread16(ioaddr + Wn7_MasterStatus))
        & 0x8000);
```

HANG!

Hardware dependence bug: Device malfunction can crash the system

Sources of hardware misbehavior

- ★ **Sources of hardware misbehavior**
  - ★ Firmware/Design bugs
  - ★ Device wear-out, insufficient burn-in
  - ★ Bridging faults
  - ★ Electromagnetic interference, radiation, heat



Sources of hardware misbehavior

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  - Device wear-out, insufficient burn-in
  - Bridging faults
  - Electromagnetic interference, radiation, heat

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

An evidence: Windows Server

Transient hardware failures caused **8%** of all crashes and **9%** of all unplanned reboots [1]

- ⋆ Systems work fine after reboots
- ⋆ Vendors report returned device was faultless

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

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

[1] Fault resilient drivers for Longhorn server, May 2004. Microsoft Corp.

How do hardware dependence bugs manifest?

1

Drivers use device
data in critical control and data paths

```
printk("%s",msg[inb(regA)]);
```

2

Drivers do not report device
malfunction to system log

```
if (inb(regA)!= 5)  {
  return; //do nothing
}
```

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		●	●	

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

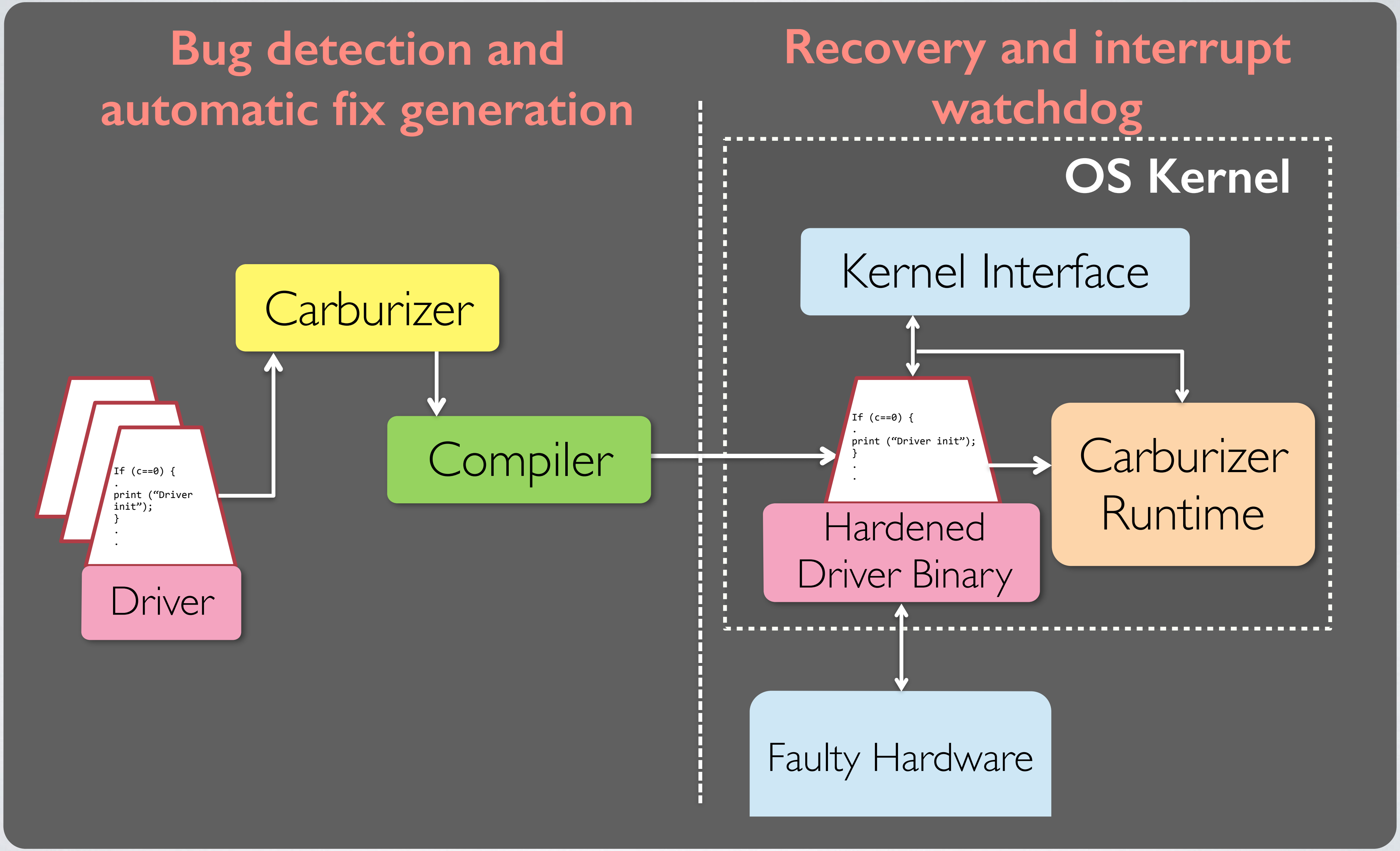
Static analysis component

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

Runtime component

- ★ Detect interrupt failures
- ★ Provide automatic recovery

Carburizer architecture



Hardening drivers

- Goal: Remove hardware dependence bugs
  - ★ 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**

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

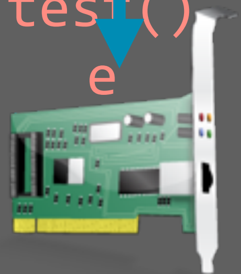
Types of device I/O

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

Tainted Variables

OS

b
c
d
test()
e



network card

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)

Hardware data used to de-reference pointers

- ★ **Tainted variables used as pointer dereference**

```
void hptitop_iop_request_callback(...)        {

arg= readl(...);
  ...
