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ADRIAN PERRIG & TORSTEN HOEFLER

Networks and Operating Systems (252-0062-00)

Chapter 10: I/O Subsystems (2)

BREAKING FULL-DISK ENCRYPTION USING FIREWIRE

There have been a number of proof-of-concept hacks using IEEE1394 devices' DMA to elevate privileges on a host machine.


The most useful application of this technique is breaking into machines that use full-disk encryption. Now there is a tool that will run from any Unix-Like host (Linux, OSX) and can unlock Windows XP, Vista, 7, 8, OSX 10.6, 10.7, 10.8, Ubuntu on both x86 and x64 hosts.

Inception is a FireWire physical memory manipulation and hacking tool exploiting IEEE 1394 SBP-2 DMA. The tool can unlock (any password accepted) and escalate privileges to Administrator/root on almost any machine you have physical access to.

It is primarily intended to do its magic against computers that utilize full disk encryption such as BitLocker, FileVault, TrueCrypt or Pointsec. There are plenty of other (and better) ways to hack a machine that doesn't pack encryption. Inception is also useful for incident response teams and digital forensics experts when faced with live machines.

BE CAREFUL WITH I/O DEVICES!

OS	Version	Unlock lock screens	Escalate privileges	Dump memory < 4 GB
Windows 8	8.1	Yes	Yes	Yes
Windows 8	8.0	Yes	Yes	Yes
Windows 7	SP1	Yes	Yes	Yes
Windows 7	SP0	Yes	Yes	Yes
Windows Vista	SP2	Yes	Yes	Yes
Windows Vista	SP1	Yes	Yes	Yes
Windows Vista	SP0	Yes	Yes	Yes
Windows XP	SP3	Yes	Yes	Yes
Windows XP	SP2	Yes	Yes	Yes
Windows XP	SP1			Yes
Windows XP	SP0			Yes
Mac OS X	Mavericks	Yes (1)	Yes (1)	Yes (1)
Mac OS X	Mountain Lion	Yes (1)	Yes (1)	Yes (1)
Mac OS X	Lion	Yes (1)	Yes (1)	Yes (1)
Mac OS X	Snow Leopard	Yes	Yes	Yes
Mac OS X	Leopard			Yes
Ubuntu (2)	Saucy	Yes	Yes	Yes
Ubuntu	Raring	Yes	Yes	Yes
Ubuntu	Quantal	Yes	Yes	Yes
Ubuntu	Precise	Yes	Yes	Yes
Ubuntu	Oneiric	Yes	Yes	Yes
Ubuntu	Natty	Yes	Yes	Yes
Ubuntu	Maverick	Yes (3)	Yes (3)	Yes
Ubuntu	Lucid	Yes (3)	Yes (3)	Yes
Linux Mint	13	Yes	Yes	Yes
Linux Mint	12	Yes	Yes	Yes
Linux Mint	12	Yes	Yes	Yes






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Our Small Quiz

- **True or false (raise hand)**
 - Open files are part of the process' address-space
 - Unified buffer caches improve the access times
 - A partition table can unify the view of multiple disks
 - Unix enables to bind arbitrary file systems to arbitrary locations
 - The virtual file system interface improves modularity of OS code
 - Programmed I/O is efficient for the CPUs
 - DMA enables devices to access virtual memory of processes
 - IOMMUs enable memory protection for devices
 - IOMMUs improve memory access performance
 - First level interrupt handlers process the whole request from the hardware
 - Software interrupts reduce the request processing latency
 - Deferred procedure calls execute second-level interrupt handlers

2



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The I/O subsystem

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Generic I/O functionality

- **Device drivers essentially move data to and from I/O devices**
 - Abstract hardware
 - Manage asynchrony
- **OS I/O subsystem includes generic functions for dealing with this data**
 - Such as...

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The I/O Subsystem

- **Caching** - fast memory holding copy of data
 - Always just a copy
 - Key to performance
- **Spooling** - hold output for a device
 - If device can serve only one request at a time
 - E.g., printing

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The I/O Subsystem

- **Scheduling**
 - Some I/O request ordering via per-device queue
 - Some OSs try fairness
- **Buffering** - store data in memory while transferring between devices or memory
 - To cope with device speed mismatch
 - To cope with device transfer size mismatch
 - To maintain “copy semantics”

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Naming and Discovery

- **What are the devices the OS needs to manage?**
 - Discovery (bus enumeration)
 - Hotplug / unplug events
 - Resource allocation (e.g., PCI BAR programming)
- **How to match driver code to devices?**
 - Driver instance \neq driver module
 - One driver typically manages many models of device
- **How to name devices inside the kernel?**
- **How to name devices outside the kernel?**

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Matching drivers to devices



- **Devices have unique (model) identifiers**
 - E.g., PCI vendor/device identifiers
- **Drivers recognize particular identifiers**
 - Typically a list...
- **Kernel offers a device to each driver in turn**
 - Driver can “claim” a device it can handle
 - Creates driver instance for it.

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Naming devices in the Unix kernel



(Actually, naming *device driver instances*)

- **Kernel creates identifiers for**
 - Block devices
 - Character devices
 - [*Network devices – see later...*]
- **Major device number:**
 - Class of device (e.g., disk, CD-ROM, keyboard)
- **Minor device number:**
 - Specific device within a class

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Unix Block Devices

- **Used for “structured I/O”**
 - Deal in large “blocks” of data at a time
- **Often look like files (seekable, mappable)**
 - Often use Unix’ shared buffer cache
- **Mountable:**
 - File systems implemented above block devices

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Character Devices

- **Used for “unstructured I/O”**
 - Byte-stream interface – no block boundaries
 - Single character or short strings get/put
 - Buffering implemented by libraries
- **Examples:**
 - Keyboards, serial lines, mice
- **Distinction with block devices somewhat arbitrary...**

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Naming devices outside the kernel

- **Device files: special type of *file***
 - Inode encodes <type, major num, minor num>
 - Created with `mknod()` system call
- **Devices are traditionally put in /dev**
 - `/dev/sda` – First SCSI/SATA/SAS disk
 - `/dev/sda5` – Fifth partition on the above
 - `/dev/cdrom0` – First DVD-ROM drive
 - `/dev/ttyS1` – Second UART


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Pseudo-devices in Unix

- Devices with no hardware!
- Still have major/minor device numbers. Examples:



```
/dev/stdin  
/dev/kmem  
/dev/random  
/dev/null  
/dev/loop0
```

etc.

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Old-style Unix device configuration

- All drivers compiled into the kernel
- Each driver probes for any supported devices
- System administrator populates `/dev`
 - Manually types `mknod` when a new device is purchased!
- Pseudo devices similarly hard-wired in kernel

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Linux device configuration today

- **Physical hardware configuration readable from /sys**
 - Special fake file system: `sysfs`
 - Plug events delivered by a special socket
- **Drivers dynamically loaded as kernel modules**
 - Initial list given at boot time
 - User-space daemon can load more if required
- **/dev populated dynamically by udev**
 - User-space daemon which polls /sys

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Interface to network I/O

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Unix interface to network I/O




- You already know the data path
 - BSD sockets
 - `bind()`, `listen()`, `accept()`, `connect()`, `send()`, `recv()`, etc.
- Have not yet seen:
 - Device driver interface
 - Configuration
 - Routing

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Software routing




The diagram illustrates the software routing architecture. It is divided into two horizontal sections by a dashed line: 'User space' above and 'Kernel space' below. In the user space, there is a box labeled 'Routing daemon'. In the kernel space, there are two boxes: 'Protocol stack' and 'FIB (forwarding information base)'. A double-headed vertical arrow connects the 'Routing daemon' to the 'Protocol stack', with the label 'Routing protocol messages' next to it. Another double-headed vertical arrow connects the 'Routing daemon' to the 'FIB', with the label 'Routing control' next to it. Below the 'Protocol stack' and 'FIB' boxes, there is a box labeled 'Network' with a double-headed vertical arrow connecting it to the 'Protocol stack'.

