Making Peace Between Mortal Enemies: Running a Database Management System in the Linux Kernel

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CARNEGIE MELLON
DATABASE GROUP

The OS Is Not Our Friend

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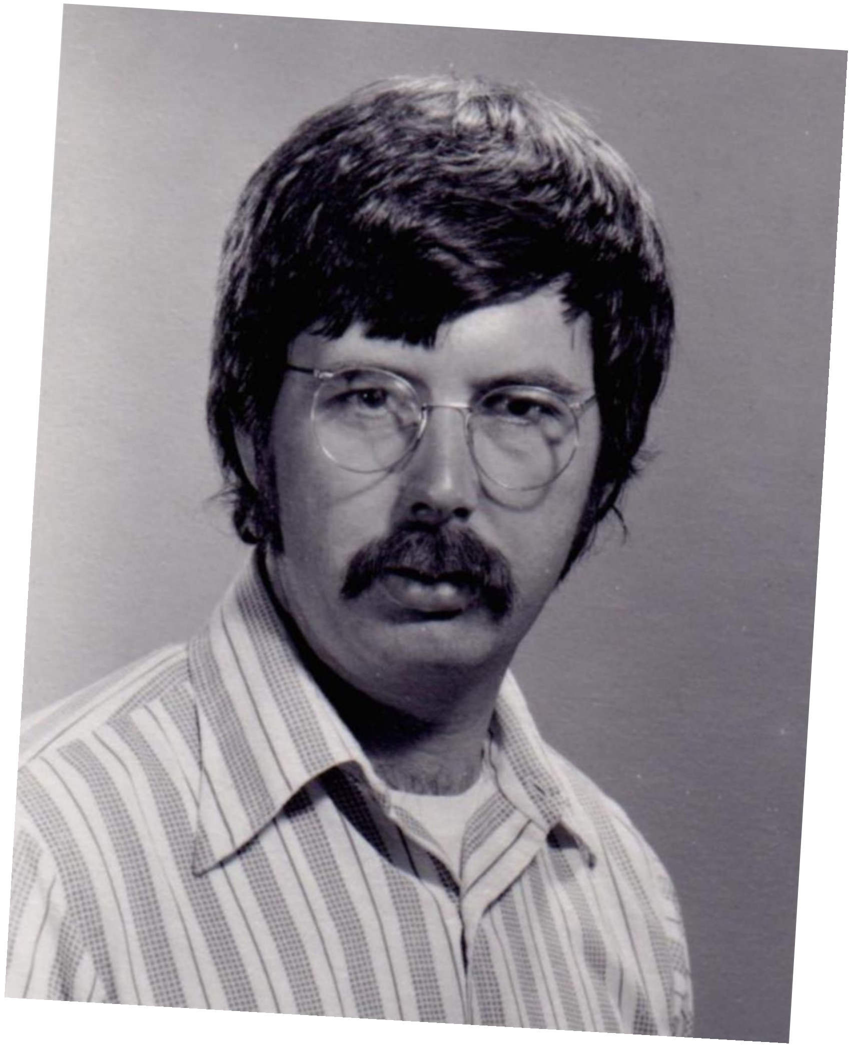
“The bottom line is that operating system services in many existing systems are either too slow or inappropriate.”

Michael Stonebraker. Operating System Support for Database Management. *Commun. ACM*. 1981.



My friend Mike

The Feud Goes On...

The Feud Goes On…

[Async I/O] is a horrible ad-hoc design, with the main excuse being "other, less gifted people, made that design, and we are implementing it for compatibility because database people - **who seldom have any shred of taste** - actually use it".

Linus Torvalds. Re: [PATCH 09/13] aio: add support for async openat(). *LKML*. 2016.