if (readl(&req->result) == IOP_SUCCESS)  {
    arg->result = HPT_IOCTL_OK;
  }
}
```

Highpoint SCSI driver(hptiop.c)

*Code simplified for presentation purposes

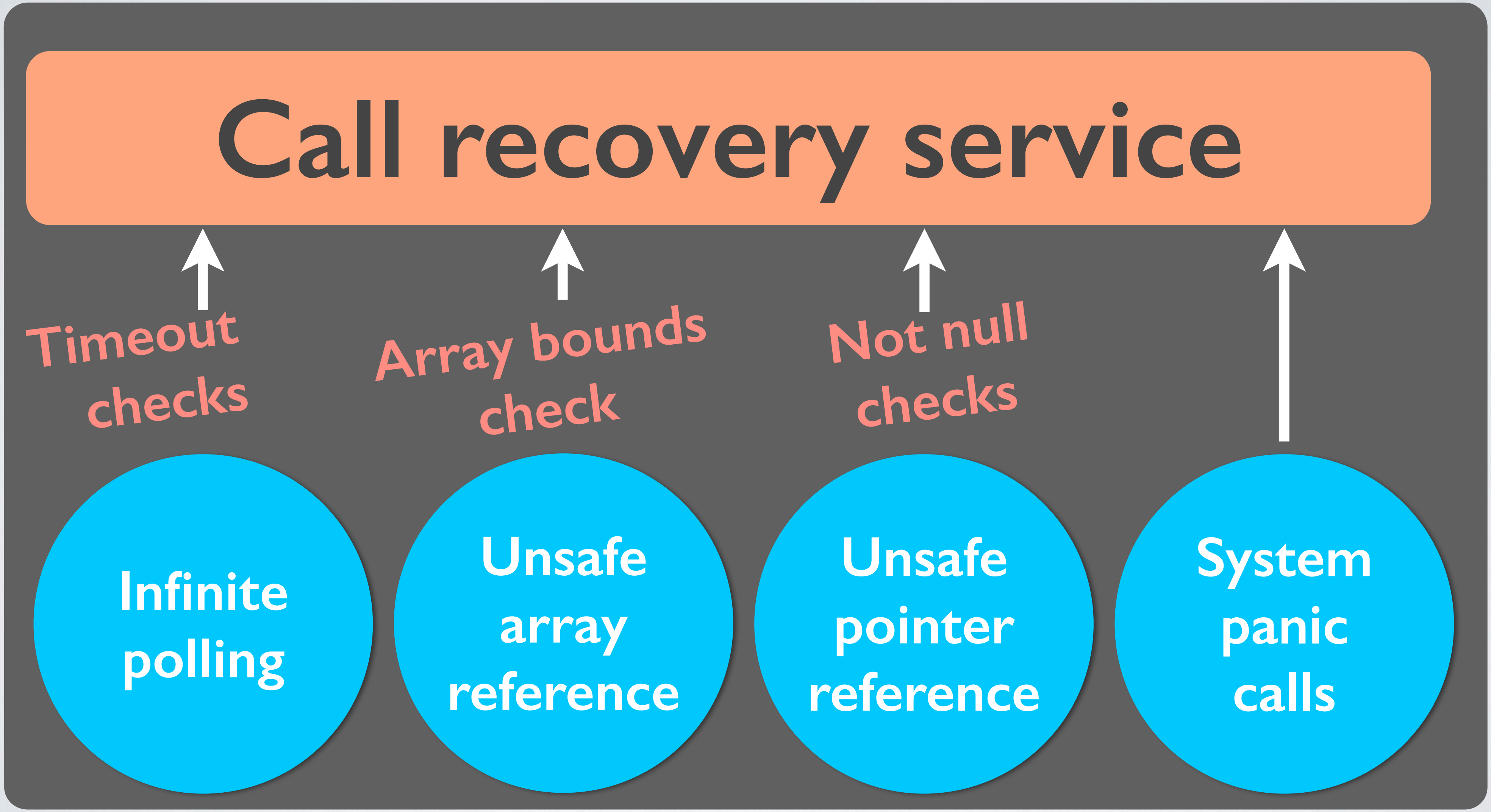
Analysis results over the Linux kernel

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

Lightweight and usable technique to find hardware dependence bugs

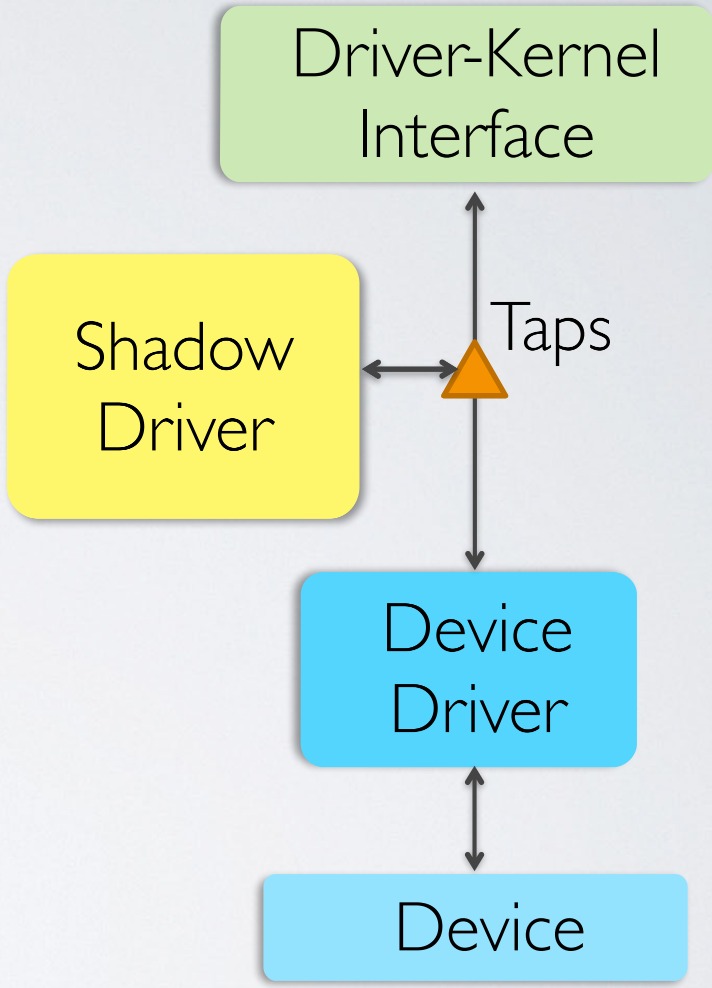
- ⋆ **Analyzed/Built 6300 driver files (2.8 million LOC) in 37 min**
- ⋆ **Found 992 hardware dependence bugs in driver code**
- ⋆ **False positive rate: 7.4% (manual sampling of 190 bugs)**

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

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

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

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	●	●	●		●
	Wrap I/O memory access	●	●	●	●	

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

Impact

- ★ 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`

Outline

