Cornflakes: Zero-Copy Serialization for Microsecond-Scale Networking

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NIC speeds increase, CPUs are stagnant

20 Gbit/s throughput

2008

~100µs end-host RTT

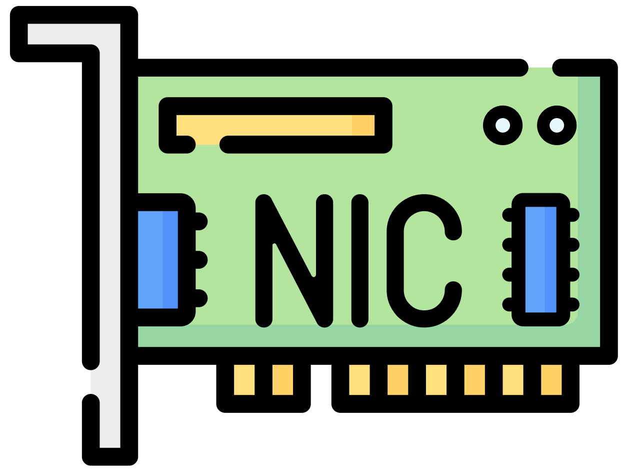
20x

20x

400 Gbit/s throughput

2023

~5µs end-host RTT

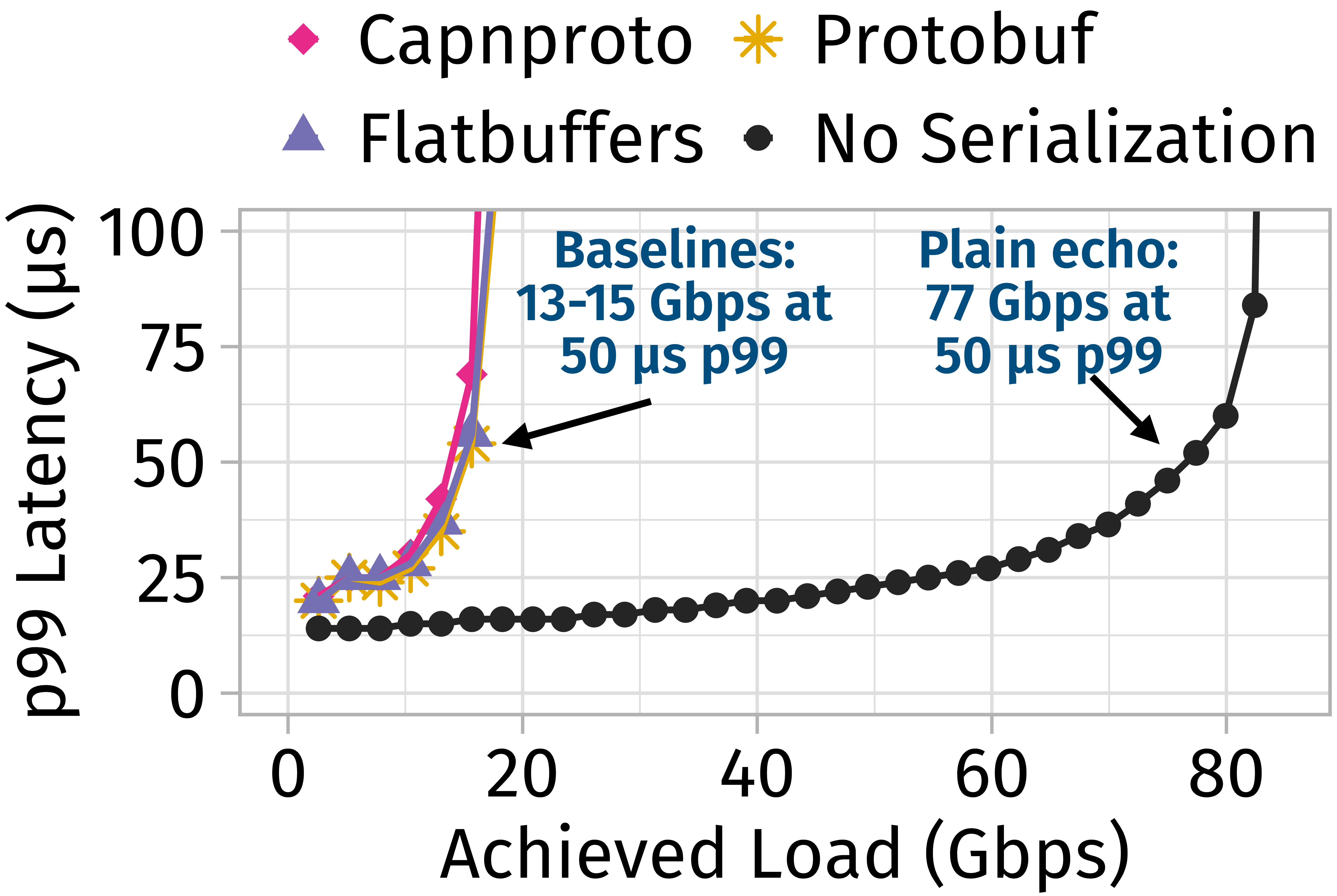


- ***Shaving down CPU time*** is important for modern microsecond-scale apps
  - CPU frequencies stagnated at ***3-4 GHz***
  - Multicore helps, but not always

Serialization is a bottleneck for (10s of)-µs-scale apps

- Serialization: converting in-memory data structures to on-the-wire formats for communication

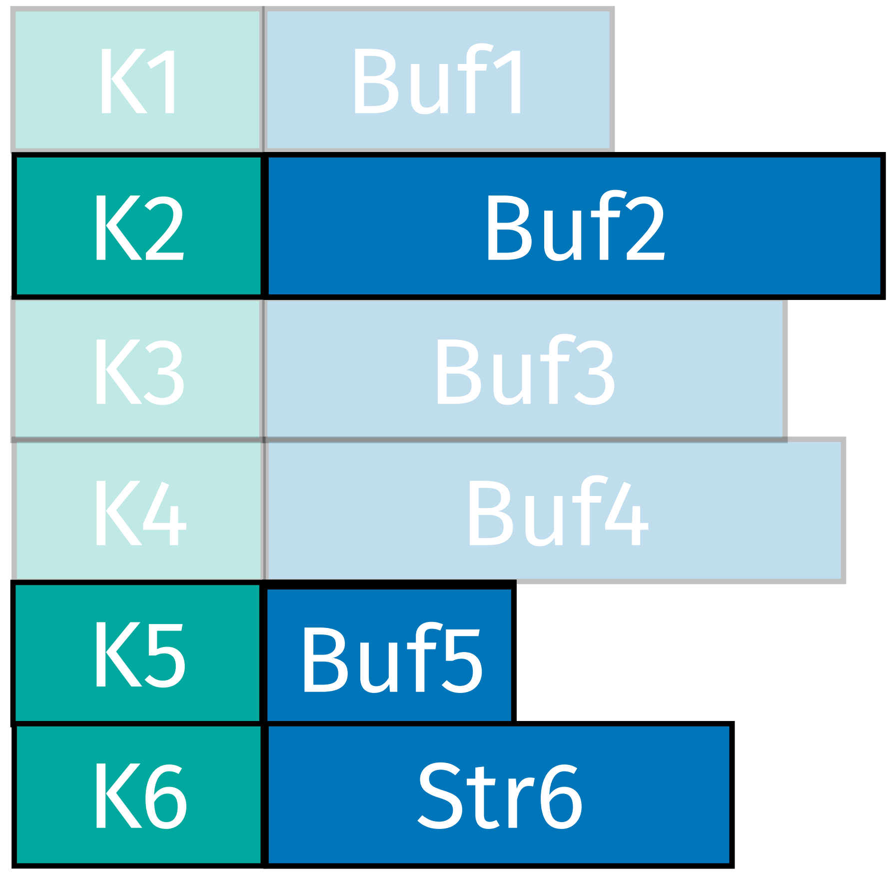
- Experimental takeaway: serialization ***reduces achievable throughput by 80%***



- ***Message size***: 4096 bytes
- ***Serialized struct***: 2 equal-sized bytes fields
- ***Networking stack:*** minimal UDP stack (100 Gb NIC)

Networked serialization’s core task is data movement

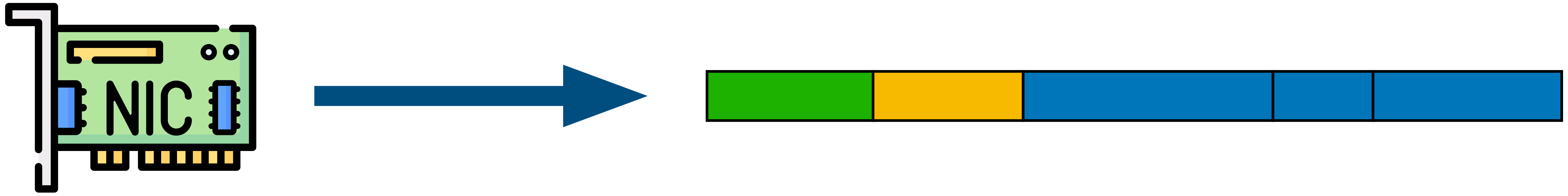
Application Layer




```
let getm = GetM::new();
getm.init_vals(3);
getm.get_mut_vals().append(&buf2);
getm.get_mut_vals().append(&buf5);
getm.get_mut_vals().append(&str6);
netstack.send(getm.serialize_to_bytes());
```

