KSplit: Automating Device Driver Isolation

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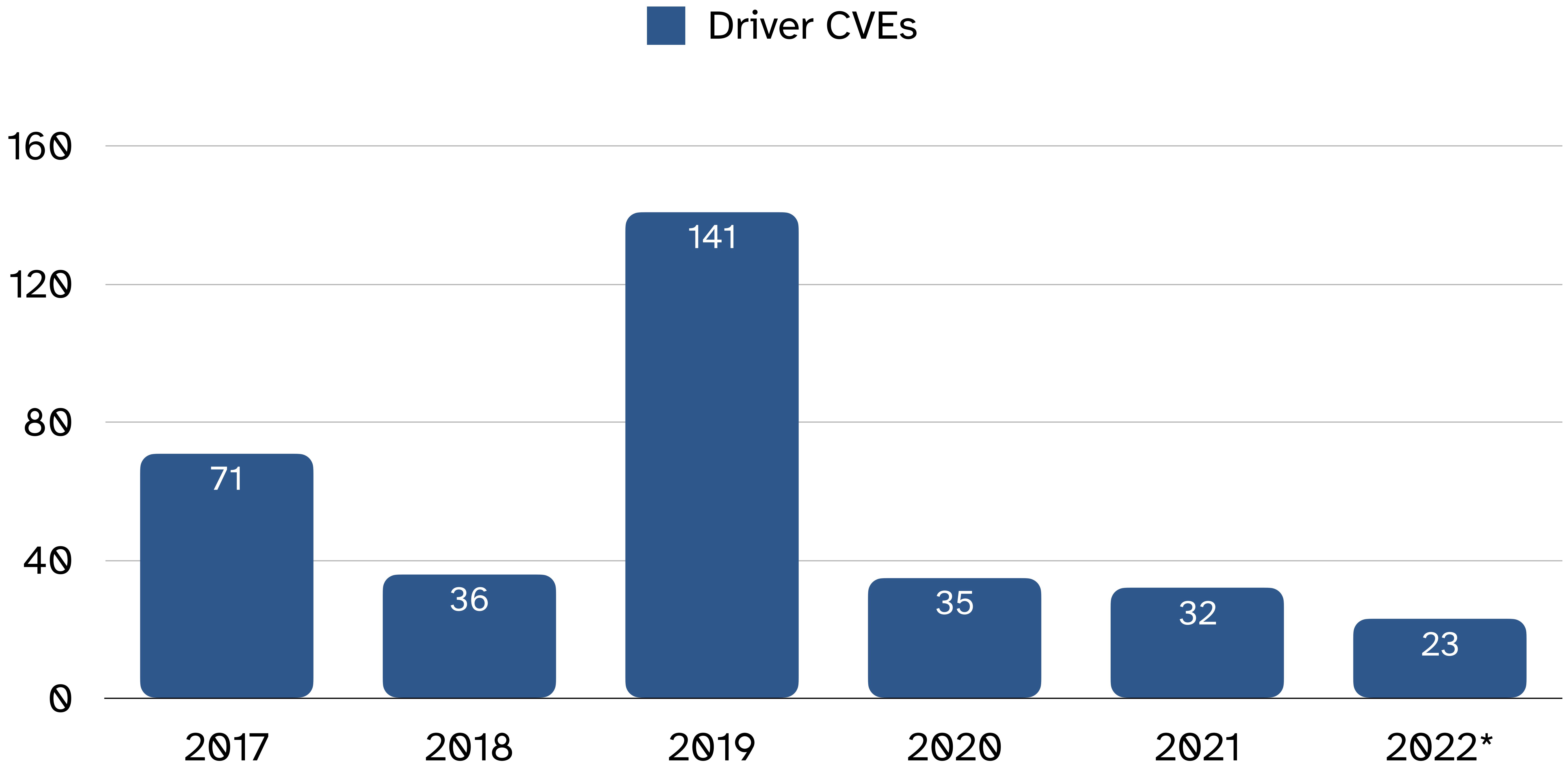
Driver vulnerabilities

- 16-50 % of all Linux kernel CVEs



LXDs: Towards Isolation of Kernel Subsystems

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...Bauer
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VirtuOS: an operating system with kernel virtualization

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Lightweight Kernel Isolation with Virtualization and VM Functions

Tolerating Malicious Device Drivers in Linux

Silas Boyd-Wickizer and Nickolai Zeldovich
MIT CSAIL

MIT/LCS/TR-196

FINAL REPORT OF THE MULTICS KERNEL DESIGN PROJECT

by

M.D. Schro...
D.D. Clark
J.H. Saltz...
D.H. Wells

June 30, 19...

Decaf: Moving Device Drivers to a Modern Language

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Microdrivers: A New Architecture for Device Drivers

Vinod Ganapathy, Arini Balakrishnan, Michael M. Swift
Computer Sciences Department, Universit...

Nooks: An Architecture for Reliable Device Drivers *

...Swift, Steven Martin, Henry M. Levy, and Susan J. Eggers
...Computer Science and Engineering
...Washington
...195, USA
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The SawMill Multiserver Approach

Alain Gefflaut, Trent Jaeger, Yoonho Park
Jochen Liedtke *, Kevin J. Elphinstone †, Volkmar Uhlig †

Driver Isolation Architecture

kernel code

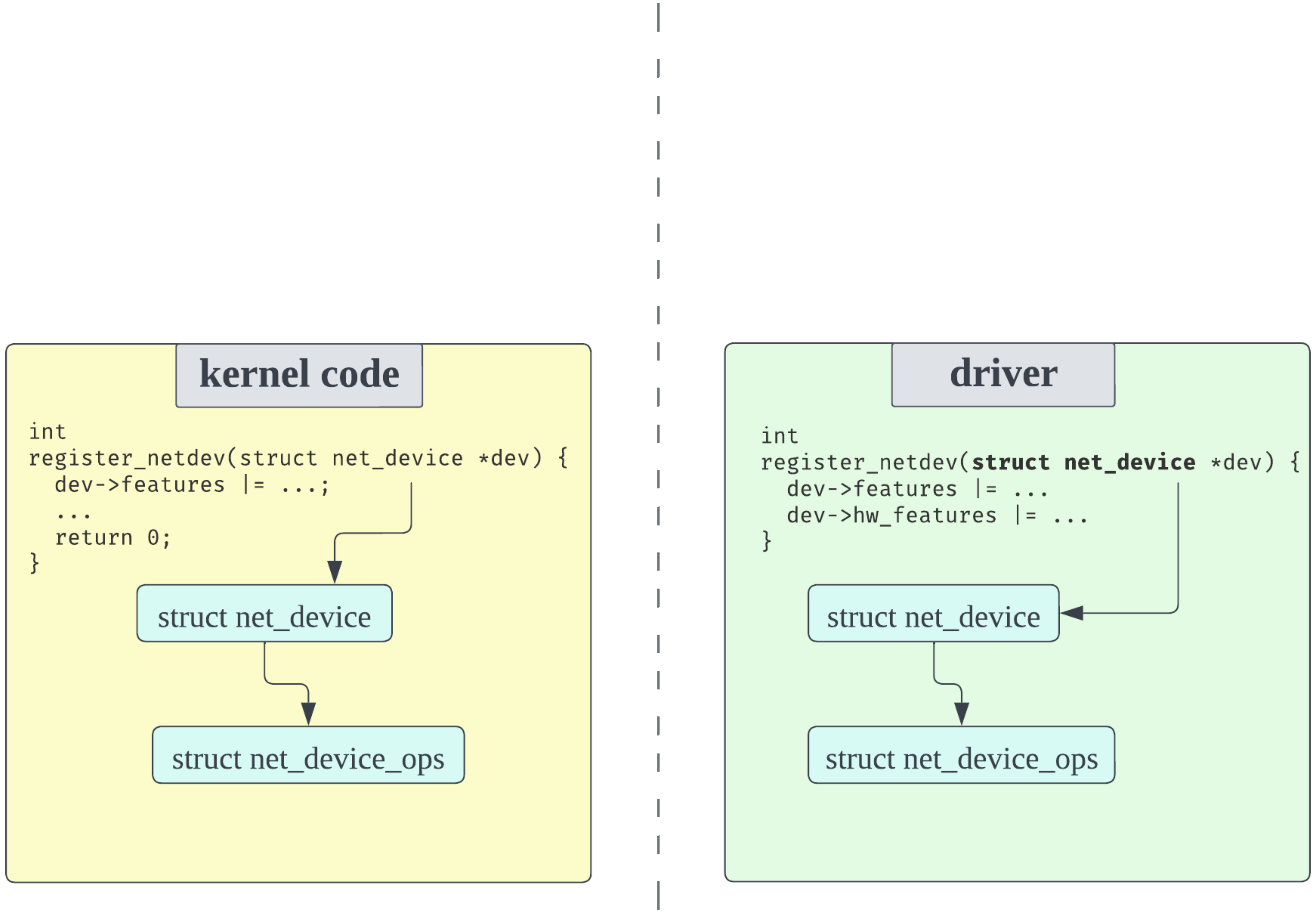
```
int
register_netdev(struct net_device *dev) {
  dev->features |= ...;
  ...
  return 0;
}
```

driver

```
int
register_netdev(struct net_device *dev) {
  dev->features |= ...
  dev->hw_features |= ...
}
```