Tolerate device failures

Understand drivers and potential opportunities

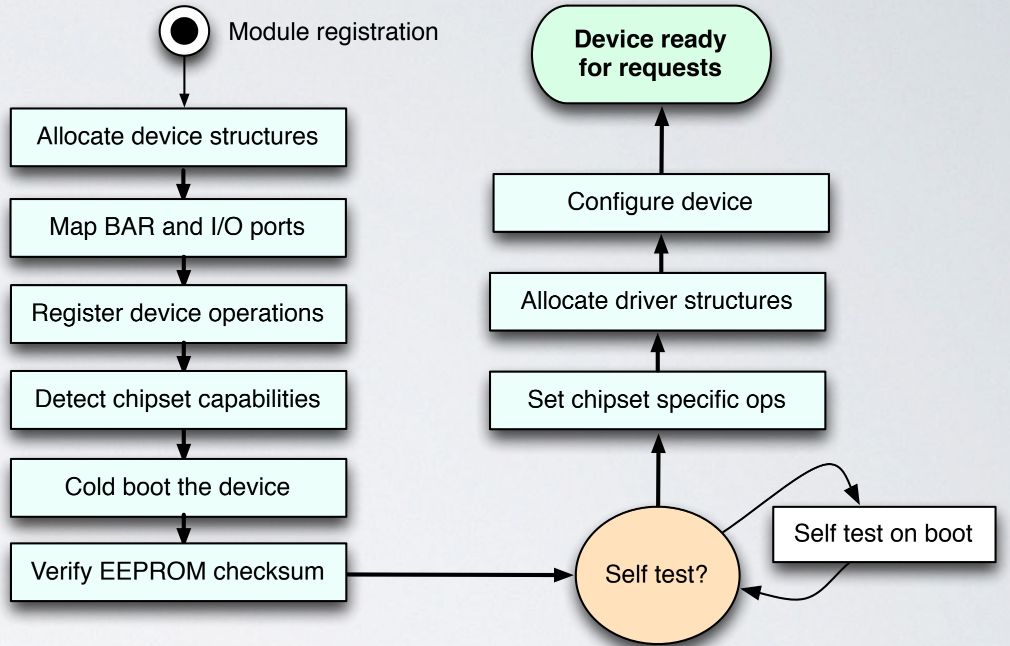
Overview

Recovery-specific results

Transactional approach for cheap recovery

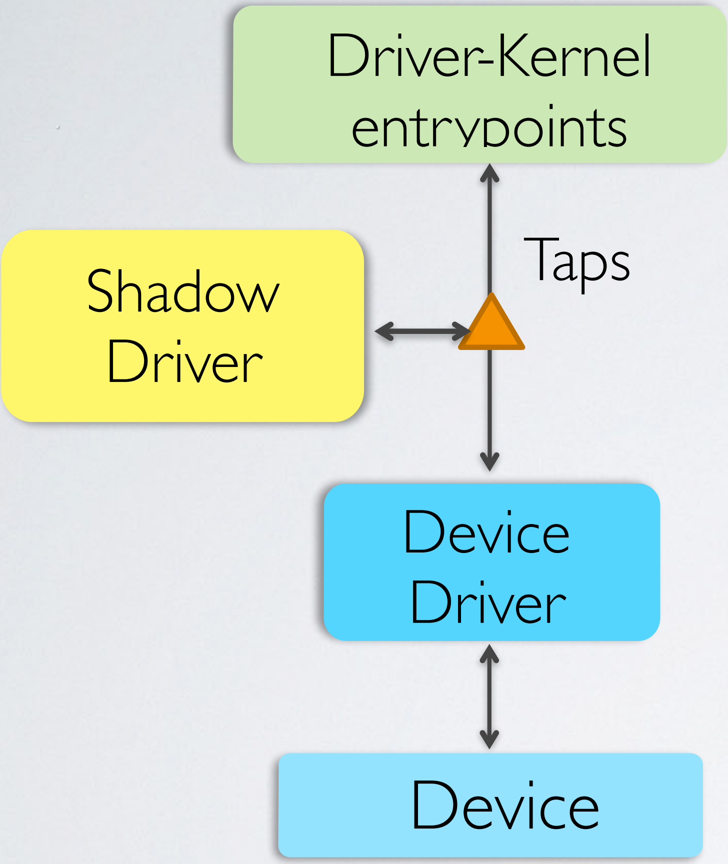
Recovery performance: device initialization is slow

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



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

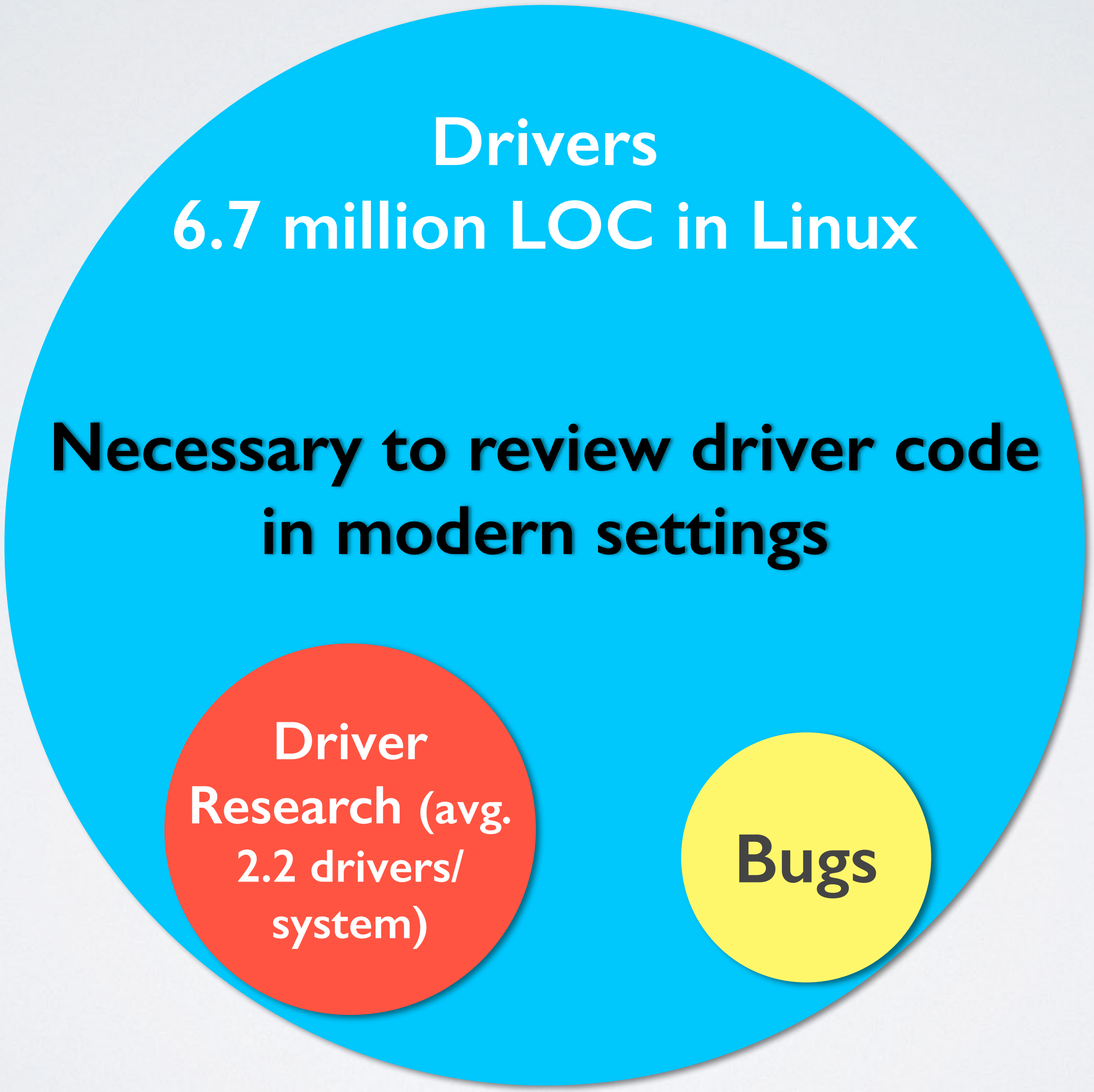
Recovery functionality: assumes drivers follow class behavior



- ★ **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?**

How many drivers obey class behavior?

Our view of drivers is narrow



Understanding Modern Device Drivers[ASPLOS 2012]

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

Driver properties

- Code properties
- Verify research assumptions

Driver interaction

- Driver kernel & device interaction
- Driver architecture

Driver similarity

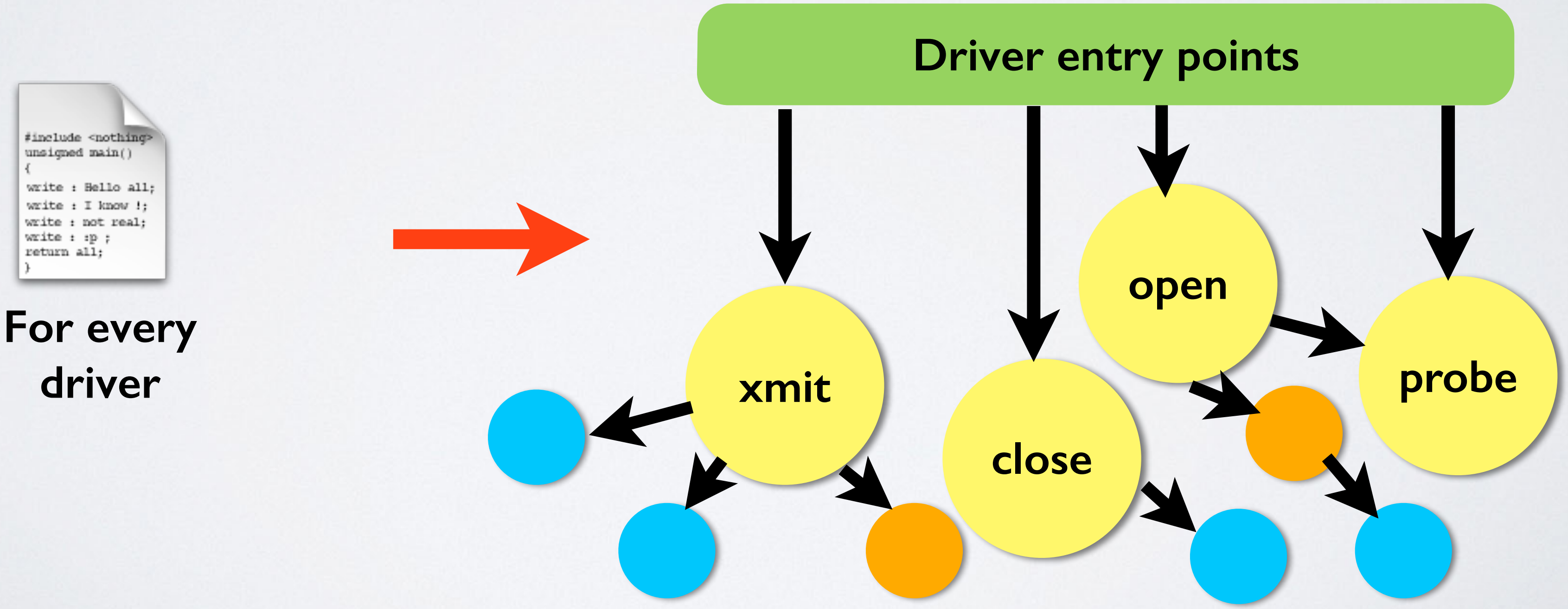
- 7 million lines of code needed?

