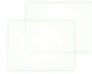
Device Drivers

COMP9242
2011/S2 Week 5



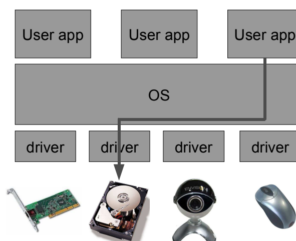
Some statistics

- 70% of OS code is in device drivers
  - 3,448,000 out of 4,997,000 loc in Linux 2.6.27
- A typical Linux laptop runs ~240,000 lines of kernel code, including ~72,000 loc in 36 different device drivers
- Drivers contain 3—7 times more bugs per loc than the rest of the kernel
- 70% of OS failures are caused by driver bugs

Lecture outline

- Part 1: Introduction to device drivers
- Part 2: Overview of research on device driver reliability
- Part 3: Device drivers research at ERTOS

Part 1: Introduction to device drivers



OS archeology

The first (?) device drivers: I/O libraries for the IBM 709 batch processing system [1958]

OS archeology

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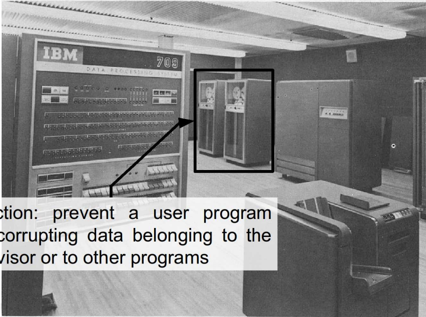

Protection: prevent a user program from corrupting data belonging to the supervisor or to other programs

OS archeology

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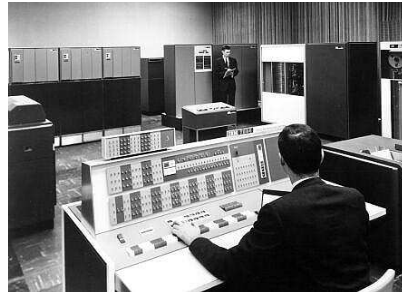
IBM 7094 [1962] supported a wide range of peripherals: tapes, disks, teletypes, flexowriters, etc.



OS archeology

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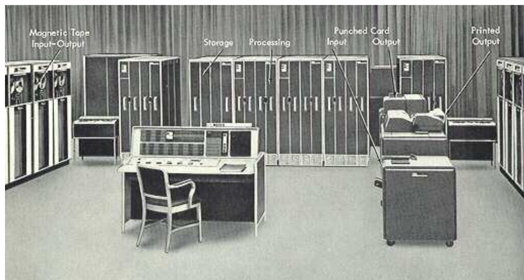
IBM 7090 [1959] introduced I/O channels, which allowed I/O and computation to overlap



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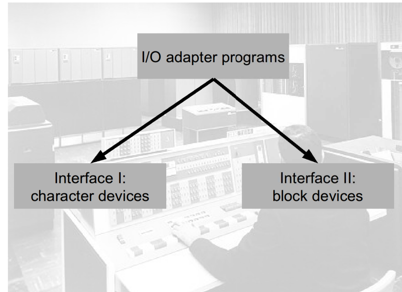

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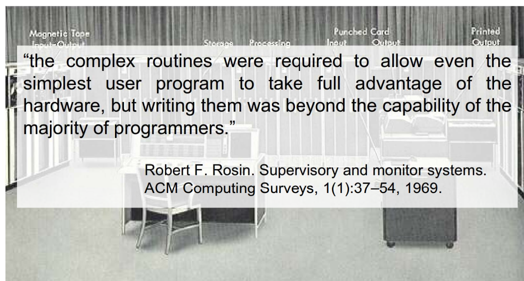

"the complex routines were required to allow even the simplest user program to take full advantage of the hardware, but writing them was beyond the capability of the majority of programmers."

Robert F. Rosin. Supervisory and monitor systems. ACM Computing Surveys, 1(1):37–54, 1969.

