Tolerating Hardware Device Failures in Software

Asim Kadav, Matthew J. Renzelmann, Michael M. Swift
University of Wisconsin-Madison

THE UNIVERSITY of WISCONSIN MADISON

Current state of OS-hardware interaction

- Many device drivers assume device perfection
  - » Common Linux network driver: 3c59x .c

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

Hardware dependence bug: Device malfunction can crash the system

Current state of OS-hardware interaction

- Hardware dependence bugs across driver classes

```
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

How do the hardware bugs manifest?

- Drivers often trust hardware to always work correctly
  - Drivers use device data in critical control and data paths
  - Drivers do not report device malfunctions to system log
  - Drivers do not detect or recover from device failures

An example: Windows servers

- 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 driver:
  - » Crashes reduced from 8% to 3%
- Driver isolation systems not yet deployed

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

Carburizer

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

- Static analysis tool - analyze and insert code to:
  - » Detect and fix hardware dependence bugs
  - » Detect and generate missing error reporting information

- Runtime
  - » Handle interrupt failures
  - » Transparently recover from failures

Outline

- Background
- Hardening drivers
- Reporting errors
- Runtime fault tolerance
- Cost of carburizing
- Conclusion

Hardware unreliability

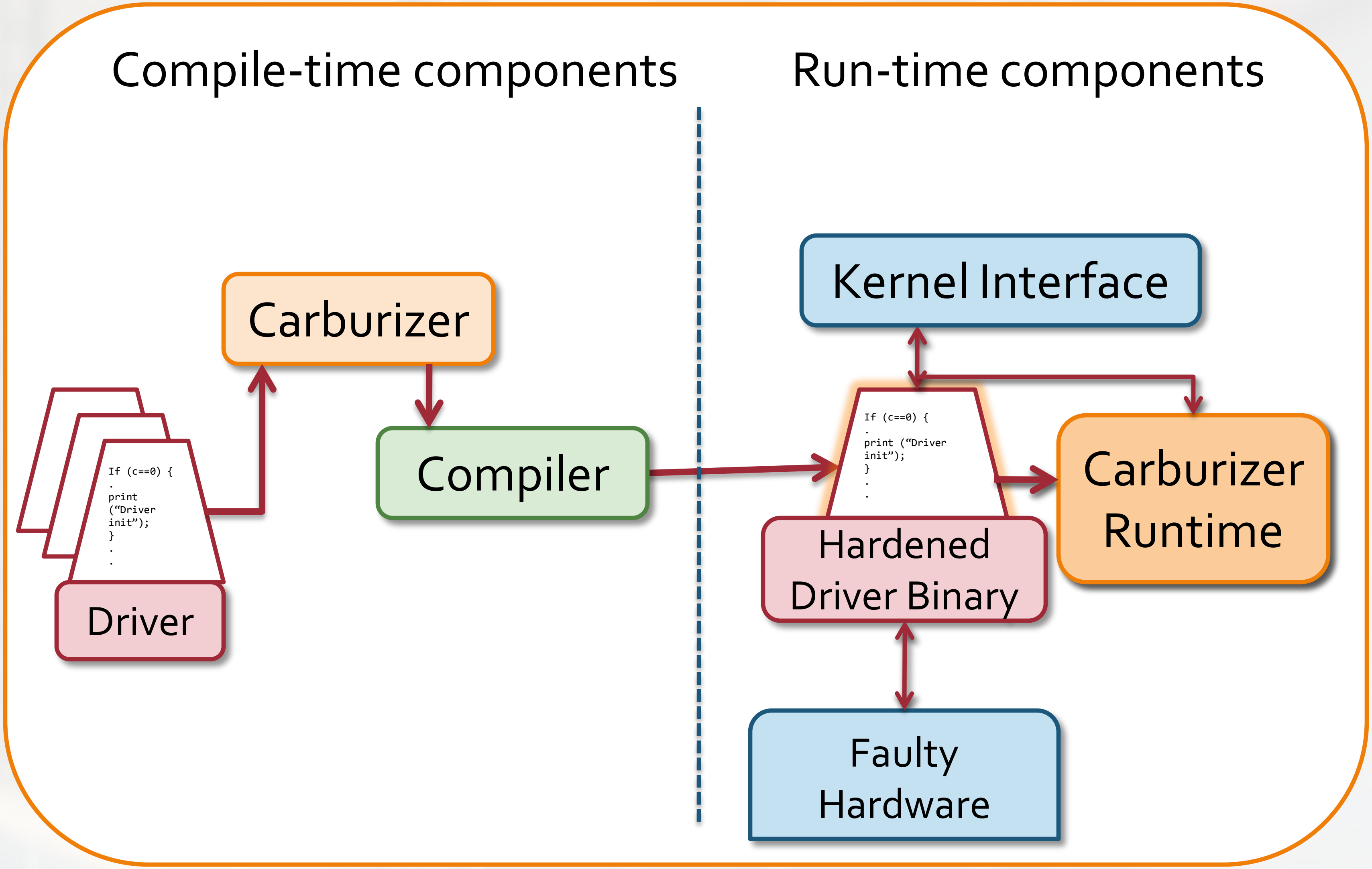
- Sources of hardware misbehavior:
  - » Device wear-out, insufficient burn-in
  - » Bridging faults
  - » Electromagnetic radiation
  - » Firmware bugs
- Result of misbehavior:
  - » Corrupted/stuck-at inputs
  - » Timing errors/unpredictable DMA
  - » Interrupt storms/missing interrupts

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	●	●	●	
Reporting	Report all failures	●	●	●	
Recovery	Handle all failures		●	●	
	Cleanup correctly	●	●		
	Do not crash on failure	●		●	●
	Wrap I/O memory access	●	●	●	●

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

Carburizer architecture



Outline

- Background
- Hardening drivers
  - Finding sensitive code
  - Repairing code
- Reporting errors
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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 from
  - » Infinite polling
  - » Unsafe static/dynamic array reference
  - » Unsafe pointer dereferences
  - » System panic calls

Hardening drivers

- Finding sensitive code
  - » First pass: Identify tainted variables

Finding sensitive code

First pass: Identify tainted variables

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