Study methodology

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

Driver properties

- ★ **Identify driver entry points, kernel and bus callouts**
  - ★ **Device class, sub-class, chipsets**
  - ★ **Bus properties & other properties (like module params)**
  - ★ **Driver functions registered as entry points (purpose)**



Study methodology

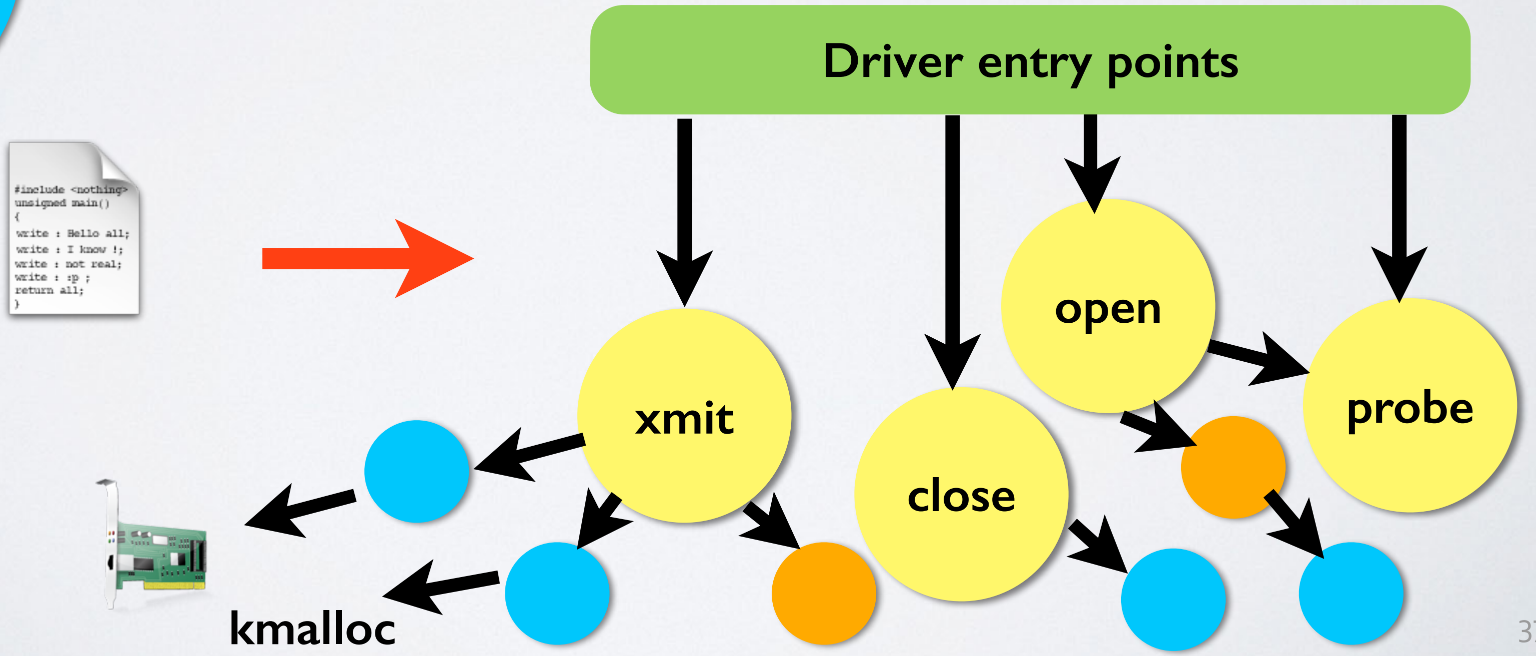
★ **Static source analysis of 3200 drivers in Linux 2.6.37.6 (May 2011)**

Driver properties

★ **Identify driver entry points, kernel and bus callouts**

Driver interactions

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



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

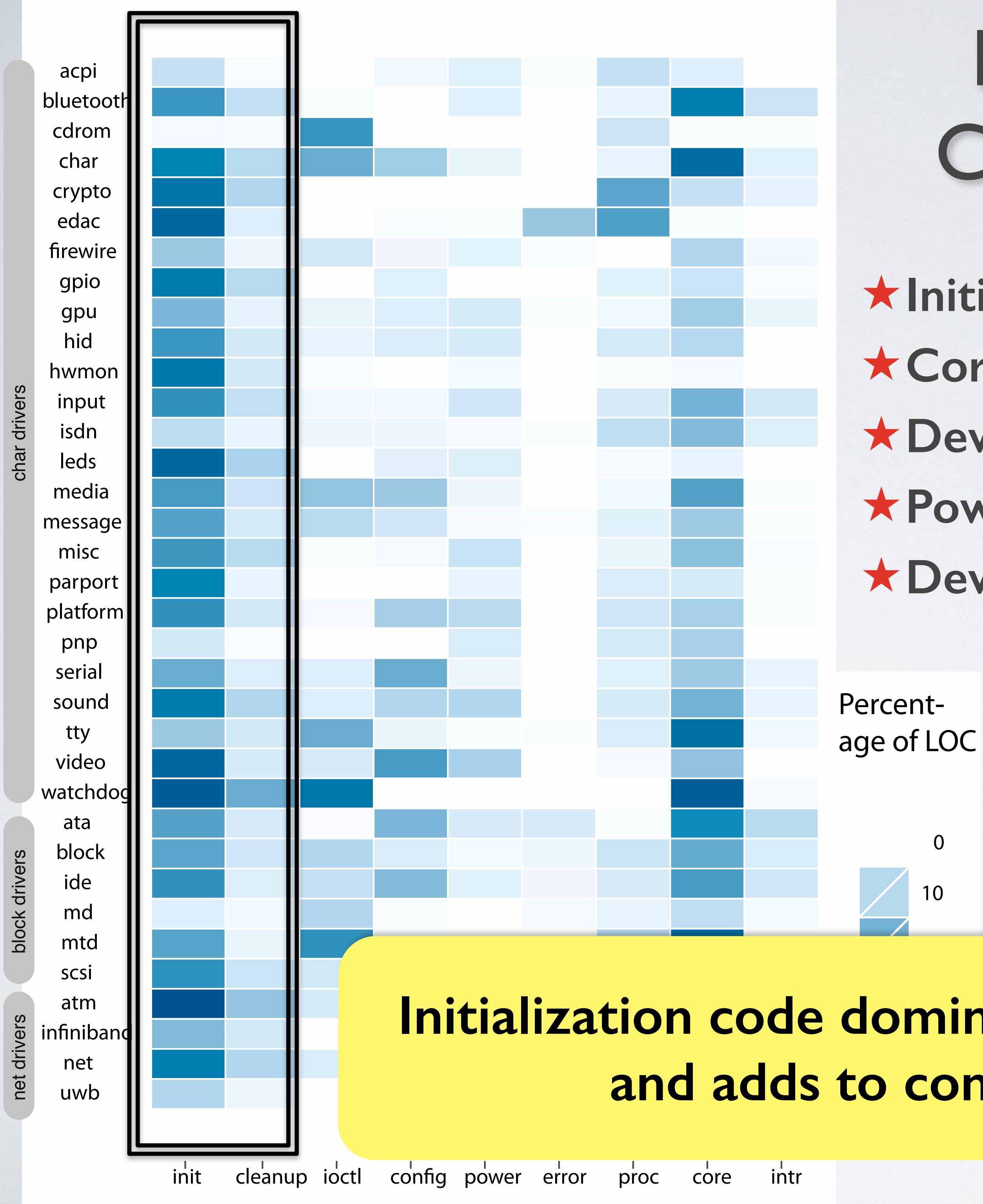