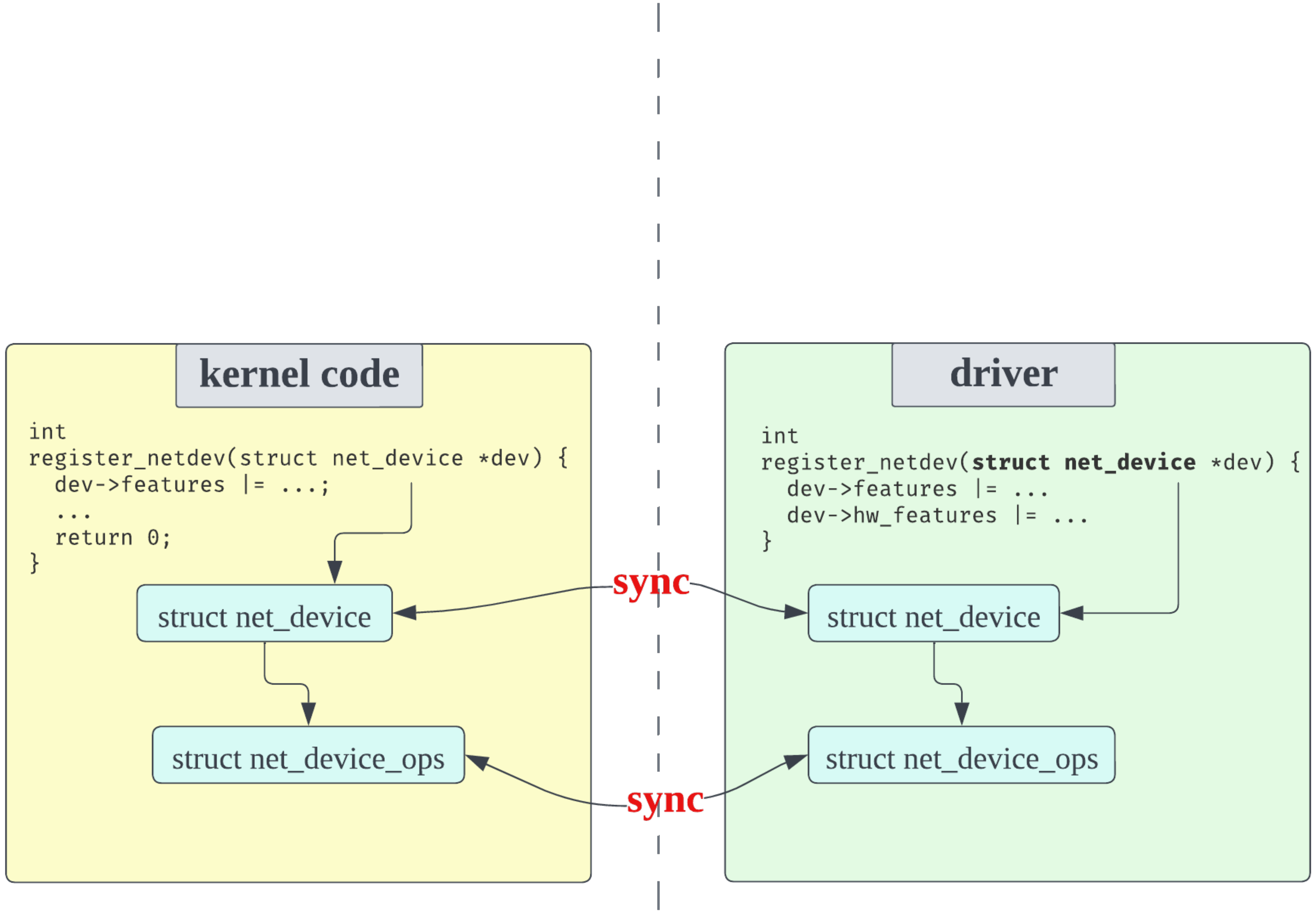
- Separate memory space

Driver isolation architecture



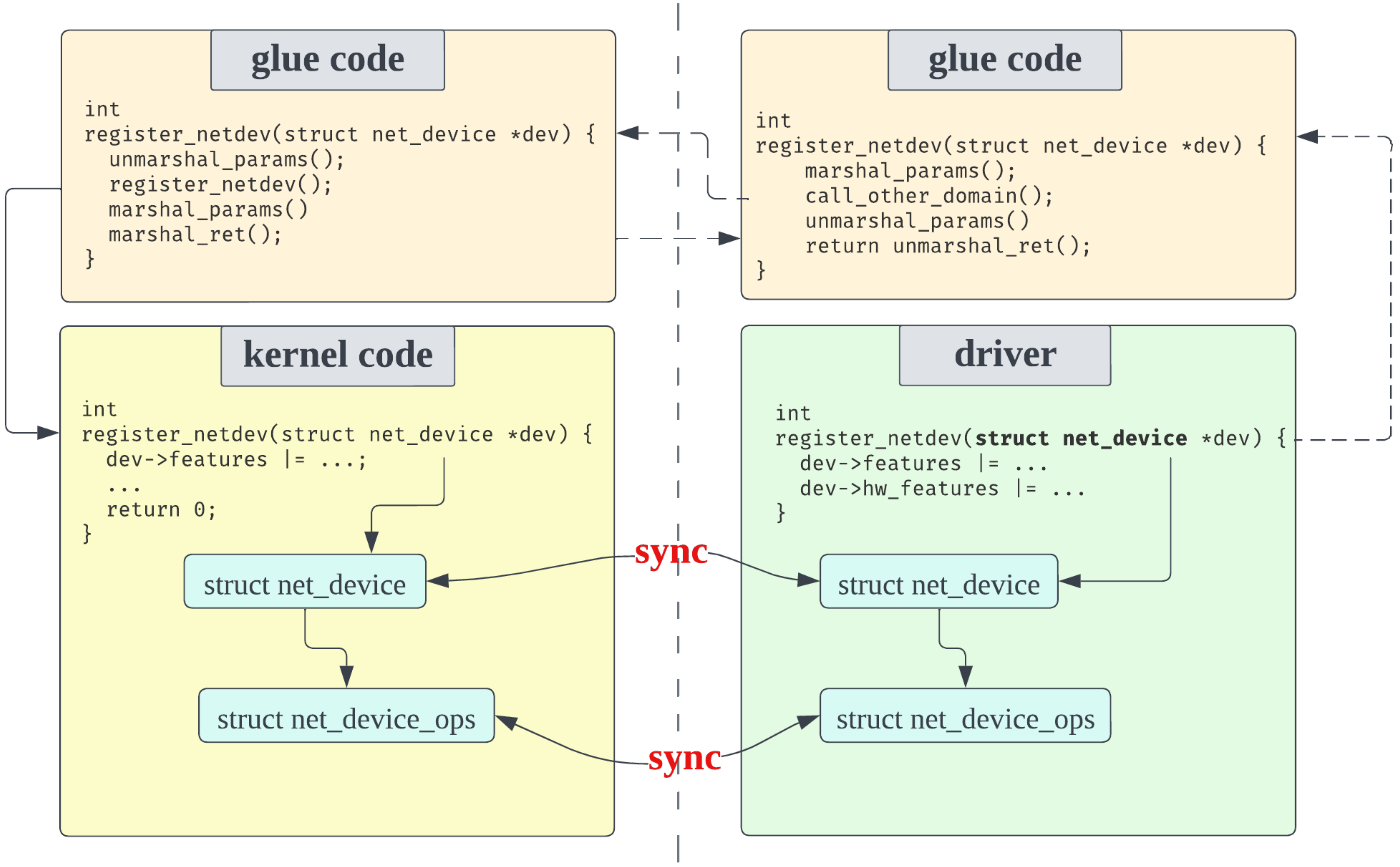
- Separate memory space
  - Two copies of object hierarchies

Driver isolation architecture



- Separate memory space
  - Two copies of object hierarchies
  - Keep them synchronized

Driver isolation architecture



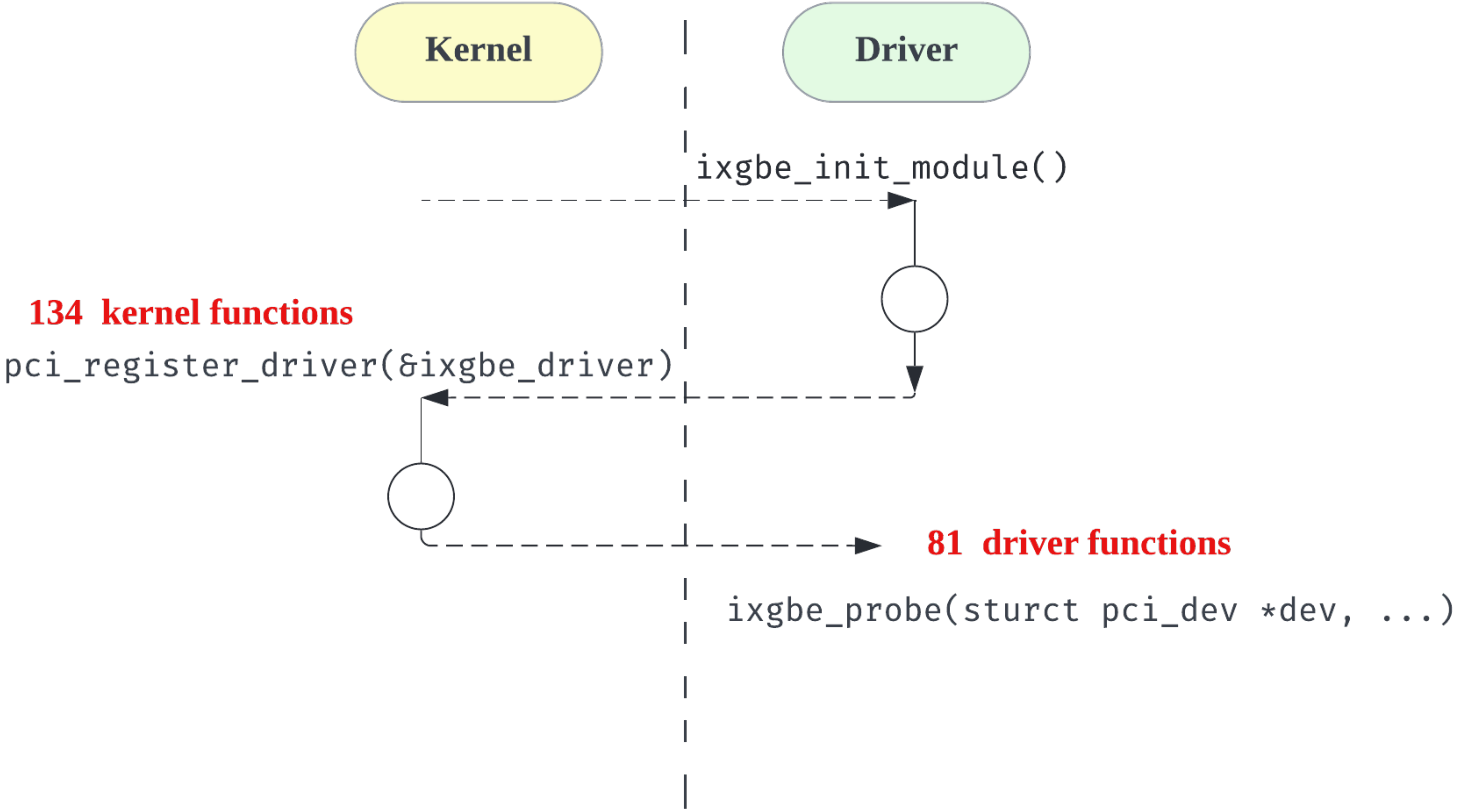
- Separate memory space
  - Two copies of object hierarchies
  - Keep them synchronized
- Glue code
  - Marshal/unmarshal params
  - Interface definition language (IDL) spec
  - Generated with IDL compiler

