Linux Network stack overview

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Problems

several general Linux are also true for network stack:

- Hardware:
  - 1 cpu vs. SMP
  - LTE? WLAN? 40Gbit Ethernet?
- Usage:
  - Desktop, Server, Router, Bridge, ...
  - Server $\neq$ server: e.g. Database workload vs. file server

$\rightarrow$ low Latency, high throughput, low cpu cycles/resource usage, large feature set (IPSEC, NAT, traffic shaping and accuting, ...)

Agenda

- RX: how do packets end up in a program?
- TX: how does data get from program out to the network?
- tricks: GSO, GRO, RSS, XPS, ...
- Byte Queue Limits, TSQ, ...

how does the kernel receive/collect packets from hardware?

3 Ways:

1. interrupt + percpu backlog
2. softinterrupt: NAPI
3. busypoll: `SO_BUSY_POLL` setsockopt – reduce latency at cpu cost

Simple ('obsolete') nic/driver

- (very) small memory buffer to hold 1 or 2 packets
- interrupt handler allocates memory, copies packets from hardware memory
- packet is placed on a per-cpu queue for later processing in softirq

Interrupt

- asynchonous event, inerrupts currently running program
- high irq/s: $\rightarrow$ system becomes unusable

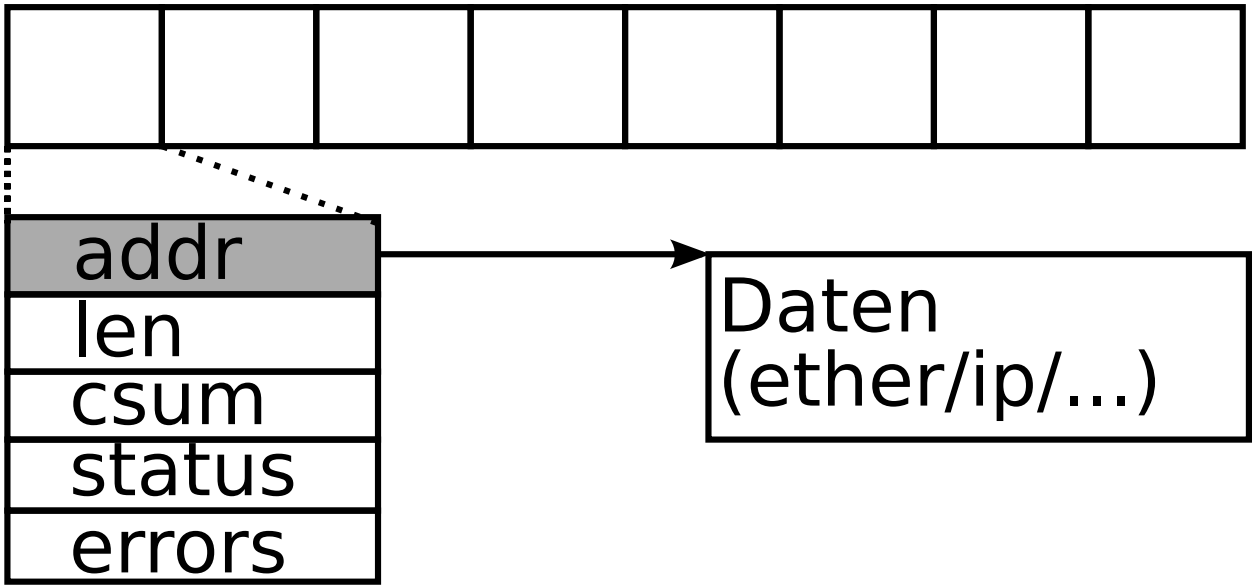
NAPI: mixes interrupt model with polling

