Dynamic memory in practice

I/O and Network buffers

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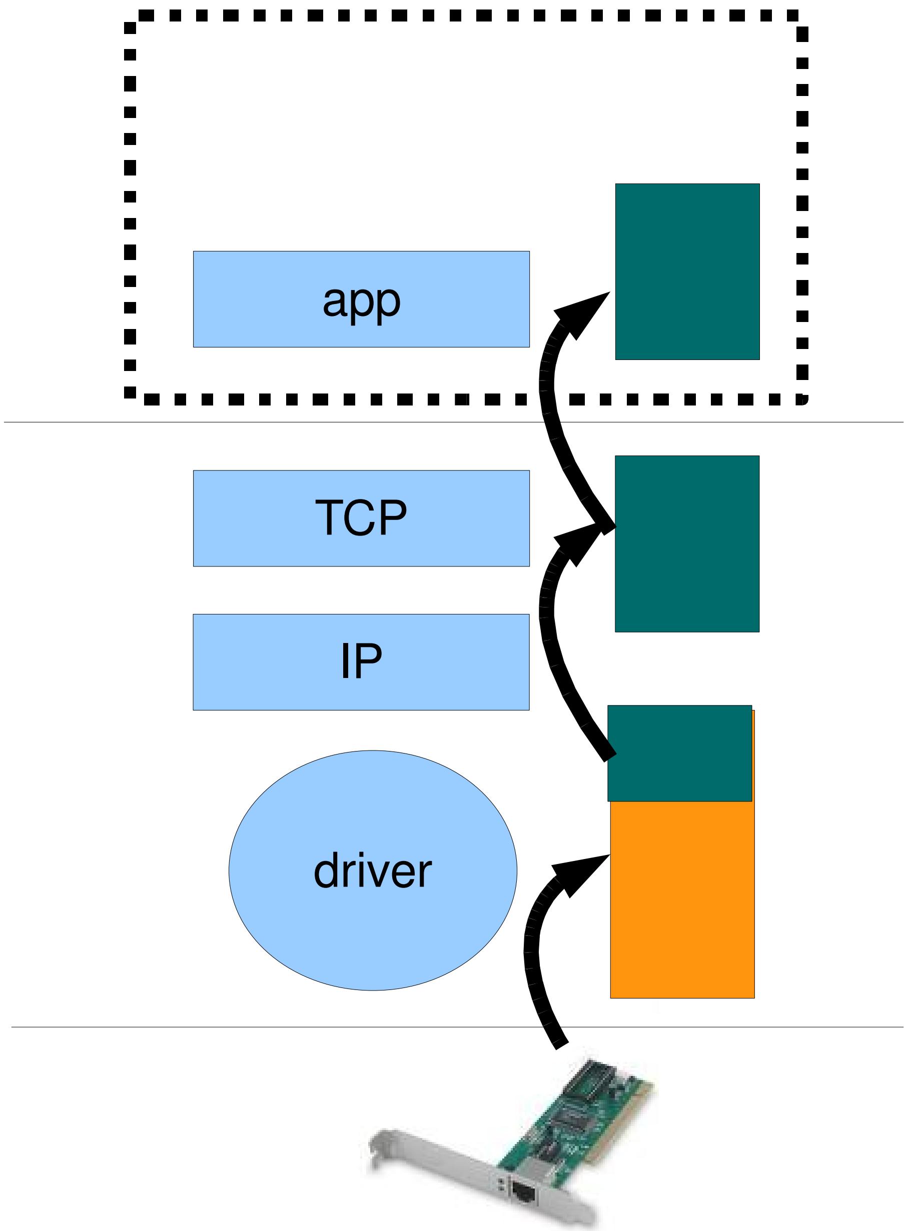
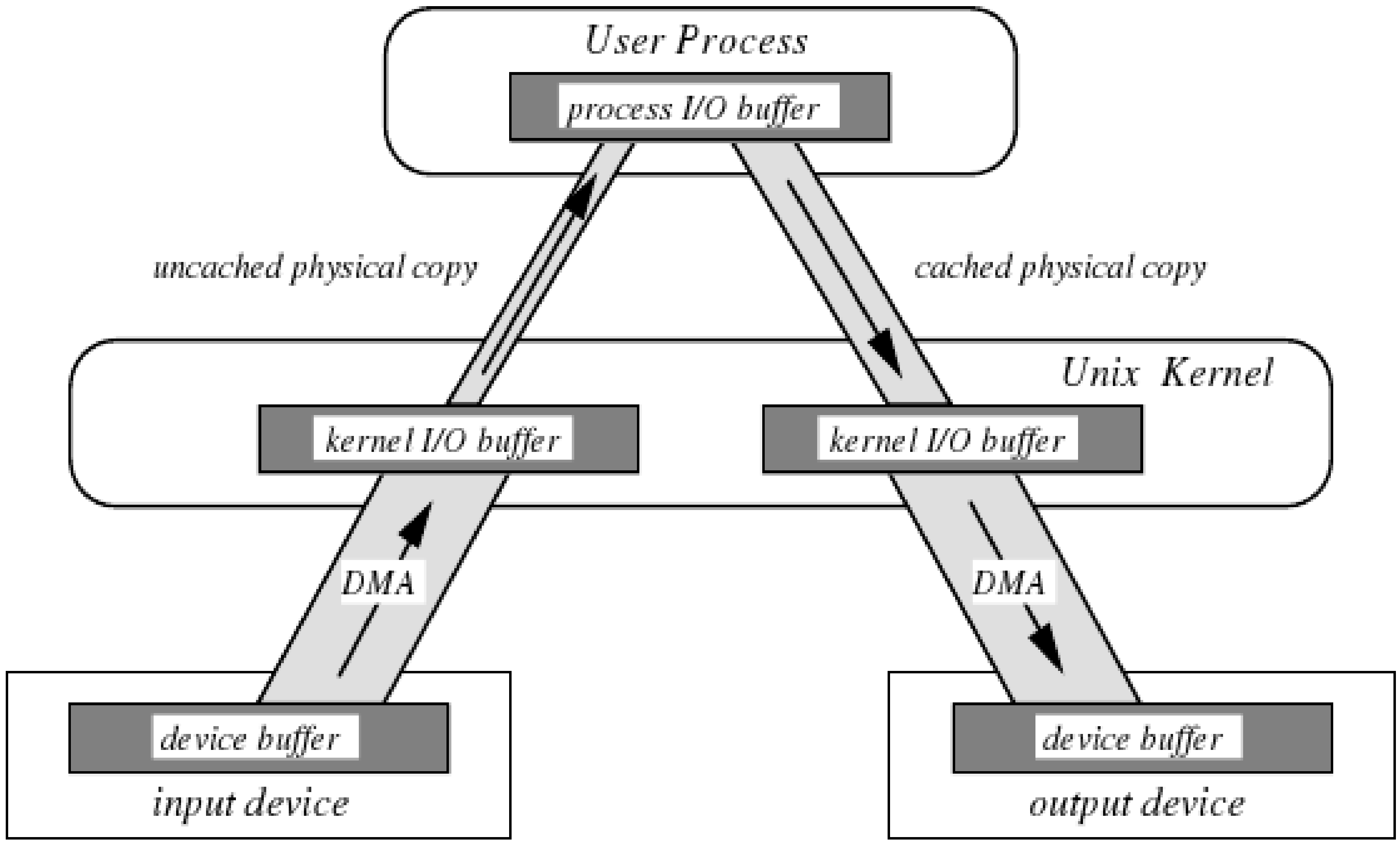
The slow way to do it

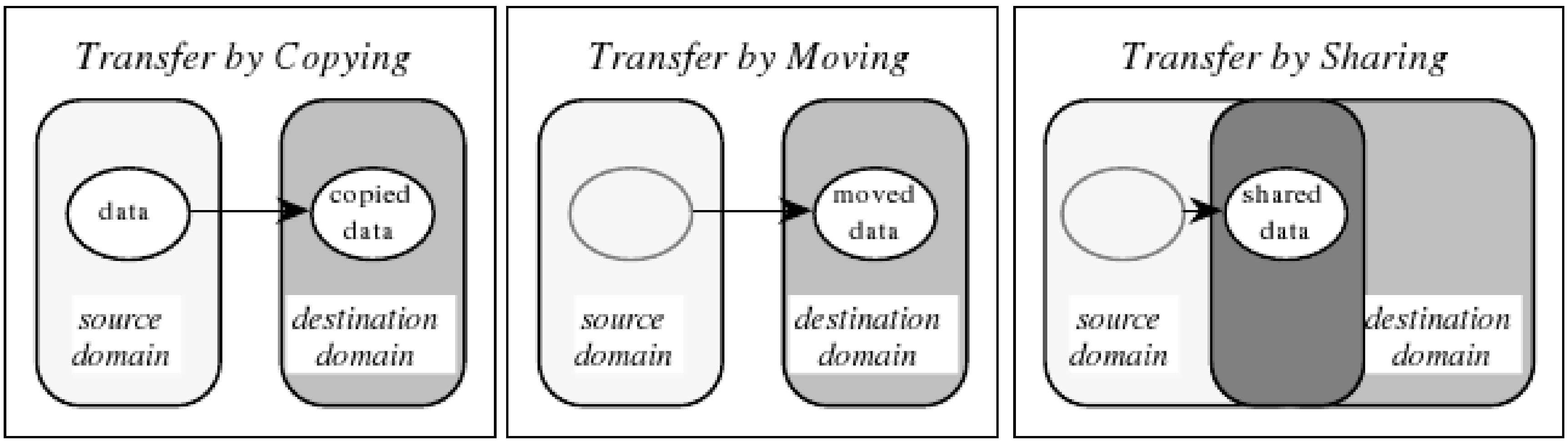
- Rx data on NIC: Interrupt
- Driver
  - allocates memory
  - Copies data to buffer
- Network stack process pkt
- TCP copies it to reassemble stream
- When app does read, copy to userland
- Lots of signalling