OS archeology

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GE-635 [1963] introduced the master CPU mode. Only the hypervisor running in the master mode could execute I/O instructions

Functions of a driver

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- Encapsulation
  - Hides low-level device protocol details from the client
- Unification
  - Makes similar devices look the same
- Protection (in cooperation with the OS)
  - Only authorised applications can use the device
- Multiplexing (in cooperation with the OS)
  - Multiple applications can use the device concurrently

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I/O device: a high-level view

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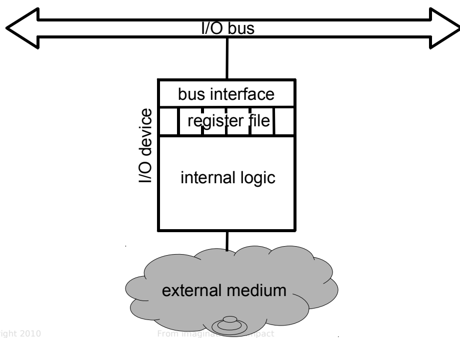

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I/O devices in a typical desktop system

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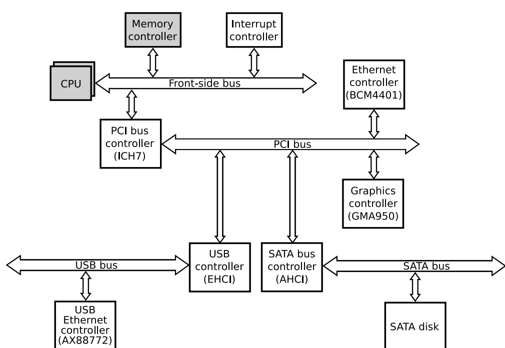

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PCI bus overview

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- PCI bus
  - Conventional PCI
    - Developed and standardised in early 90's
    - 32 or 64 bit shared parallel bus
    - Up to 66MHz (533MB/s)
  - PCI-X
    - Up to 133MHz (1066MB/s)
  - PCI Express
    - Consists of serial p2p links
    - Software-compatible with conventional PCI
    - Up to 16GB/s per device

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PCI bus overview: memory space

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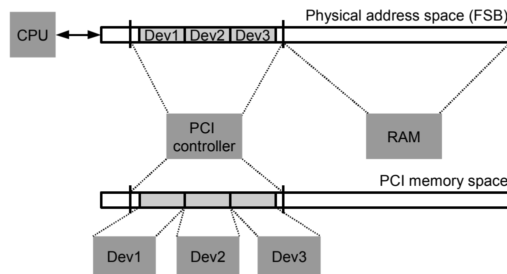

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PCI bus overview: DMA

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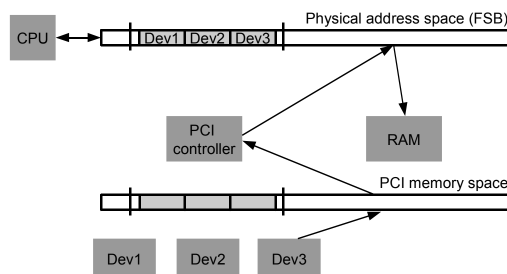

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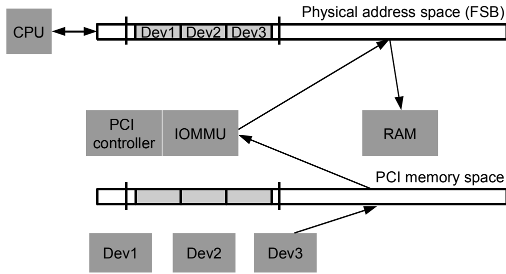
PCI bus overview: DMA



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PCI bus overview: config space

- PCI configuration space
  - Used for device enumeration and configuration
  - Contains standardised device descriptors

31		16 15	0	
Device ID		Vendor ID		00h
Status		Command		04h
Class Code			Revision ID	08h
BIST	Header Type	Lat. Timer	Cache Line S.	0Ch
Base Address Registers				10h 14h 18h 1Ch 20h 24h
Cardbus CIS Pointer				28h
Subsystem ID		Subsystem Vendor ID		2Ch
Expansion ROM Base Address				30h
Reserved			Cap. Pointer	34h
Reserved				38h
Max Lat.	Min Gnt.	Interrupt Pin	Interrupt Line	3Ch

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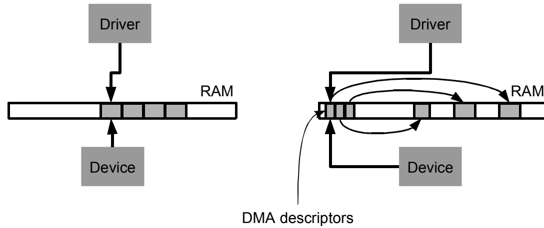
DMA descriptors