Isolation performance

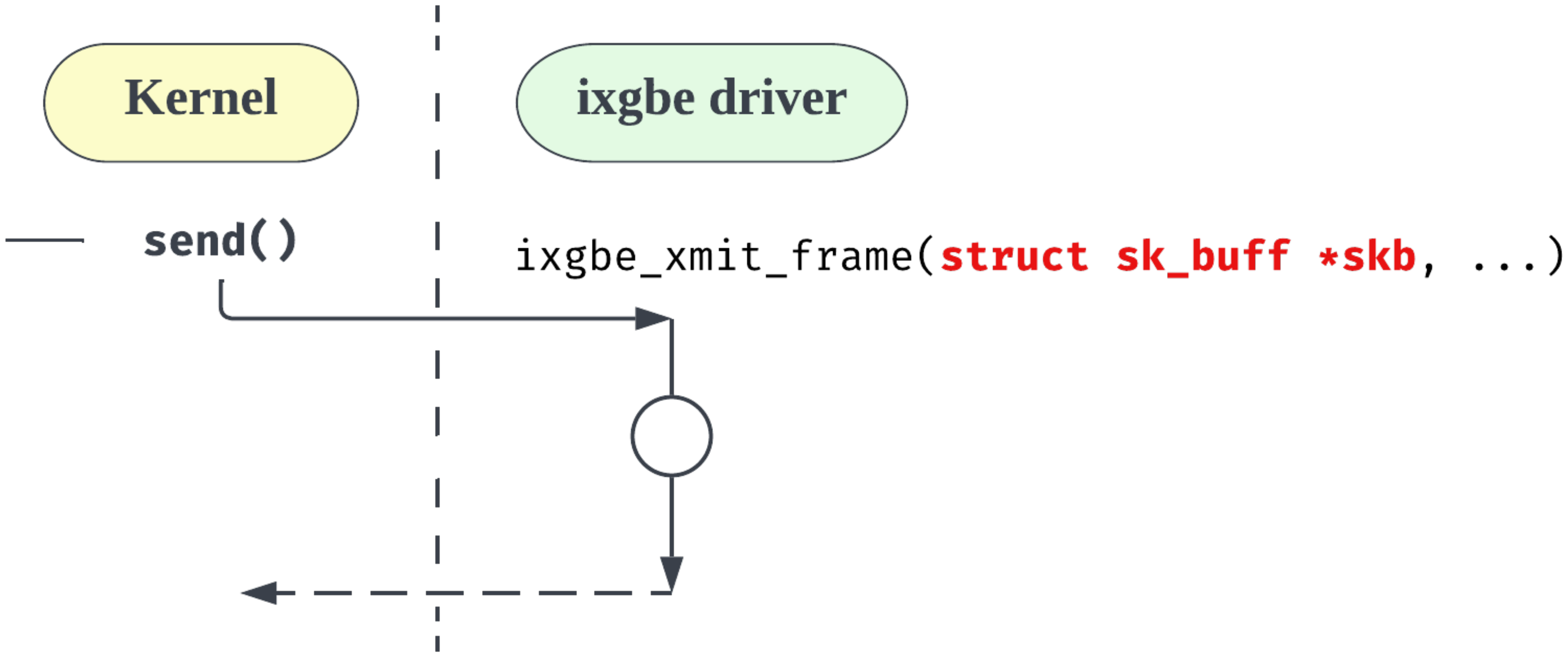
- Paging (834 cycles)
- Recent CPU mechanisms
  - VMFUNC - 396 cycles
  - MPK 11-260 cycles
  - Save/restore general/extended regs, pick a stack, etc.

Manually specifying the IDL for data synchronization between domains has become the major challenge

Challenge: Large interface boundary

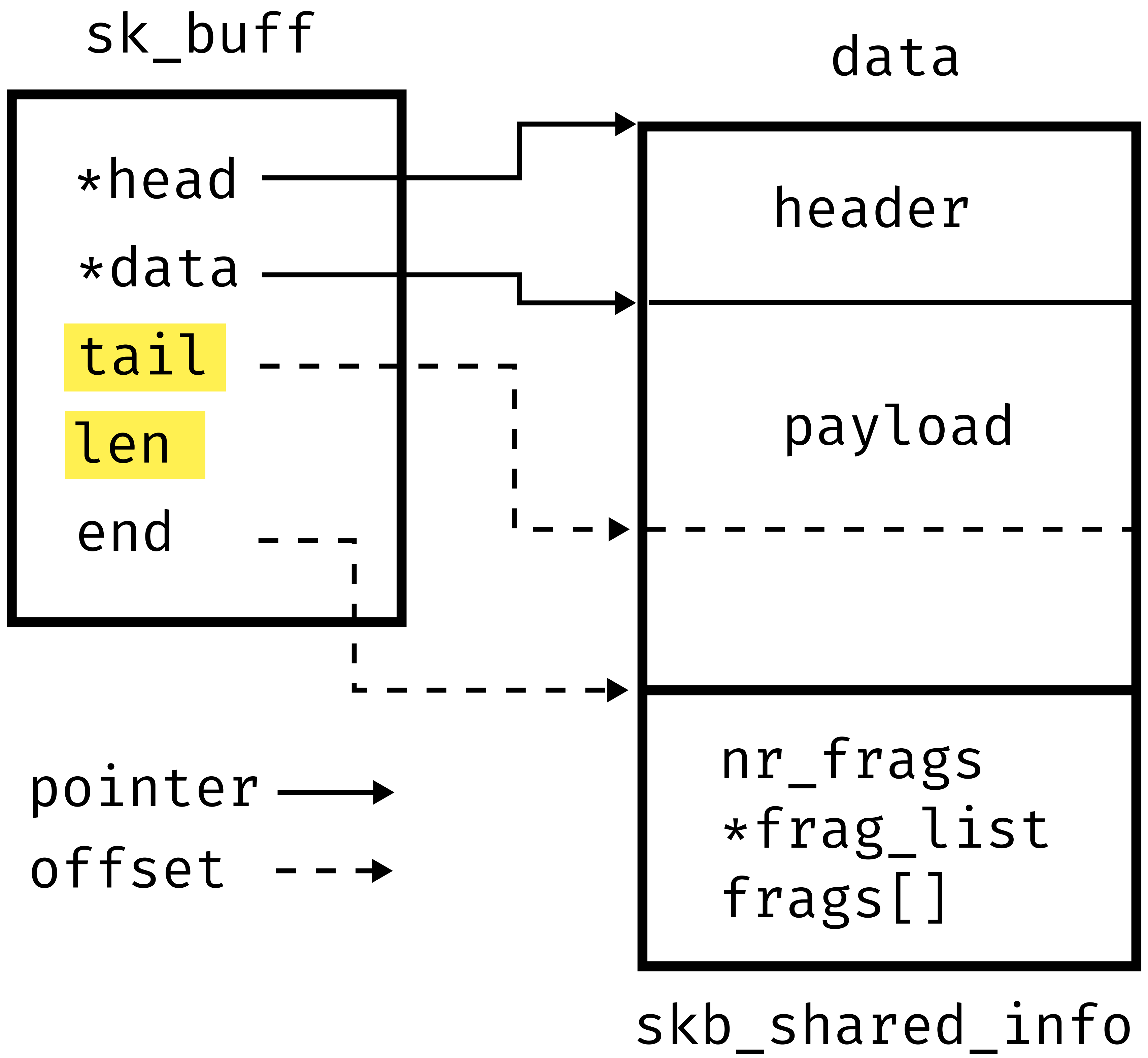


Challenge: Complex data exchange



Challenge: Complex data structures

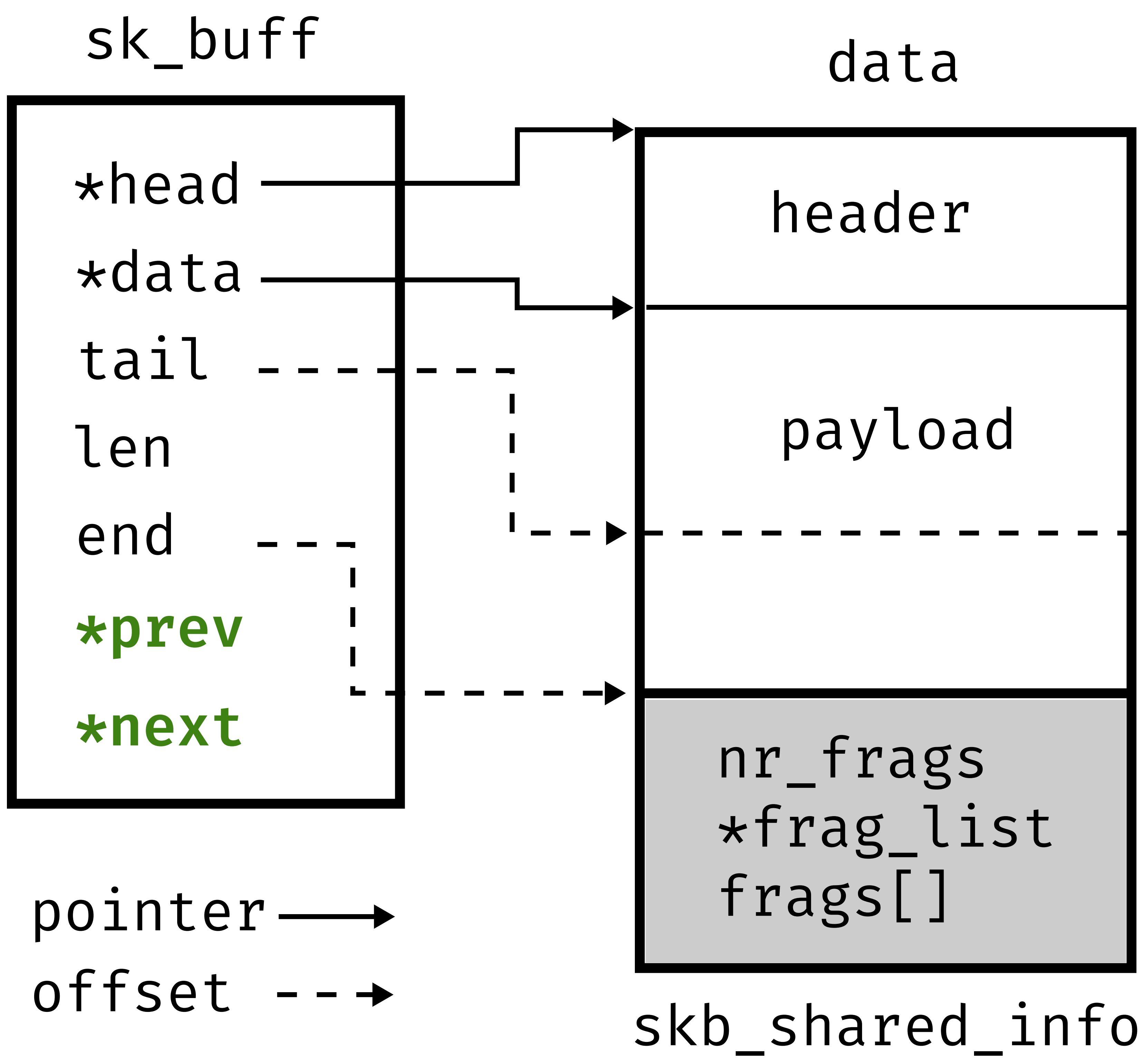
```
ixgbe_xmit_frame(struct sk_buff *skb, …)
```



- Represents a network packet
- Has 66 fields (5 pointers)
- 3,132 fields (1,214 pointers) are recursively reachable
- But only a small subset are accessed by both kernel and driver (shared)
  - 8 shared fields for this API