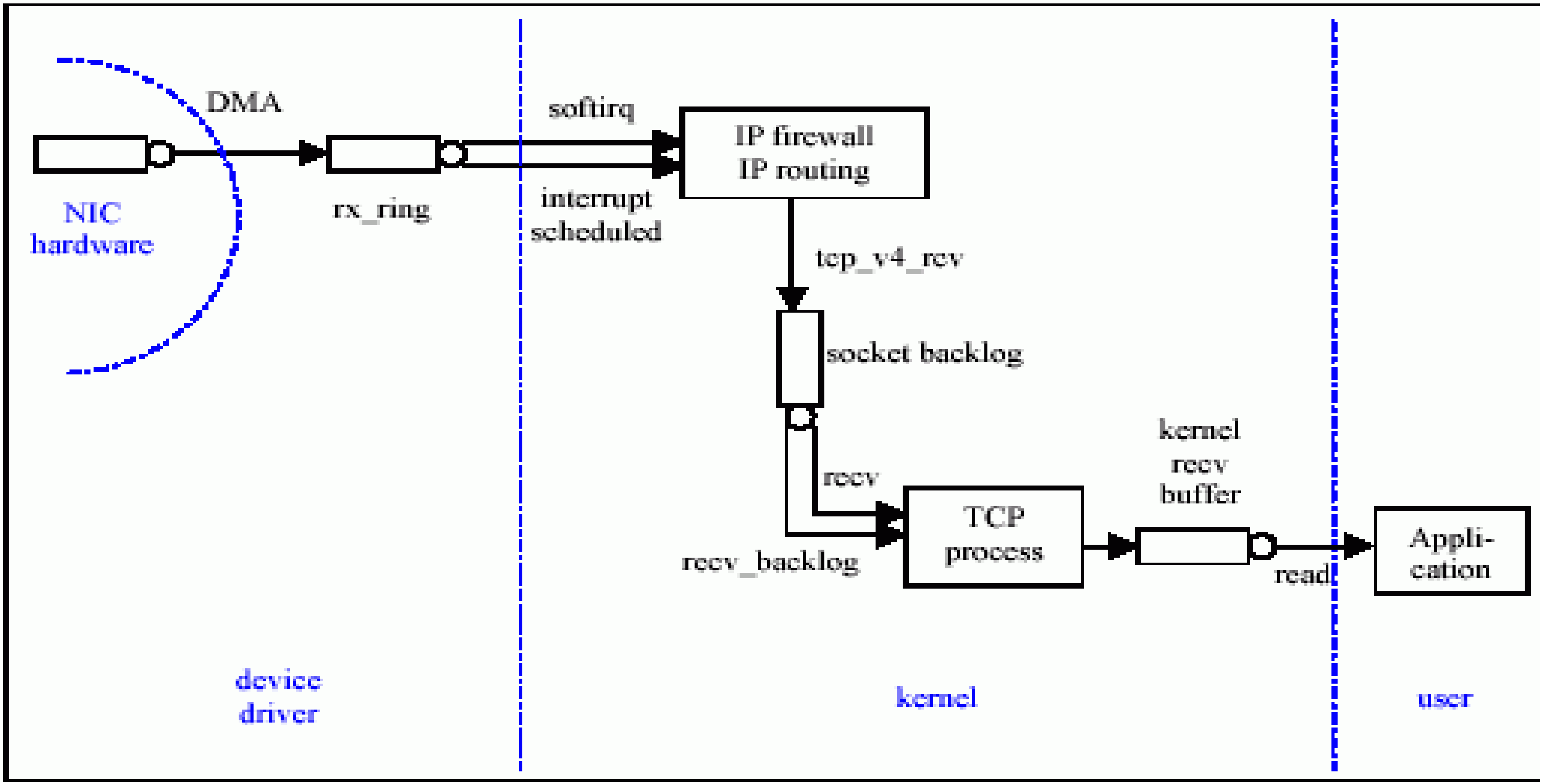
copy performance

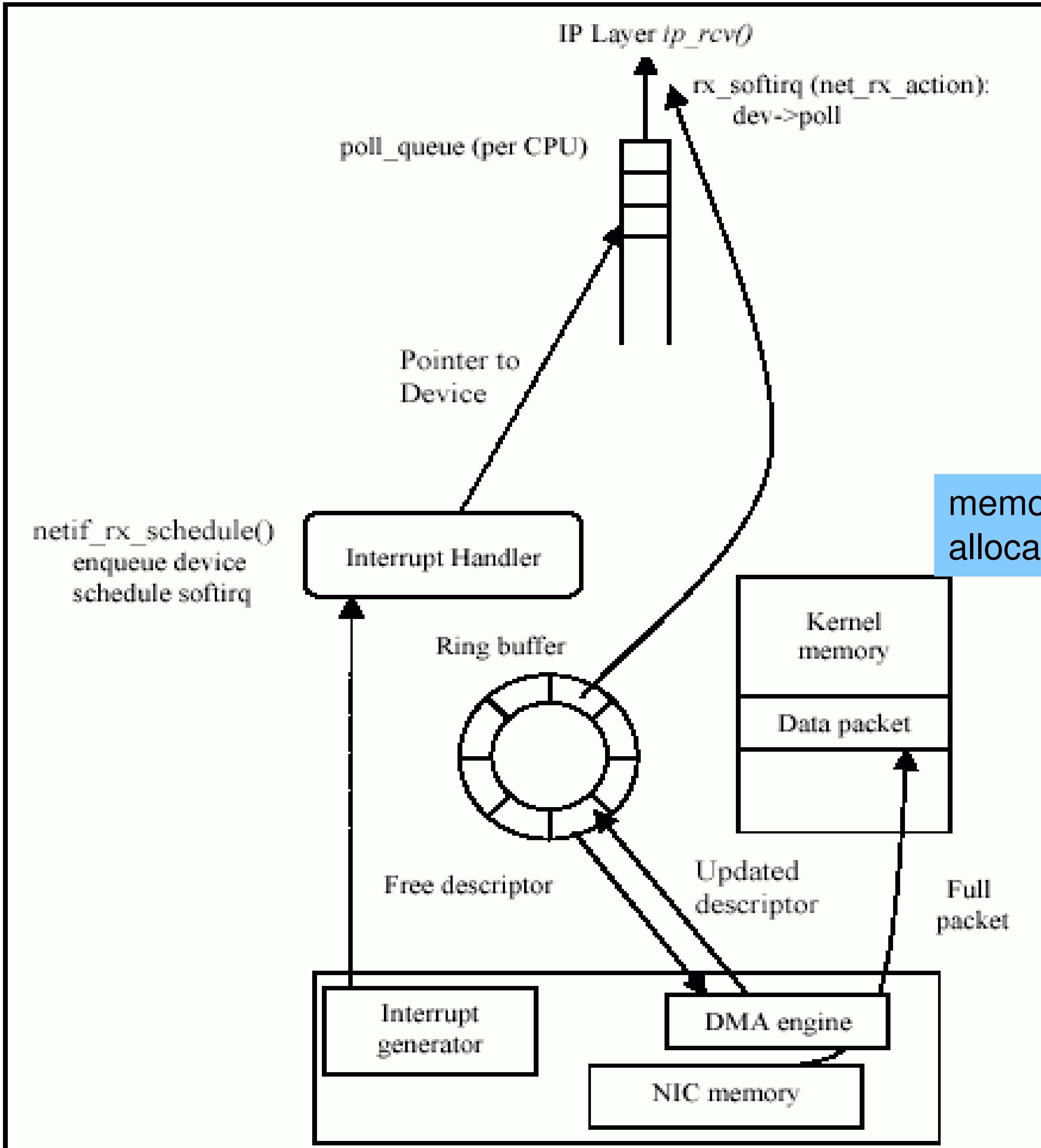


different ways to transfer data



The Linux way



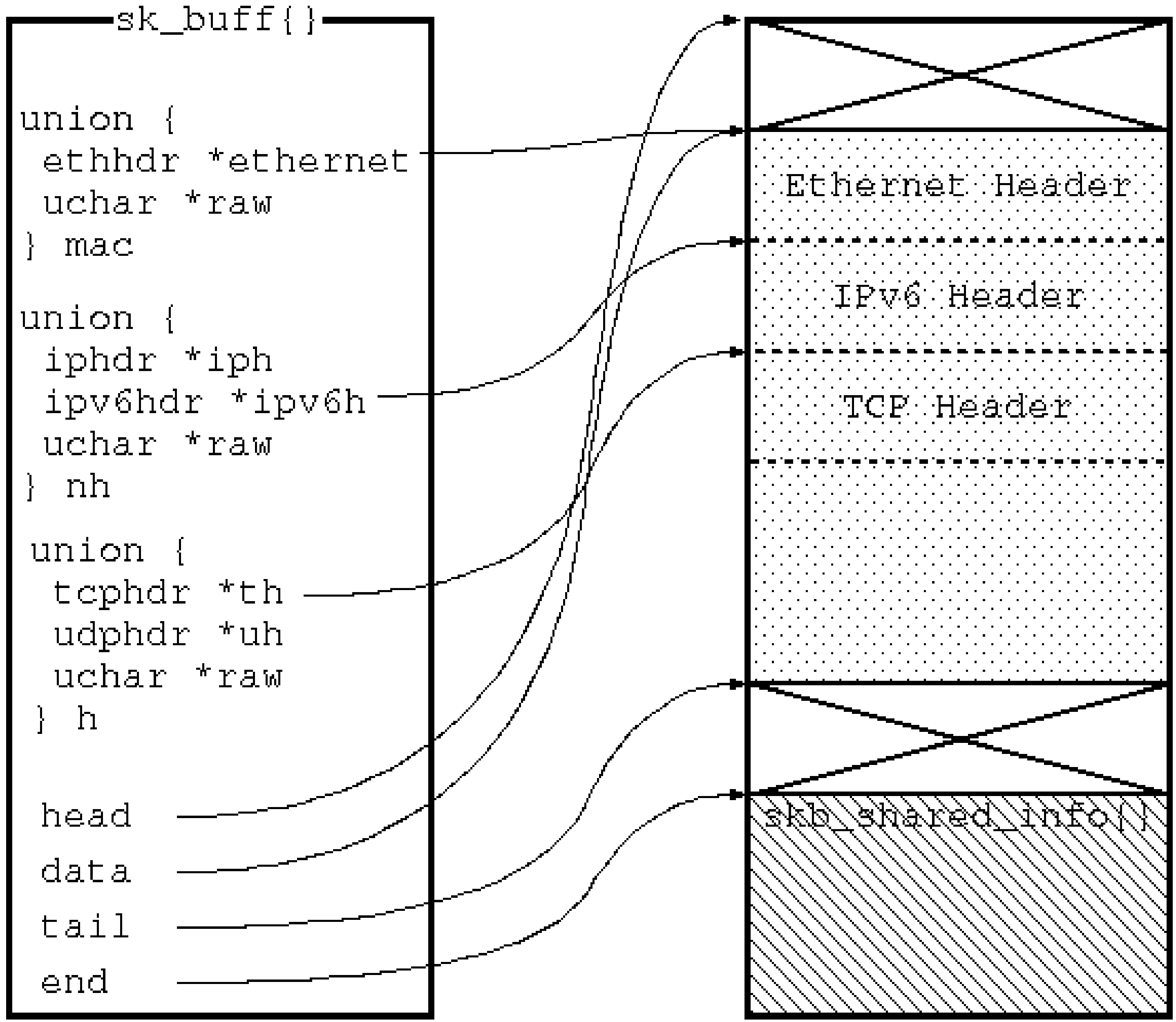


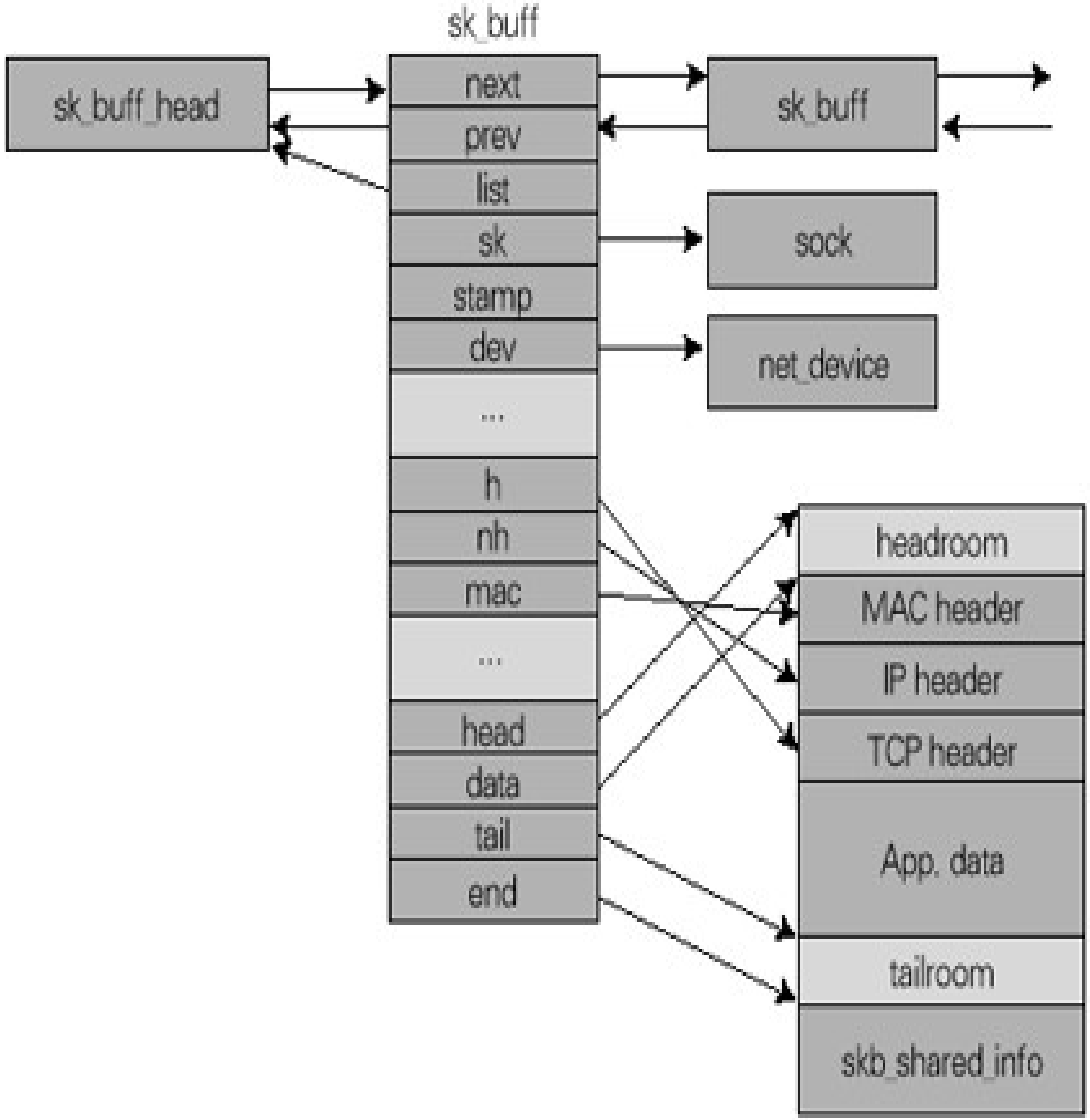
memory for data