Serialization Library

Networking Stack



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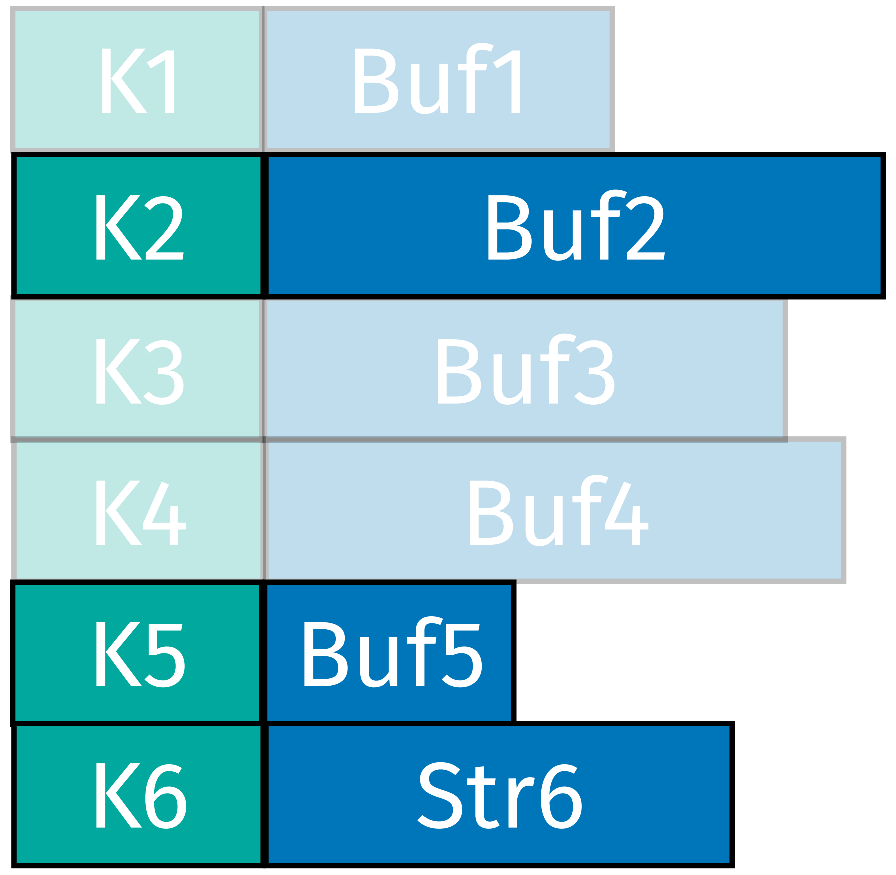


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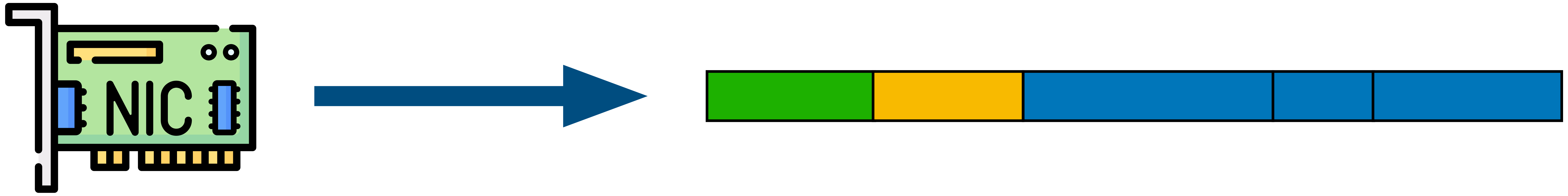
Copy 1