Permanent DMA mappings
- Set up during driver initialisation
- Data must be copied to/from DMA buffers

Streaming mappings
- Created for each transfer
- Data is accessed in-place



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PCI bus overview: I/O space

- I/O space
  - obsolete

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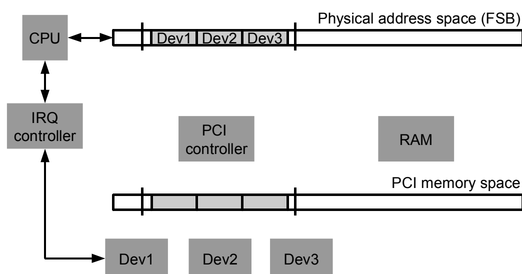
PCI bus overview: interrupts



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Writing a driver for a PCI device

- Registration
  - Tell the OS which PCI device ID's the driver supports
- Instantiation
  - Done by the OS when it finds a driver with a matching ID
- Initialisation
  - Allocate PCI resources: memory regions, IRQ's
  - Enable bus mastering
  - Permanent DMA mappings: disable caching

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Writing a driver for a PCI device

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- Interrupt handler
  - Return ASAP to re-enable interrupts; perform heavy-weight processing in a separate thread
- DMA
  - Streaming mappings: may require bounce buffers
- Power management
  - Prepare the device for a transition into a low-power state
  - Restore device configuration during wake-up

I/O devices in a typical desktop system

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Memory controller
Interrupt controller
CPU
Front-side bus
Ethernet controller (BCM4401)
PCI bus controller (ICH7)
PCI bus
Graphics controller (GMA950)
USB bus
USB controller (EHCI)
SATA bus controller (AHCI)
SATA bus
USB Ethernet controller (AX88772)
SATA disk

USB bus overview

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- USB bus
  - Host-centric
  - Distributed-system-style architecture (packet-based transfers)
  - Hot plug
  - Power management
    - Bus-powered and self-powered devices
  - USB 1.x
    - Up to 12Mb/s
  - USB 2.0
    - Up to 480Mb/s
  - USB 3.0
    - Up to 4.8Gb/s

Driver stacking

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Memory controller
Interr contr
CPU
Front-side bus
PCI bus controller (ICH7)
USB bus
USB controller (EHCI)
USB Ethernet controller (AX88772)

USB bus overview

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Device 3
Device 4
Device 1
Device 2
Hub
Root hub
DMA
USB bus controller
DMA
Transfer descriptors
Completions

Driver stacking

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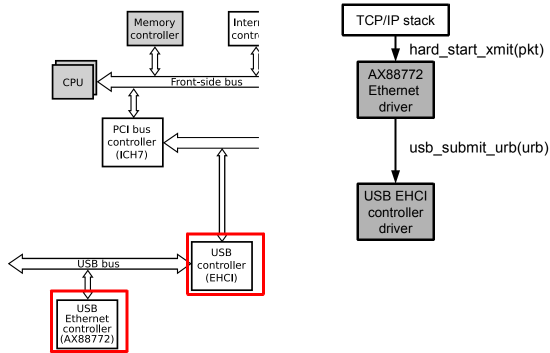
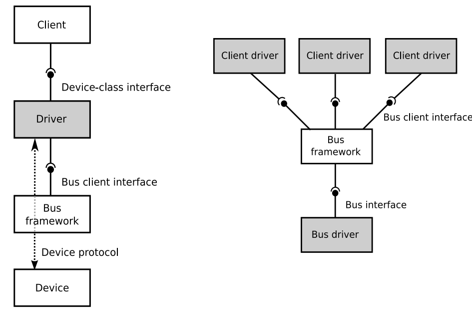
Memory controller
Interr contr
CPU
Front-side bus
PCI bus controller (ICH7)
USB bus
USB controller (EHCI)
USB Ethernet controller (AX88772)
TCP/IP stack
hard_start_xmit(pkt)
AX88772 Ethernet driver