allocated via kmalloc

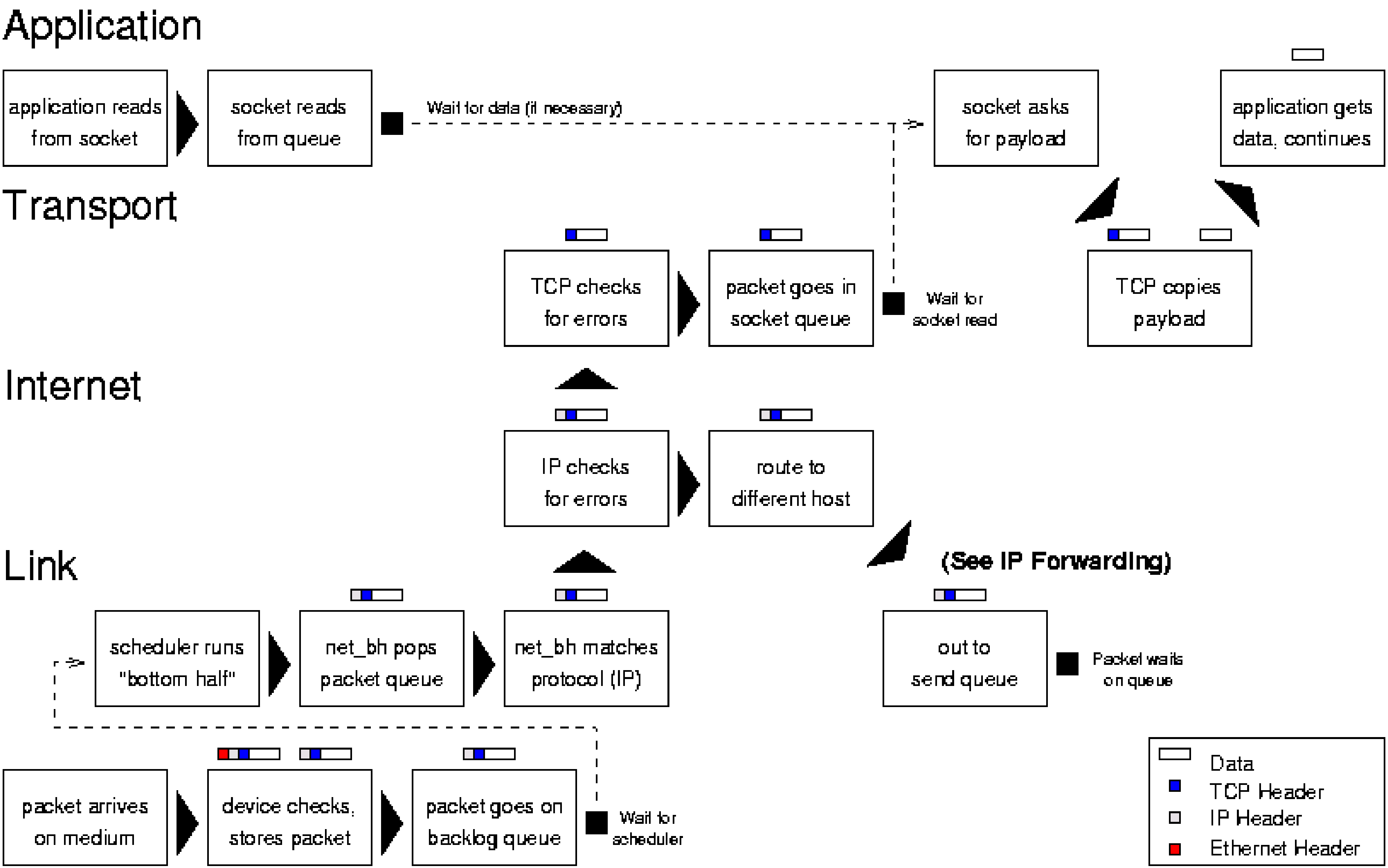
The Linux way

- skbuff: a complex, common pkt data structure
- all layers fill in appropriate info
- copying is fairly minimal
- skbufs are cached (see slab caches!) + reused
- quite large and hairy