- OS protocol stacks include routing functionality
- Routing **protocols** typically in a user-space daemon
 - Non-critical
 - Easier to change
- **Forwarding** information typically in kernel
 - Needs to be fast
 - Integrated into protocol stack



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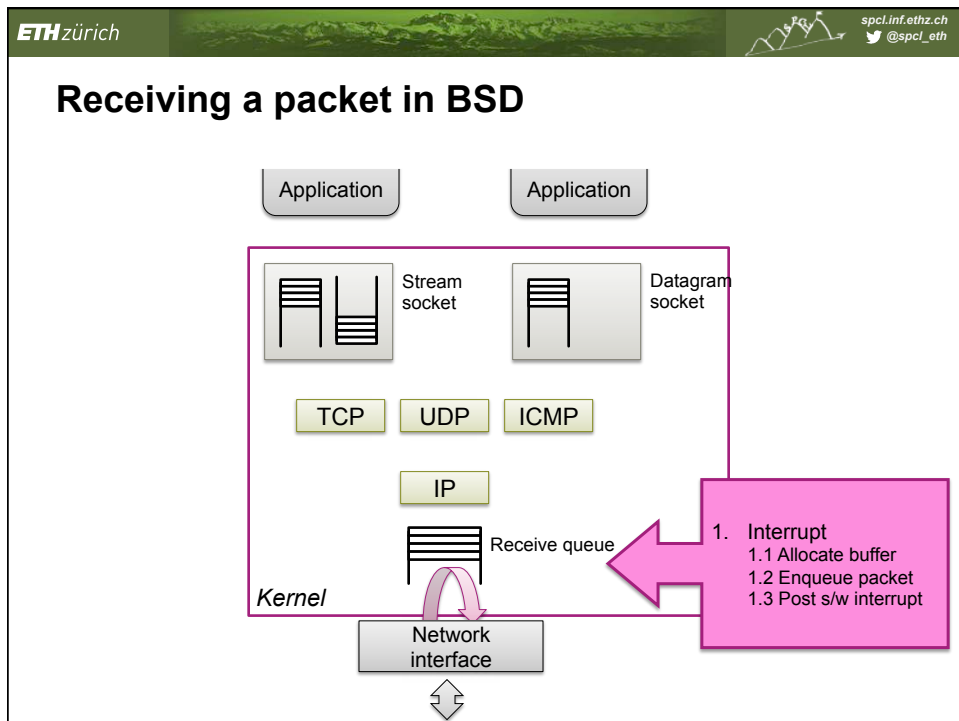
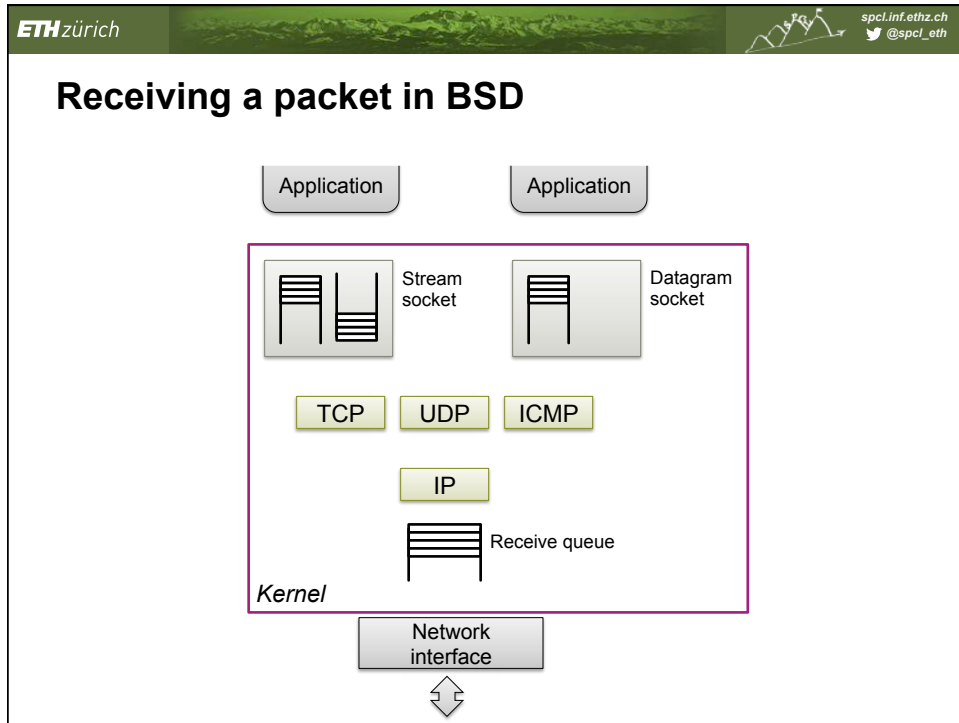
Network stack implementation

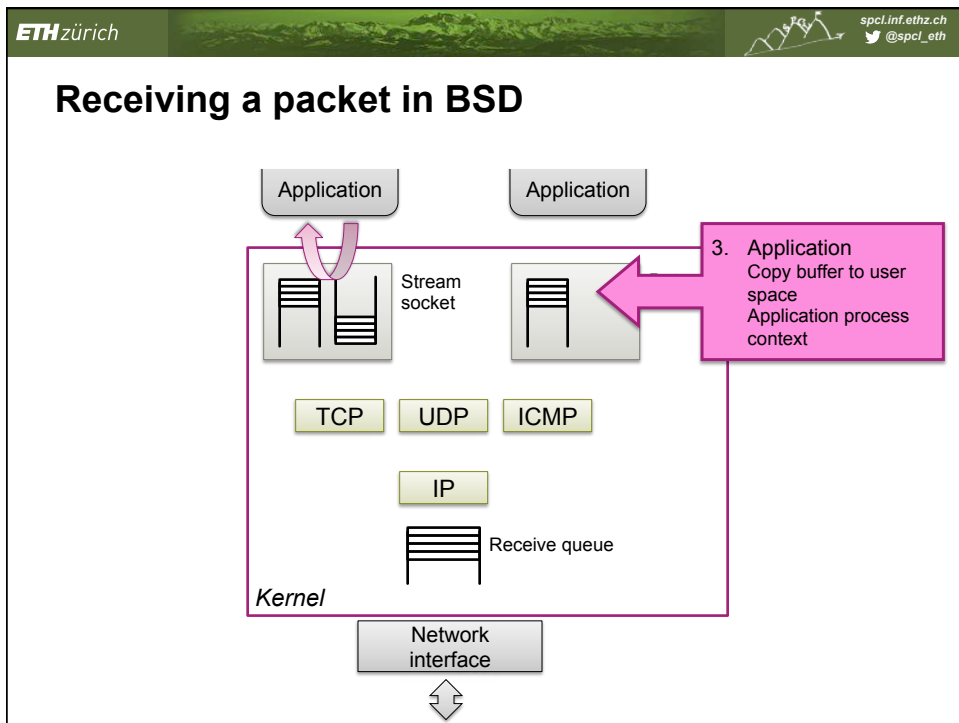
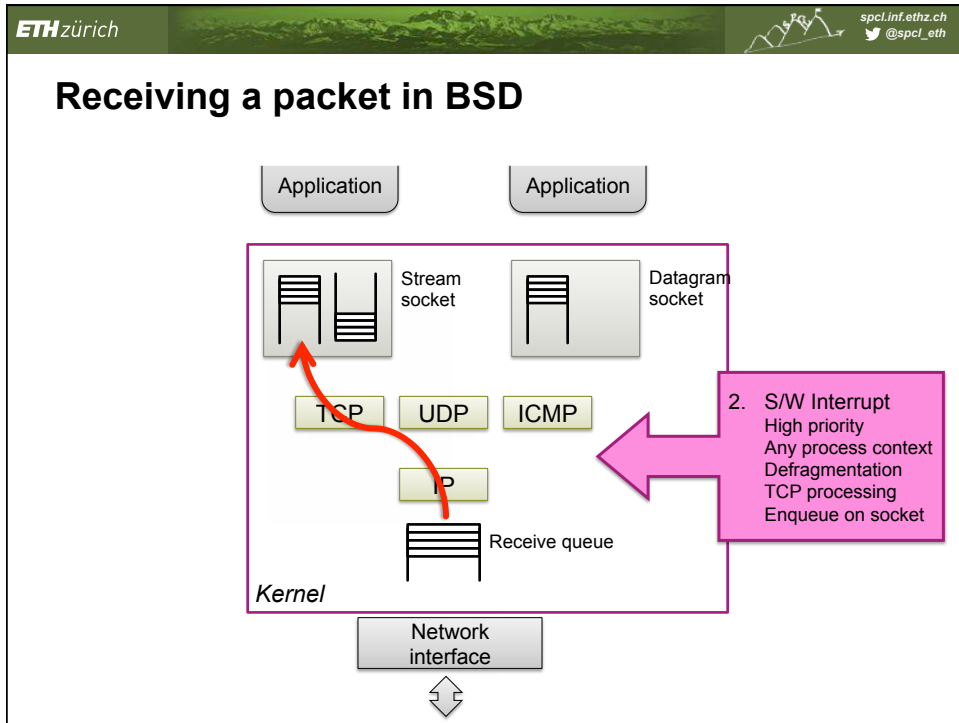