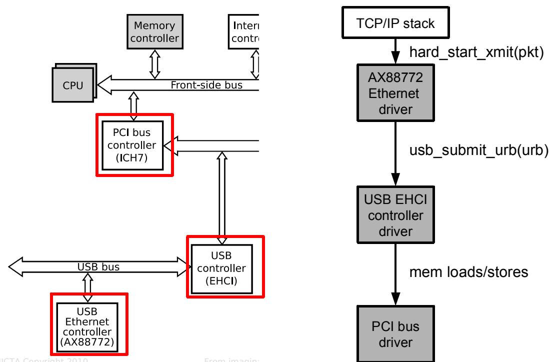
Driver stacking



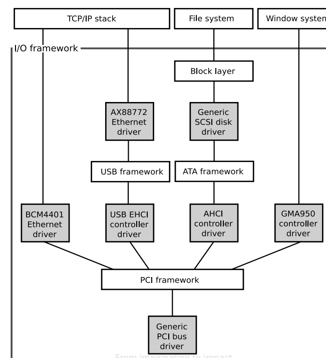
Driver framework design patterns



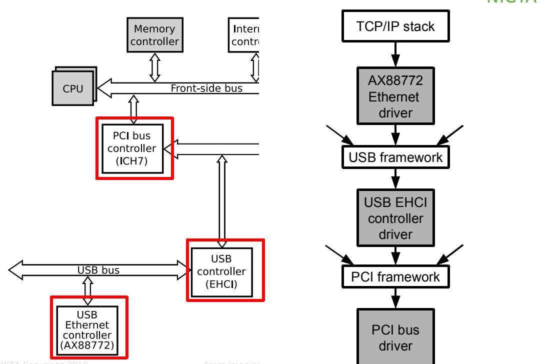
Driver stacking



Driver framework software architecture



Driver stacking



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Questions?

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Part 2: Overview of research on device driver reliability

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Understanding driver bugs

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- Driver failures
  - Memory access violations
  - OS protocol violations
    - Ordering violations
    - Data format violations
    - Excessive use of resources
    - Temporal failure
  - Device protocol violations
    - Incorrect use of the device state machine
    - Runaway DMA
    - Interrupt storms
  - Concurrency bugs
    - Race conditions
    - Deadlocks

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User-level device drivers

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- User-level drivers
  - Each driver is encapsulated inside a separate hardware protection domain
  - Communication between the driver and its client is based on IPC
  - Device memory is mapped into the virtual address space of the driver
  - Interrupts are delivered to the driver via IPC's

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Understanding driver bugs

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- Driver failures

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User-level drivers in μ-kernel OSs

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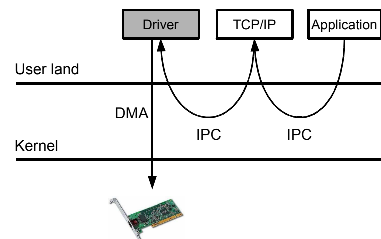

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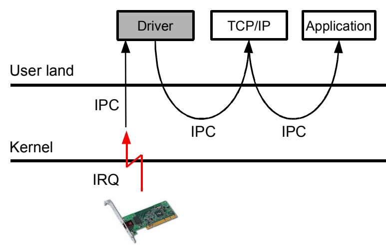
User-level drivers in μ-kernel OSs



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Driver performance characteristics

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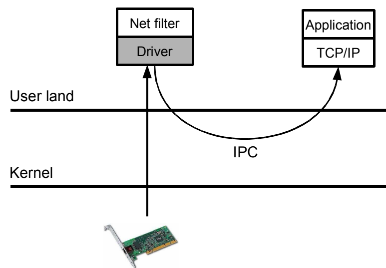
User-level drivers in μ-kernel OSs



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Driver performance characteristics

- I/O throughput
  - Can the driver saturate the device?
- I/O latency
  - How does the driver affect the latency of a single I/O request?
- CPU utilisation
  - How much CPU overhead does the driver introduce?

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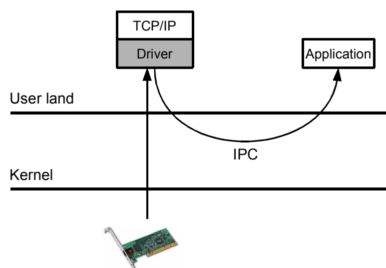
User-level drivers in μ-kernel OSs



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Improving the performance of ULD

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Improving the performance of ULD

- Ways to improve user-level driver performance
  - Shared-memory communication
  - Request queueing
  - Interrupt coalescing

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Early implementations of ULD