sk	pointer to owning socket
stamp	arrival time
dev	pointer to receiving/transmitting device
h	pointer to transport layer header
nh	pointer to network layer header
mac	pointer to link layer header
dst	pointer to dst_entry
cb	TCP per-packet control information
len	actual data length
csum	checksum
protocol	packet network protocol
truesize	buffer size
head	pointer to head of buffer
data	pointer to data head
tail	pointer to tail
end	pointer to end
destructor	pointer to destruct function


sk_buff{}
union {
ethhdr *ethernet
uchar *raw
} mac
union {
iphdr *iph
ipv6hdr *ipv6h
uchar *raw
} nh
union {
tcphdr *th
udphdr *uh
uchar *raw
} h
head
data
tail
end
Ethernet Header
IPv6 Header
TCP Header
skb_shared_info{}


sk_buff
sk_buff_head
next
prev
list
sk
stamp
dev
...
h
nh
mac
...
head
data
tail
end
sk_buff
sock
net_device
headroom
MAC header
IP header
TCP header
App. data
tailroom
skb_shared_info


Application
application reads from socket
socket reads from queue
Wait for data (if necessary)
socket asks for payload
application gets data, continues
Transport
TCP checks for errors
packet goes in socket queue
Wait for socket read
TCP copies payload
Internet
IP checks for errors
route to different host
Link
(See IP Forwarding)
scheduler runs "bottom half"
net_bh pops packet queue
net_bh matches protocol (IP)
out to send queue
Packet waits on queue
packet arrives on medium
device checks, stores packet
packet goes on backlog queue
Wait for scheduler
Data
TCP Header
IP Header
Ethernet Header

that is pretty good

- but...

that is pretty good

- but we need to copy across each protection domain boundary
- still a lot of dynamic allocation and de-allocation
- very complex
- <u>sub-optimal!</u>

Can we do better?

- Fbufs (SOSP'93) and IO-Lite (SOSP'99)

Fbufs

- in micro-kernel lots of boundaries (elsewhere also?)
- in practice: one side writes, intermediate read, one side consumes

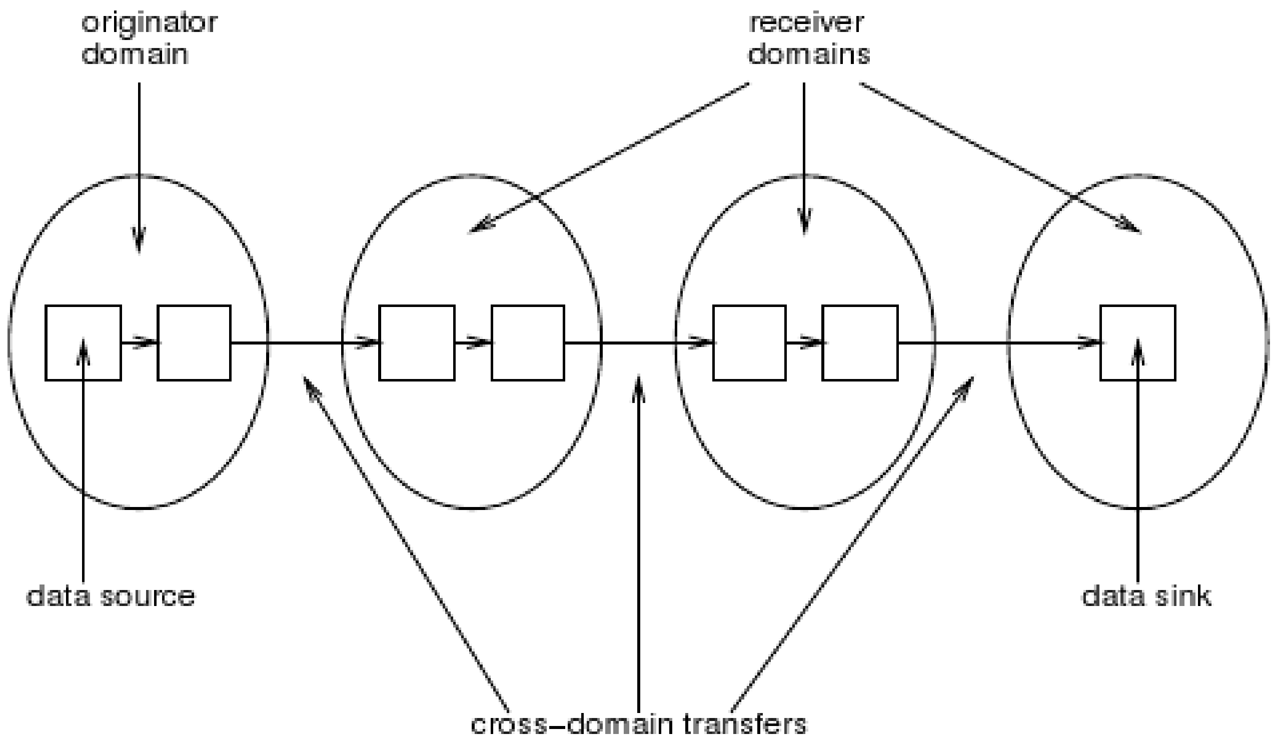
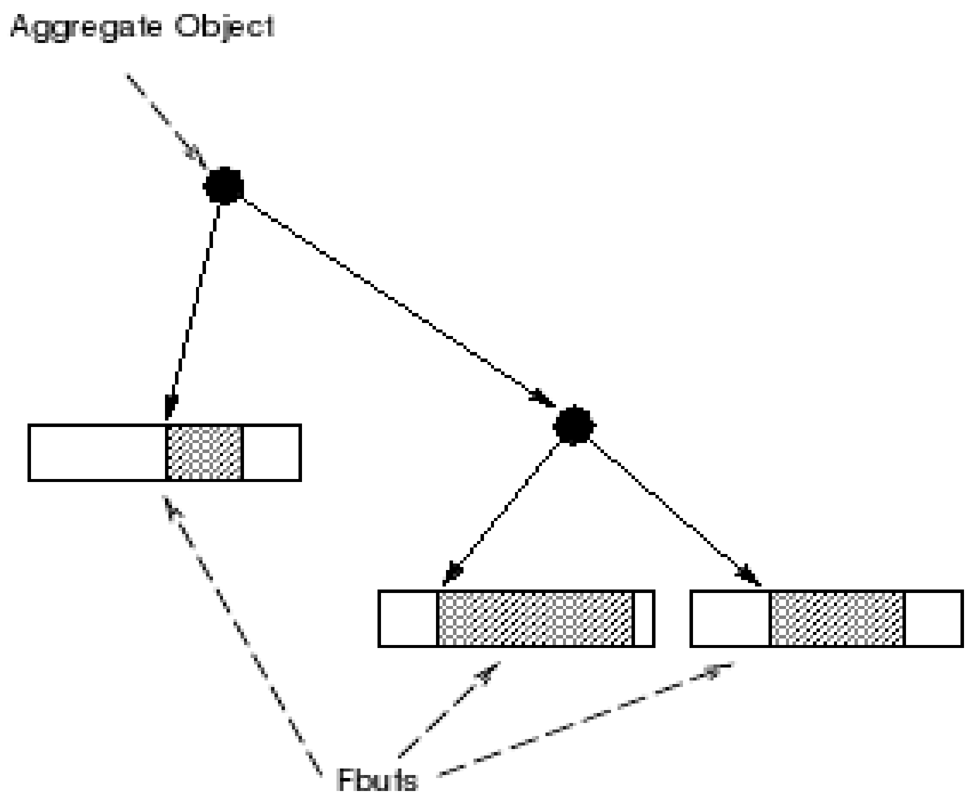


Figure 1: Layers Distributed over Multiple Protection Domains

Fbufs

- IO by means of Fbufs
  - one or more contiguous VM pages
  - protection domain either allocates an Fbuf or receives it via IPC
  - ADT can be layered on top of Fbufs



Fbufs

- Let us make buffers immutable
- Share by (re-)mapping
- transfer works as follows

Fbuf transfer

1. Allocate an Aggregate Object (Originator)
   (a) Find and allocate a free virtual address range in the originator (per-fbuf)
   (b) Allocate physical memory pages and clear contents (per-page)
   (c) Update physical page tables (per-page)
2. Send Aggregate Object (Originator)
   (a) Generate a list of fbufs from the aggregate object (per-fbuf)
   (b) Raise protection in originator (read only or no access) (per-fbuf)
   (c) Update physical page tables, ensure TLB/cache consistency (per-page)

Fbuf transfer

3. Receive Aggregate Object (Receiver)

   (a) Find and reserve a free virtual address range in the receiver (per-fbuf)

   (b) Update physical page tables (per-page)

   (c) Construct an aggregate object from the list of fbufs (per-fbuf)

4. Free an Aggregate Object (Originator, Receiver)

   (a) Deallocate virtual address range (per-fbuf)

   (b) Update physical page table, ensure TLB/cache consistency (per-page)

   (c) Free physical memory pages if there are no more references (per-page)

Fbuf transfer

- substantial overhead!