Understand drivers and potential opportunities

Overview

Recovery specific results

Transactional approach for cheap recovery

Driver Code Characteristics

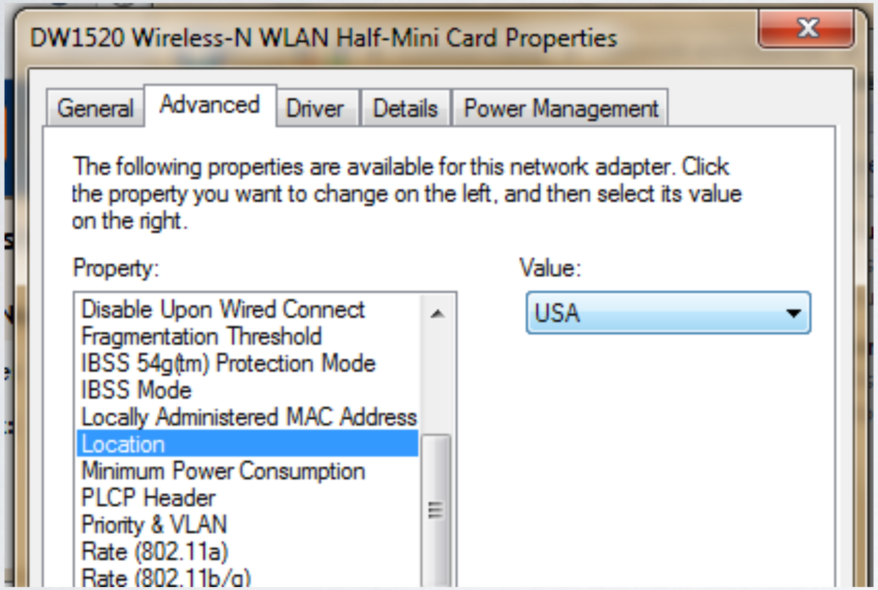


- ★ Initialization/cleanup – 36%
- ★ Core I/O & interrupts – 23%
- ★ Device configuration – 15%
- ★ Power management – 7.4%
- ★ Device ioctl – 6.2%

Initialization code dominates driver LOC and adds to complexity

Problem (a): Drivers do behave outside class definitions

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



Windows WLAN card config via private ioctls

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

Linux sound card config via sysfs

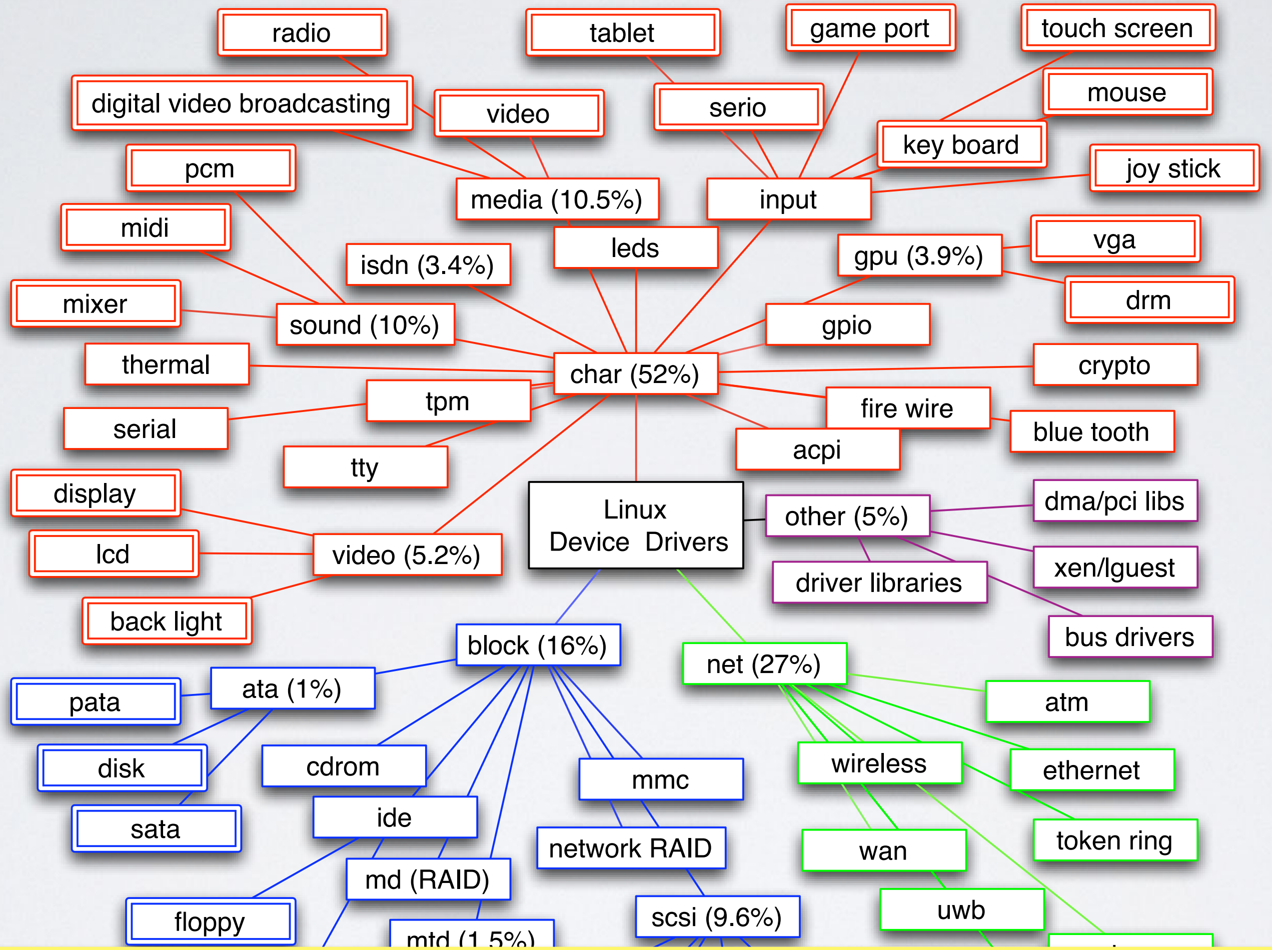
Do drivers belong to classes?