```
 Tainted
Variables
    a
    b
    c
    d
  test()
    e
```

Detecting risky uses of tainted variables

- Finding sensitive code
  - » 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

Example: Infinite polling

Finding sensitive code

```
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)

Not all bugs are obvious

```
while (DAC960_PD_StatusAvailableP(ControllerBaseAddress))
{
     DAC960_V1_CommandIdentifier_T CommandIdentifier= DAC960_PD_ReadStatusCommandIdentifier
                                                           (ControllerBaseAddress);
     DAC960_Command_T *Command = Controller ->Commands [CommandIdentifier-1];
     DAC960_V1_CommandMailbox_T *CommandMailbox = &Command->V1.CommandMailbox;
     DAC960_V1_CommandOpcode_T CommandOpcode=CommandMailbox->Common.CommandOpcode;
     Command->V1.CommandStatus =DAC960_PD_ReadStatusRegister(ControllerBaseAddress);
     DAC960_PD_AcknowledgeInterrupt(ControllerBaseAddress);
     DAC960_PD_AcknowledgeStatus(ControllerBaseAddress);
     switch (CommandOpcode)
       {
       case DAC960_V1_Enquiry_Old:
          DAC960_P_To_PD_TranslateReadWriteCommand(CommandMailbox);
          …
}
```

DAC960 Raid Controller(DAC960.c)

Detecting risky uses of tainted variables

- Example II: Unsafe array accesses
  - » Tainted variables used as array index into static or dynamic arrays
  - » Tainted variables used as pointers