- Michigan Terminal System [1970's]
  - OS for IBM System/360
  - Apparently, the first to support user-level drivers
- Mach [1985-1994]
  - Distributed multi-personality µ-kernel-based multi-server OS
  - High IPC overhead
  - Eventually, moved drivers back into the kernel
- L3 [1987-1993]
  - Persistent µ-kernel-based OS
  - High IPC overhead
  - Improved IPC design: 20-fold performance improvement
  - No data on driver performance available

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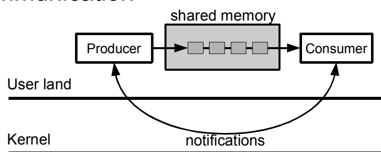
Implementing efficient shared-memory communication



- Issues:
  - Resource accounting
  - Safety
  - Asynchronous notifications

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More recent implementations

- Sawmill [~2000]
  - Multiserver OS based on automatic refactoring of the Linux kernel
  - Hampered by software engineering problems
  - No data on driver performance available
- DROPS [1998]
  - L4 Fiasco-based real-time OS
  - ~100% CPU overhead due to user-level drivers
- Fluke [1996]
  - ~100% CPU overhead
- Mungi [1993—2006]
  - Single-address-space distributed L4-based OS
  - Low-overhead user-level I/O demonstrated for a disk driver

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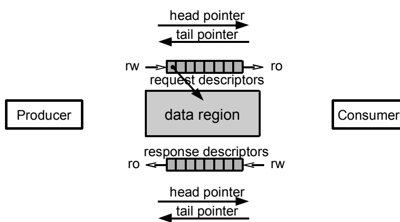
Rbufs

- Proposed in the Nemesis microkernel-based multimedia OS



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Currently active systems

- Research
  - seL4
  - MINIX3
  - Nexus
- Commercial
  - OKL4
  - QNX
  - GreenHills INTEGRITY

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User-level drivers in a monolithic OS

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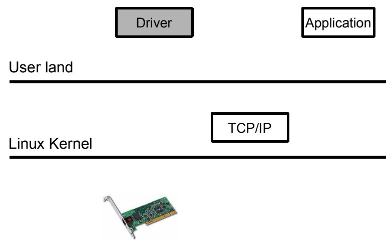
Ben Leslie et al. User-level device drivers: Achieved performance, 2005



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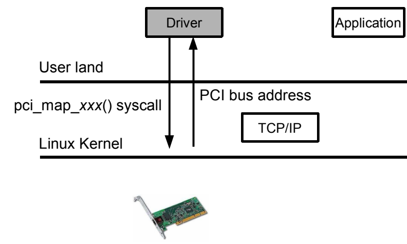

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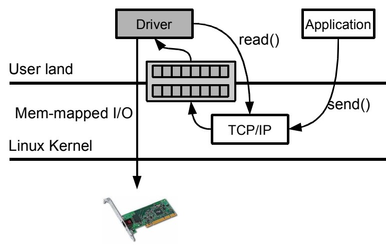

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User-level drivers in a monolithic OS

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Ben Leslie et al. User-level device drivers: Achieved performance, 2005

- Performance
  - Up to 7% throughput degradation
  - Up to 17% CPU overhead
  - Aggressive use of interrupt rate limiting potentially affects latency (not measured).

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User-level drivers in a monolithic OS

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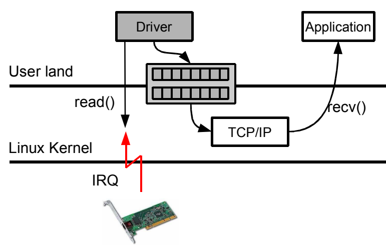

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Nooks

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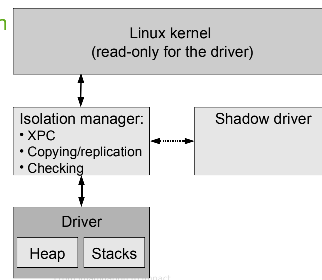
- A complete device-driver reliability solution for Linux:
  - Fault isolation
  - Fault detection
  - Recovery



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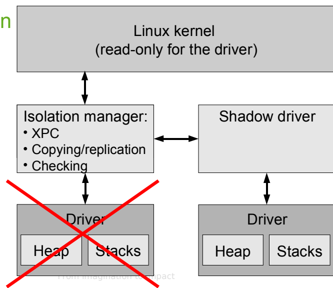