1. first interrupt disables further interrupts from nic
2. schedule a polling cycle (softirq)
3. next softinterrupt will process packets from nic
4. softinterrupt takes too long?
   `ksoftirqd` $\rightarrow$ network stack processing moves under scheduler control
5. no more packets? re-enable nic rx interrupt

new nic drivers

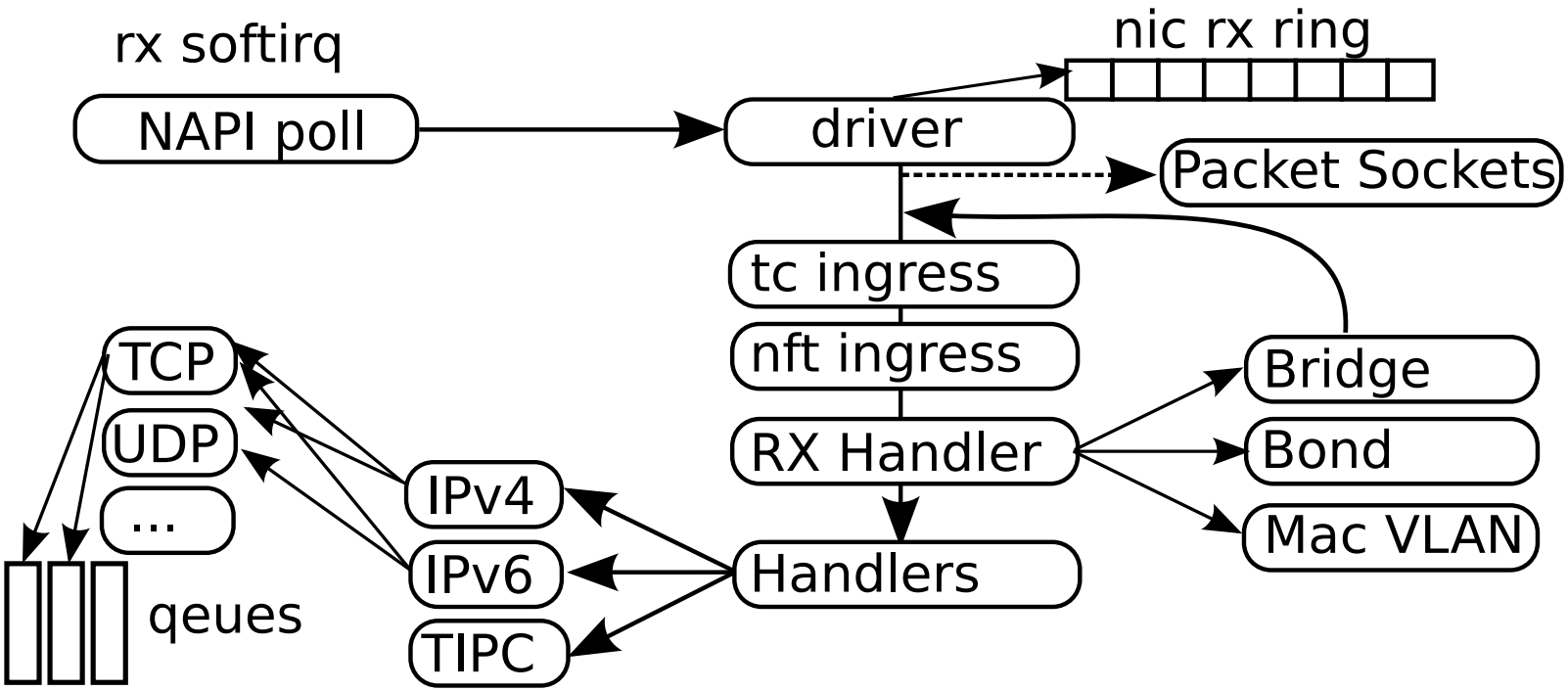
- 10, 40, 56 (oder mehr) GBit
- NAPI – all packet processing occurs via sofirq
- Ring-Buffer / Array ("RX Queues")
- driver allocates buffer for each ring buffer slot
- hardware DMAs incoming data into these buffers
- hardware also performs other tasks: checksum offload, rxhash, ...
- multiple TX and RX queues, interrupts per queue, RSS – map rxqueue $\rightarrow$ CPU

nic rx ring (example)