Example: Unsafe array accesses

Unsafe array accesses

```
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

- Analyzed drivers in 2.6.18.8 Linux kernel
  - » 6300 driver source files
  - » 2.8 million lines of code
  - » 37 minutes to analyze and compile code

- Additional analyses to detect existing validation code

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

Many cases of poorly written drivers with hardware dependence bugs

Repairing drivers

- Hardware dependence bugs difficult to test
- Carburizer automatically generates repair code
  - » Inserts timeout code for infinite loops
  - » Inserts checks for unsafe array/pointer references
  - » Replaces calls to panic() with recovery service
  - » Triggers generic recovery service on device failure

Carburizer automatically fixes infinite loops

```
timeout = rdstcll(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)
           rdstcll(_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));

}
```

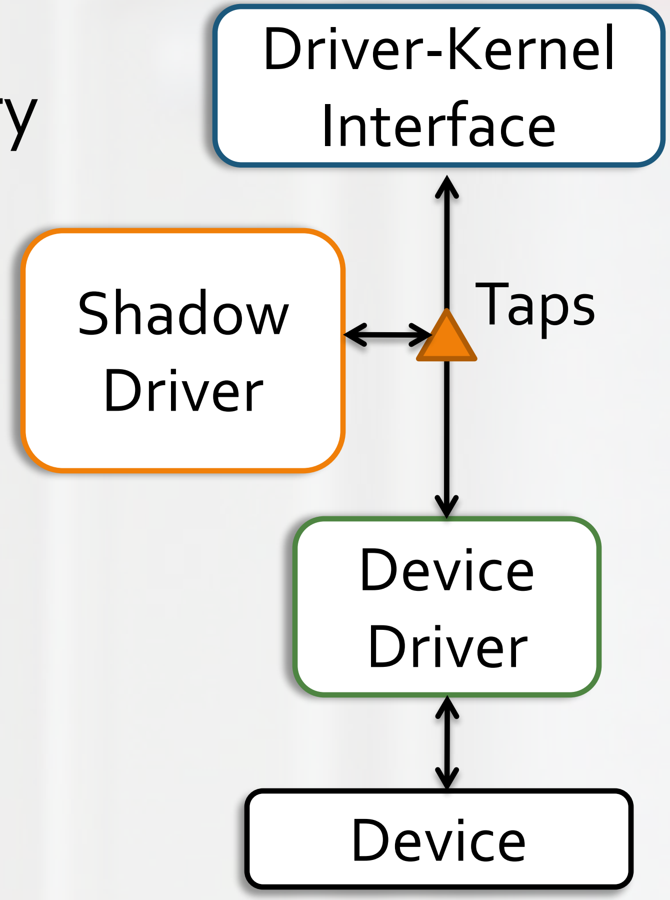
Array bounds check added

Pro Audio Sound driver (pas2_card.c)

*Code simplified for presentation purposes

Runtime fault recovery

- Low cost transparent recovery
  - » Based on shadow drivers
  - » Records state of driver
  - » Transparent restart and state replay on failure
- Independent of any isolation mechanism (like Nooks)



Experimental validation

- Synthetic fault injection on network drivers
- Results

Device/Driver	**Original Driver**		**Carburizer**		
	Behavior	Detection	Behavior	Detection	Recovery
3COM 3C905	CRASH	None	RUNNING	Yes	Yes

Carburizer failure detection and transparent recovery work well for transient device failures

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Reporting errors

- Drivers often fail silently and fail to report device errors
  - » Drivers should proactively report device failures
  - » Fault management systems require these inputs
- Driver already detects failure but does not report them
- Carburizer analysis performs two functions
  - » Detect when there is a device failure
  - » Report unless the driver is already reporting the failure

Detecting driver detected device failures

- Detect code that depends on tainted variables
  - Perform unreported loop timeouts
  - Returns negative error constants
  - Jumps to common cleanup code