Serialization Library

Networking Stack

Pinned (unswappable) Memory



Networked serialization's core task is data movement

Application Layer

K1	Buf1
K2	Buf2
K3	Buf3
K4	Buf4
K5	Buf5
K6	Str6

```
let getm = GetM::new();
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```

Copy 1

Serialization Library

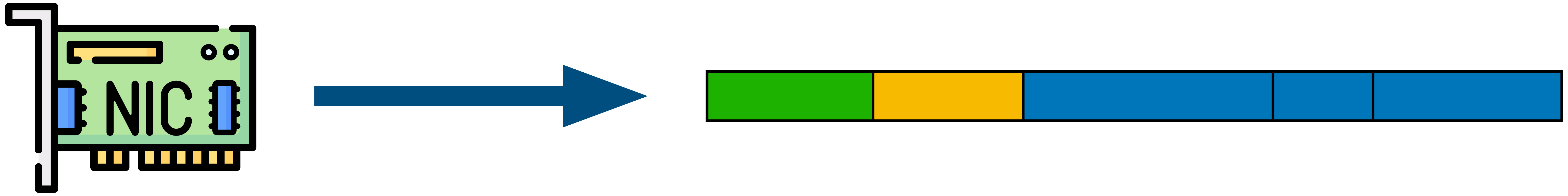
Obj Hdr	Buf2	Buf5	Str6

Copy 2

Networking Stack

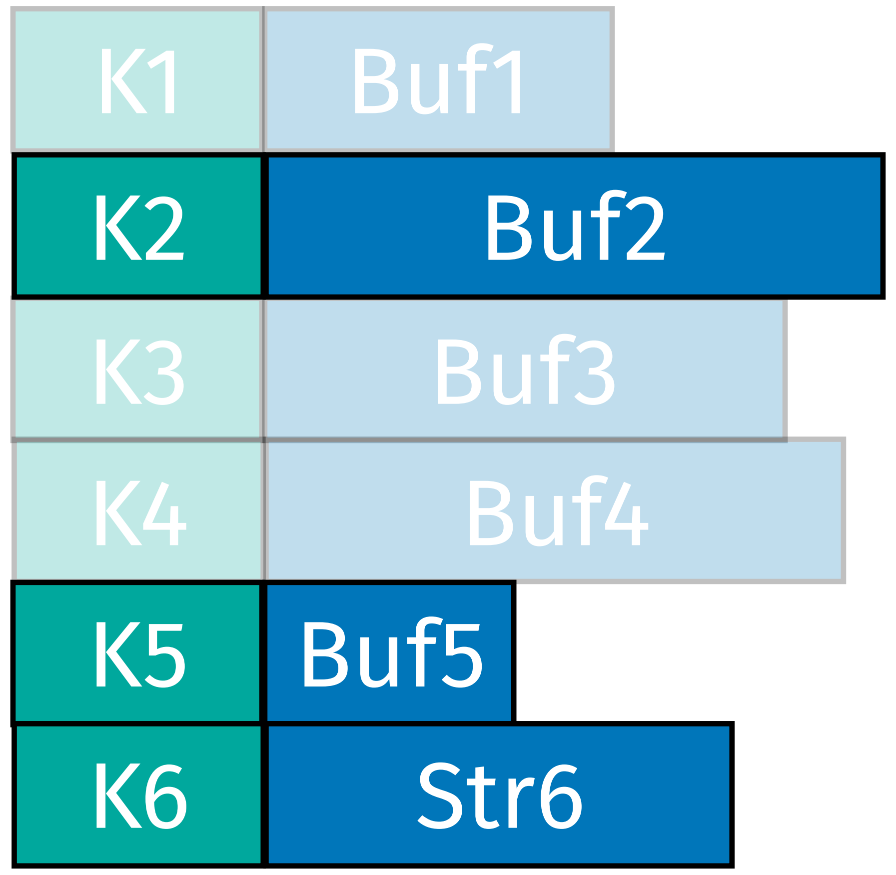
Pkt Hdr	Obj Hdr	Buf2	Buf5	Str6

Pinned (unswappable) Memory



Networked serialization’s core task is data movement

Application Layer

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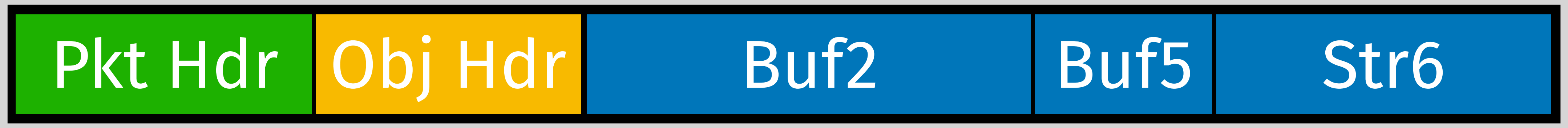
Copy 1

Serialization Library

Copy 2

Networking Stack



Pinned (unswappable) Memory

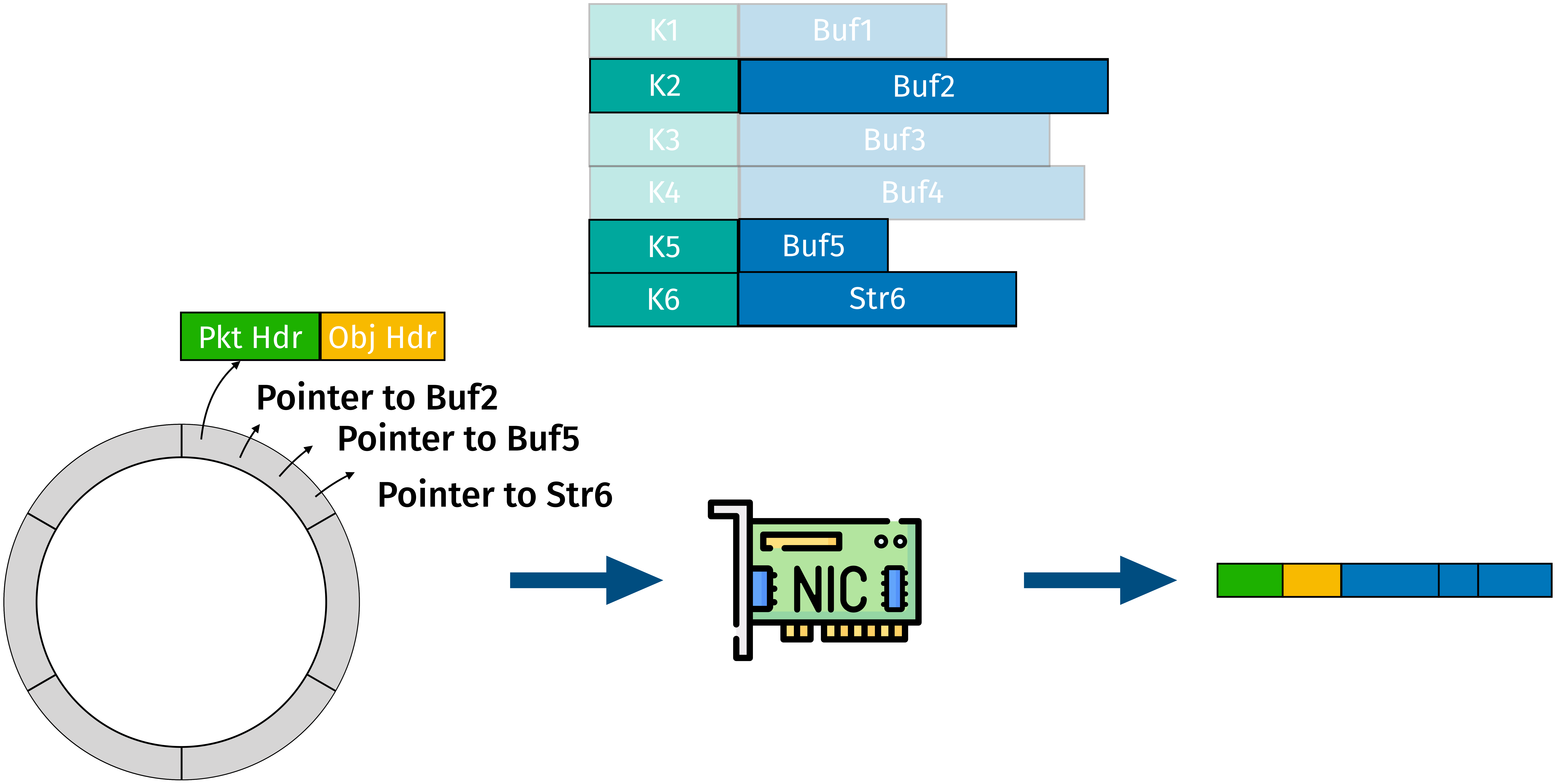
Networked serialization today involves up to two data copies. Can existing zero-CPU-copy APIs remove copies and reduce overhead?

Yes, but it's complicated….

Talk Agenda

- Introduction and background
- Motivation for using zero-copy APIs in serialization and challenges
- Design of ***Cornflakes***: a new, general-purpose, zero-copy, serialization library
- Implementation
- Evaluation

Zero-CPU-copy avoids copies through DMA



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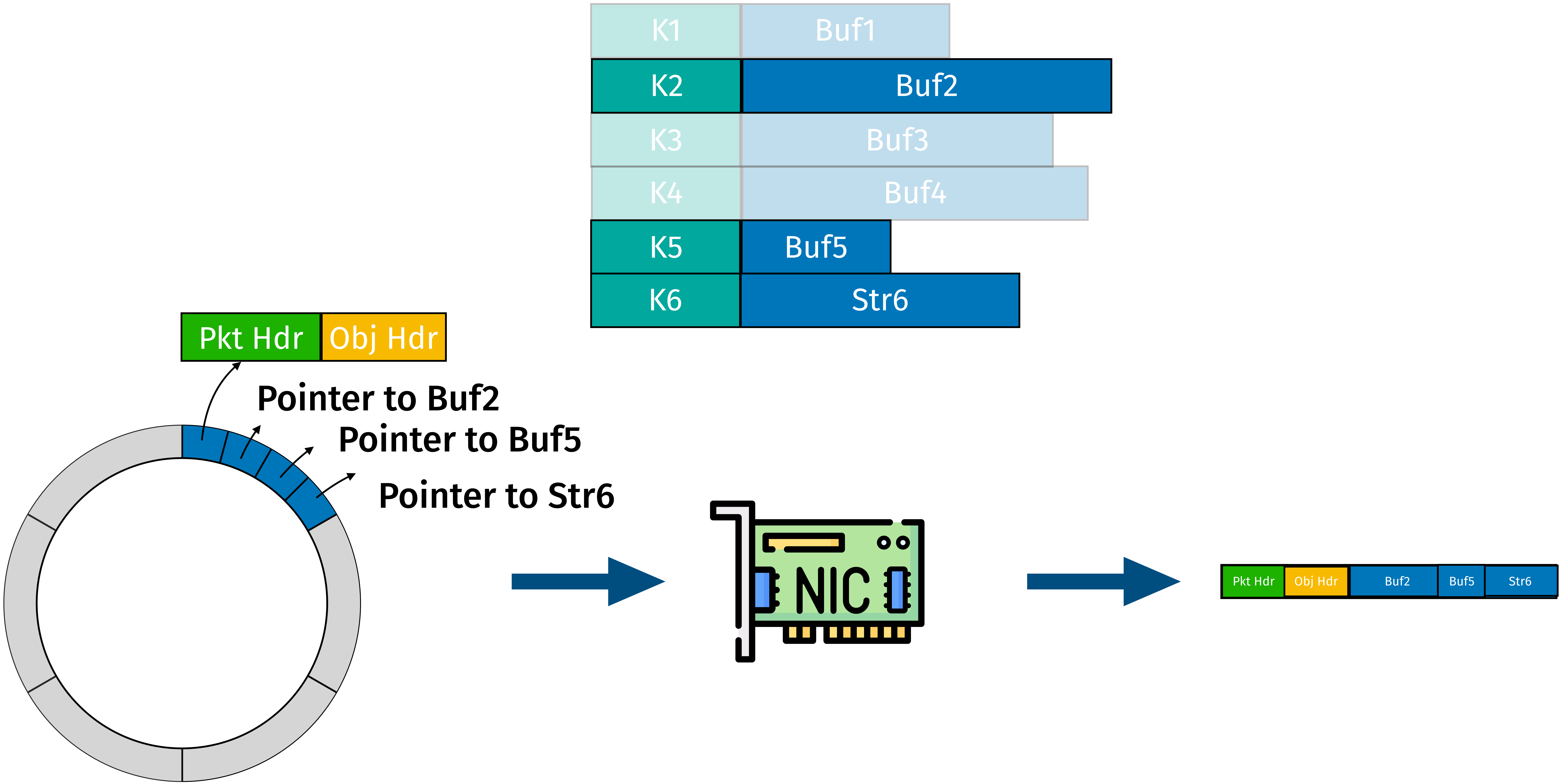
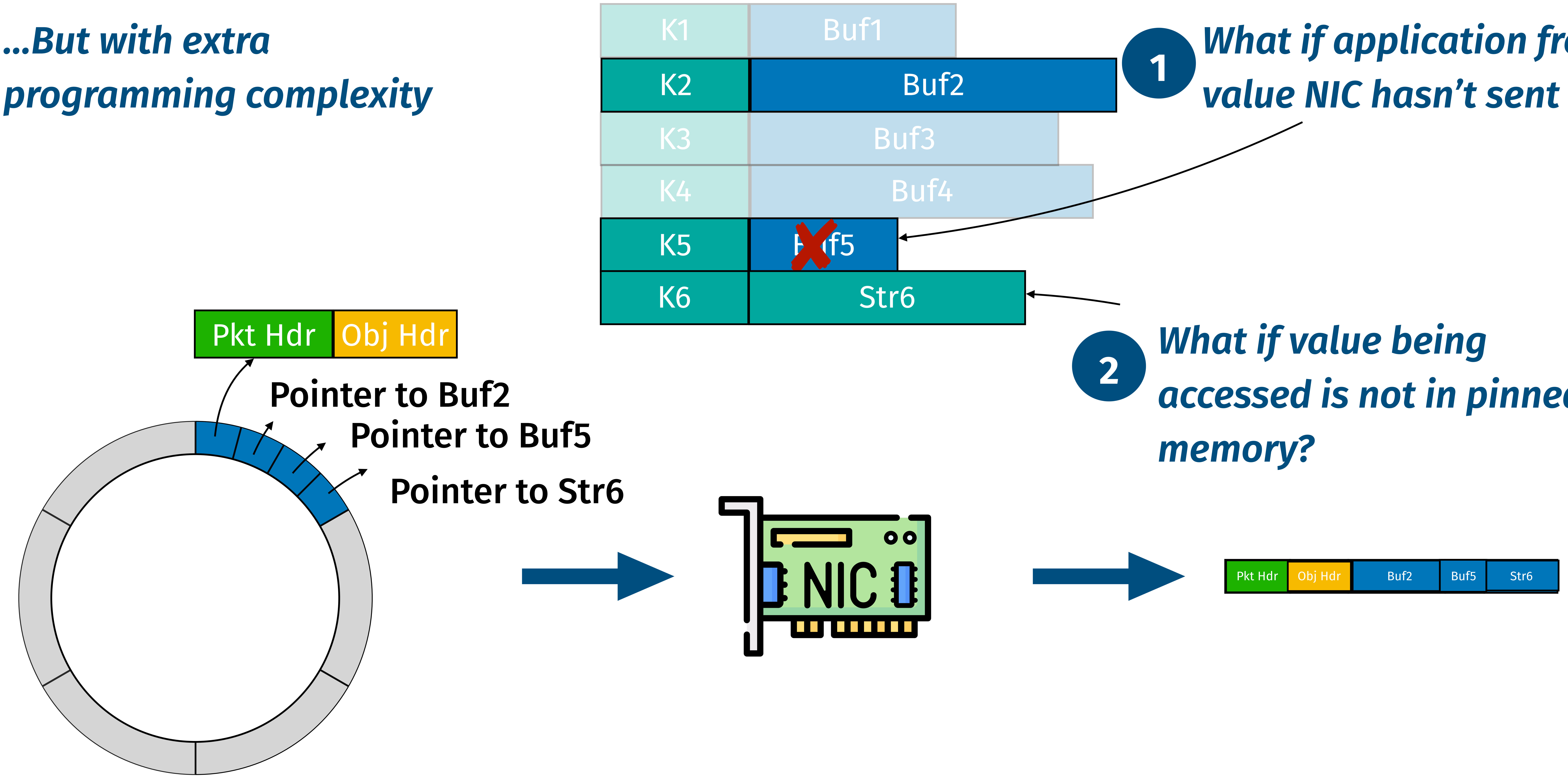


Zero-CPU-copy avoids copies through DMA

…But with extra programming complexity



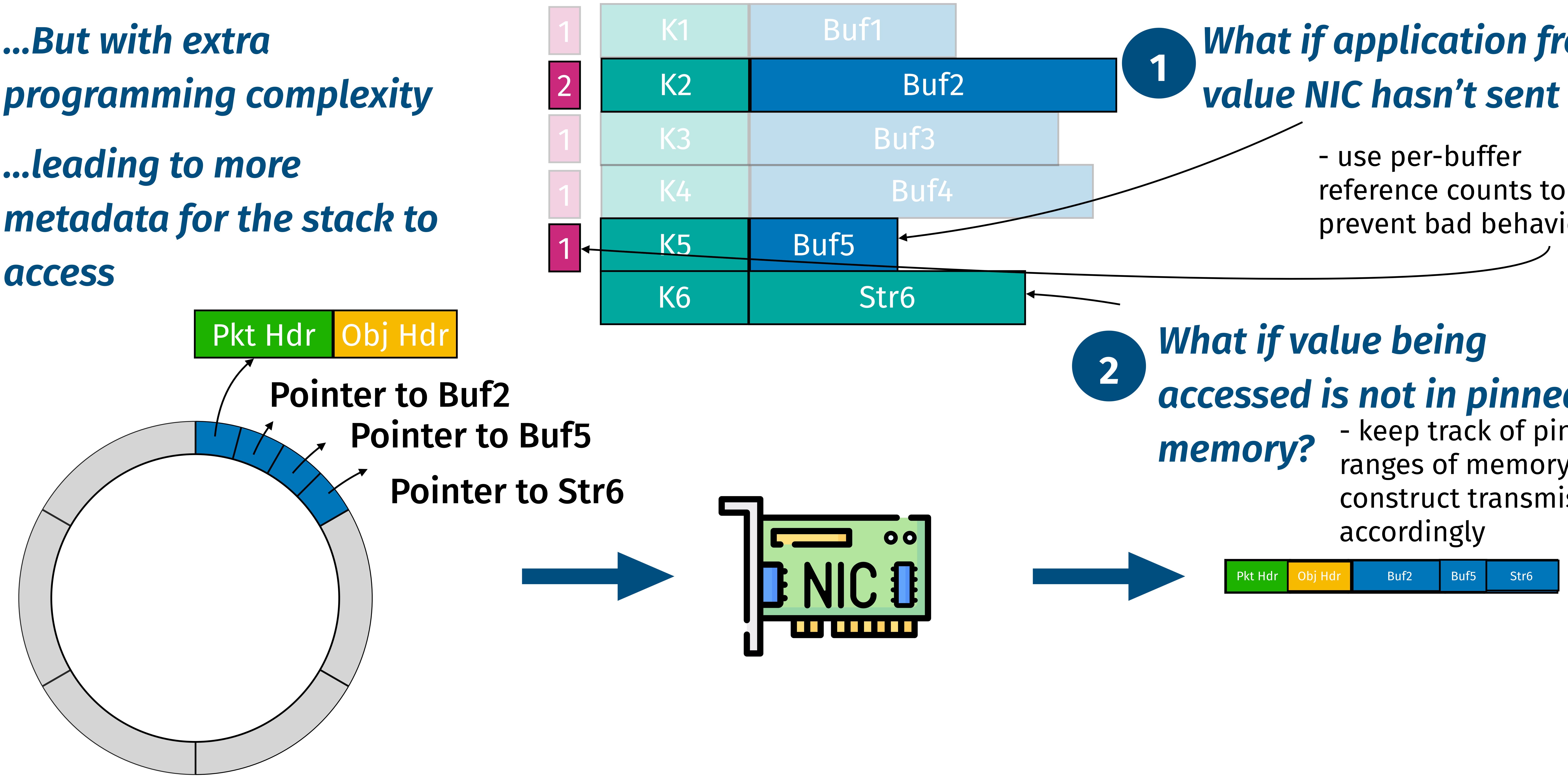
1 ***What if application frees value NIC hasn't sent yet?***

2 ***What if value being accessed is not in pinned memory?***

Zero-CPU-copy avoids copies through DMA

...But with extra programming complexity

...leading to more metadata for the stack to access