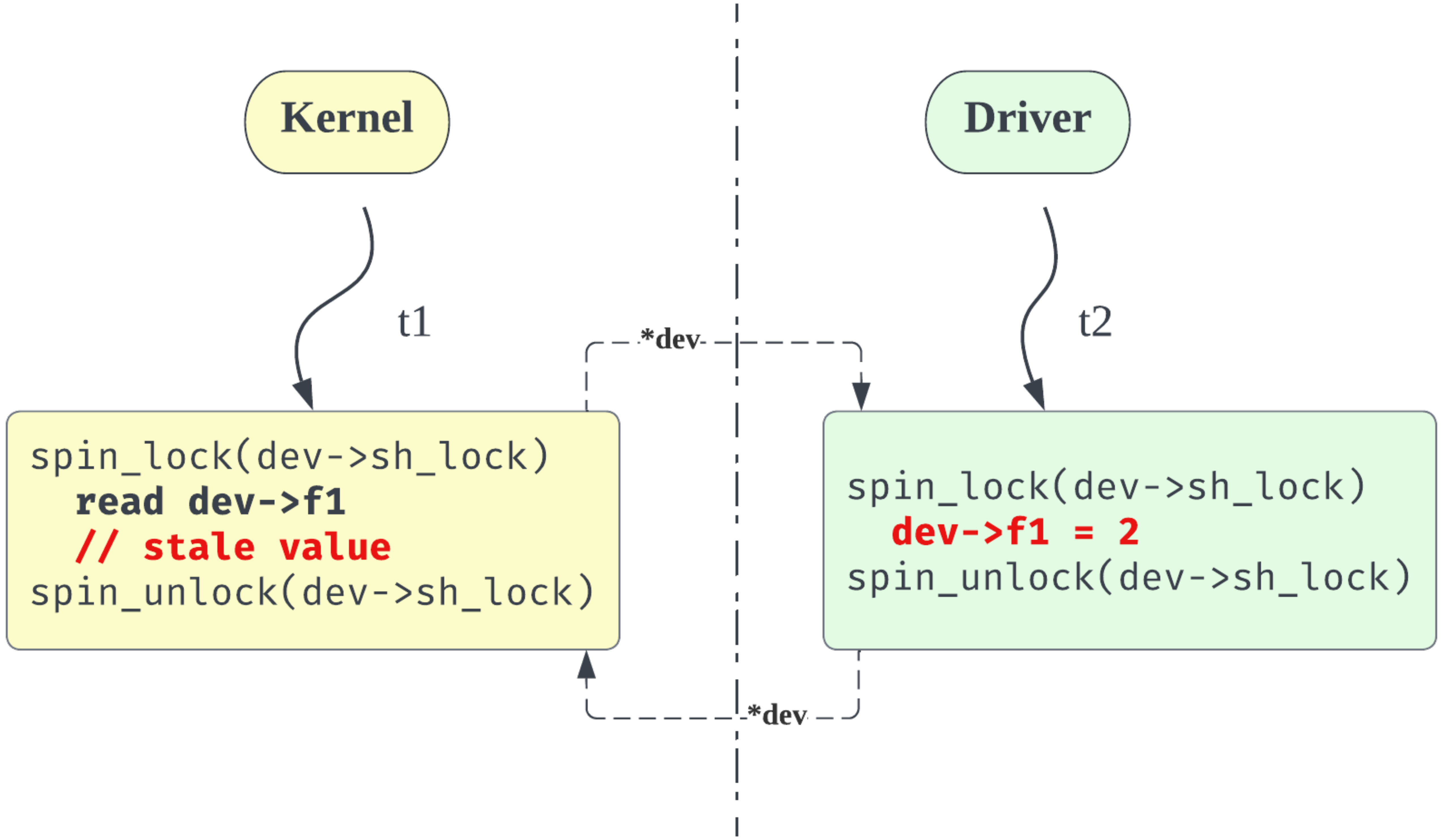
Challenge: Low-level kernel/C idioms

```
int ixgbe_xmit_frame(struct sk_buff* skb, …)
```



- Pointers
  - Singleton, array
  - Linked list
  - Collocated data structures
- Sized and sentinel arrays
- Special pointers (e.g., `__user`, `__iomem`)
- Tagged unions
- Return error as ptr (e.g., `ERR_PTR`)

Challenge: Concurrency primitives



- spin/mutex lock
- driver specific lock, e.g., rtnl_lock
- atomic operations, e.g., set_bit
- read-copy update (RCU)
- sequential lock

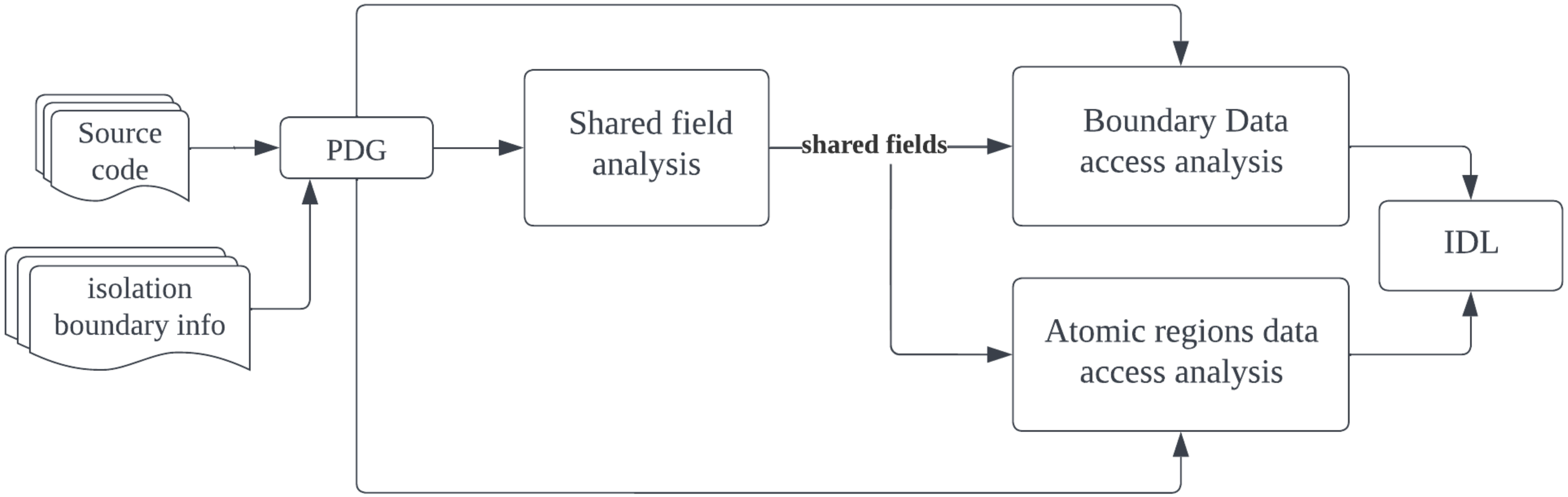
KSplit goals

- Build a set of static analyses to generate the IDL automatically (mostly) to
  - Isolate the complete driver
  - Identify shared/private data on the large interface boundary
  - Ensure each domain has the updated copy of the data structure
  - Identify marshaling requirements for the low-level kernel idioms
  - Identify atomic regions that access shared data
- Prior work
  - *Microdrivers* (isolated the control plane of the driver)

KSplit design choices

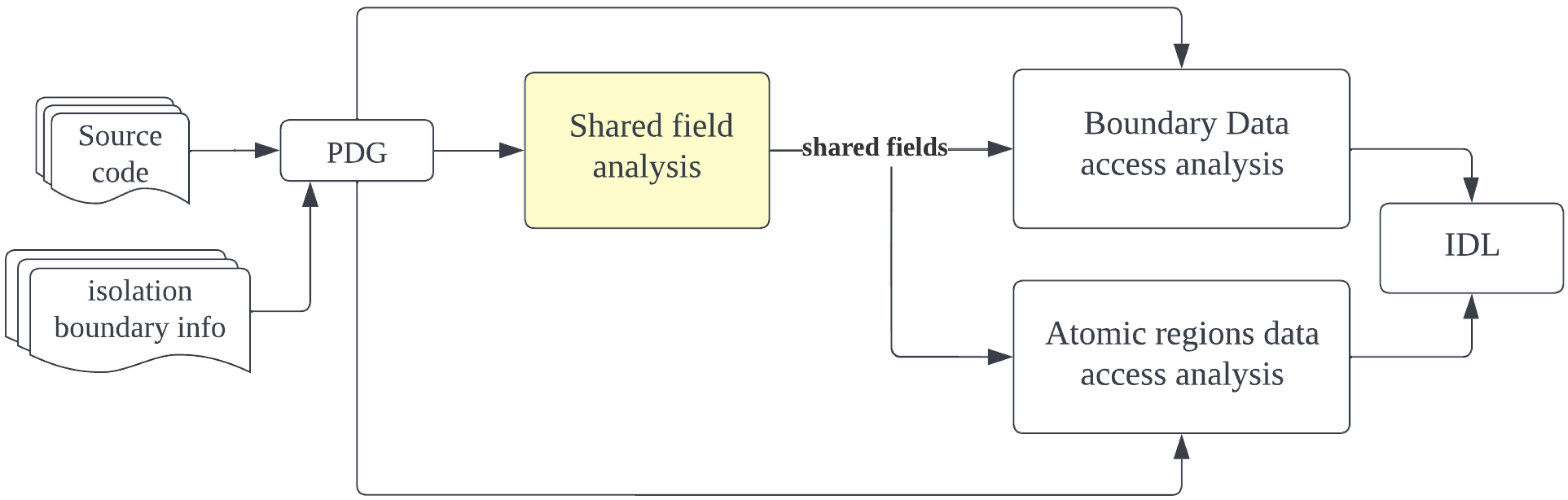
- Kernel is huge
  - Identify the relevant kernel code that the driver interacts with
- Aim to detect all shared data (sound)
  - We might classify some private data as shared
- Aim to infer marshaling requirements for low-level idioms
  - Provide warning for the cases that we cannot infer
- Aim to infer marshaling requirements for shared critical sections
  - Hypothesis: There are not many shared critical sections