```
while (ioread16 (regA) == 0x0f)  {
  if (timeout++ == 200)  {
    sys_report("Device timed out %s.\n", mod_name);
    return (-1);
  }
}
```

Reporting code added by Carburizer

Detecting existing reporting code

Carburizer detects function calls with string arguments

```
static u16 gm_phy_read(...)
{
  ...
 if (__gm_phy_read(...))
   printk(KERN_WARNING "%s: ...\n”, ...);
```

Carburizer detects existing reporting code

SysKonnect network driver(skge.c)

Evaluation

- Manual analysis of drivers of different classes

Driver	Class	Driver detected device failures	Carburizer reported failures
bnx2	network	24	17
mptbase	scsi	28	17
ens1371	sound	10	9

- No false positives

Carburizer *automatically* improves the fault diagnosis capabilities of the system

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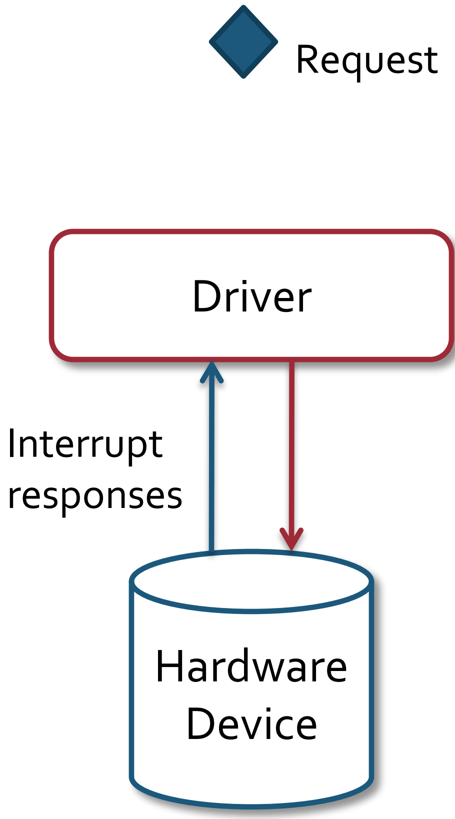
Runtime failure detection

- Static analysis cannot detect all device failures