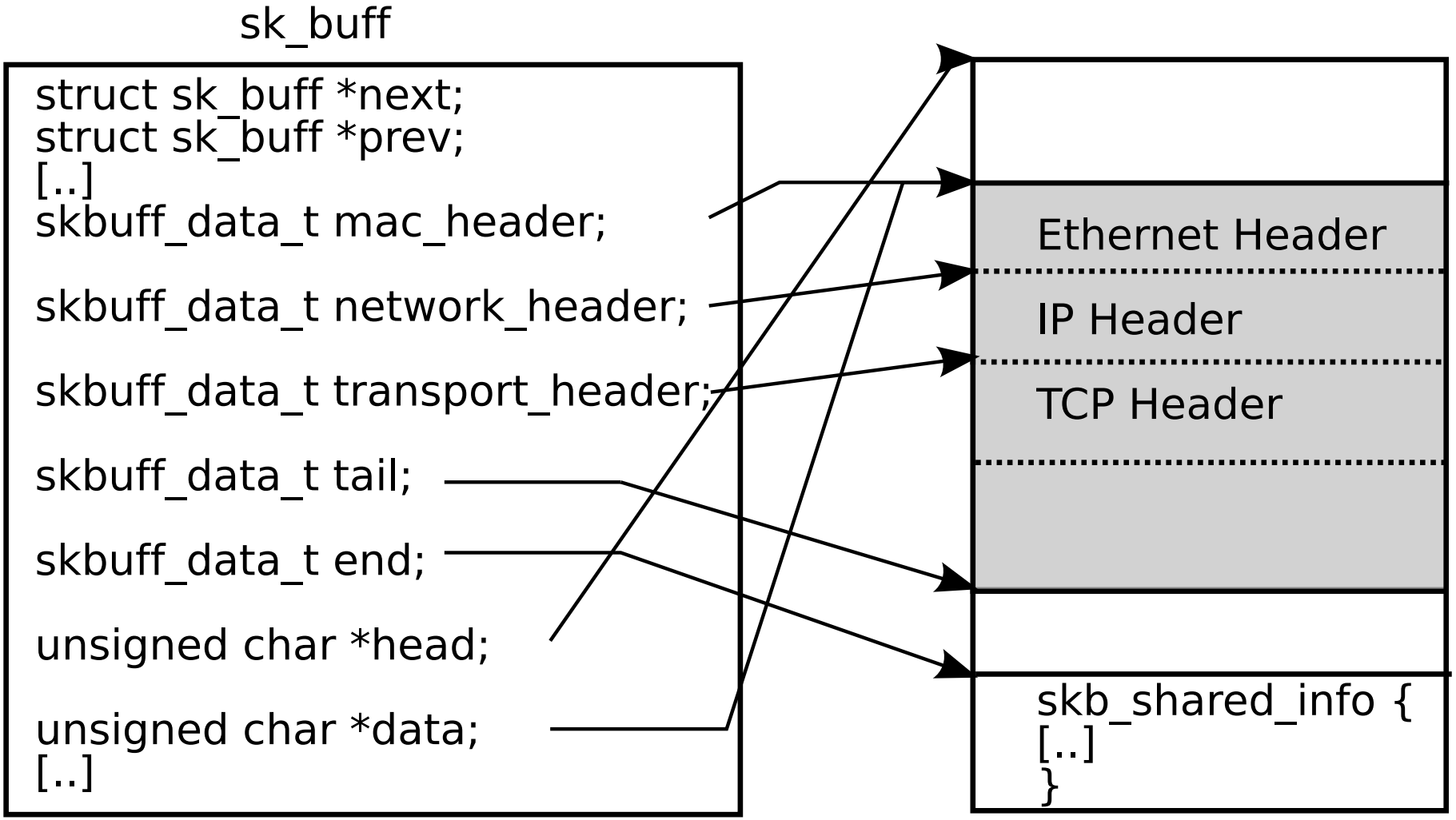
- driver checks status bit of next descriptor
- no data? reenable rx irq and done
- otherwise proess the pacet

packet rx


rx softirq
NAPI poll
nic rx ring
driver
Packet Sockets
tc ingress
nft ingress
RX Handler
Handlers
Bridge
Bond
Mac VLAN
TCP
UDP
...
qeues
IPv4
IPv6
TIPC

socket buffer

- skb: "socket buffer", kerne data strcture to represent a packet
- RX/incoming: allocation done in the driver
- locally generated packets: allocation doe in tcp/udp etc. stack
- contains metadata, e.g. incoming interface, routing information, etc.
- len vs. truesize – socket mem accounting