Virtualisation and user-level drivers

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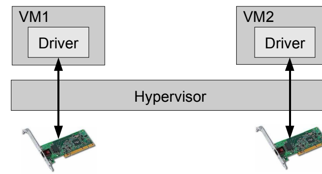
- Direct I/O



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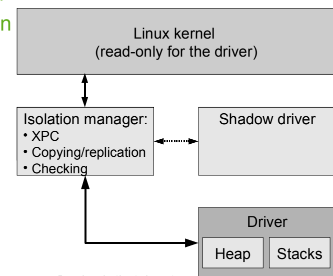

Virtualisation and user-level drivers

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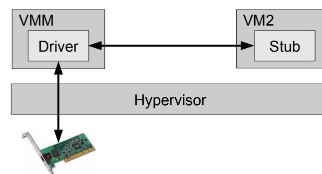
- Paravirtualised I/O



Nooks

NICTA

- A complete device-driver reliability solution for Linux:
  - Fault isolation
  - Fault detection
  - Recovery
- Problems
  - The driver interface in Linux is not well defined. Nooks must simulate the behaviour of hundreds of kernel and driver entry points.
- Performance
  - 10% throughput degradation
  - 80% CPU overhead

Paravirtualised I/O in Xen

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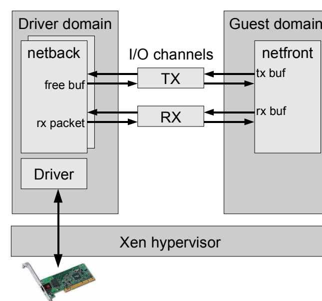

- Xen I/O channels are similar to rbufs, but use a single circular buffer for both requests and completions and rely on mapping rather than sharing

Xen I/O channels

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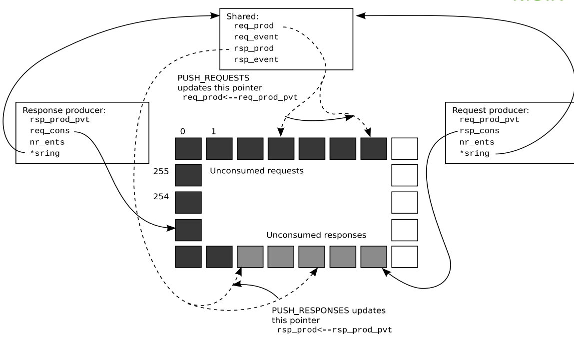

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Other driver reliability techniques

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- Implementing drivers using safe languages
  - Singularity OS
    - The entire OS is implemented in Sing#
    - Every driver is encapsulated in a separate software-isolated process
    - Processes communicated via messages sent across channels
    - Sing# provides means to specify and statically enforce channel protocols

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Paravirtualised I/O in Xen

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- Performance overhead of the original implementation: 300%
  - Long critical path (increased instructions per packet)
  - Higher TLB and cache miss rates (more cycles per instructions)
  - Overhead of mapping
- Optimisations
  - Avoid mapping on the send path (the driver does not need to “see” the packet content)
  - Replace mapping with copying on the receive path
  - Avoid unaligned copies
  - Optimised implementation of page mapping
  - CPU overhead down to 97% (worst-case receive path)

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Other driver reliability techniques

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- Static analysis
  - SLAM, Blast, Coverity
  - Generic programming faults
    - Release acquired locks; do not acquire a lock twice
    - Do not dereference user pointers
    - Check potentially NULL-pointers returned from routine
  - Driver-specific properties
    - “if a driver calls another driver that is lower in the stack, then the dispatch routine returns the same status that was returned by the lower driver”
    - “drivers mark I/O request packets as pending while queuing them”
  - Limitations
    - Many properties are beyond reach of current tools or are theoretically undecidable (e.g., memory safety)

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Other driver reliability techniques

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- Implementing drivers using safe languages
  - Java OSs: KaffeOS, JX
    - Every process runs in a separate protection domain with a private heap. Process boundaries are enforced by the language runtime. Communication is based on shared heaps.
  - House (Haskell OS)
    - Bare-metal Haskell runtime. The kernel and drivers are in Haskell.
    - User programs can be written in any language.
  - SafeDrive
    - Extends C with pointer type annotations enforced via static and runtime checking
    -
```
unsigned n;
struct e1000 buffer * count(n) bufinfo;
```

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Questions?

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