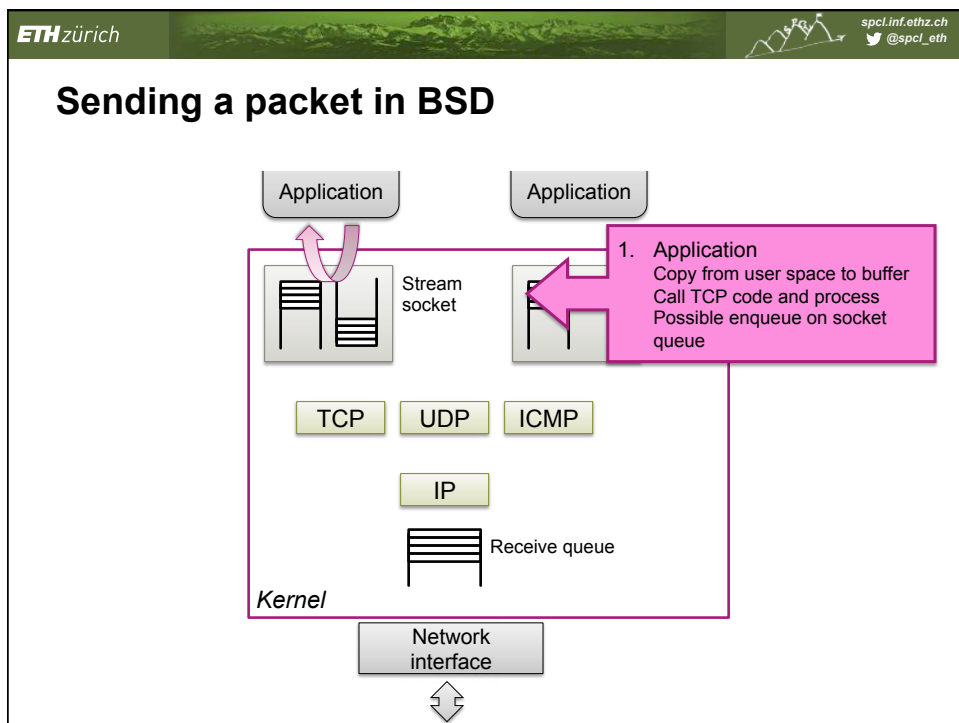
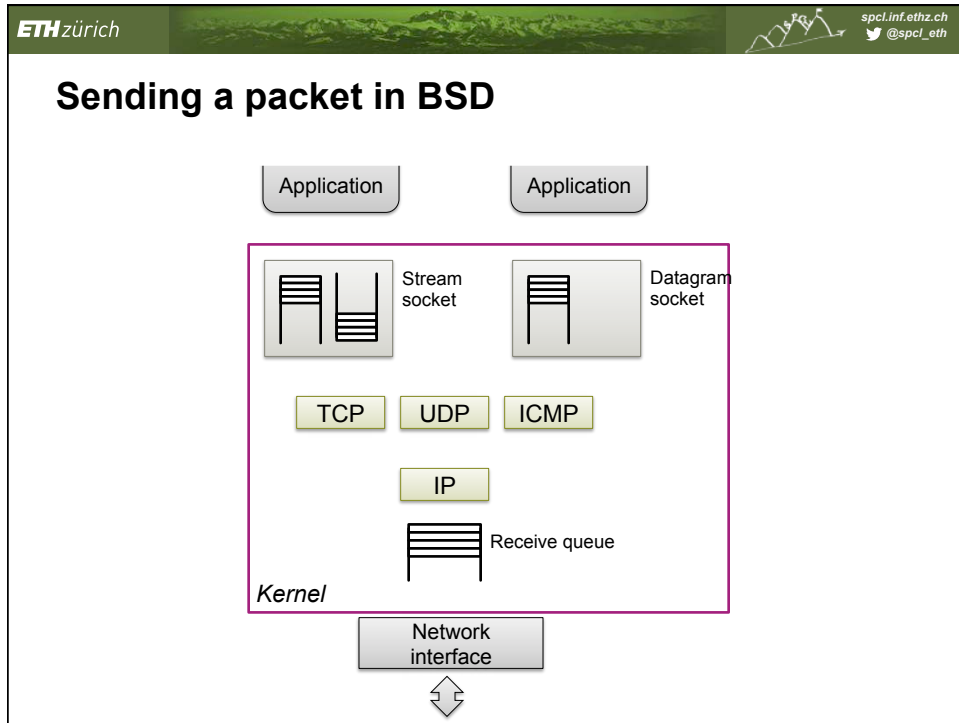
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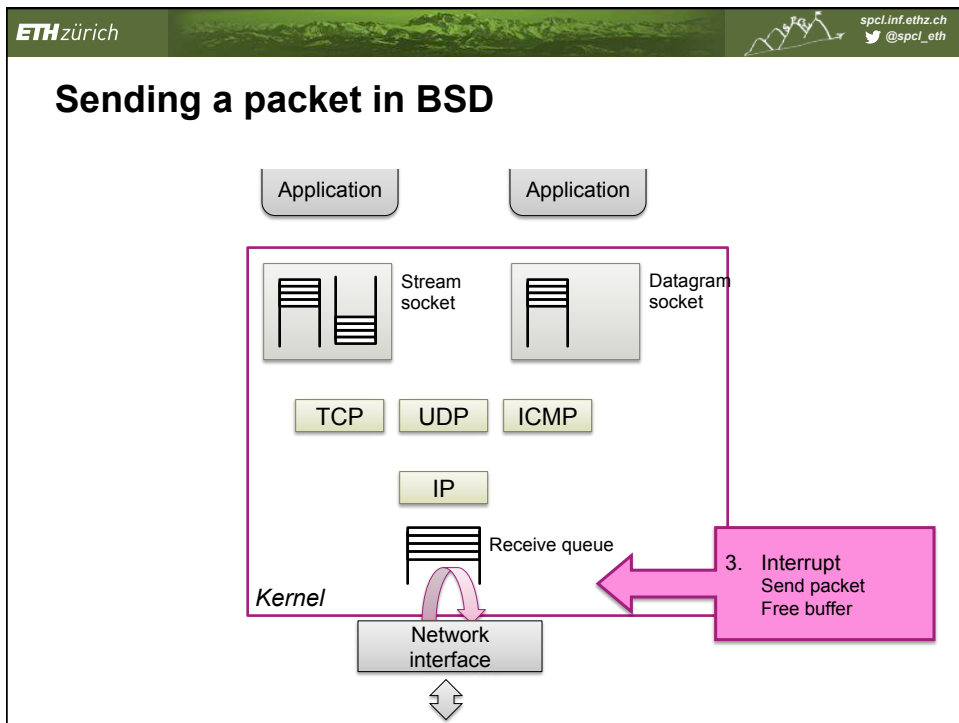
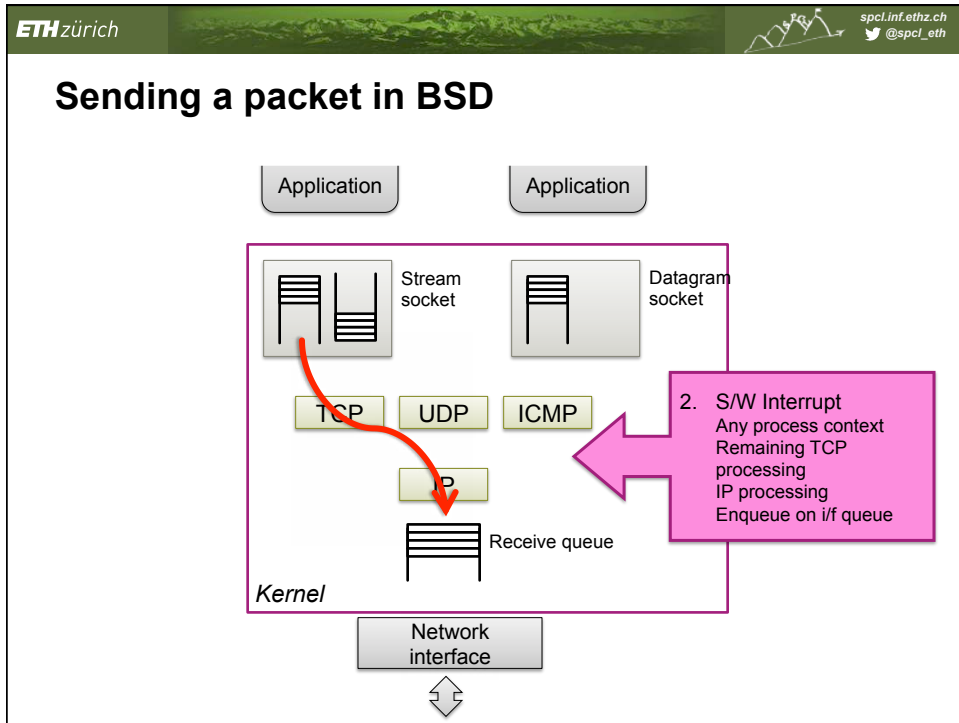
Networking stack