KSplit workflow

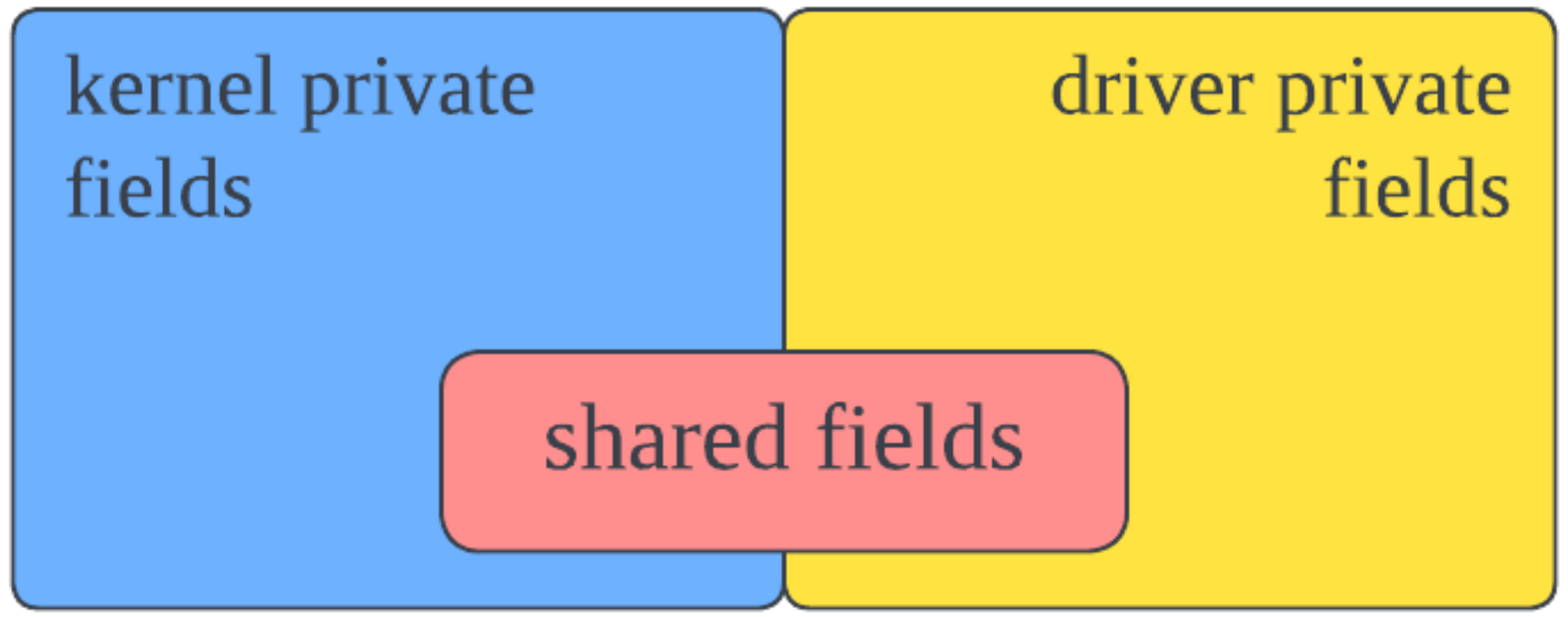


- **Input**: source code of kernel and target isolated driver
- **Output**: IDL file that specifies the communication interfaces and data synchronization requirements

Shared field analysis

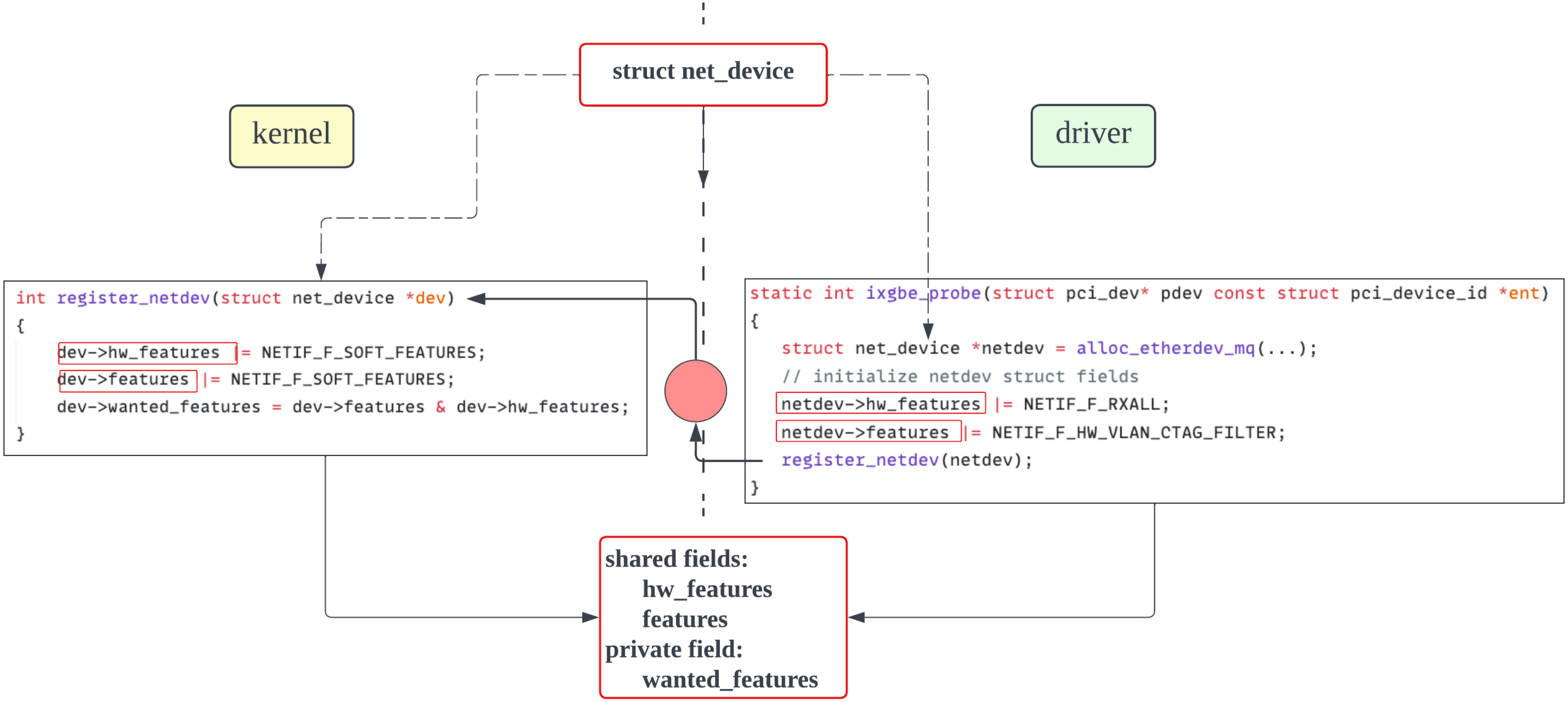


Shared field analysis

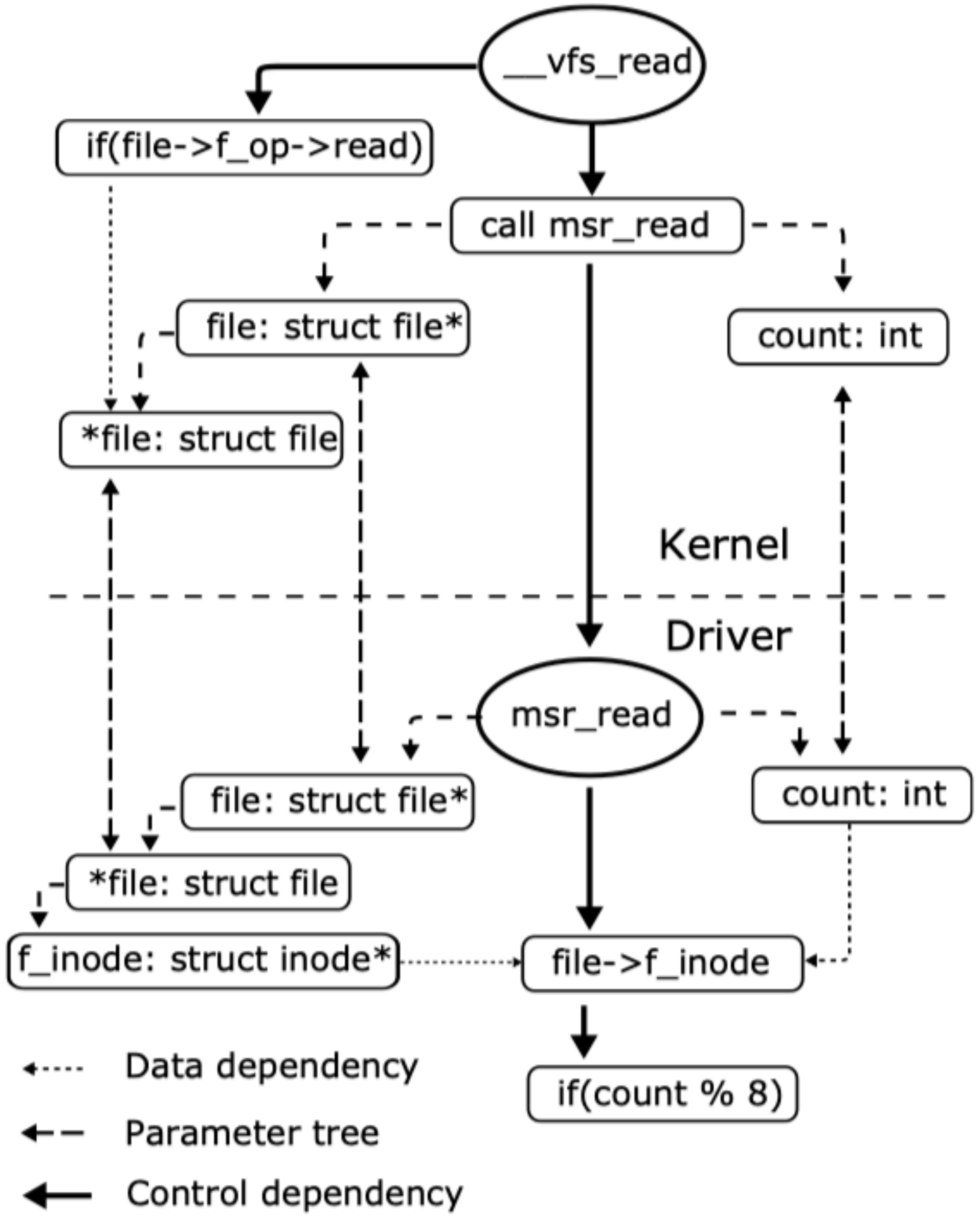


- **Input:**
  - data structure types on all the interface functions for the driver under analysis
- **Output:**
  - the set of struct fields accessed by both the kernel and this driver

Shared field analysis



Program Dependence Graph



- **PDG**: represents program dependencies
  - inter-procedural pointer alias relations
  - field-sensitive
  - data dependencies
  - control dependencies/flow