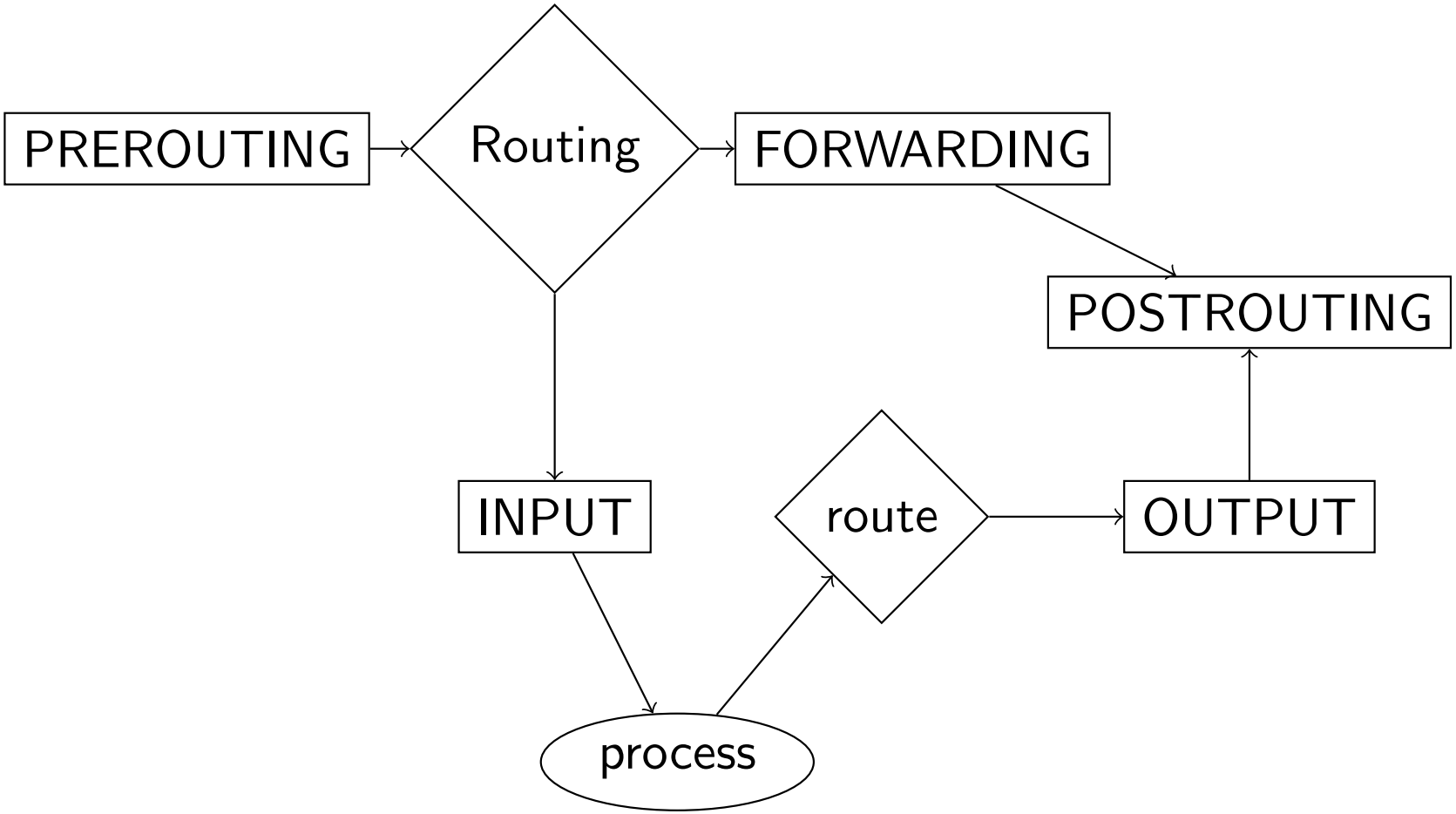


`next/prev`: for lists, e.g. send and receive queues

`sk_buff_data_t`: offset with start of particular protocol headers

others: socket, routing information, rxhash, IPSEC, . . . on rx, most fields will be unset/empty and are filled in while packet is passed to next layers