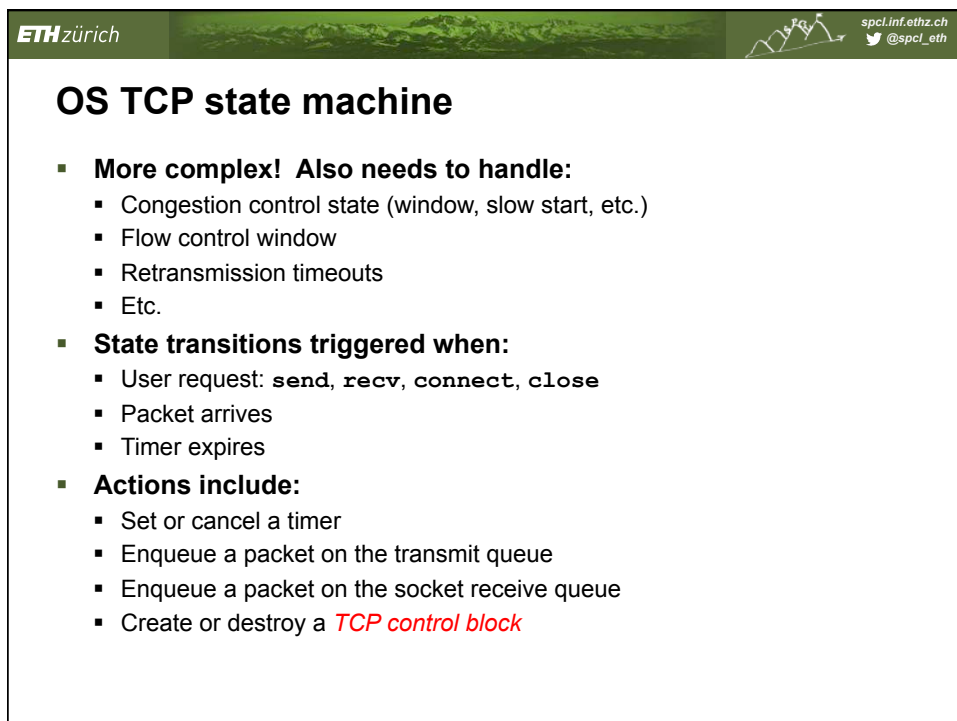
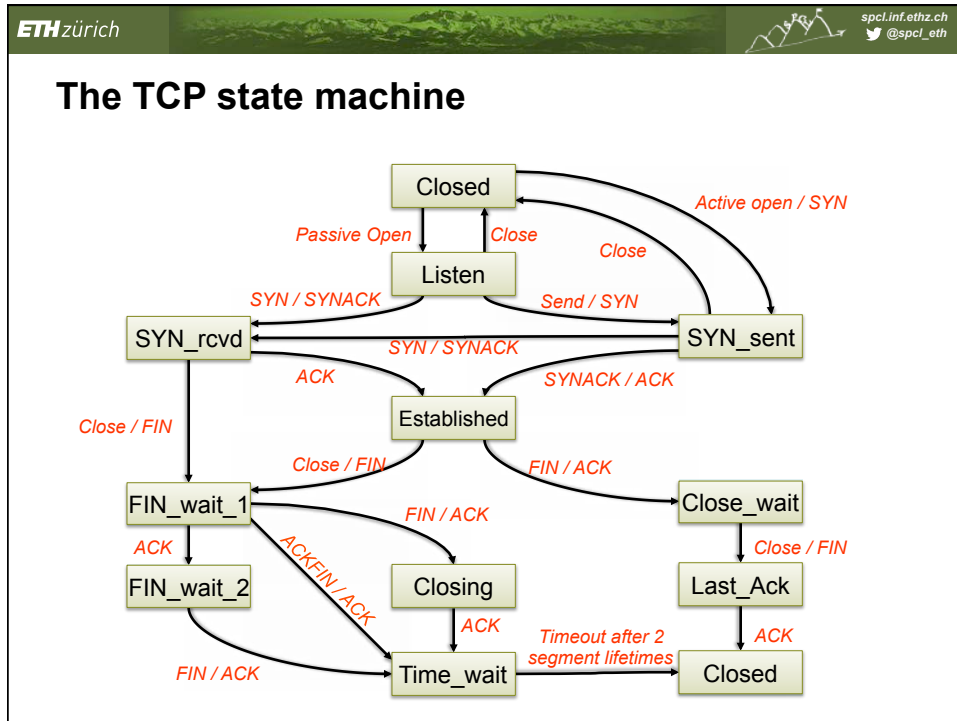
- **Probably most important peripheral**
 - GPU is increasingly not a peripheral
 - Disk interfaces look increasingly like a network
- **But...**
 - NO standard OS textbook talks about the network stack!
- **Good references:**
 - The 4.4BSD book (for Unix at least)
 - George Varghese: "Network Algorithmics" (up to a point)