CCS'17

PtrSplit: Supporting General Pointers in Automatic Program Partitioning

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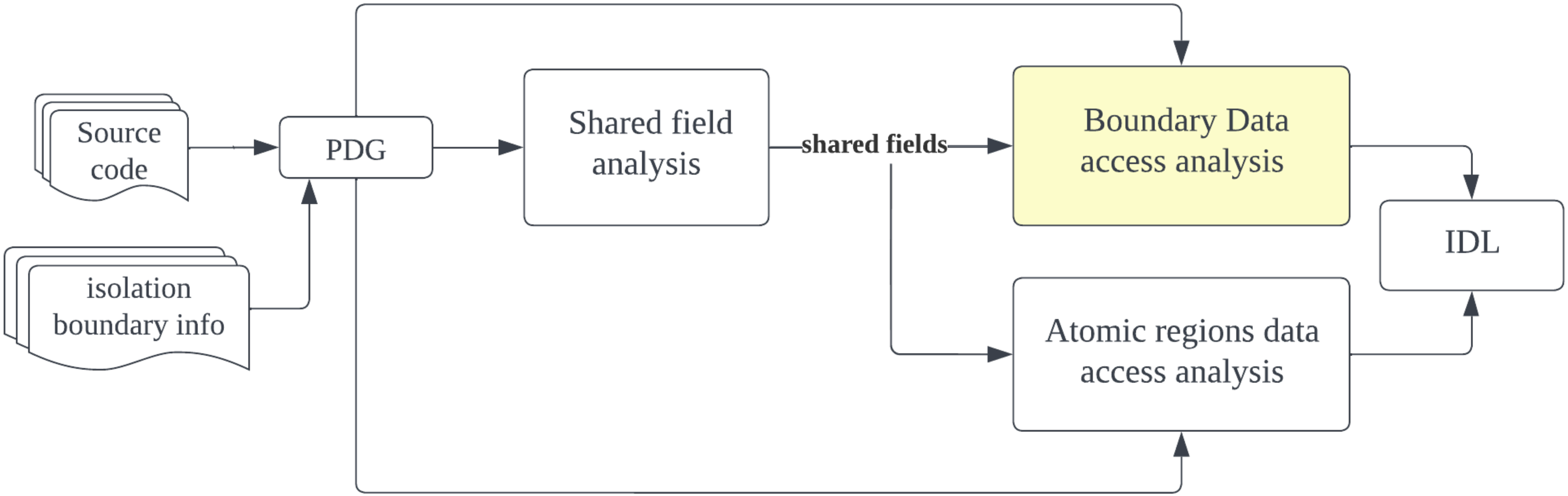
Boundary data access analysis



Boundary data access analysis

- **Purpose**:
  - Infer synchronization requirements for every interface call and return
- **How**:
  - figure out the subset of shared fields that are read/written in an interface function
  - synchronize data **read by callee** at the function call
  - synchronize data **updated by callee** at the function return

Boundary Data Access Analysis: example

kernel | **driver**

call edge
return edge

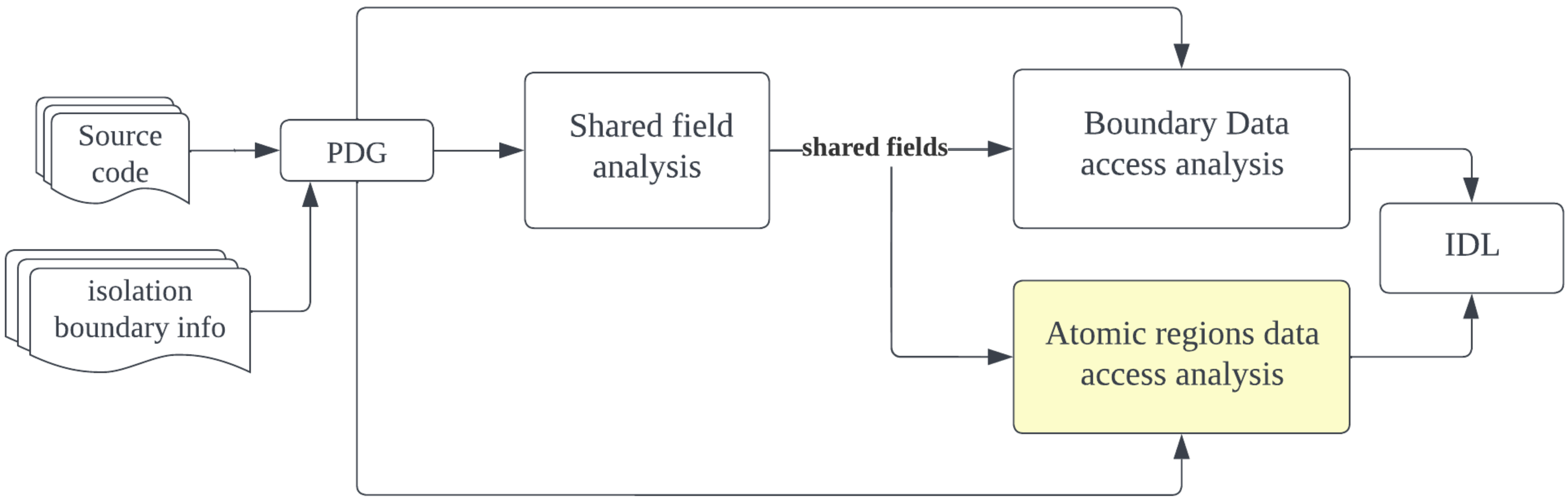
```
/* ixgbe driver */
int ixgbe_probe(struct pci_dev *pdev, ...) {
  struct net_device *dev = alloc_etherdev(...);
  /* initialize struct fields */
  dev->features |= NETIF_F_GSO_PARTIAL;
  dev->hw_features |= NETIF_F_HW_TC;
  register_netdev(dev);
  ...
}
```

sync fields:
hw_features
features

```
/* kernel code */
int register_netdev(struct net_device *dev) {
  dev->features |= NETIF_F_SOFT_FEATURES;
  dev->wanted_features = dev->features & dev->hw_features;
  if (dev->hw_features & NETIF_F_TSO)
    dev->hw_features |= NETIF_F_TSO_MANGLED;
  ...
  return ret;
}
```

sync fields:
hw_features
features

Atomic Region Analysis



Atomic Region Analysis

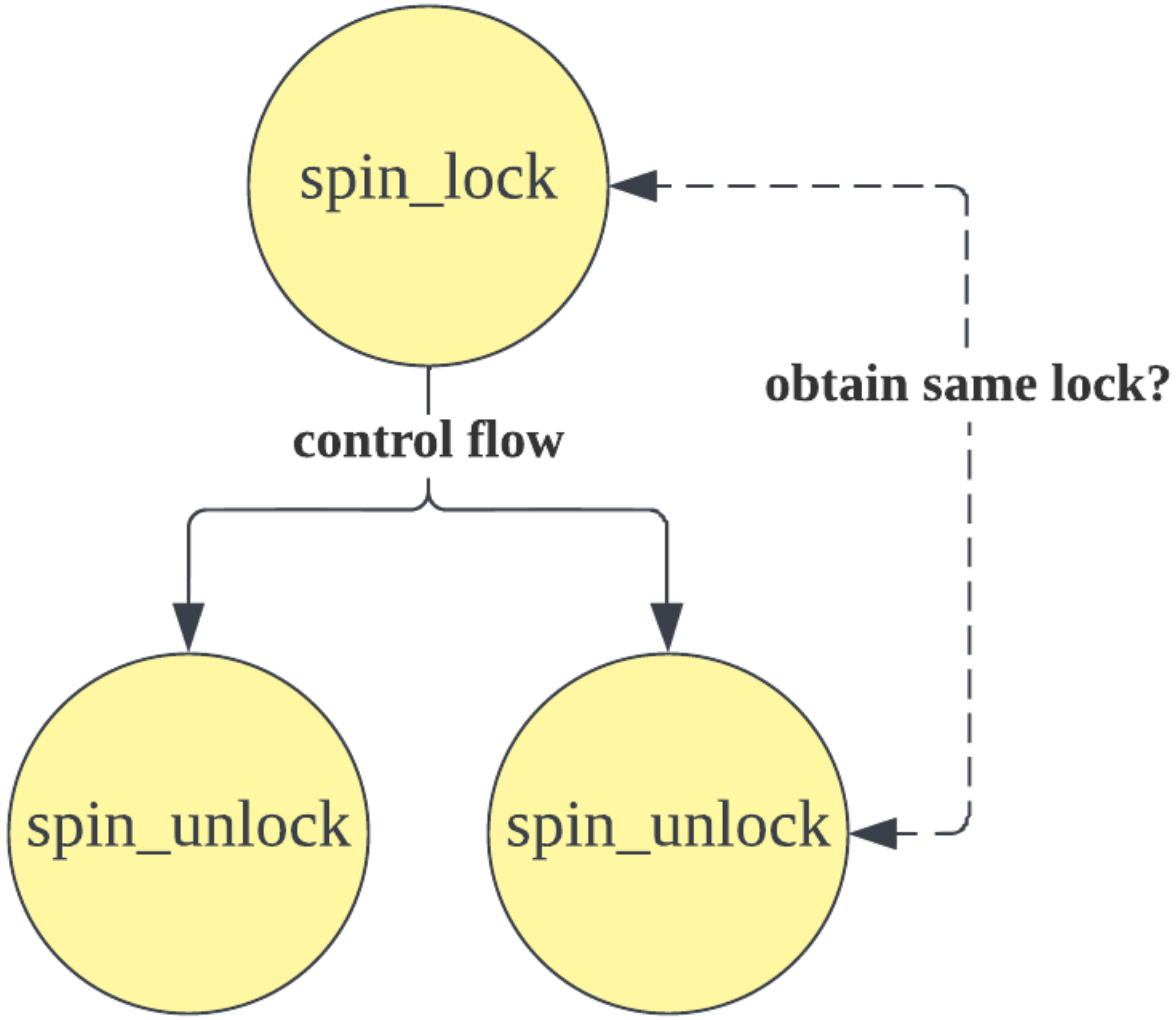
- **Purpose**:
  - Find shared data accessed within the atomic regions
  - Infer synchronization requirements for shared atomic regions
- **When to synchronize**:
  - after/before the **entry/exit** of each atomic region.

```
spin_lock(&lock)
   sync_call(read data)
   ...
   sync_call(updated data)
spin_unlock(&lock)
```