1 *What if application frees value NIC hasn't sent yet?*

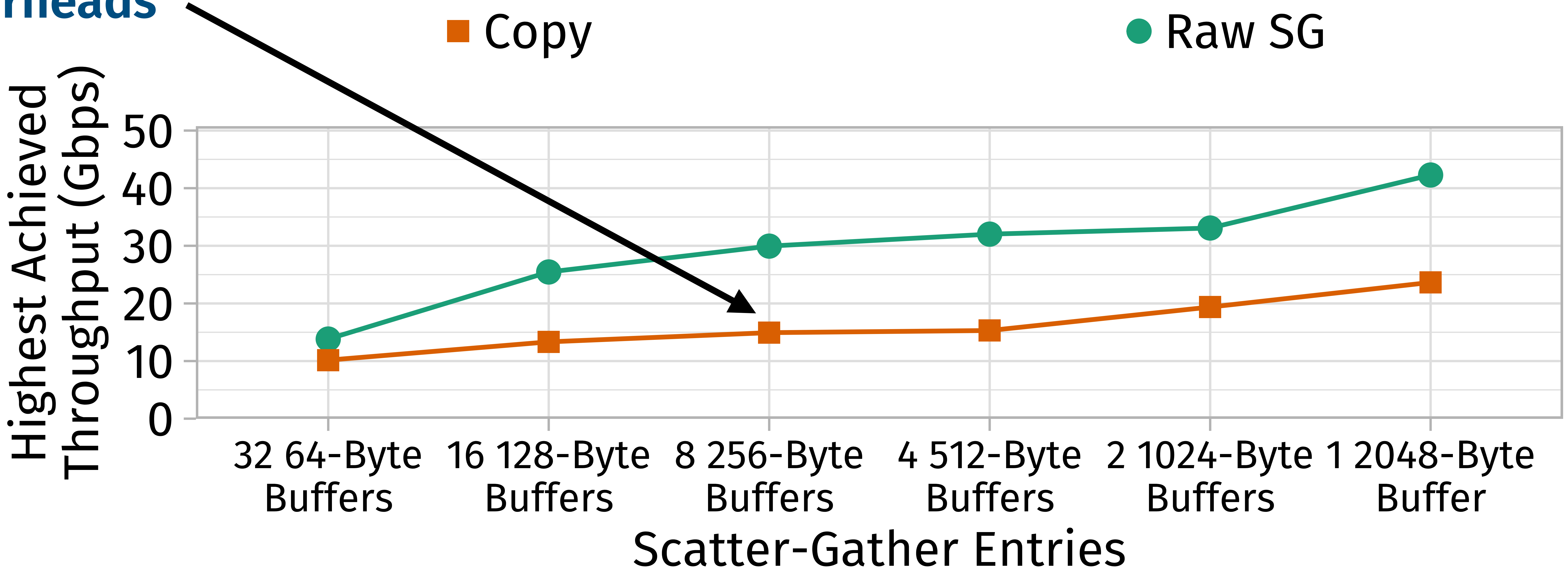
- use per-buffer reference counts to prevent bad behavior

2 *What if value being accessed is not in pinned memory?*

- keep track of pinned ranges of memory and construct transmission accordingly

Reference counting imposes cache misses, which add overhead

For 256 bytes and below, copy better than SG w/ overheads



- Workload: Server serves client requests for individual segments from large array of physical segments using copy or scatter-gather

When considering cache misses, copy beats zero-copy for small objects

Challenges of applying zero-copy APIs to serialization:

- ***Not always good to zero-copy***: for small objects, reference count access is not worth it
- Programmer ***must manually choose*** between copy/zero-copy (based on memory location and performance)
- ***Separating serialization from networking*** adds overhead

Cornflakes applies zero-copy to serialization and contributes:

- ***Measurement study*** that shows when zero-copy is useful
- ***Efficient, hybrid copy/zero-copy API*** that hides complexity from programmer
- Co-designed API between serialization and networking which allows for ***combined serialize-and-send***

Cornflakes library design tackles three challenges

Which values should be zero-copied?

Efficient heuristic to ***choose mechanism*** at runtime, based on ***measurement study***

How can the hybrid API be transparent?

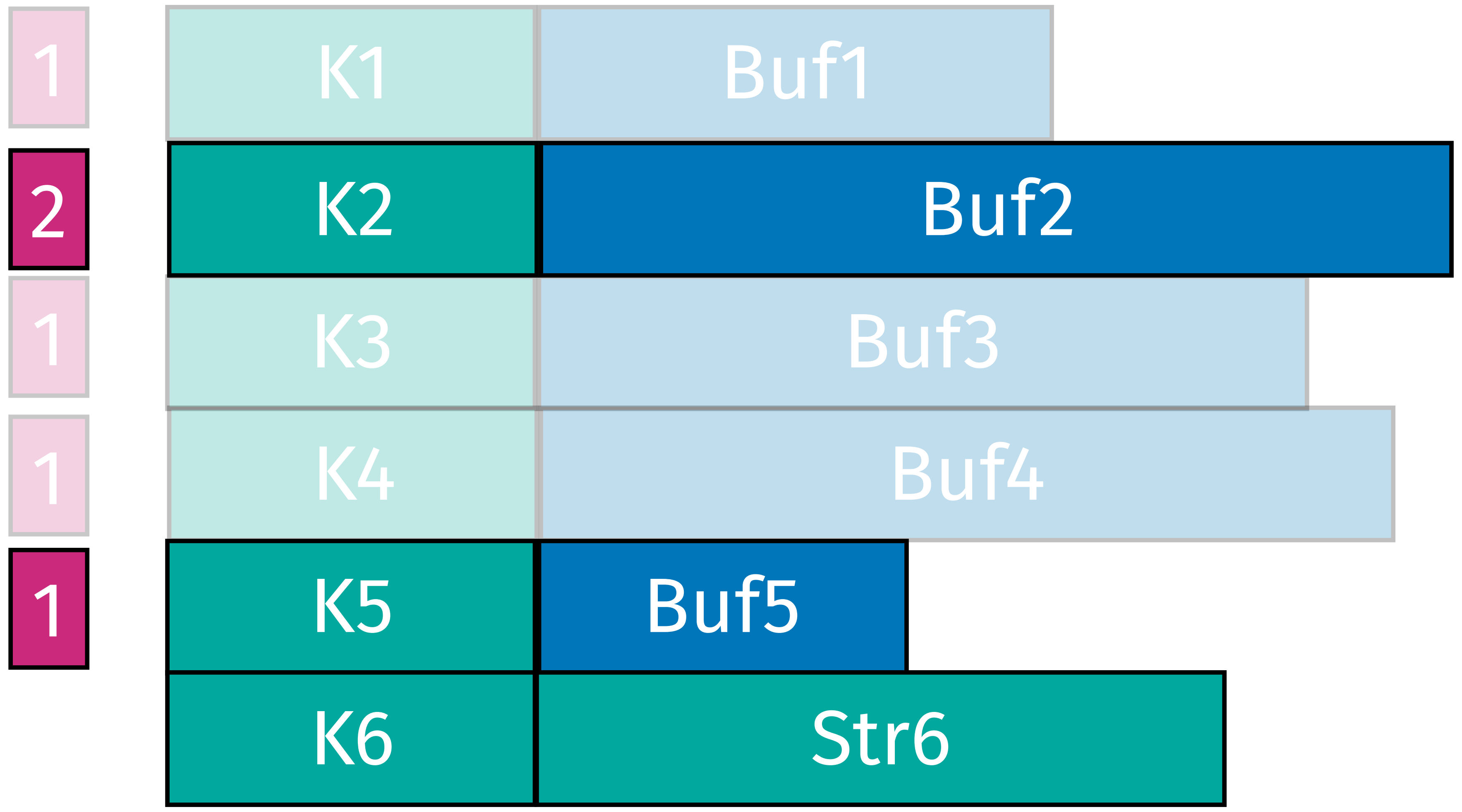
Represents data as ***either copy or zero-copy,*** without extra programmer effort

What API should exist between serialization and networking?

Novel ***serialize-and-send*** optimization

Cornflakes uses a greedy heuristic based on a threshold

Which values should be zero-copied?