Optimisations

- Restricted Dynamic Read Sharing
  - 2 restrictions:
    - only remap from a limited, globally shared range of virtual addresses
    - write access by receiver, or by sender when receiver holds a reference to the fbuf, is illegal → SEGV

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Optimisations

- Fbuf Caching
  - exploit locality in IPC : once a PDU has travelled along a certain path, it is likely that more will follow
  - do not de-allocate fbuf, do not remove mappings
    → just return to originator with W permission

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Optimisations

- integrated buffer management/caching
  - let us skip this one for now

Optimisations

- volatile fbufs
  - so far we removed, for safety reasons, W permission from originator, but:
    - not needed for trusted components
    - not needed for some user applications

2. Send Aggregate Object (Originator)

   (a) Generate a list of fbufs from the aggregate object (per-fbuf)

   ~~(b) Raise protection in originator (read only or no access) (per-fbuf)~~

   (c) Update physical page tables, ensure TLB/cache consistency (per-page)

what remains is pretty fast

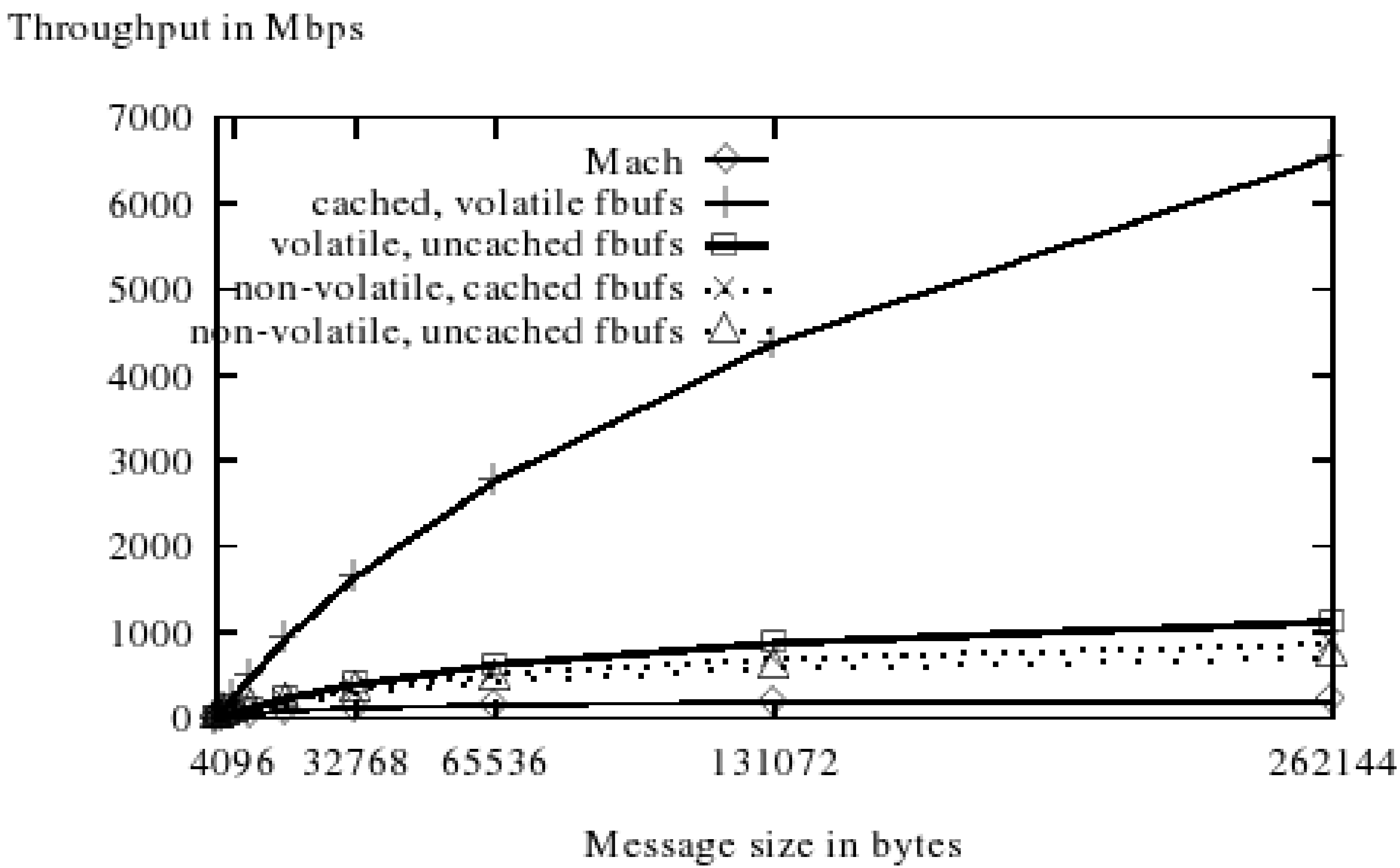


Figure 3: Throughput of a single domain boundary crossing

Fbufs and IO-Lite

- Fbufs were later generalised
  - include the page cache
  - Fbufs immutable but aggregate object are not
  - impressive work

problems

- when will it not provide benefits?

beltway buffers

- disadvantages fbufs
  - fbufs and io-lite introduce a new, slightly more complex API
  - still some VM overhead at runtime
  - different fbufs travelling in same IO path not necessarily contiguous → why is this an issue? TLB!
  - no in-place modifications possible

let us try something new

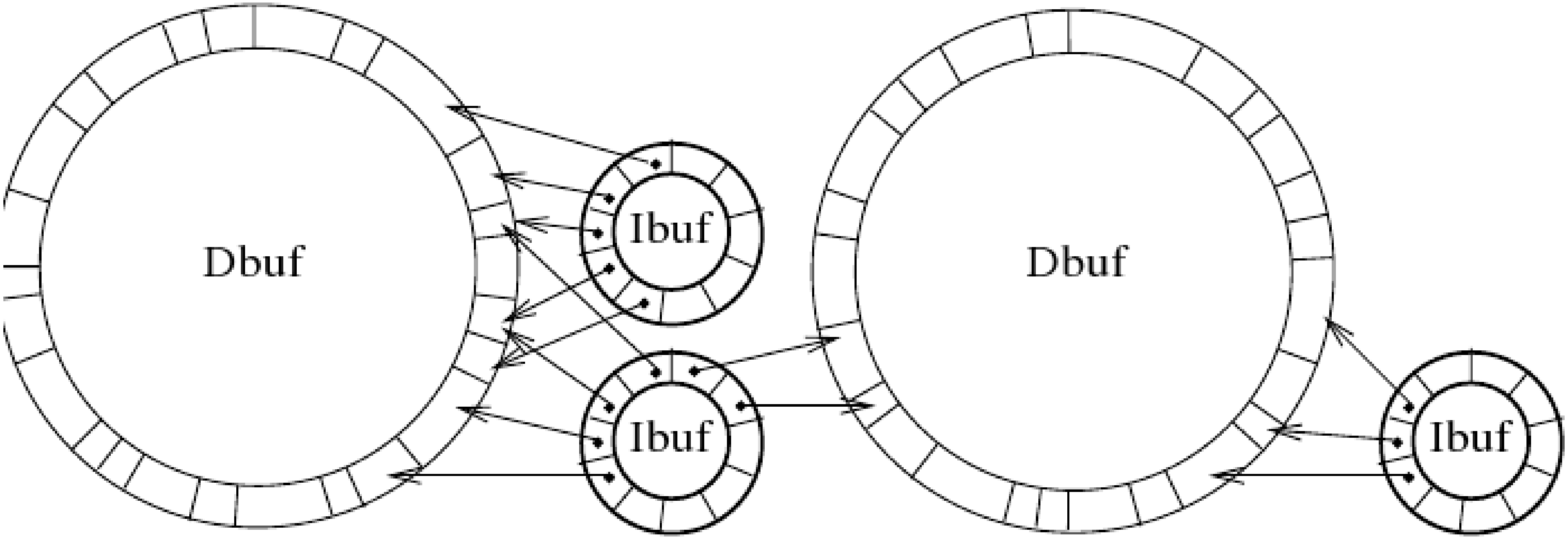
- no runtime copy or vm overhead
- ring buffers: good for streaming
- a ring may contain many data blocks
- rings permanently mapped

why not a single ring?