- ★ **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
  - ★ 16% of drivers use ioctl that *may* include non-standard behavior

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

Problem (b): Too many classes



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

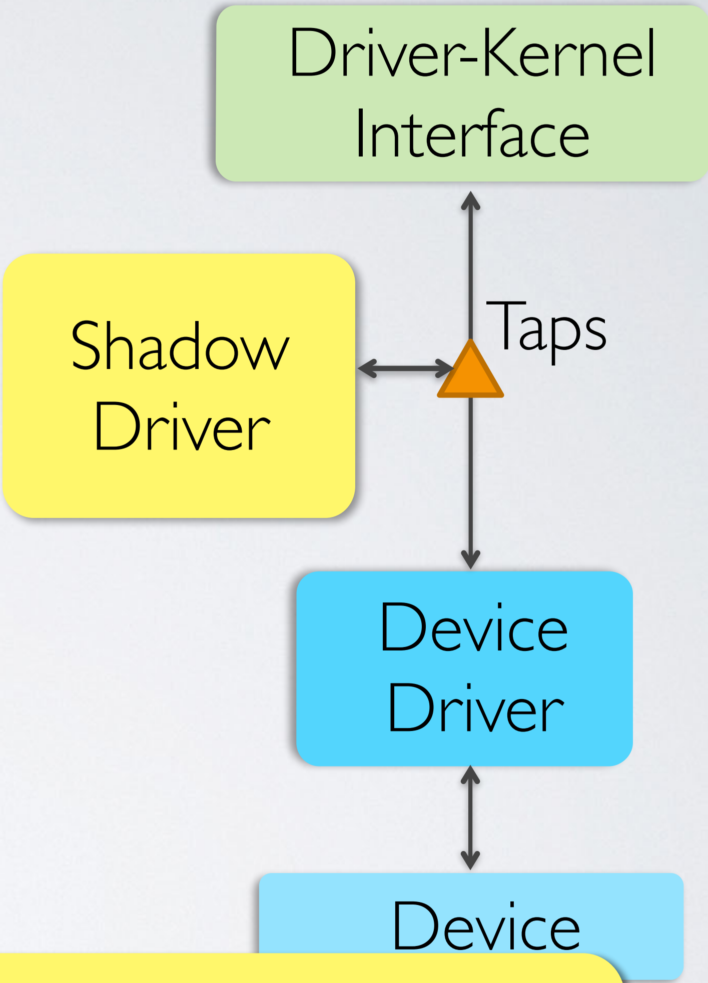
Checkpoint/restore

FGFT

Future work and conclude

Limitations of restart/replay recovery

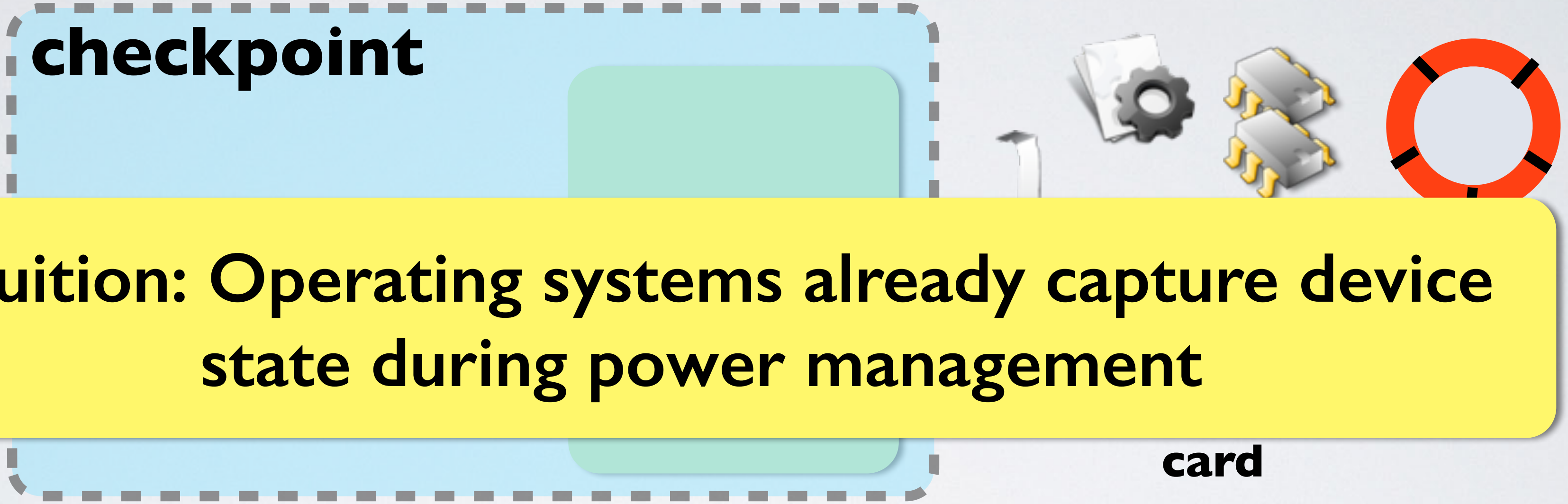
- **Device save/restore limited to restart/ replay**
  - Slow: Device initialization is complex (multiple seconds)
  - Incomplete: Unique device semantics not captured
  - Hard: Need to be written for every class of drivers
  - Large changes: Introduces new, large kernel subsystem



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



Intuition: Operating systems already capture device state during power management

★ Device state is not captured

- ★ Device configuration space
- ★ Internal device registers and counters
- ★ 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

Checkpoint (Suspend)

- Save config state
- Save register state
- Disable device
- Save DMA state
- Susp…

Restore (Resume)

- Restore config state
- Restore register state
- Restore or reset DMA state
- Re-attach/Enable device
- …dy

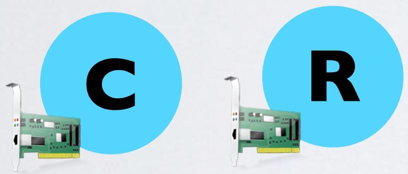
Suspend/resume code provides device checkpoint functionality

Fine-Grained Fault Tolerance[ASPLOS 2013]

- Goal: Improve driver recovery with minor changes to drivers
- Solution: Run drivers as transactions using device checkpoints

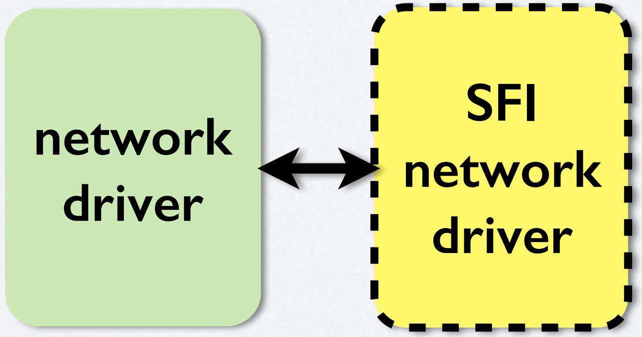
Device state

- Developers export checkpoint/restore fn.