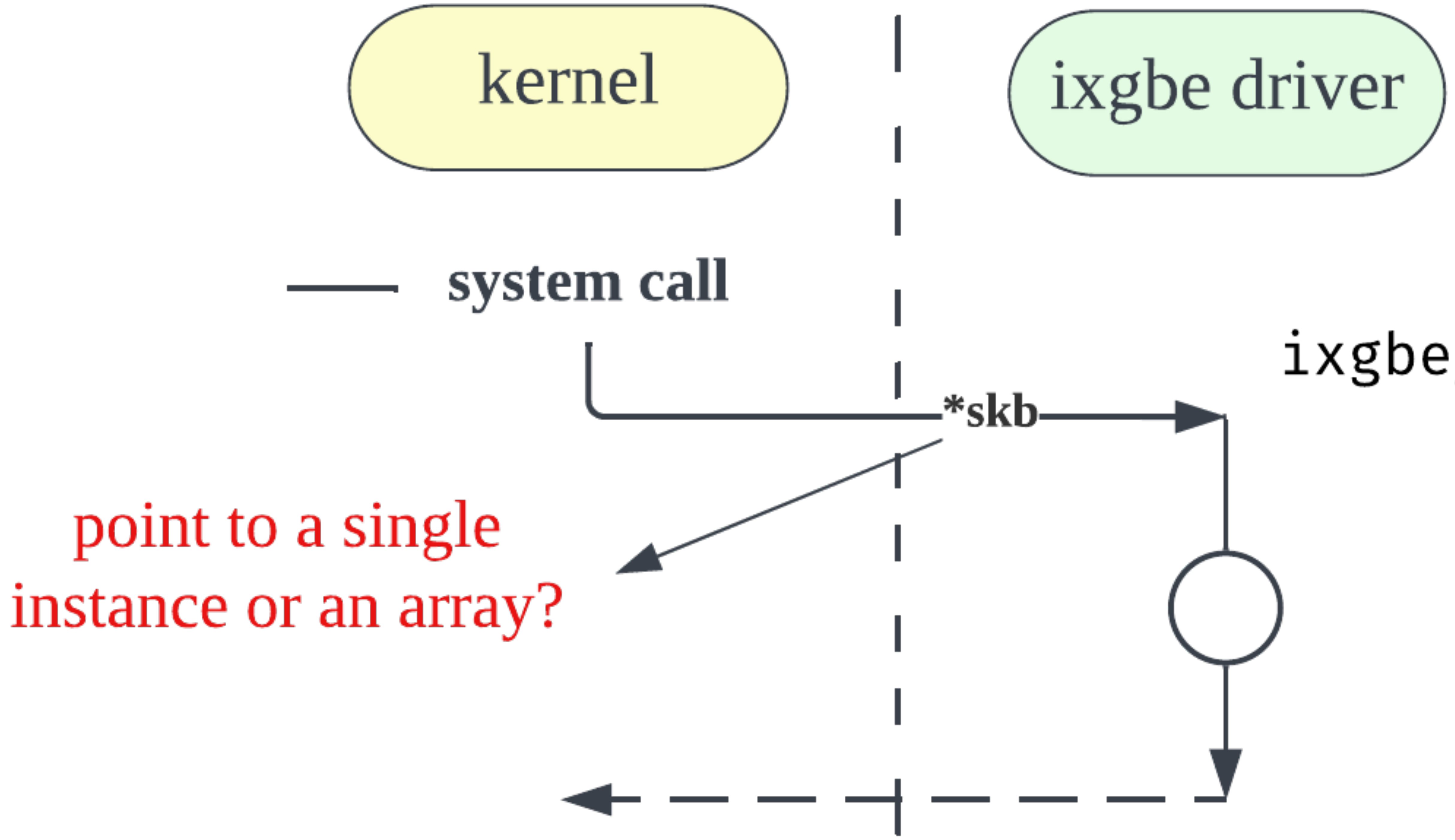
Atomic Region Analysis

- Compute atomic regions using control flow graph

```
spin_lock(&lock)
  ...
spin_unlock(&lock)
```

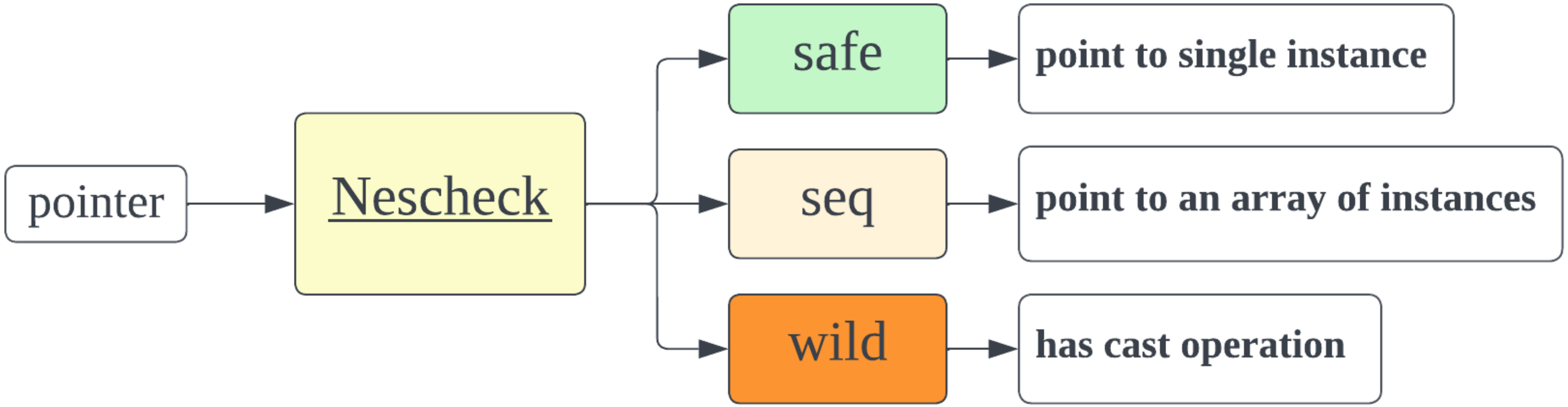


Infer marshaling requirements for pointers




```
ixgbe_xmit_frame(struct sk_buff *skb, ...)
```

Classify Pointers with Nescheck



POPL'2002

CCured: Type-Safe Retrofitting of Legacy Code

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AsiaCCS'17

Memory Safety for Embedded Devices with nesCheck

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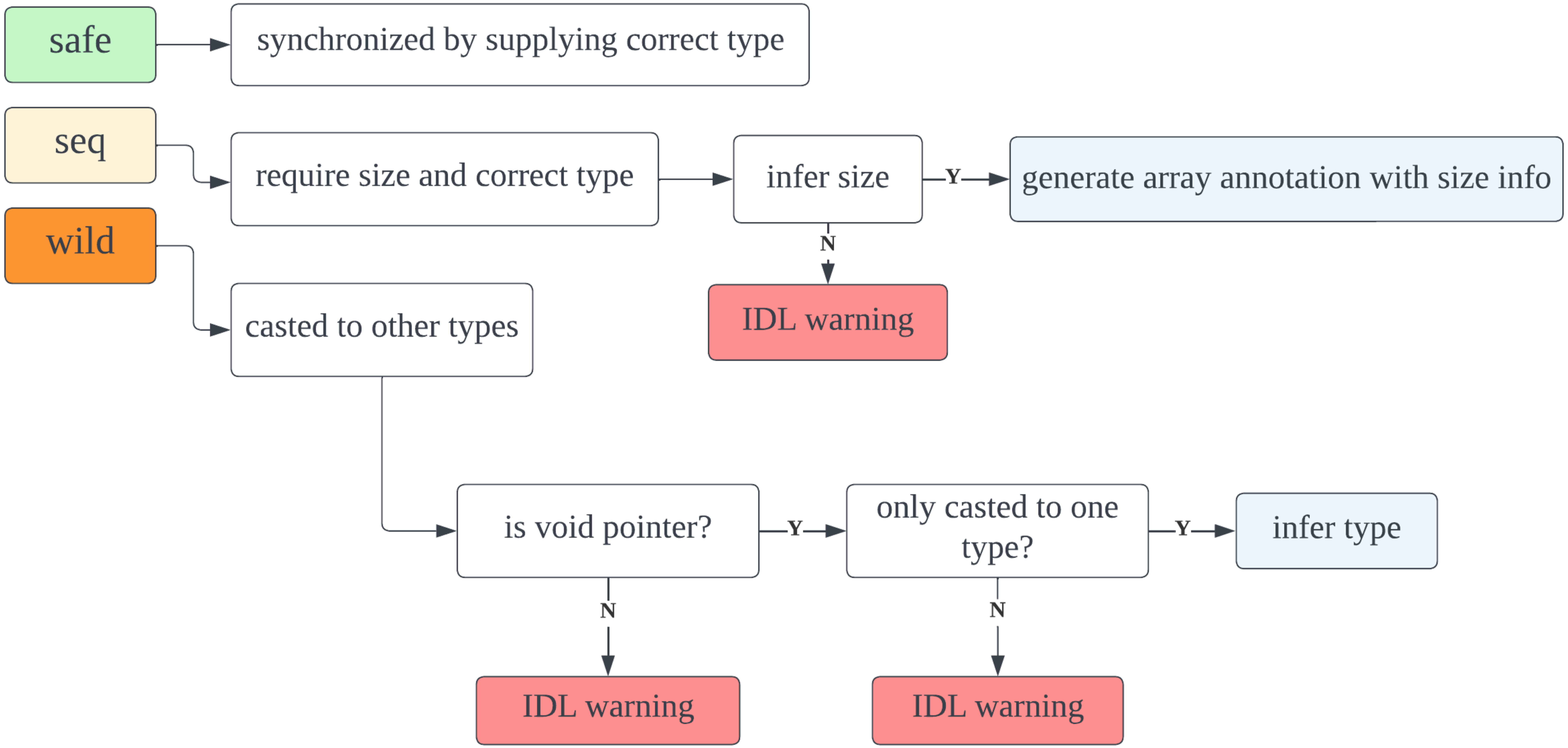
Classify Pointers with Nescheck