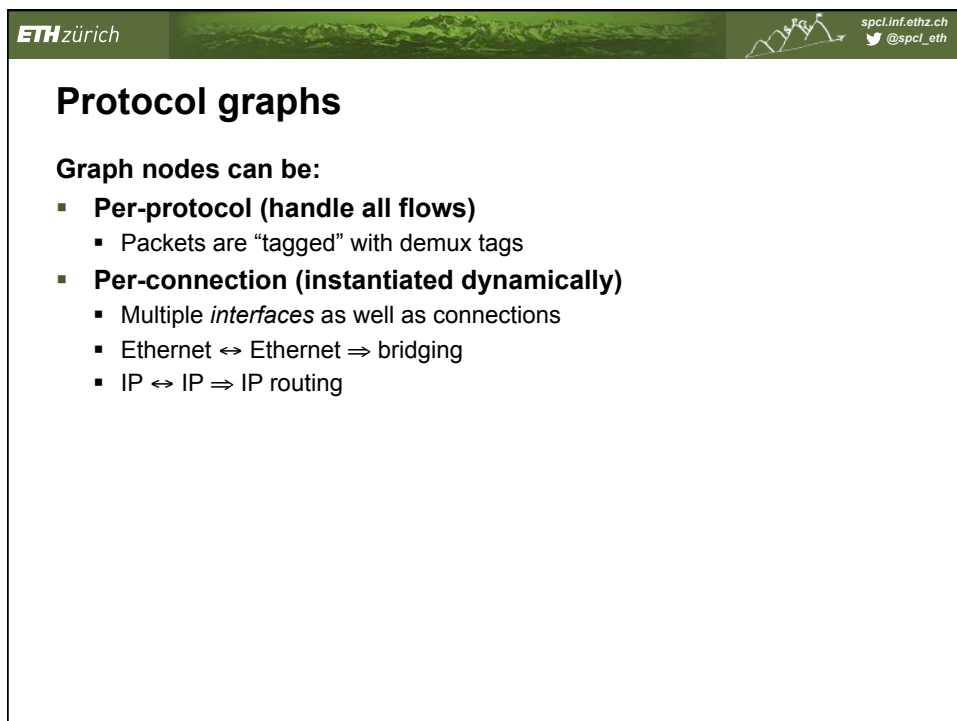
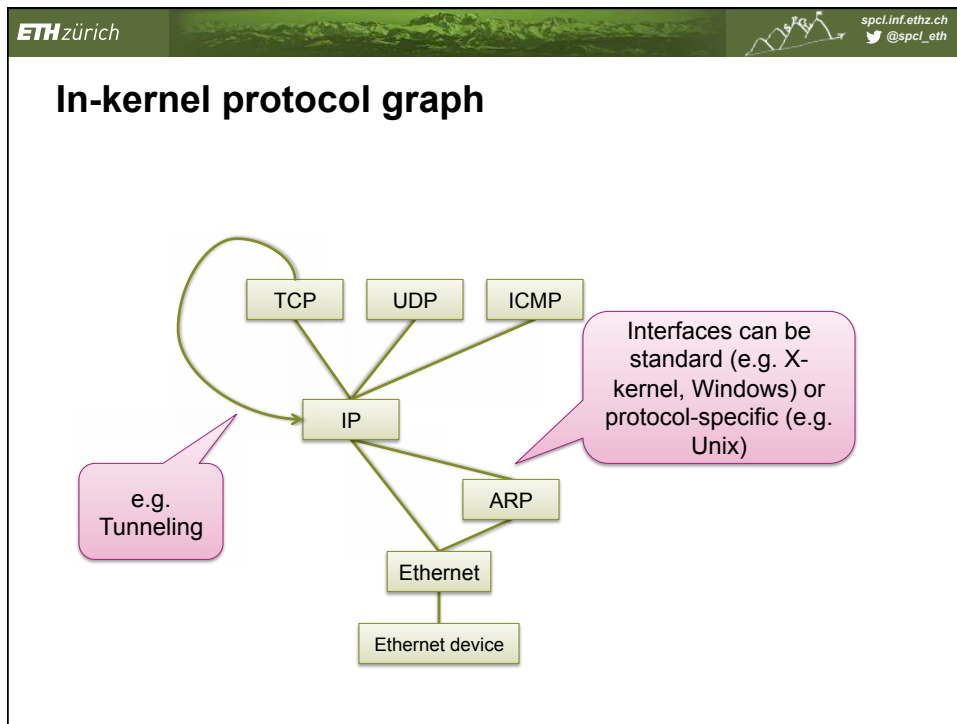
















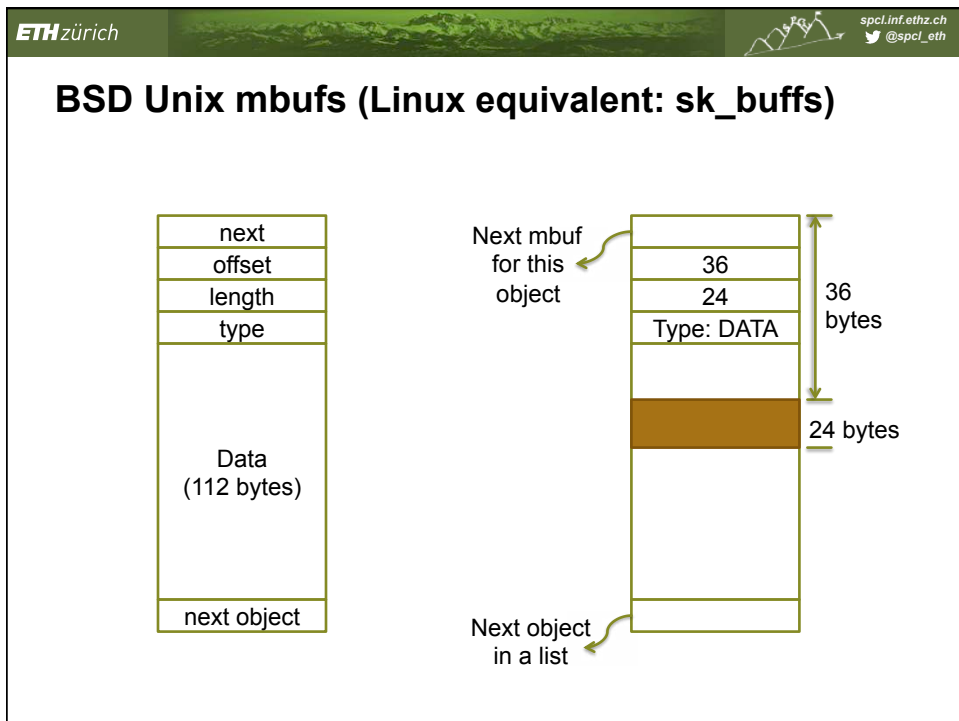
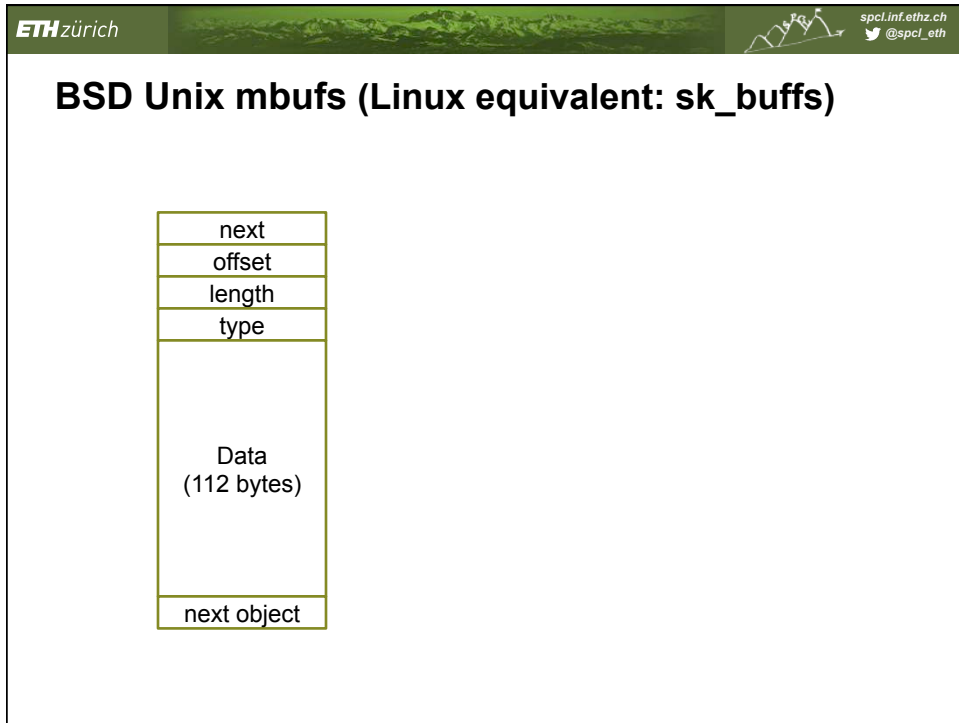
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Memory management