Driver state

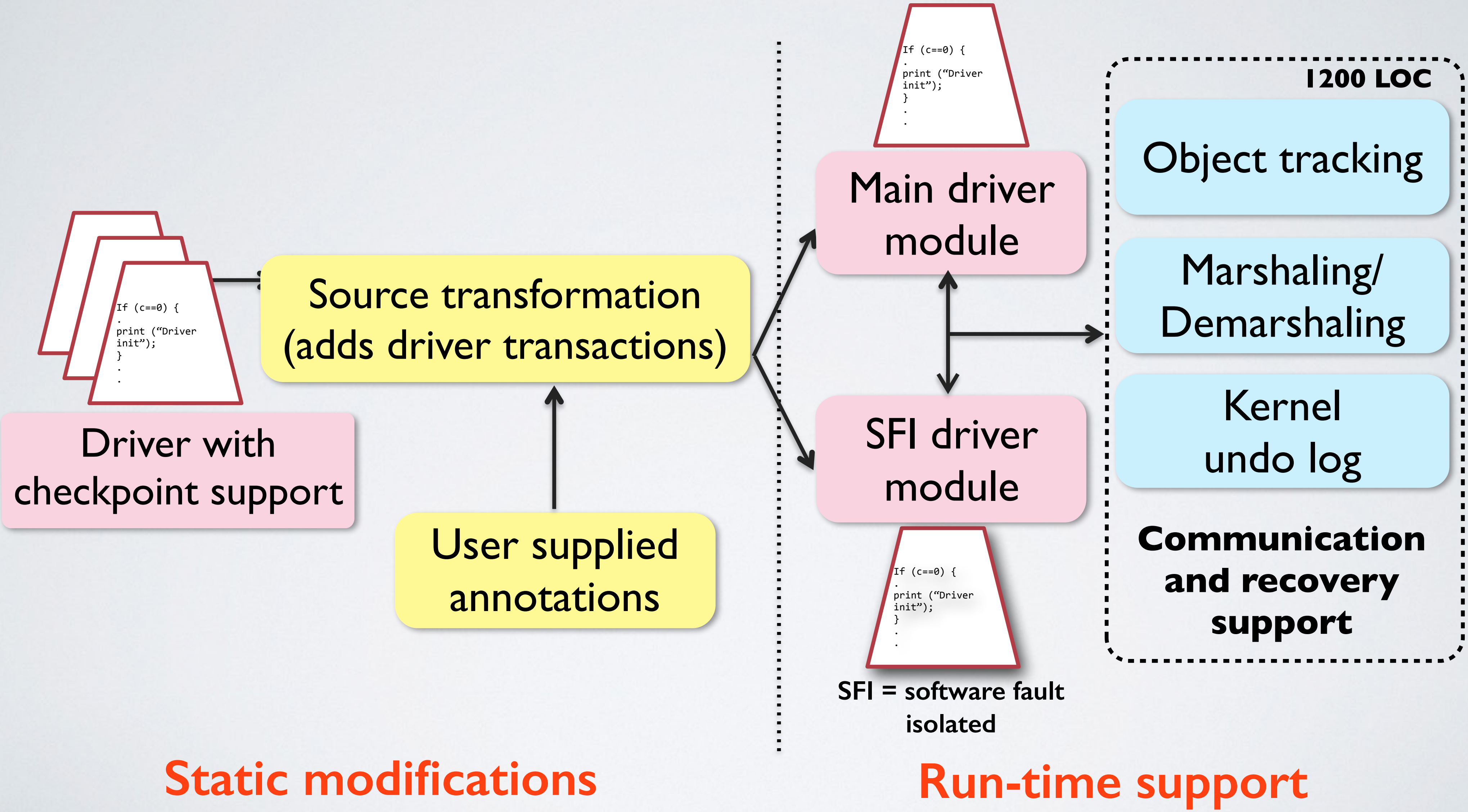
- Run drivers invocations as memory transactions
- Use source transformation to copy parameters and run on separate stack



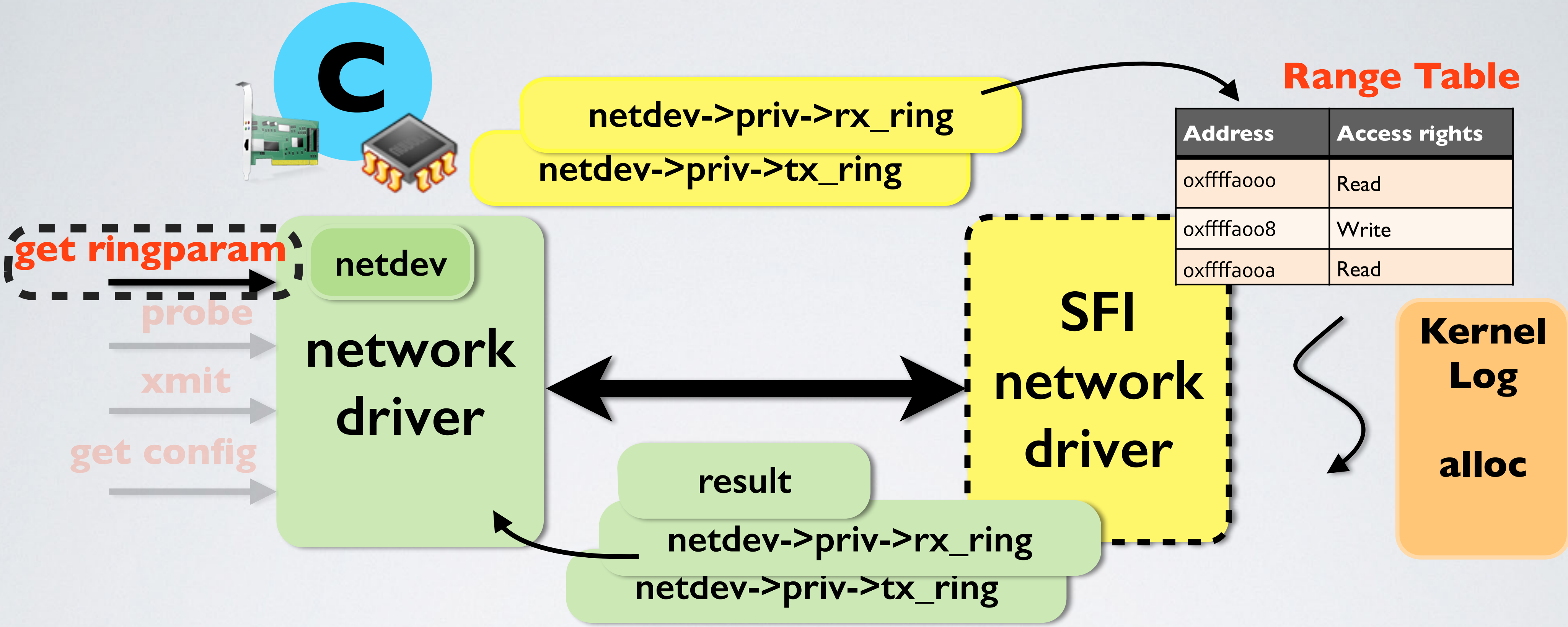
Execution model

- 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



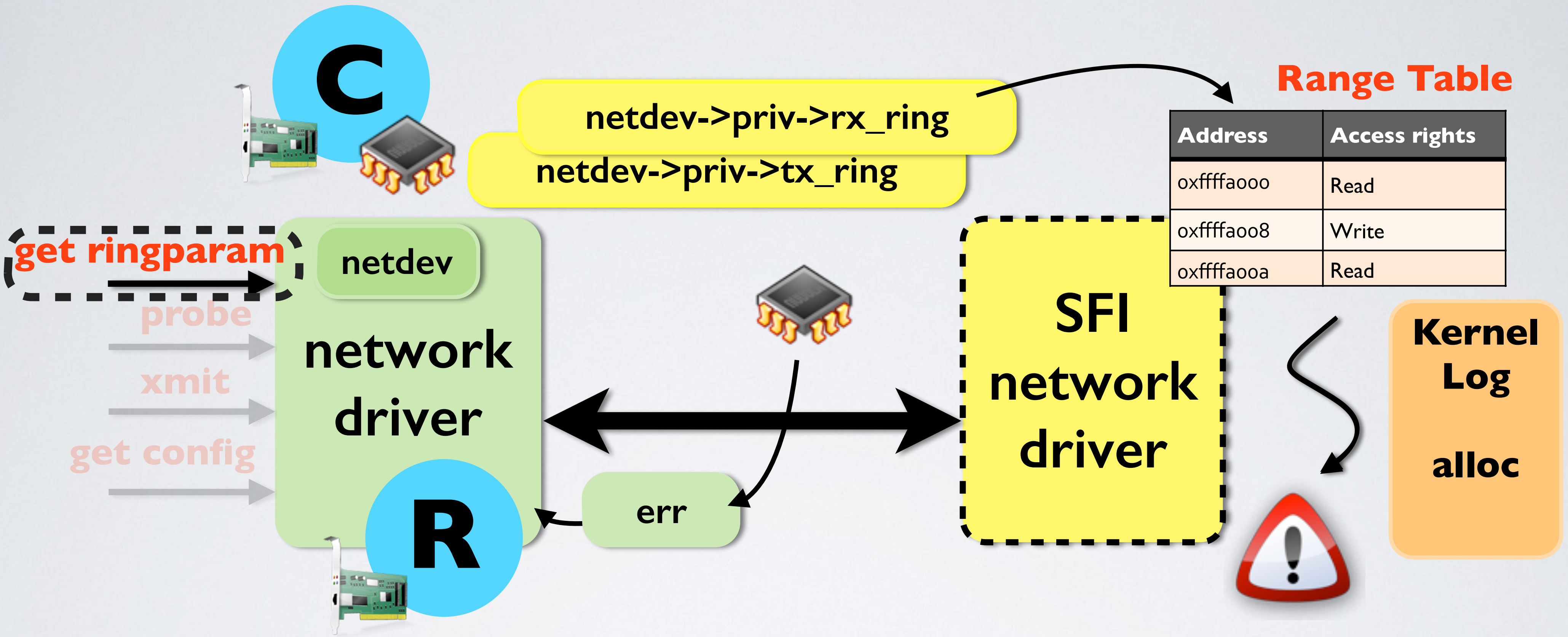
Transactional execution of drivers



★ 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



Address	Access rights
oxffffaooo	Read
oxffffaoo8	Write
oxffffaooa	Read

FGFT provides transactional execution of driver entry points