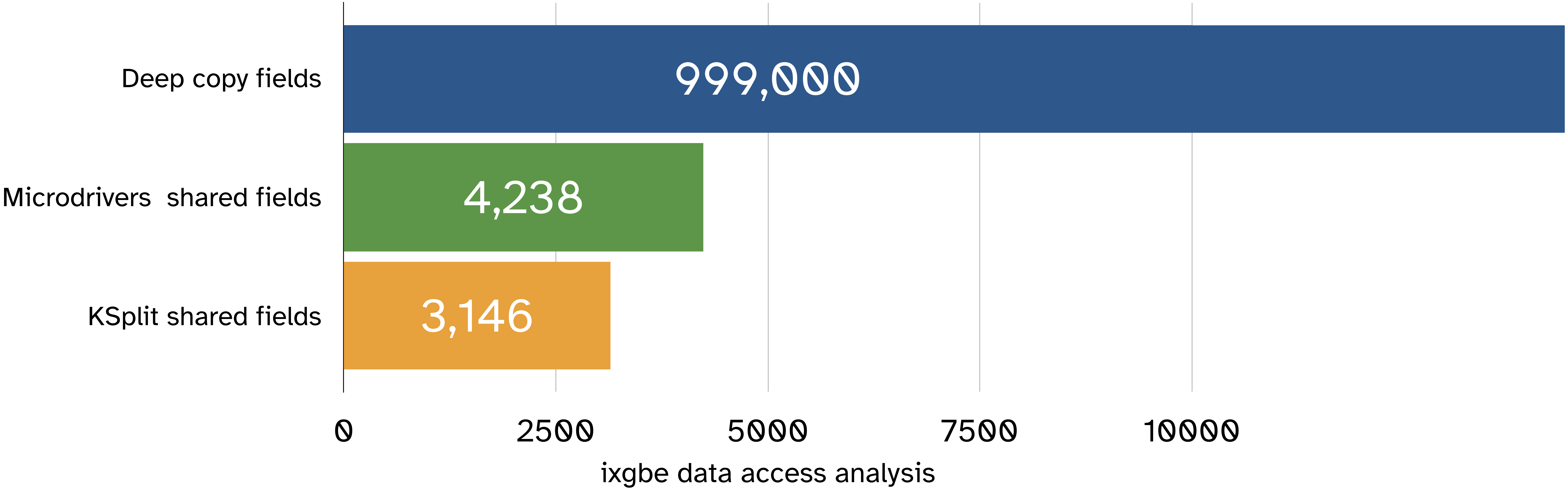


Evaluation

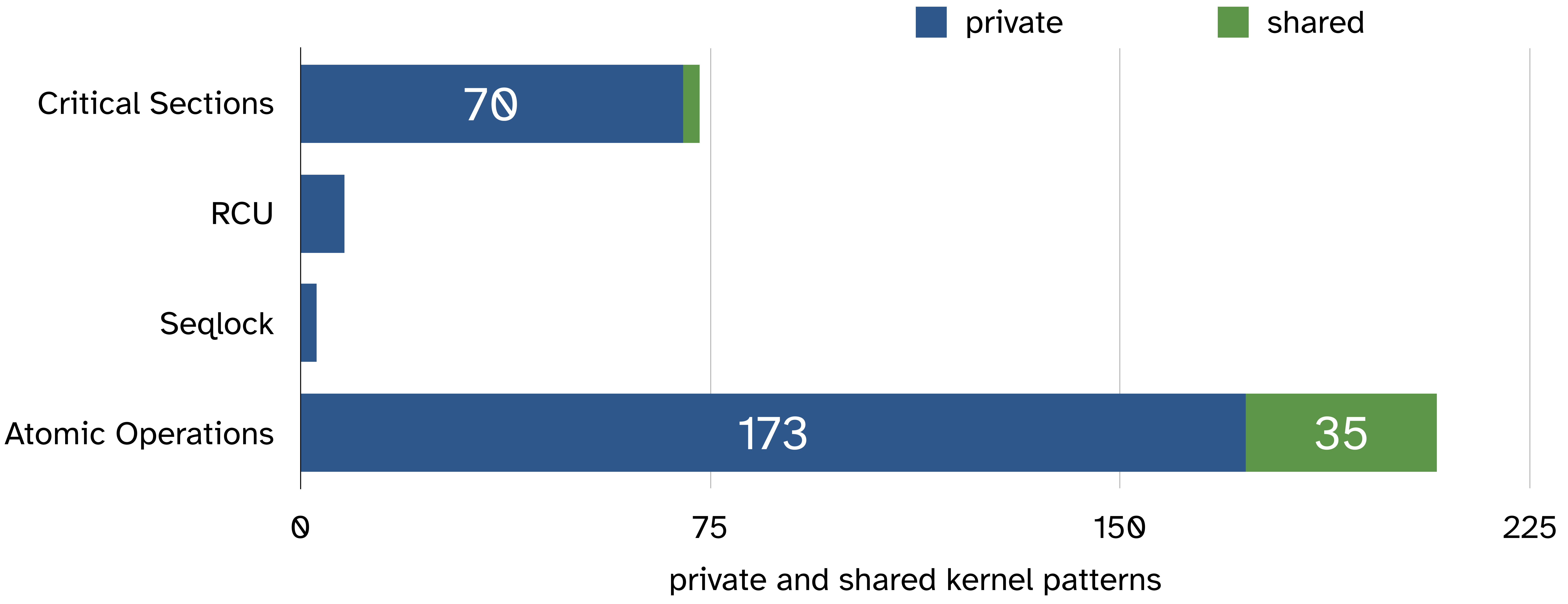
- **Research questions:**
  - How much data synchronization can we reduce?
  - How much manual work required?
  - How to test correctness of the isolated drivers?
- Compare to *Microdrivers*
- Run KSplit on **354** drivers from **9** subsystems
- Fully isolate and 10 drivers and validate the correctness
- **Performance Overhead**:
  - Memcached benchmark

Case study: Ixgbe driver

Ixgbe: data synchronization optimization



Ixgbe: synchronization primitives



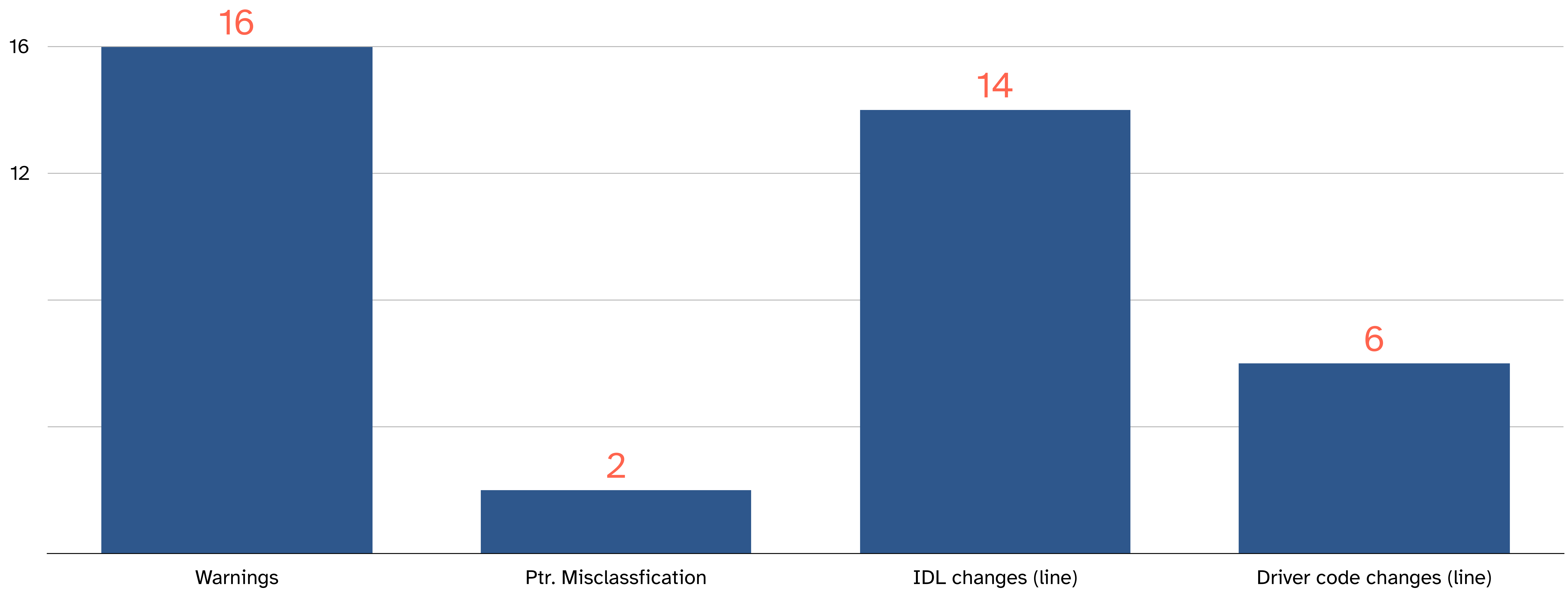
Ixgbe: pointer classification

	singleton	array	string	wild pointer (void)	wild pointer (other)
manual	0	27	0	1	3
handled	1261	92	2	142	1

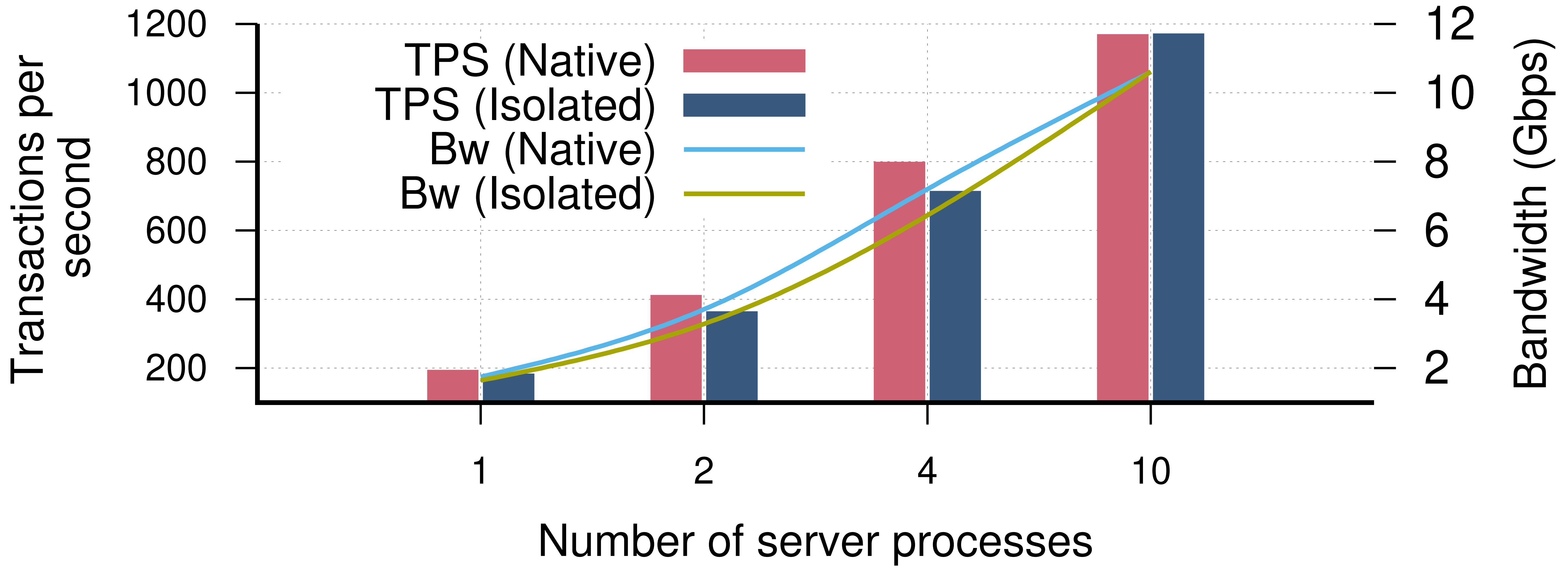
Ixgbe: Manual work

- Source code - 27,000 lines
- Generated IDL spec - 2000 lines
- Pointer misclassifications - 7
- Warnings - 65 (33 anonymous unions, 16 arrays, wild pointers)
  - IDL (changes) - 53 lines
  - Driver (changes) - 19 lines

Manual Work (average across isolated drivers)



Performance overhead: memcached



VEE'20

Lightweight Kernel Isolation with Virtualization and VM Functions

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- Memcached/memaslap
- 64B keys, 1024B values (90% set, 10% get)
- We report the bandwidth and transactions per second
- For 1-4 threads, KSplit overhead (5-18%)
- With 10 threads, we saturate the network bandwidth

Conclusions

- We are moving closer to low-overhead isolation mechanisms
- Complexity of isolation becomes a major challenge
- Static analysis framework with small manual effort

ARTIFACT EVALUATED usenix ASSOCIATION AVAILABLE

ARTIFACT EVALUATED usenix ASSOCIATION FUNCTIONAL

ARTIFACT EVALUATED usenix ASSOCIATION REPRODUCED

The source code is available at: https://github.com/ksplit/ksplit-artifacts

Thank you