  - » Missing interrupts: expected but never arrives
  - » Stuck interrupts (interrupts storm): interrupt cleared by driver but continues to be asserted

Tolerating missing interrupts



- Detect when to expect interrupts
  - » Detect driver activity via referenced bits
  - » Invoke ISR when bits referenced but no interrupt activity
- Detect how often to poll
  - » Dynamic polling based on previous invocation result

Tolerating stuck interrupts

- Driver interrupt handler is called too many times
- Convert the device from interrupts to polling

Driver Type	Driver Name	Throughput reduction due to polling
Disk	ide-core,ide-disk, ide-generic	Reduced by 50%
Network	e1000	Reduced from 750 Mb/s to 130 Mb/s
Sound	ens1371	Sounds plays with distortion

Carburizer ensures system and device make forward progress

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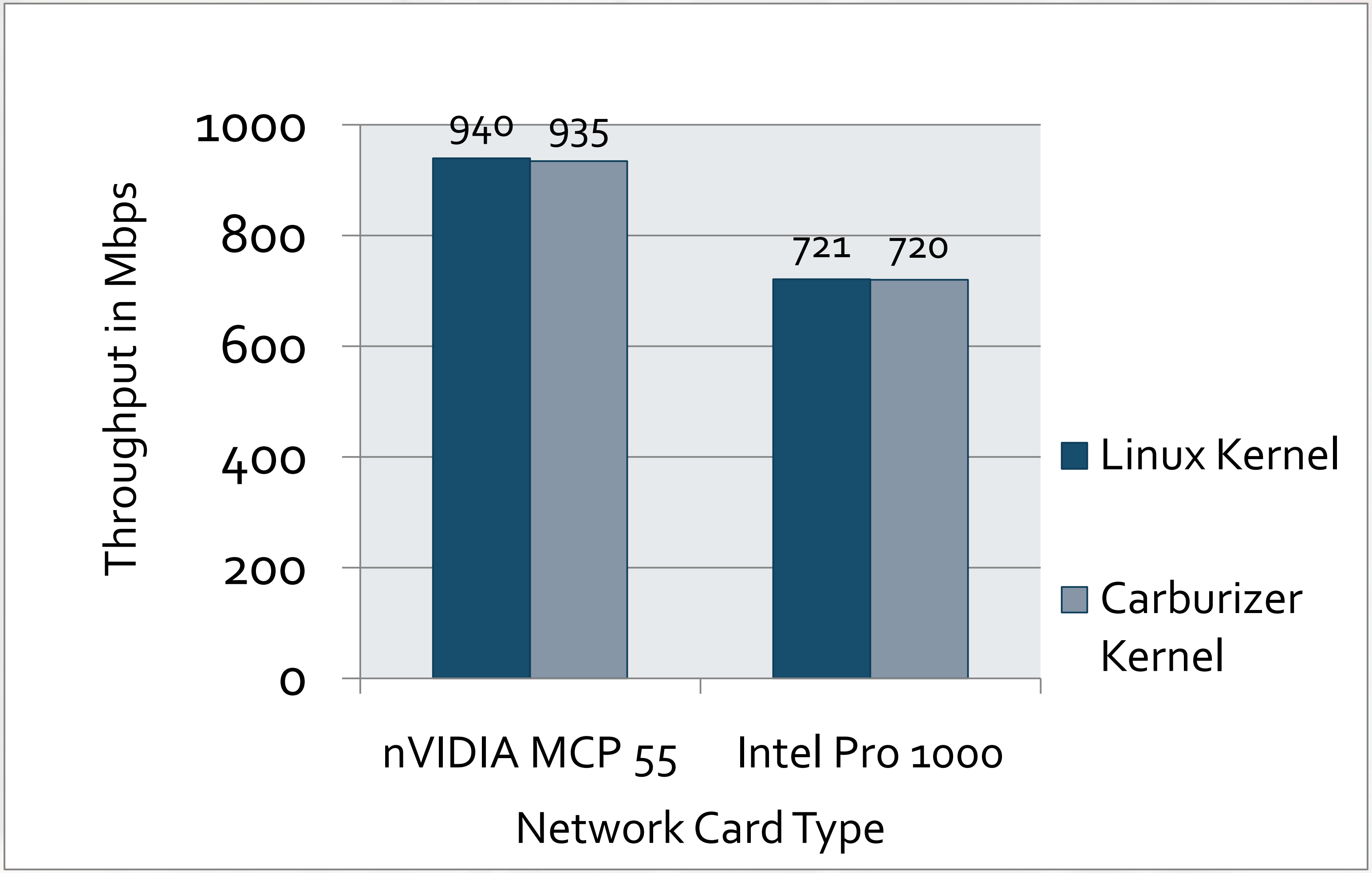