```
getm.get_mut_vals().append(&buf2);
```

Use zero-copy (incr reference count)

Use copy (access data)

How can the hybrid API be transparent?

Decide on copy / zero-copy greedily

```
append(&buf2) => zero-copy (R2++)
```

Buf2 >= Threshold

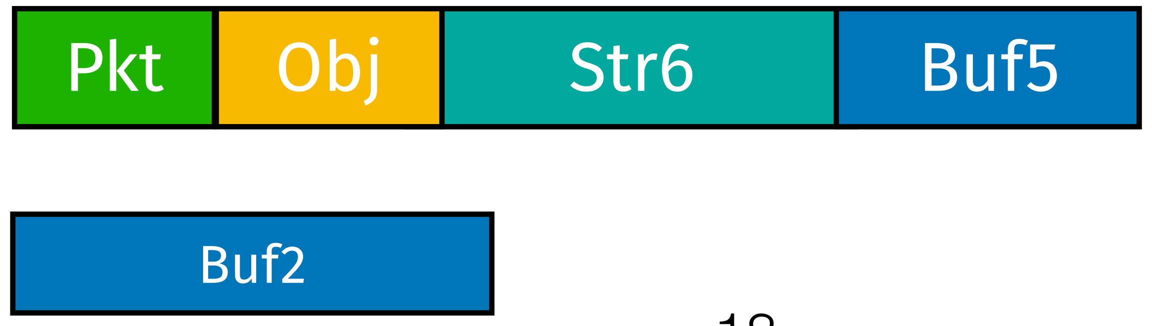
```
append(&buf5) => use copy repr
```

Buf5 < Threshold

```
append(&str6) => use copy repr
```

We use a ***measurement study to determine*** the threshold value for ***our hardware: 512 bytes***

What API should exist between serialization and networking?



Serialize-and-send eliminates intermediate representations

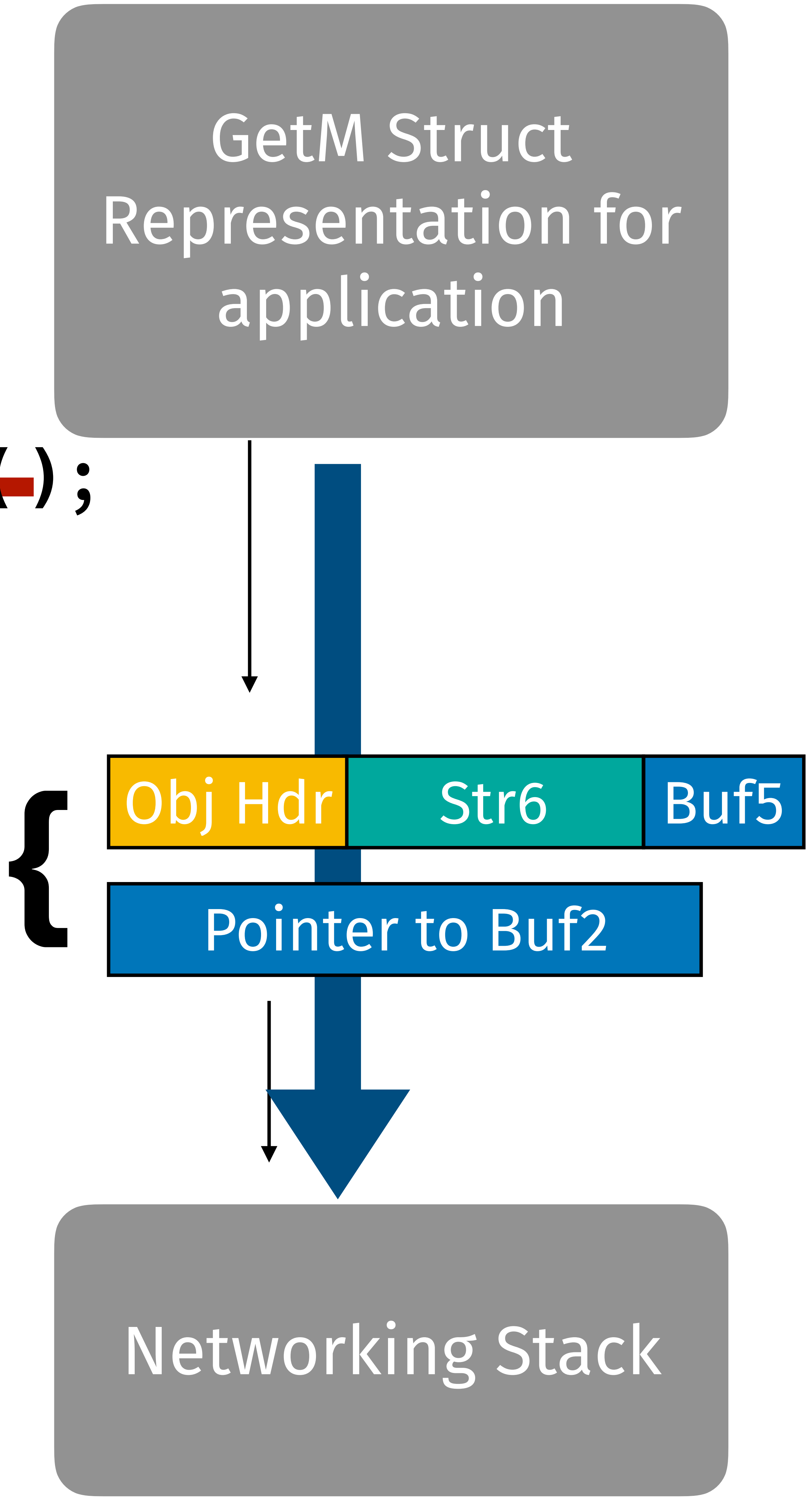
Which values should be zero-copied?

How can the hybrid API be transparent?

What API should exist between serialization and networking?