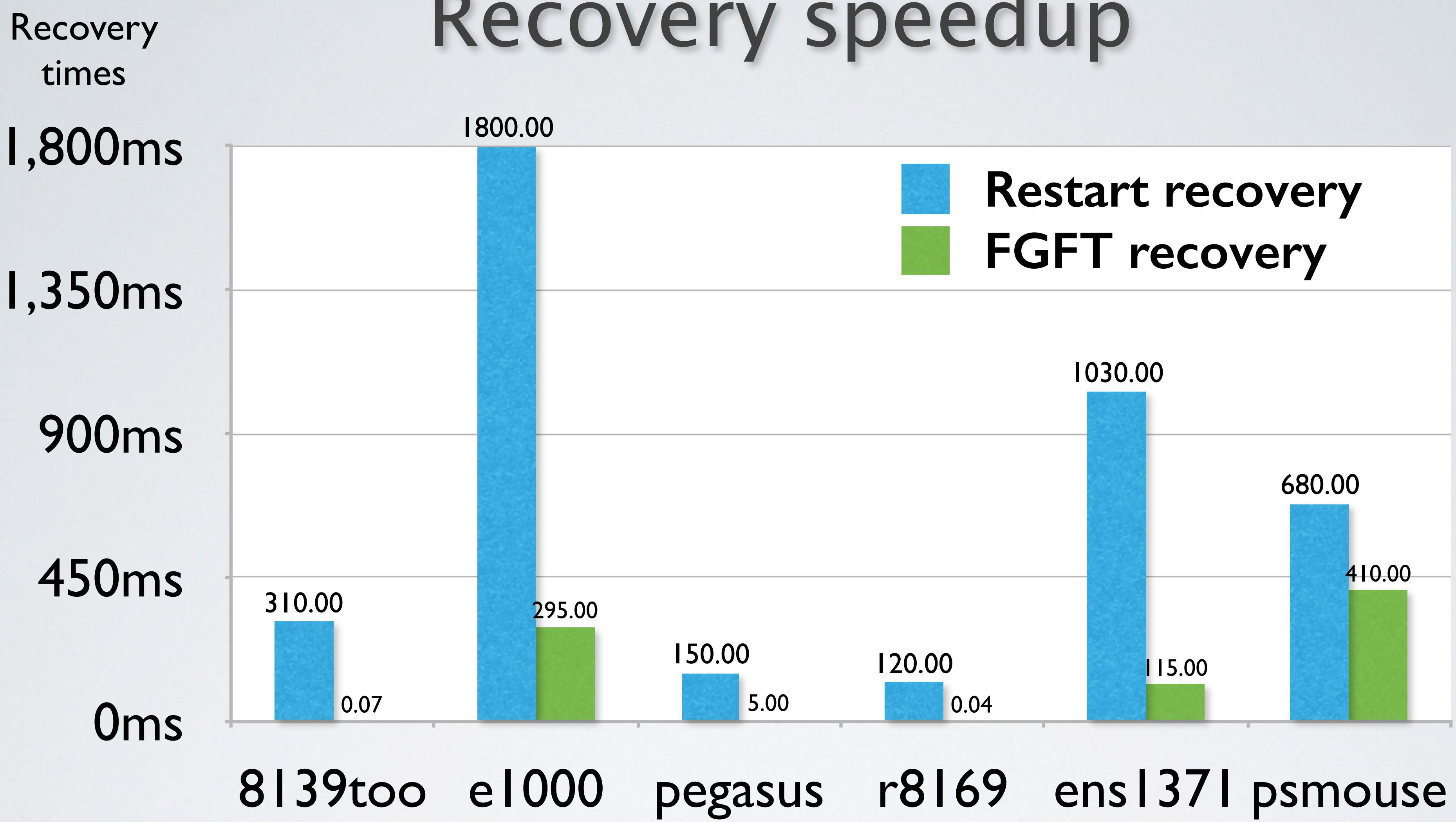
How does this give us transactional execution?

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

- 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



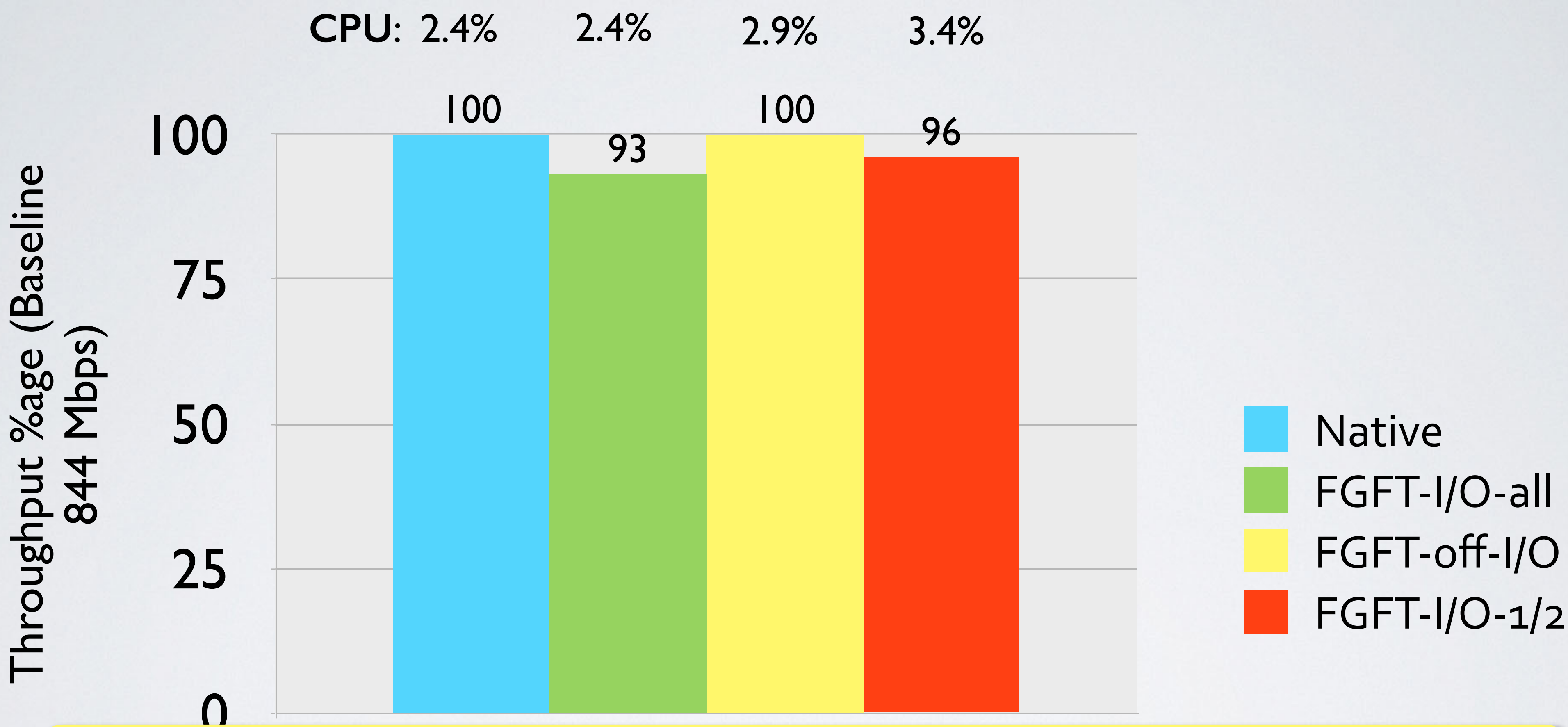
FGFT provides significant speedup in driver recovery and improves system availability

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



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

Thanks to all my collaborators

Michael Swift

- **www.cs.wisc.edu/~swift**

Extra slides