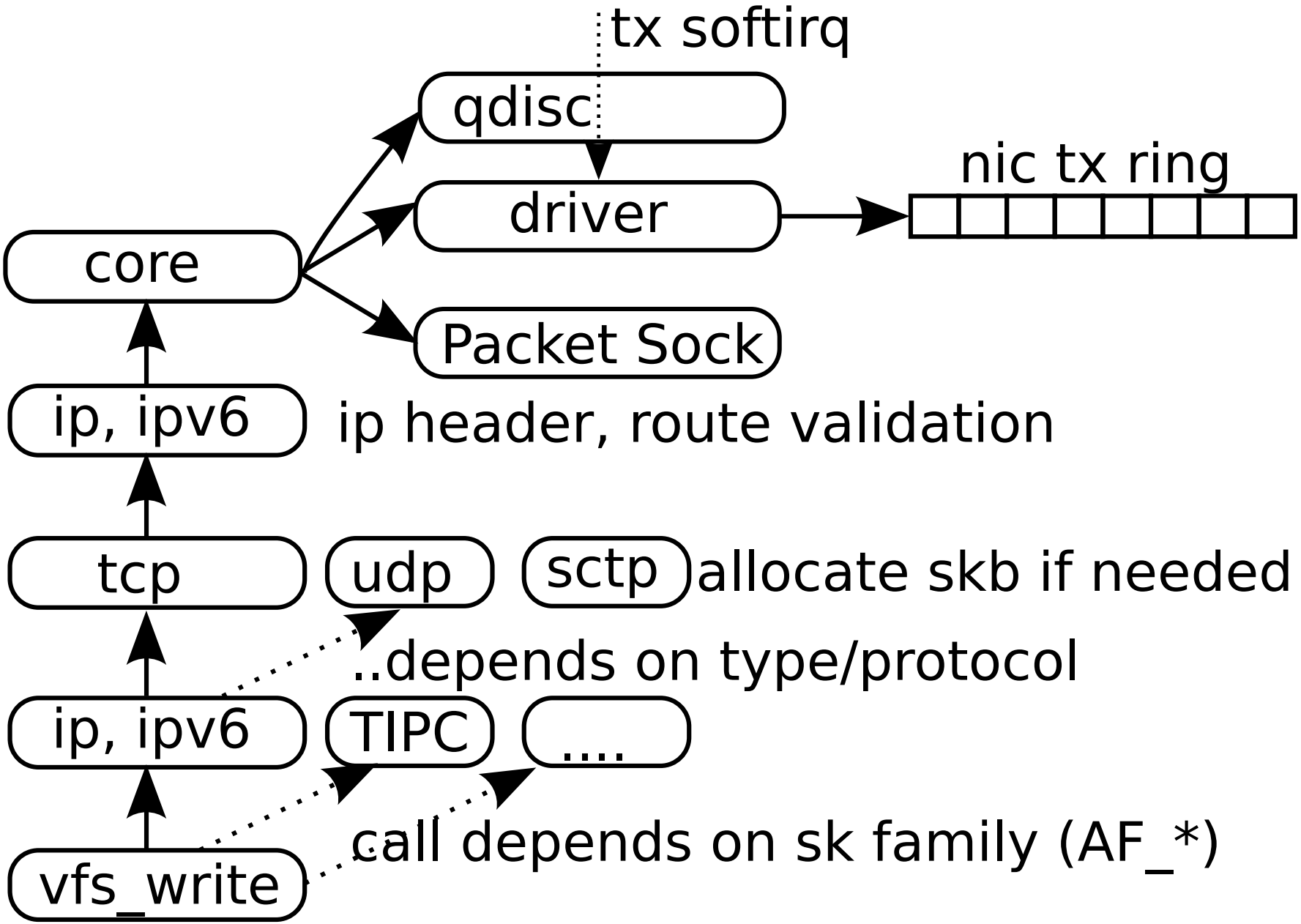
IPv4 Architektur



how does data end up in the network?