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Memory management

- **Problem: how to ship packet data around**
- **Need a data structure that can:**
 - Easily add, remove headers
 - Avoid copying lots of payload
 - Uniformly refer to half-defined packets
 - Fragment large datasets into smaller units
- **Solution:**
 - Data is held in a linked list of “buffer structures”



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Case Study: Linux 3.x

- **Implementing a simple protocol over Ethernet**
- **Why?**
 - You want to play with networking equipment (well, RAW sockets are easier)
 - You want to develop specialized protocols
E.g., application-specific "TCP"
E.g., for low-latency cluster computing
 - You'll understand how it works!

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Sending Data in Linux 3.x

```

graph TD
    Socket((Socket)) -- char* --> tcp_send_msg[tcp_send_msg]
    tcp_send_msg -- struct sk_buff --> tcp_transmit_skb[tcp_transmit_skb]
    tcp_transmit_skb -- struct sk_buff, TCP Header --> ip_queue_xmit[ip_queue_xmit]
    ip_queue_xmit --> ip_fragment[ip_fragment]
    ip_fragment --> ip_route_output_flow[ip_route_output_flow]
    ip_route_output_flow --> ip_forward[ip_forward]
    ip_route_output_flow --> dev_queue_xmit[dev_queue_xmit]
    dev_queue_xmit --> Driver((Driver))
  
```

- **Many layers**
- **Most use the sk_buf struct**

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Register a receive hook

- **Fill packet_type struct:**
 - .type = your ethertype
 - .func = your receive function
- **Receive handler recv_hook(...)**
 - Gets sk_buff, packet_type, net_device, ...
 - Called for each incoming frame
 - Reads skb->data field and processes protocols



Receive hook table:

0x0800	IPv4 hdr.
0x8864	PPPOE hdr.
0x8915	RoCE hdr.
...	

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Interaction with applications

- **Socket Interface**
 - Need to implement handlers for connect(), bind(), listen(), etc.
- **Call sock_register(struct net_proto_family*)**
 - Register a protocol family
 - Enables user to create socket of this type

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Anatomy of struct sk_buff

- **Called “skb” in Linux jargon**
 - Allocate via `alloc_skb()` (or `dev_alloc_skb()` if in driver)
 - Free with `kfree_skb()` (`dev_kfree_skb()`)
 - Use `pskb_may_pull(skb, len)` to check if data is available
 - `skb_pull(skb, len)` to advance the data pointer
... it even has a webpage! <http://www.skbuff.net/>

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SKB Fields

- **Double-linked list, each skb has .next/.prev**
 - `.data` contains payload (size of data field is set by `skb_alloc`)
 - `.sk` is the socket this skb is owned by
 - `.mac_header`, `.network_header`, `.transport_header` contain headers of various layers
 - `.dev` is the device this skb uses
 - ... 58 member fields total

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Case Study: TCP Fragmenting

- **Linux <2.0.32:**
 - Two fragments:
 - #1
 - Offset: 0
 - Length: 100
 - #2
 - Offset: 100
 - Length: 100

```

// Determine the position of this fragment
end = offset + iph->tot_len - ihl; #1: 100, #2: 200
// Check for overlap with preceding fragment, and, if needed,
// align things so that any overlaps are eliminated.
if (prev != NULL && offset < prev->end) {
    i = prev->end - offset;
    offset += i; /* ptr into datagram */
    ptr += i; /* ptr into fragment data */
}
// initialize segment structure
fp->offset = offset; #1: 0, #2: 100
fp->end = end; #1: 100, #2: 200
fp->len = end - offset; #1: 100, #2: 100
.... // collect multiple such fragments in queue
// process each fragment
if(count+fp->len > skb->len) {
    error_to_big;
}
memcpy((ptr + fp->offset), fp->ptr, fp->len);
count += fp->len;
fp = fp->next;
    
```

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Case Study: TCP Fragmenting

- **Linux <2.0.32:**
 - Two fragments:
 - #1
 - Offset: 0
 - Length: 100
 - #2
 - Offset: 10
 - Length: 20

```

// Determine the position of this fragment
end = offset + iph->tot_len - ihl; #1: 100, #2: 30
// Check for overlap with preceding fragment, and, if needed,
// align things so that any overlaps are eliminated.
if (prev != NULL && offset < prev->end) {
    i = prev->end - offset; #2: 100-10=90
    offset += i; /* ptr into datagram */ #2: 100
    ptr += i; /* ptr into fragment data */
}
// initialize segment structure
fp->offset = offset; #1: 0, #2: 100
fp->end = end; #1: 100, #2: 30
fp->len = end - offset; #1: 100, #2: -70
.... // collect multiple such fragments in queue
// process each fragment
if(count+fp->len > skb->len) {
    error_to_big;
}
memcpy((ptr + fp->offset), fp->ptr, fp->len);
count += fp->len;
fp = fp->next;
    
```

(size_t)-70 = 4294967224

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Case Study: TCP Fragmenting

Windows

A fatal exception 0E has occurred at 0028:C1891963 in UXD ctpci9x(85) + 00001853. The current application will be terminated.

- * Press any key to terminate the current application.
- * Press CTRL+ALT+DEL again to restart your computer. You will lose any unsaved information in all applications.

Press any key to continue _

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2.0.32 ... that's so last century!