- protection
- multicore sharing → cache conflicts
  (same is true for meta-data)
- embedded devices may have their own rings
- data transformation

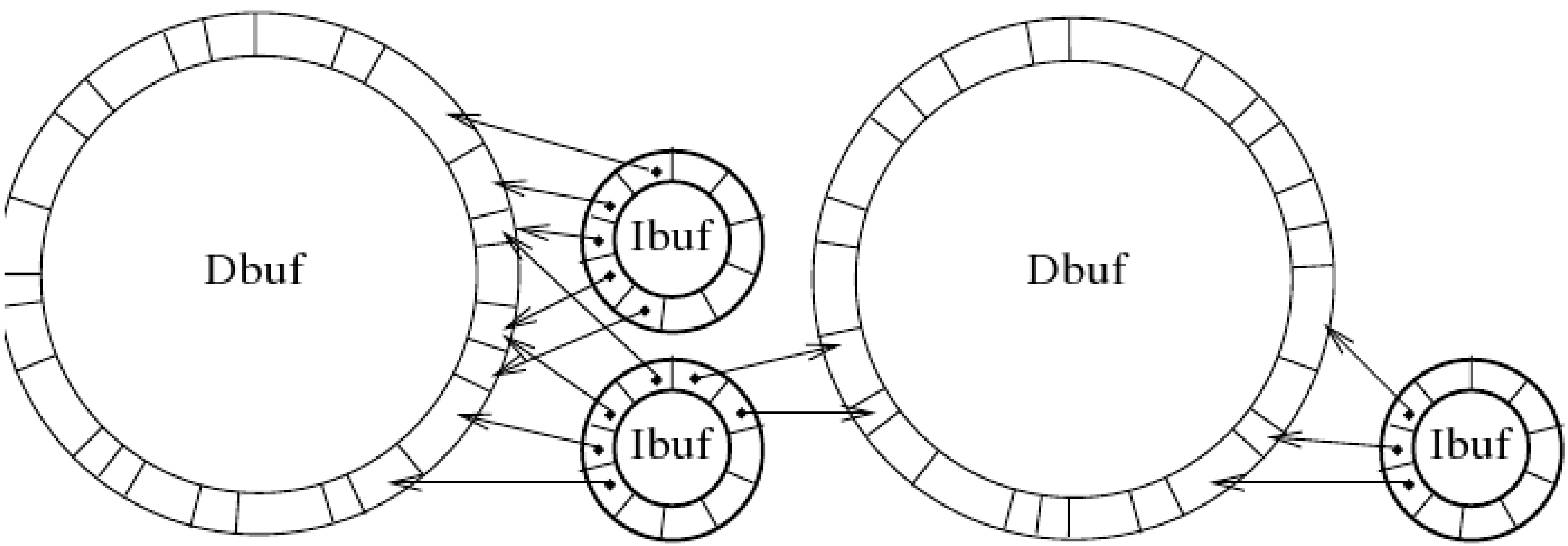
separate data and metadata

- data buffers can be shared (Unix file permissions)
- Ibufs
  - provide private view
  - minimise copying



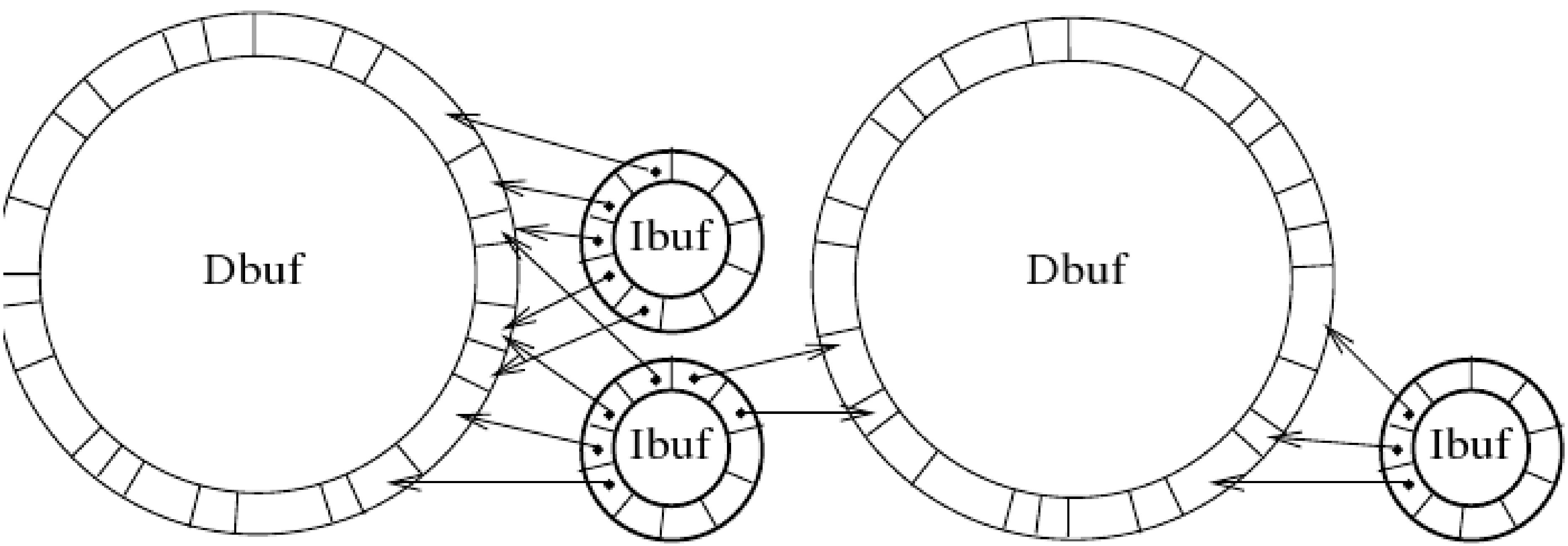
separate data and metadata

- mappings are permanent
- open, close, read, write on buffers
- we cover many protection domains