```
let getm = GetM::new();
getm.init_vals(3);
getm.get_mut_vals().append(&buf2);
getm.get_mut_vals().append(&buf5);
getm.get_mut_vals().append(&str6);
let sg_array = getm.serialize();
netstack.send(sg_array);
netstack.send(getm);
```

APIs like DPDK's require materializing intermediate lists of pointers



Cornflakes implementation

- ***Application library***
  - Rust code + C bindings
- ***Networking stack support***
  - Mellanox OFED, Intel ICE direct drivers
  - Partial demikernel integration
- ***Applications***
  - Custom key value store, echo server
  - Redis

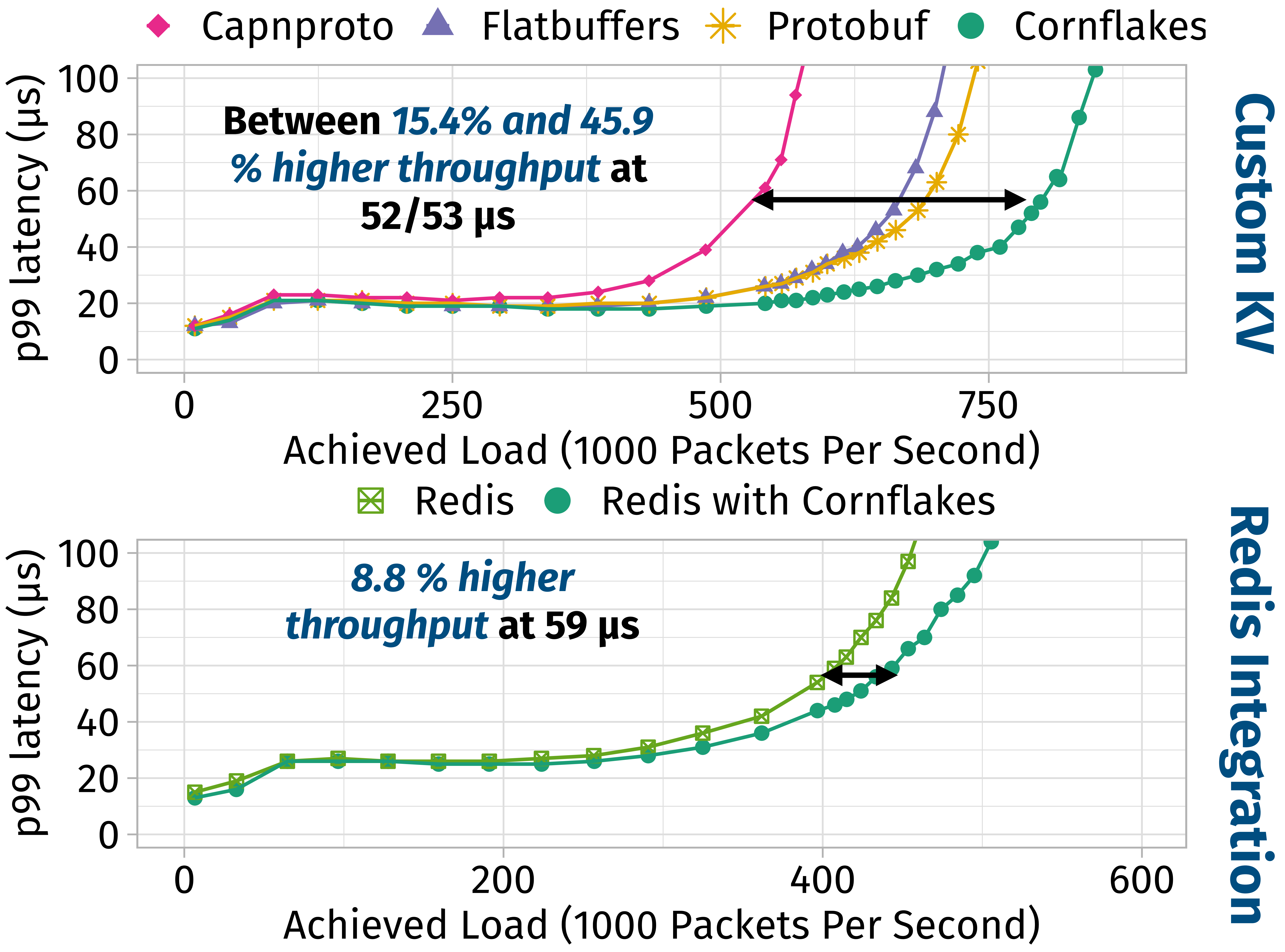
Evaluation setup

- Cloudlab c6525-100g nodes: 2-3 24-core AMD 7402P servers with Mellanox ConnectX-5 EX 100 Gb NICs, and a Dell S5296F switch
  - Jumbo frames turned on (9000 bytes)
- Cornflakes ***sustain a higher throughput***, for the ***same p99 latency***, compared to existing software serialization approaches?

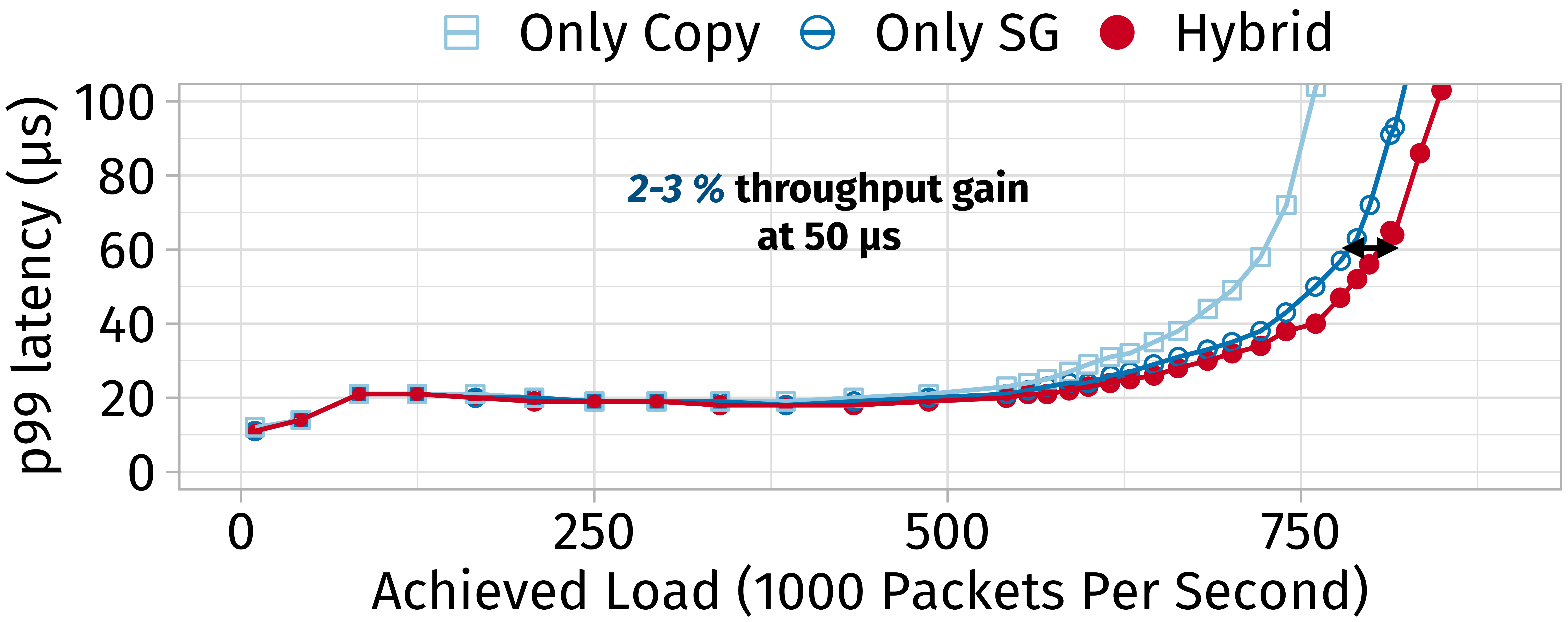
Benefits over existing approaches for Twitter cache trace

- Workload:
  - Twitter Cache Trace # 4*
- Size distribution:
  - 32 % of values queried are larger than 512 bytes

*A large scale analysis of hundreds of in-memory cache clusters at Twitter (OSDI 2020), Yang et. al.



Gains of hybrid approach for Twitter cache trace (Custom KV)



- While gains are limited here, ***hybrid allows us to use one library / deployment to serve workloads with different characteristics***

Limitations + future work

- So far, we only explored tradeoffs for certain hardware + implementations of system
  - Goal: explore measurement study on more hardware, alternate implementations of ideas

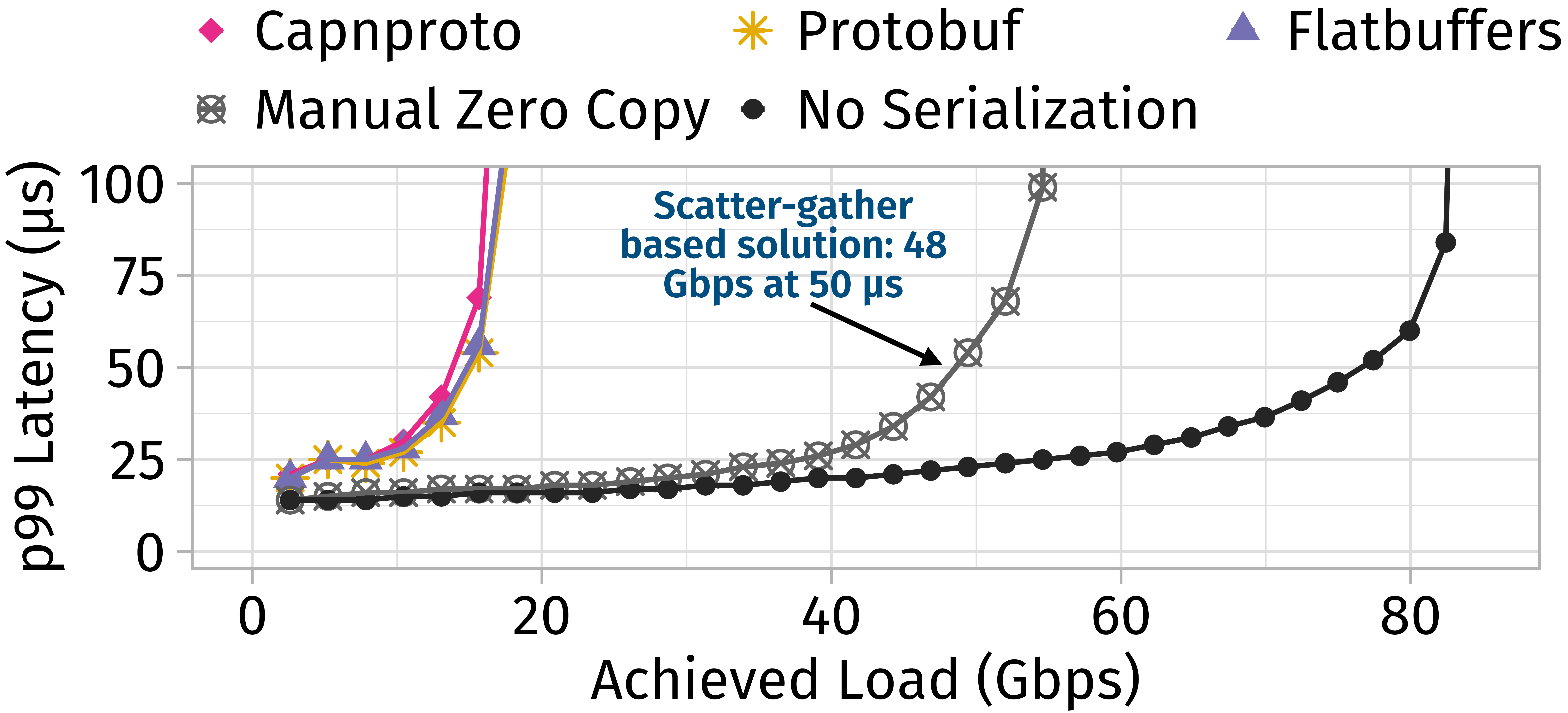
Cornflakes accelerates serialization without new hardware with NIC scatter-gather

- We learned:
  - Serialization benefits from coalescing data in NIC, but ***copying outperforms hardware offload for small buffers, due to reference count accesses***
  - Performance benefits from co-designed serialization / networking interface that ***removes extra intermediate representations of data***

- Getting started with Cornflakes:
  - Implementation: https://github.com/deeptir18/cornflakes
  - Reproducibility instructions: https://github.com/deeptir18/cornflakes-scripts

deeptir@cs.stanford.edu

Removing copies improves throughput in microsecond networks



Cornflakes compiles serialization code from protobuf schemas

1 Developer-provided schema