Security TechCenter > Security Bulletins > Microsoft Security Bulletin MS09-050

Microsoft Security Bulletin MS09-050 - Critical

Vulnerabilities in SMBv2 Could Allow Remote Code Execution (975517)

Published: Tuesday, October 13, 2009 | Updated: Wednesday, October 14, 2009

Version: 1.1

General Information

Executive Summary

This security update resolves one publicly disclosed and two privately reported vulnerabilities in Server Message Block Version 2 (SMBv2). The most severe of the vulnerabilities could allow remote code execution if an attacker sent a specially crafted SMB packet to a computer running the Server service. Firewall best practices and standard default firewall configurations can help protect networks from attacks that originate from outside the enterprise perimeter. Best practices recommend that systems that are connected to the Internet have a minimal number of ports exposed.

This security update is rated Critical for supported editions of Windows Vista and Windows Server 2008. For more information, see the subsection, **Affected and Non-Affected Software**, in this section.

The security update addresses the vulnerabilities by correctly validating the fields inside the SMBv2 packets, correcting the way that SMB handles the command value in SMB packets, and correcting the way that SMB parses specially crafted SMB packets. For more information about the vulnerabilities, see the Frequently Asked Questions (FAQ) subsection for the specific vulnerability entry under the next section, **Vulnerability Information**.

This security update also addresses the vulnerability first described in [Microsoft Security Advisory 975497](#).

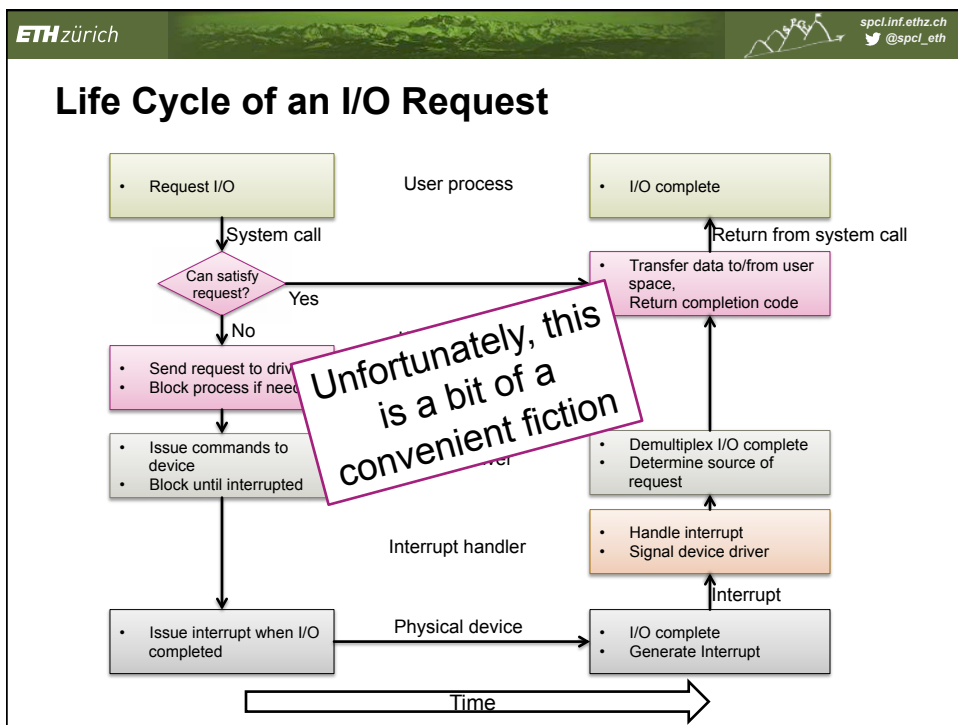
Recommendation. The majority of customers have automatic updating enabled and will not need to take any action because this security update will be downloaded and installed automatically. Customers who have not enabled automatic updating need to check for updates and install this update manually. For information about specific configuration options in automatic updating, see [Microsoft Knowledge Base Article 294871](#).


For administrators and enterprise installations, or end users who want to install this security update manually, Microsoft recommends that customers apply the update immediately using update management software, or by checking for updates using the [Microsoft Update](#) service.

See also the section, **Detection and Deployment Tools and Guidance**, later in this bulletin.


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Performance issues



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Consider 10 Gb/s Ethernet



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At full line rate for 1 x 10Gb port

- **~1GB (gigabyte) per second**
 - ⇒ ~ **700k** full-size Ethernet frames per second
 - ⇒ At 2GHz, must process a packet in **≤ 3000** cycles
- **This includes:**
 - IP and TCP checksums
 - TCP window calculations and flow control
 - Copying packet to user space

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A few numbers...


- **L3 cache miss (64-byte lines) \approx 300 cycles**
 - ⇒ *At most 10* cache misses per packet
 - Note: DMA ensures cache is cold for the packet!

- **Interrupt latency \approx 500 cycles**
 - Kernel entry/exit
 - Hardware access
 - Context switch / DPC
 - Etc.

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Plus...


- **You also have to send packets.**
 - Card is full duplex \Rightarrow can send at 10Gb/s
- **You have to do something useful with the packets!**
 - Can an application can make use of 1.5kB of data every 1000 machine cycles or so?
- **This card has two 10Gb/s ports.**



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And Plus ...

- **And if you thought that was fast ...**
 - Mellanox 100 Gb/s Adapter
 - Impossible to use without advanced features
 - RDMA*
 - SR-IOV*
 - TOE*
 - Interrupt coalescing*





The image shows a Mellanox ConnectX 100 Gb/s Adapter. It is a green printed circuit board (PCB) with a silver metal bracket on the left side. The bracket features two RJ45 ports labeled 'PORT 1' and 'PORT 2'. The PCB is populated with various components, including a large integrated circuit (IC) in the center, several capacitors, and other electronic components. The 'ConnectX' logo is printed in orange and black on the right side of the board.

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What to do?

- **TCP offload (TOE)**
 - Put TCP processing into hardware on the card
- **Buffering**
 - Transfer lots of packets in a single transaction
- **Interrupt coalescing / throttling**
 - Don't interrupt on every packet
 - Don't interrupt at all if load is very high
- **Receive-side scaling**
 - Parallelize: direct interrupts and data to different cores

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Linux New API (NAPI)

- **Mitigate interrupt pressure**
 1. Each packet interrupts the CPU
 2. Vs. CPU polls driver
 - NAPI switches between the two!
- **NAPI-compliant drivers**
 - Offer a poll() function
 - Which calls back into the receive path ...

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Linux NAPI Balancing

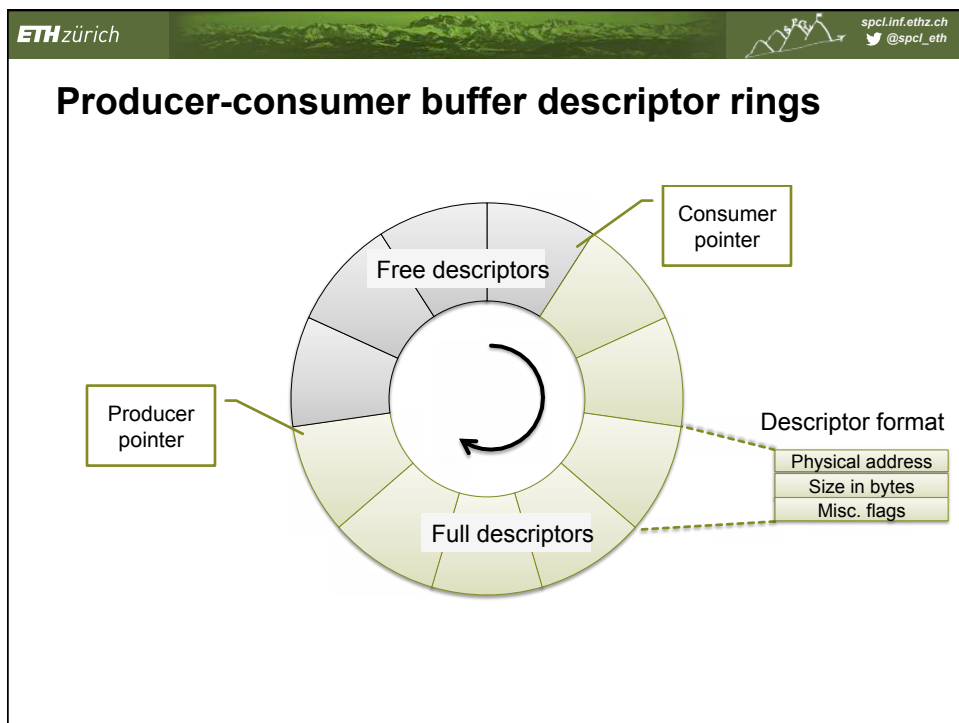
- **Driver enables polling with `netif_rx_schedule(struct net_device *dev)`**
 - Disables interrupts
- **Driver deactivates polling with `netif_rx_complete(struct net_device *dev)`**
 - Re-enable interrupts.
- → but where does the data go???