1. direct: programm sent it
2. timer, e.g. tcp retransmit, window probe, ...
3. via rx: forwarding (router, bridge), tcp acks, ...
4. tx softirq (qdisc)

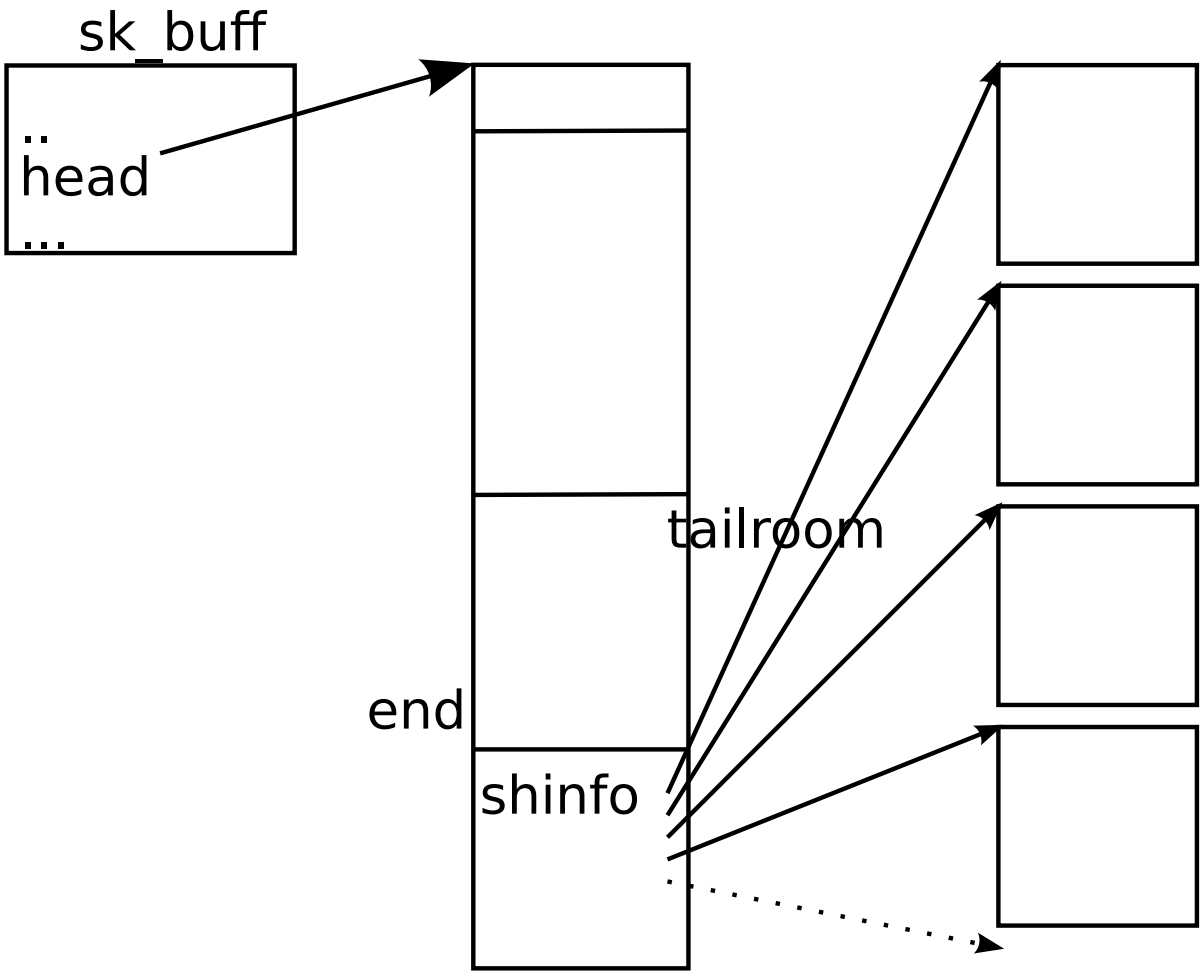
packet tx


tx softirq
qdisc
driver
nic tx ring
core
Packet Sock
ip, ipv6
ip header, route validation
tcp
udp
sctp
allocate skb if needed
..depends on type/protocol
ip, ipv6
TIPC
....
call depends on sk family (AF_*)
vfs_write