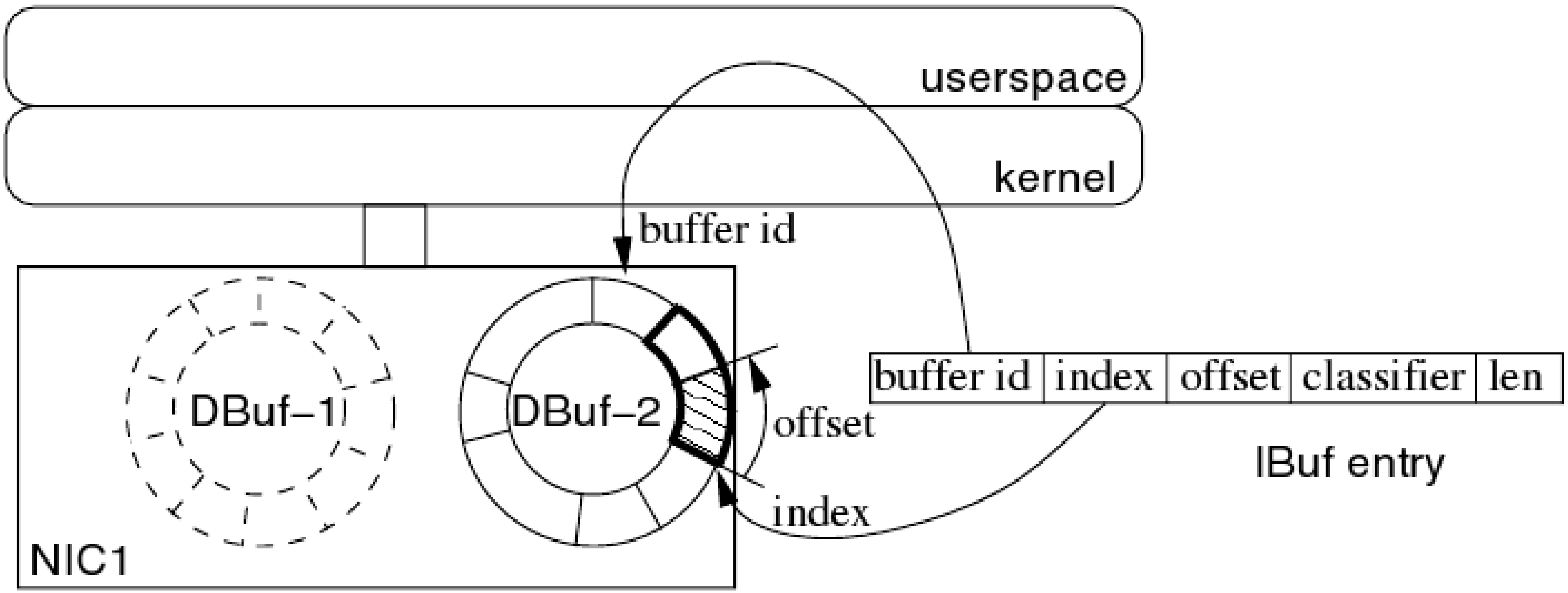
separate data and metadata

- Dbufs: can be large → good for TLB
- Ibufs: small, contiguous: good for caches

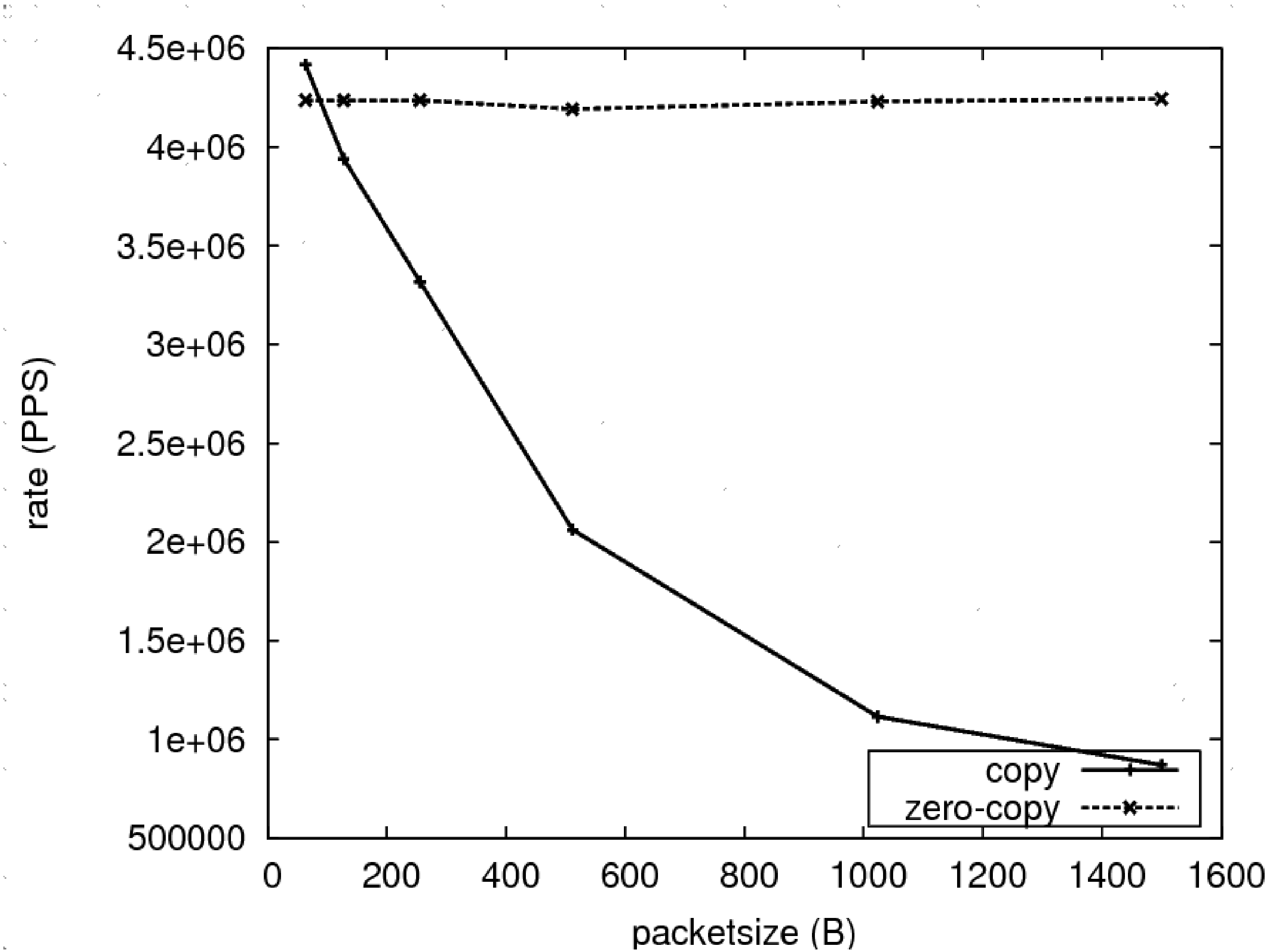


different protection domains

- zero-copy TCP reassembly
- classifier makes life easier and faster



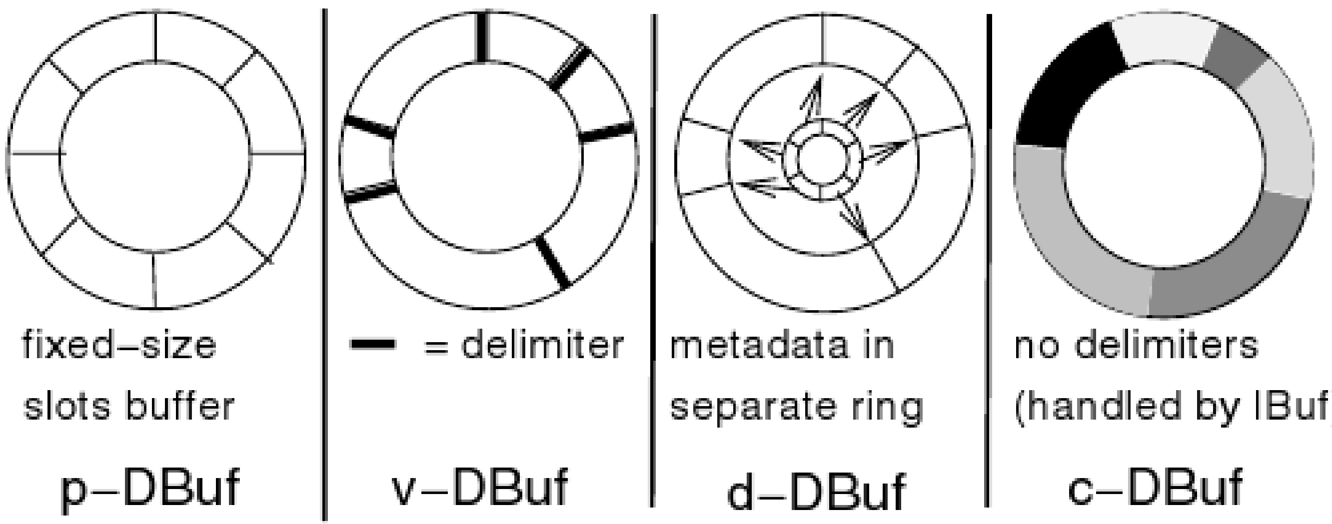
zero-copy reassembly



optimisations

under the hood many optimisations possible

- e.g. different buffer types



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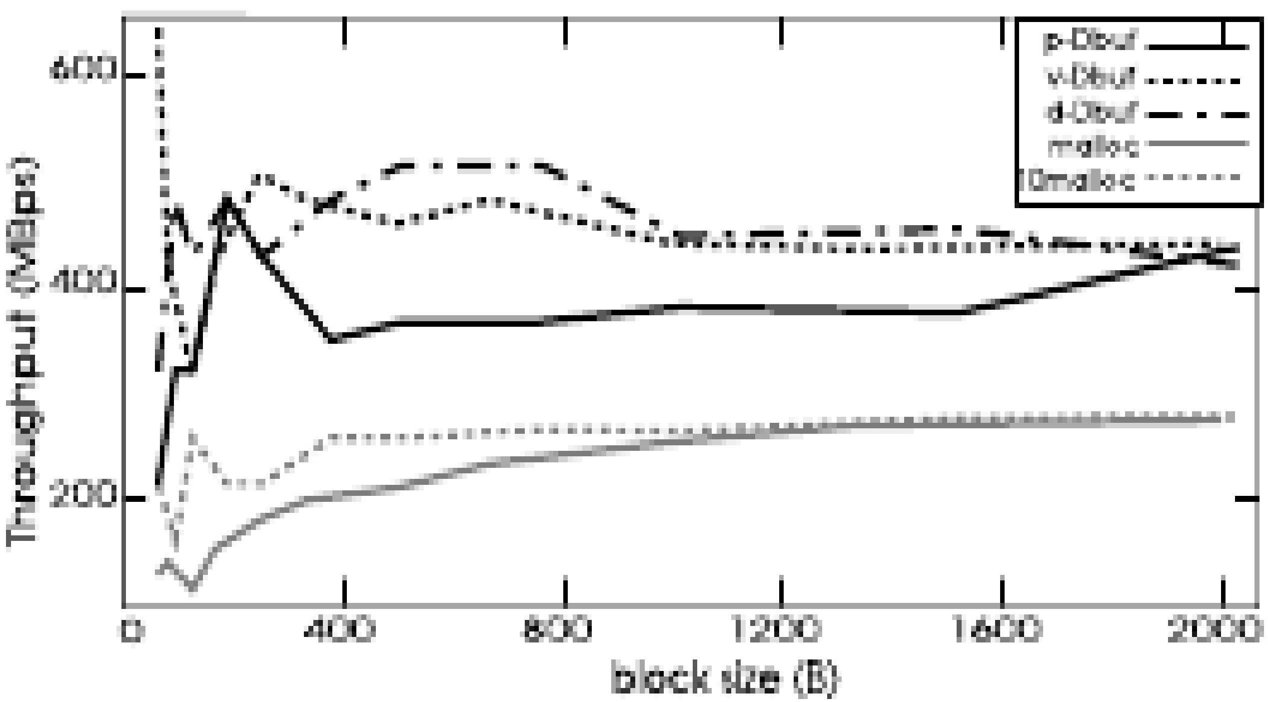