```
message GetM {
  optional uint32_t id;
  optional repeated bytes list;
  optional repeated string msg2;
}
```

2 Struct definition

```
struct GetM {
  id: uint32_t,
  list: Vec<CfPtr>,
  msg2: Vec<CfPtr>,
}
```

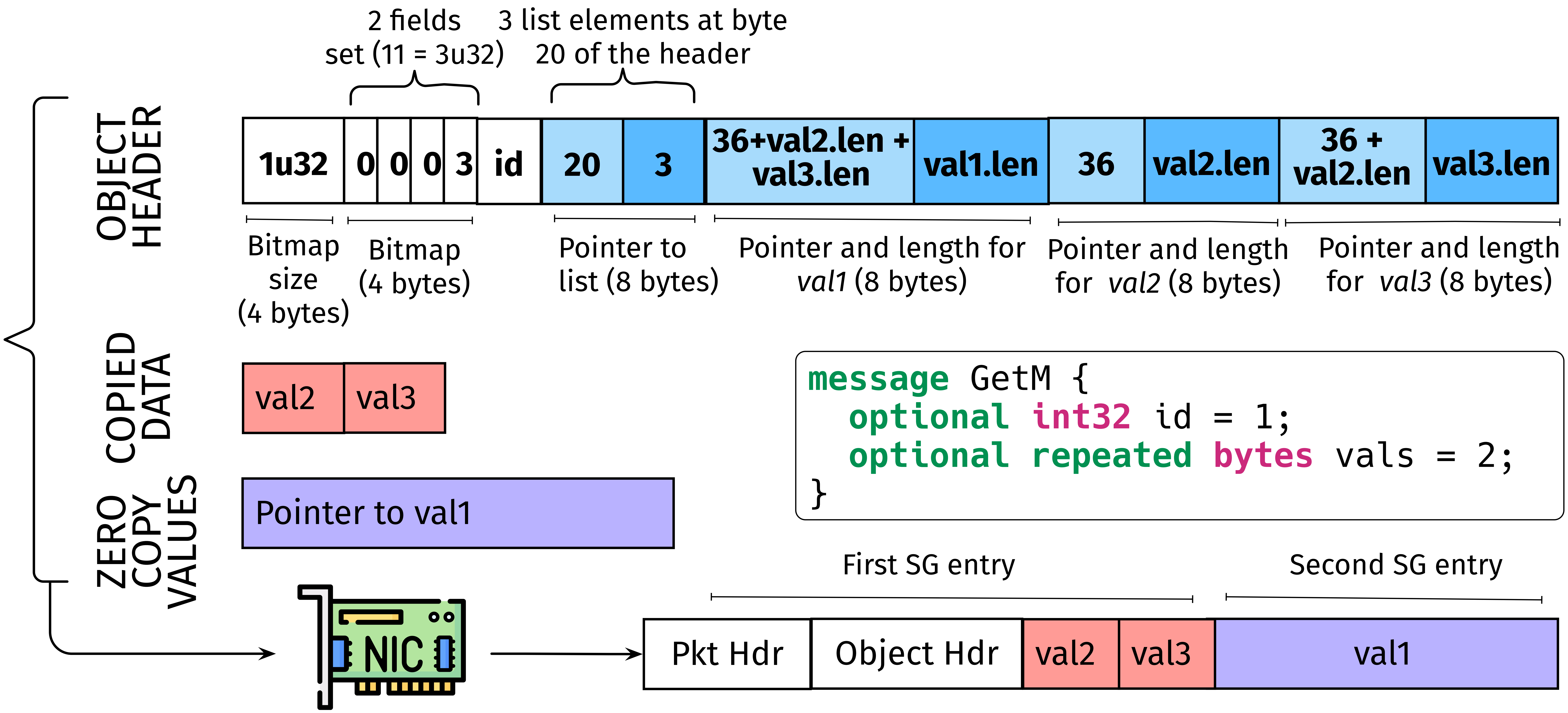
3 Struct implementation (getters/setters)