GSO, GRO

- skb ! = packet
- skbs canbe a lot larger than a physical mtu
- transmit:
  - TSO: TCP Segementation offload
  - GSO: Generic Segmentation offload
- rx:
  - GRO: Generic Receive offload
  - occurs even before packet sockets
  - driver needs to use `napi_gro_receive()` api
  - merges logically contiguous packets in one GSO skb

nonlinear skbs



pages are references via shinfo area

sendpage, gro/gso, ...

scaling: RSS Receive Side Scaling, RPS

- one IRQ per rx-queue `/proc/interrupts`:

```
           CPU0 CPU1 CPU2 CPU3 CPU4 CPU5 CPU6 CPU7
28: 31189 4389 2853 2557 6315 4035 3002 2130 eth0
```

- `/proc/irq/28/smp_affinity` – `ff` – default

  `printf %x $((1 << 7)) > /proc/irq/28/smp_affinity`

- determines which CPU can perform rx softirq
- incoming packets are distributed amng rx queues by hardware
- usually done by a hash on packet header data
- modern nics have programmable filters
- RPS: "RSS in software"
  `/sys/class/net/$dev/queues/rx/rps_cpus`

`Documentation/networking/scaling.txt`

scaling: XPS (Transmit Packet Steering)

- ideal case: CPU that runs application maps to a particular tx queue
- tx-completion occurs on the same cpu, i.e. alloc/free on same processor
- kernel saves used queue in skb/socket
- `/sys/class/net/$dev/queues/tx/xps_cpus` – set which cpus use tx queue
- `mq` scheduler, its possible to set a different qdisc for each tx queue

Byte Queue Limits (BQL)

- aims to reduce unneeded buffering:
  - buffering increases latency and jitter
  - can reduce throughput
- Idea: calculate the read transmit rate
  1. on tx start: how many bytes are transmitted?
  2. on tx completion/ende: how many bytes completed transmisiosn?
- needs to be added at driver level
- prerequisite for `xmit_more` in drivers

TX Batching, xmit-more

- `xmit_more` flag in skbuff
- problem: update of nic hardware tx tail pointer gets too expensive
- would like to set it only once when multiple packets get sent
- this already happens with gso/tso offloads
- when nic is backlogged, qdisc starts to fill up
- uses bql to estimate how much data nic can take
- dequeue multiple skbs, set `skb->xmit_more` flag on all but last skb

allows drivers to not touch tx tail descriptor in some cases

TSQ (TCP small queues)

"BQL for sockets"

- similar goals as BQL
  - increase faireness among flows
  - conserve memory
- why read more data from disk if there are 100kb of unset data in local queues...?
- idea:
  - only 2 packets per stream in qdisc or 1 ms delay or
  - `net.ipv4.tcp_limit_output_bytes`
- uses socket wmem accounting
  - when tcp has to allocate new skb it checks `sk->sk_wmem_alloc`
  - if overlimit: block or `EWOULDBLOCK`
  - nic tx completion: `skb_orphan()`

(micro-)optimizations, design choices

- place functionality in kernel modules
- otherwise: static keys (netfilter hooks, udp encap/ipsec nat-t, ...)
- even atomic ops are too slow
  - percpu data
  - RCU
- Batching: GRO, GSO, `xmit_more`...
- optional HW offloads
- `sysctl` and other interfaces for futher fine tuning depending on expected workload

current develoment focus

- zerocopy tx
- container/network namespaces/virtualzation (vrf)
- offloading: ktls, ipsec
- XDP
- (unfortunate, imo) trend to move functionality from userspace to kernel (instead of other way around) because thats easier to do