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Buffering

Key ideas:

- **Decouple sending and receiving**
 - Neither side should wait for the other
 - Only use interrupts to unblock host
- **Batch together requests**
 - Spread cost of transfer over several packets



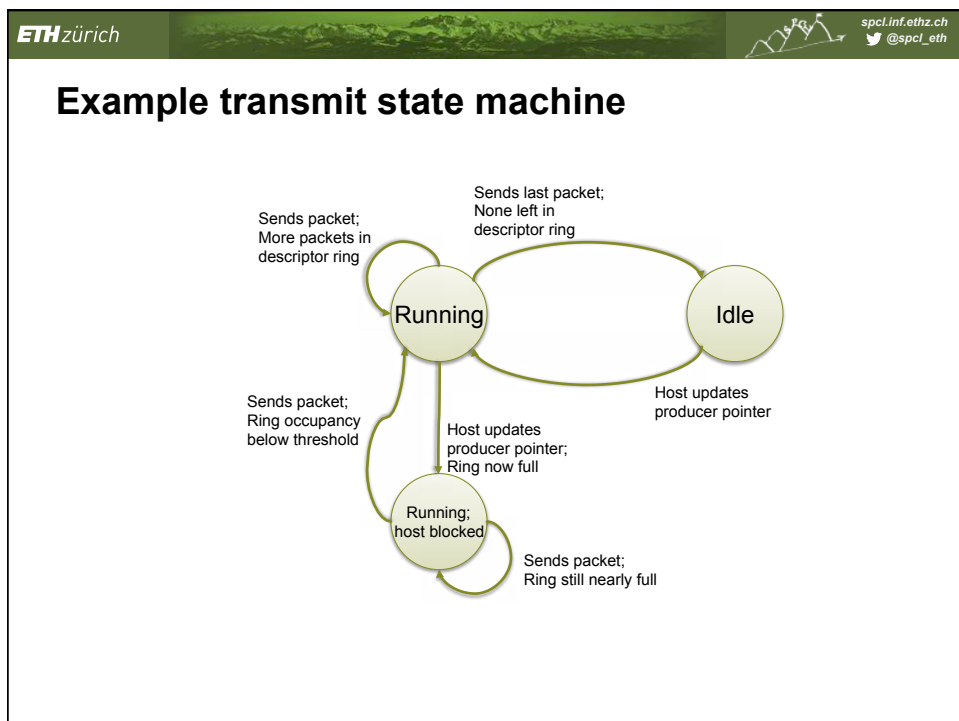
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Buffering for network cards

Producer, consumer pointers are NIC registers

- **Transmit path:**
 - Host updates producer pointer, adds packets to ring
 - Device updates consumer pointer
- **Receive path:**
 - Host updates consumer pointer, adds empty buffers to ring
 - Device updates producer pointer, fills buffers with received packets.

More complex protocols are possible...



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Transmit interrupts

- **Ring empty**
 - ⇒ all packets sent
 - ⇒ device going idle
- **Ring occupancy drops**
 - ⇒ host can now send again
 - ⇒ device continues running

Exercise: devise a similar state machine for receive!

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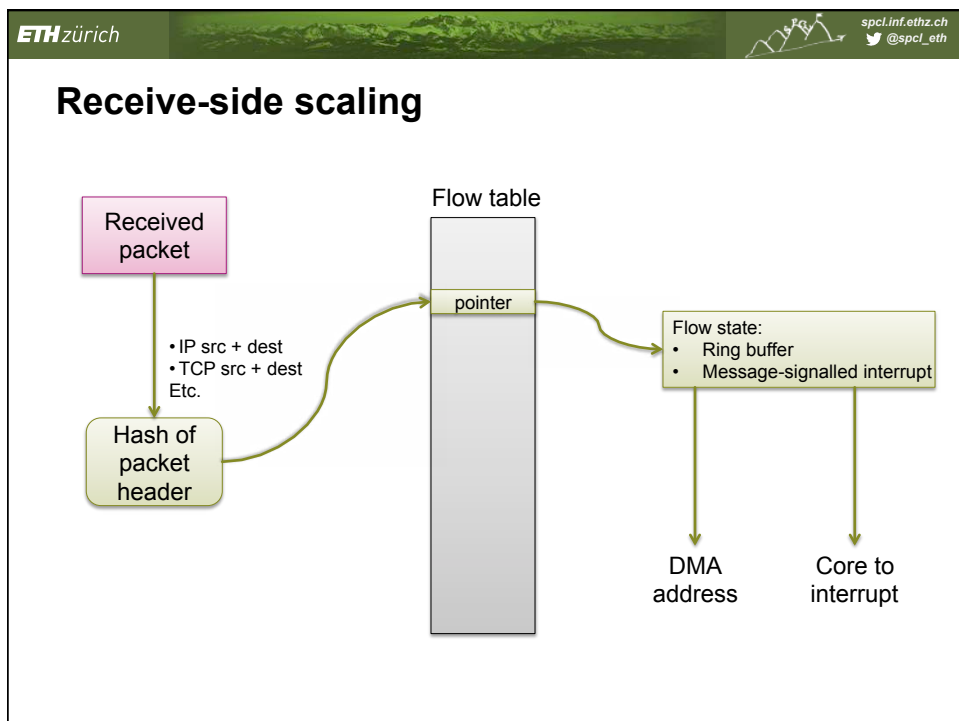
Buffering summary



- **DMA used twice**
 - Data transfer
 - Reading and writing descriptors
- **Similar schemes used for any fast DMA device**
 - SATA/SAS interfaces (such as AHCI)
 - USB2/USB3 controllers
 - etc.
- **Descriptors send ownership of memory regions**
- **Flexible – many variations possible:**
 - Host can send lots of regions in advance
 - Device might allocate out of regions, send back subsets
 - Buffers might be used out-of-order
- **Particularly powerful with multiple send and receive queues...**

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Receive-side scaling



- **Insight:**
 - Too much traffic for one core to handle
 - Cores aren't getting any faster
⇒ Must parallelize across cores
- **Key idea: handle different flows on different cores**
 - But: how to determine flow for each packet?
 - Can't do this on a core: same problem!
- **Solution: demultiplex on the NIC**
 - DMA packets to per-flow buffers / queues
 - Send interrupt only to core handling flow



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Receive-side scaling

- **Can balance flows across cores**
 - Note: doesn't help with one big flow!
- **Assumes:**
 - n cores processing m flows is faster than one core
- **Hence:**
 - Network stack and protocol graph must *scale* on a multiprocessor.
- **Multiprocessor scaling: topic for later**

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Tomorrow

- **Virtual machines**
- **Multiprocessor operating systems**