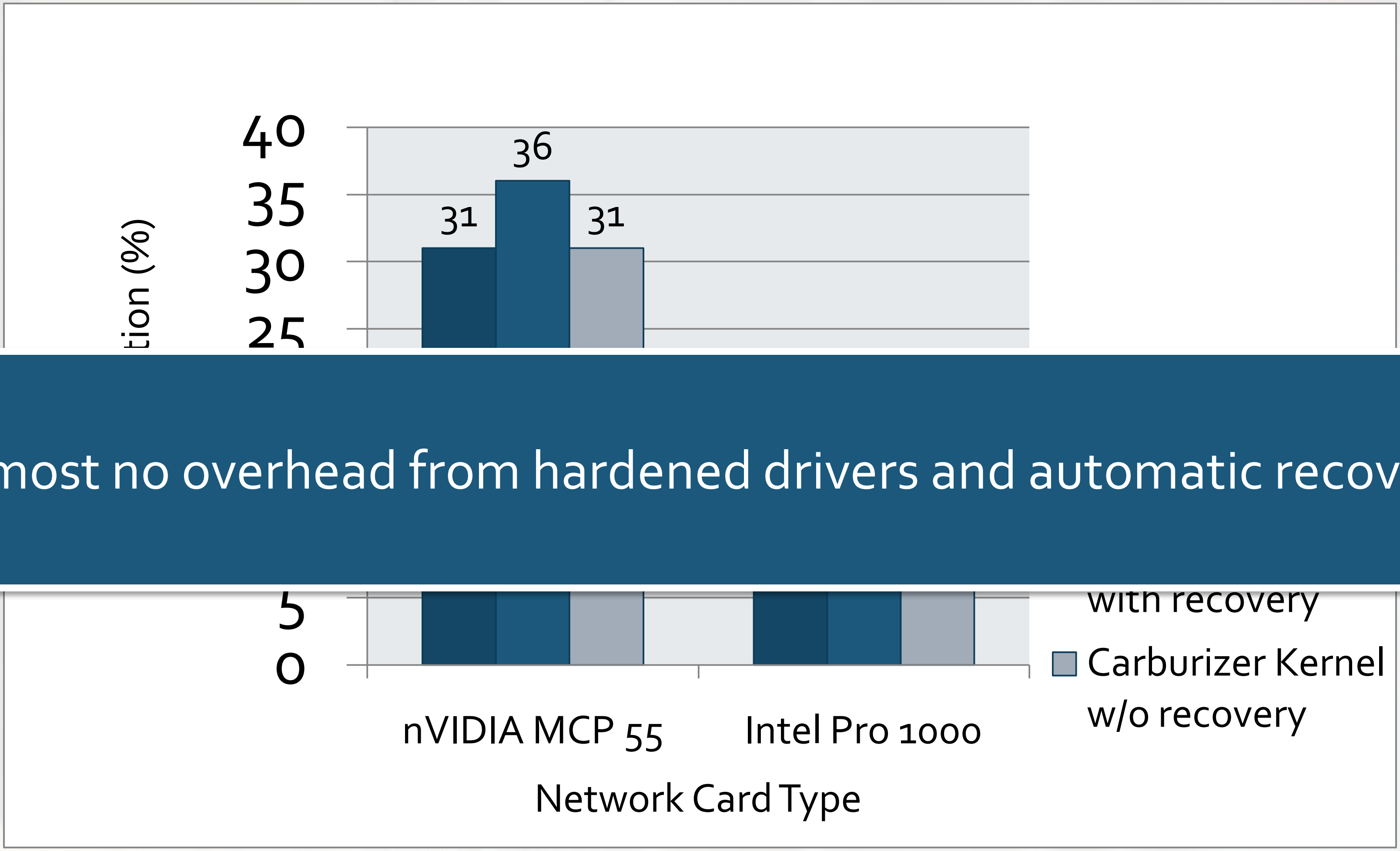
Throughput overhead



netperf on 2.2 GHz AMD machines

CPU overhead



Almost no overhead from hardened drivers and automatic recovery

netperf on 2.2 GHz AMD machines

Conclusion

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	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	●	●	●	●

Conclusion

Recommendation	Summary	Recommended by				Carburizer Ensures
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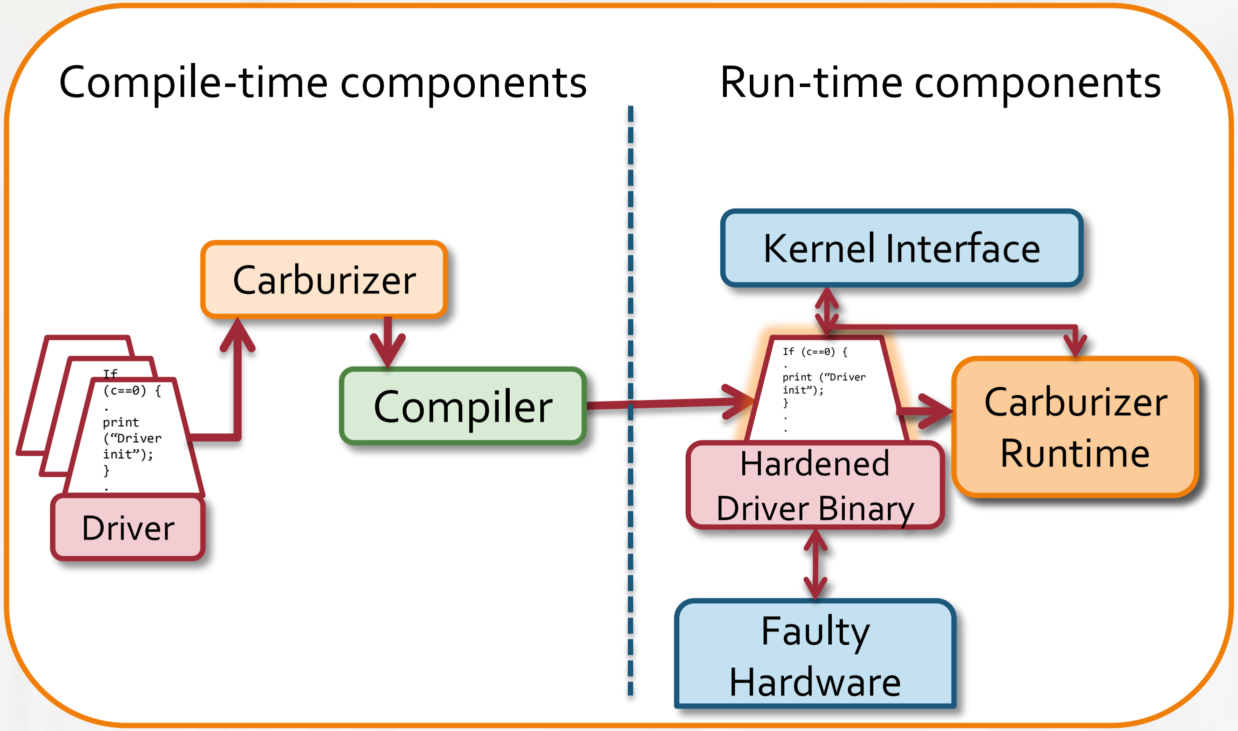
	DMA protection	●	●			
Timing	Infinite polling	●	●	●		●
Reporting	Report all failures	●	●	●		●
Recovery	Handle all failures		●	●		●
	Cleanup correctly	●	●			●
	Do not crash on failure	●		●	●	●
	Wrap I/O memory access	●	●	●	●	

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

Thank You



- Contact
  - » kadav@cs.wisc.edu
- Visit our website for research on drivers
  - » http://cs.wisc.edu/~swift/drivers

Backup slides

Improving analysis accuracy

- Detect existing driver validation code
  - » Track variable taint history
  - » Detect existing timeout code
  - » Detect existing sanity checks

```
while ((inb(nic_base + EN0_ISR) & ENISR_RDC) == 0)
      if (jiffies - dma_start> 2)   {
            ...
            break;
      }
```

```
ne2000 network driver (ne2k-pci.c)
```

Trend of hardware dependence bugs

- Many drivers either had one or two hardware bugs
  - » Developers were mostly careful but forgot in a few places
- Small number of drivers were badly written
  - » Developers did not account H/W dependence; many bugs

Implementation efforts

- Carburizer static analysis tool
  - » 3230 LOC in OCaml
- Carburizer runtime (Interrupt Monitoring)
  - » 1030 lines in C
- Carburizer runtime (Shadow drivers)
  - »19000 LOC in C
  - »~70% wrappers – can be automatically generated by scripts