```
impl GetM {
  fn new() -> Self;
  fn init_vals(&mut self, cap: usize);
  fn get_mut_vals(&mut self) -> &mut List<CFPtr>;
}
```

4 Custom networking / serialization trait

```
impl CornflakesObj for GetM {
  fn object_len(&self) -> usize
  fn write_header(&mut self, buf: &mut [u8]);
  fn deserialize(pkt: RcBuf) -> Self
  …
}
```

Wire format for simple data structure

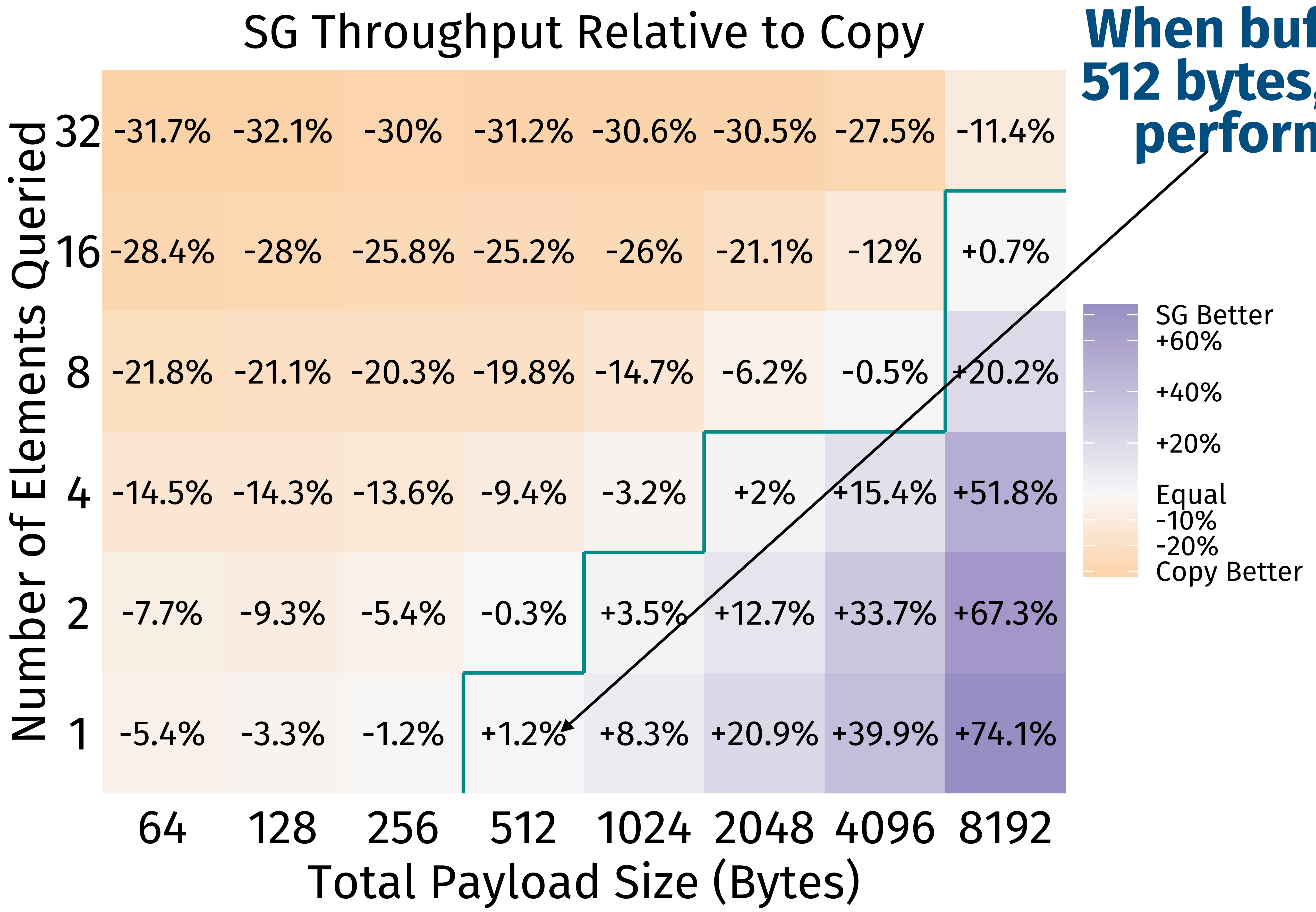


Per-hardware measurement study determines threshold

Which values should be zero-copied?

How can the hybrid API be transparent?

What API should exist between serialization and networking?



When buffers are >= 512 bytes, zero-copy performs better

- Workload: YCSB-C workload, modified to have 1 million 30-31 byte keys mapped to lists of values of various sizes (zipf = .99)
- Metric: highest throughput achieved across all offered loads
- ***Hardware***: Mellanox CX-5 NIC, AMD EPYC 7402P Servers

Cornflakes transparently copies data when it is not NIC accessible

Which values should be zero-copied?

How can the hybrid API be transparent?

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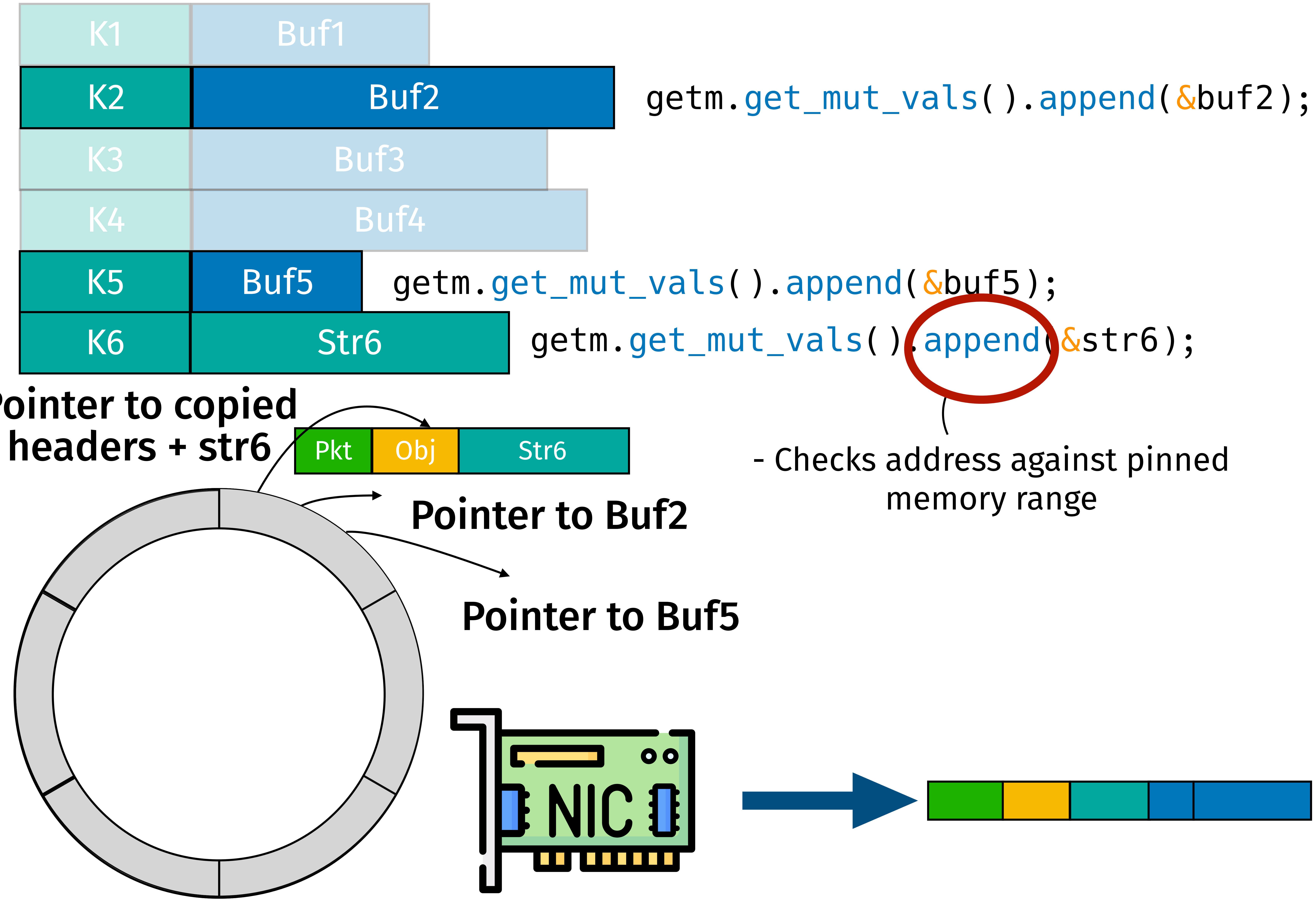

Serialize-and-send optimization improves throughput

	Twitter Trace	YCSB trace (1024x4), only zero-copy
W/o serialize-and-send	814 krps	16.1 Gbps
With serialize-and-send	***899 krps***	***18.9 Gbps***

Cornflakes performance falls back with predominantly small values

- Queried values contain lists of 1-8 elements (list length uniformly distributed over 1-8)
- Size of each item derived from Google Protobuf bytes size distribution measurement:
  - ***94 %*** of the elements are ***smaller than 512,*** about 33 % of the items are even less than 8 bytes