optimisations

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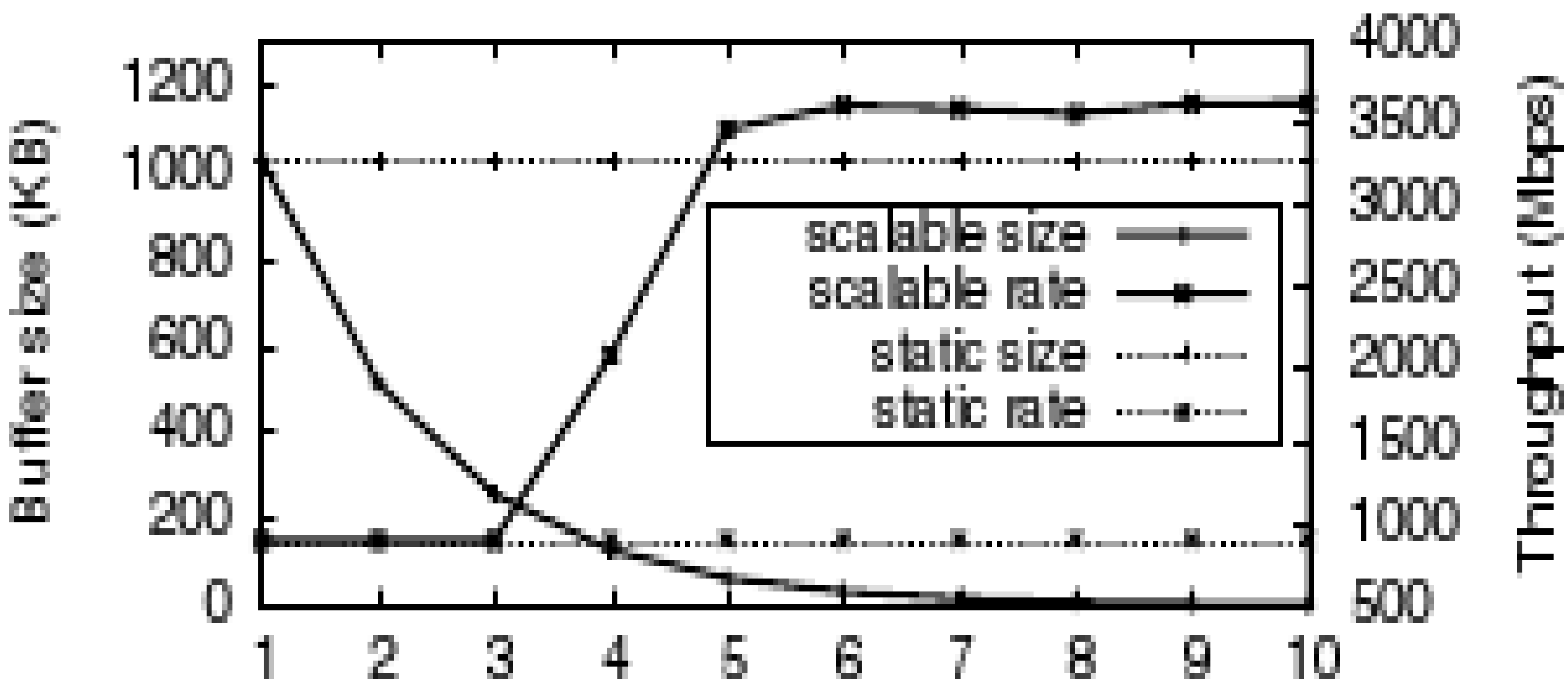
- e.g. adapt buffer size



optimisations

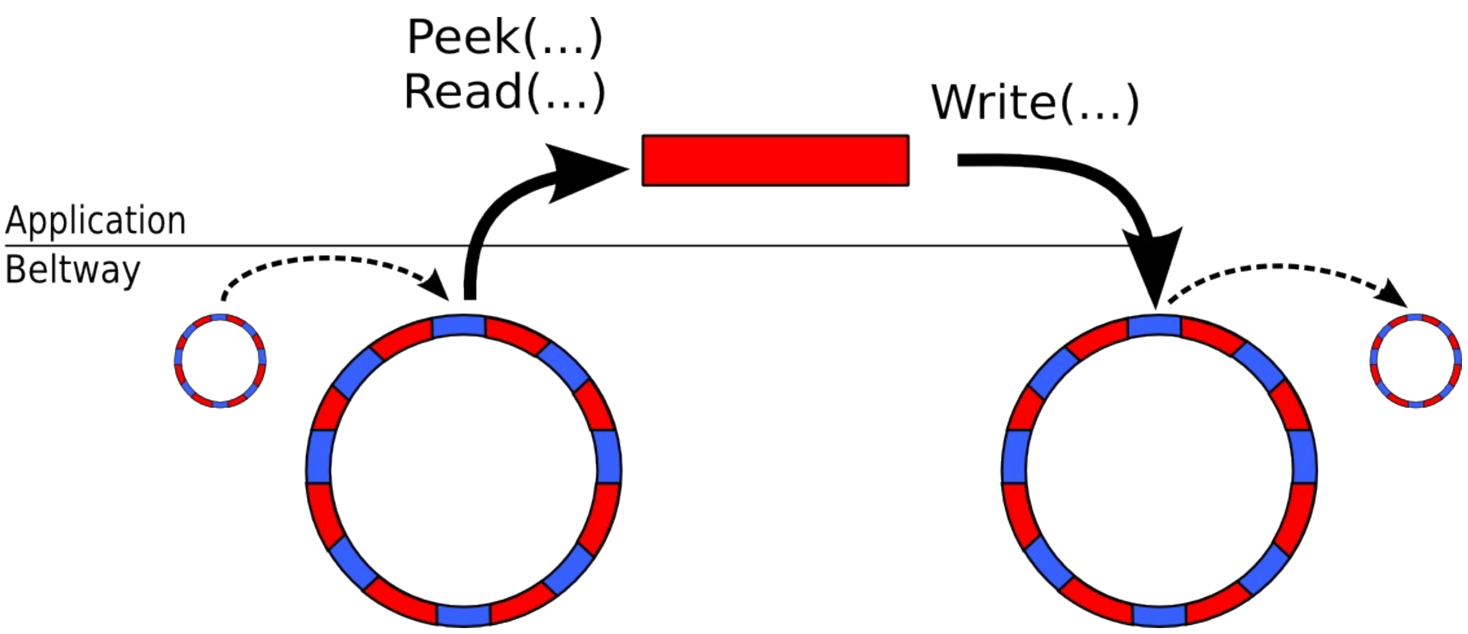
under the hood many optimisations possible

- e.g., peek in addition to read

optimisations

under the hood many optimisations possible

- splicing



optimisations

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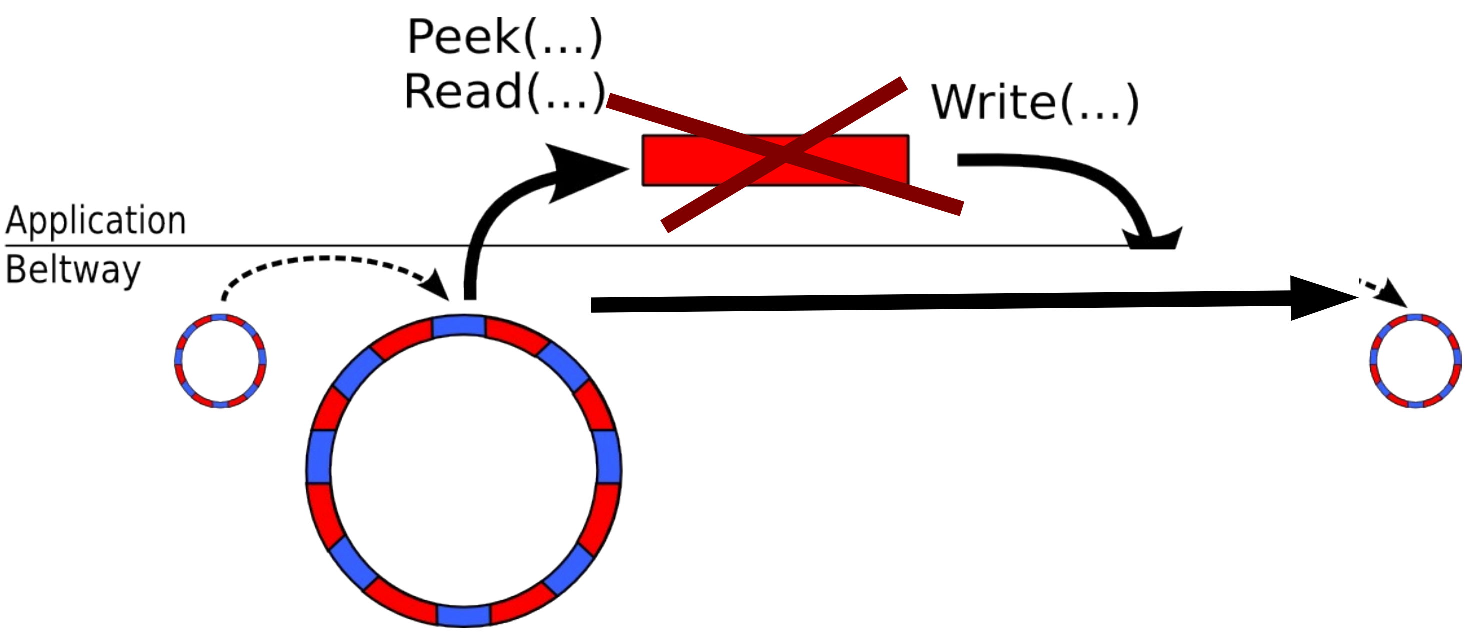

even with a small-scale project like beltway

- performance increase over Linux is significant
  - pipes: 2x
  - splicing: 3x-30x
  - libpcap: 10x

question

- why do we have sockets?

pipesfs

- future: anycore
  - large monolithic programs perhaps not the way to go
- unify IO processing (UNIX-style)
  - use common programs to manipulate IO path
  - grep, sed, compress, cp, cat, etc.
- increase IO throughput

pipesfs

- virtual file system representing kernel IO paths
- pipes
- all data streams between kernel filters accessible from user space
- manipulated from user space
  - mkdir
  - ln -s ...
  - cat /pipes/.../http/get/all | compress > log.Z

another example: scrub http requests

```
#!/bin/sh
mkdir /pipes/httpclean
mv /pipes/[...]/http/get /pipes/httpclean/
cat /pipes/[...]/http/all | grep -v '..'
    > /pipes/httpclean/all
```

- do we *really* need sockets or do we have them for lack of something better?

Thank you!