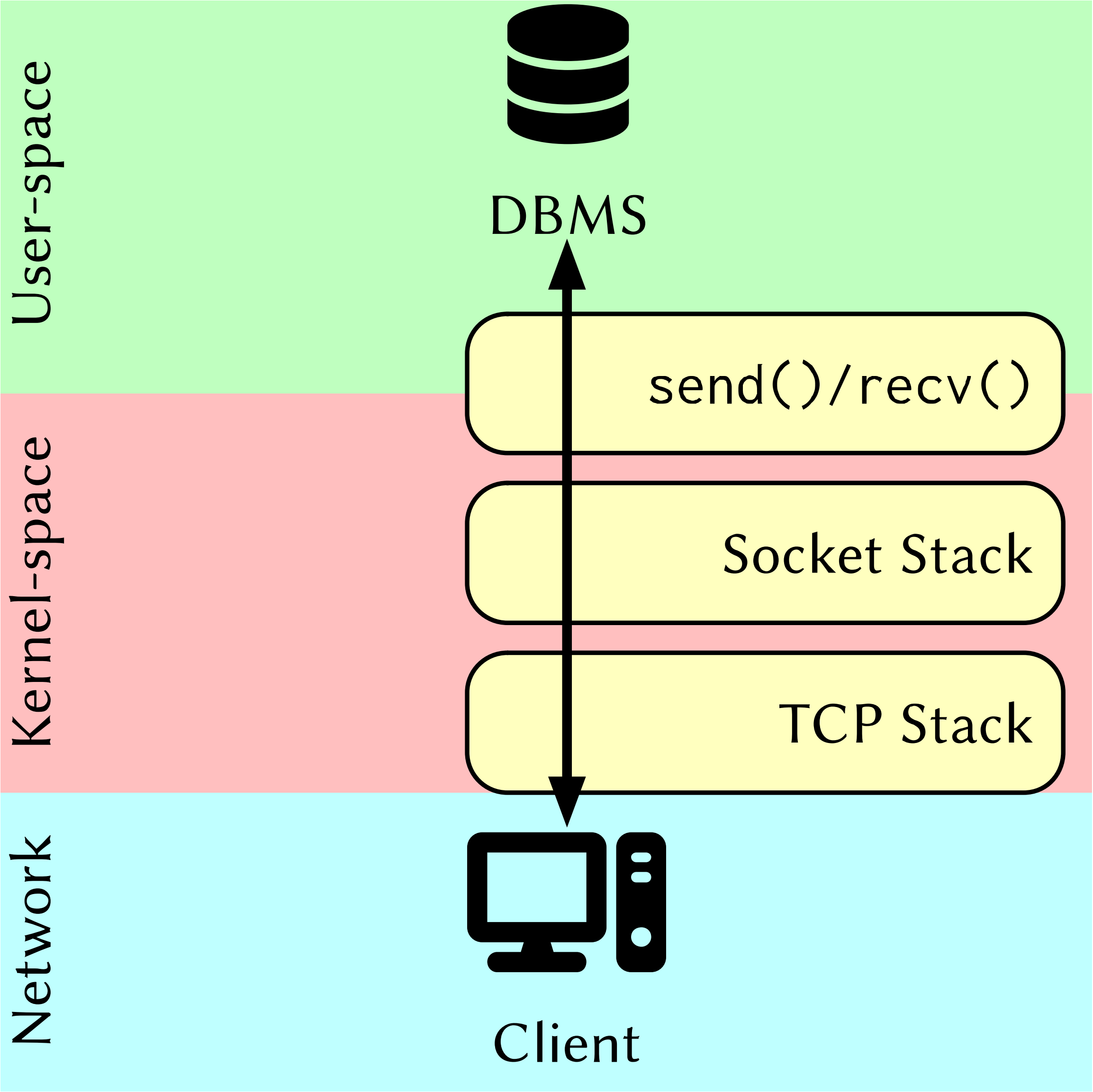
And On…

And On…

Linux tends to kill the postmaster in out-of-memory situations, because it blames the postmaster for the sum of child process sizes *including shared memory*. (**This is unbelievably stupid, but the kernel hackers seem uninterested in improving it.**)

postgres/src/backed/postmaster/fork_process.c:74

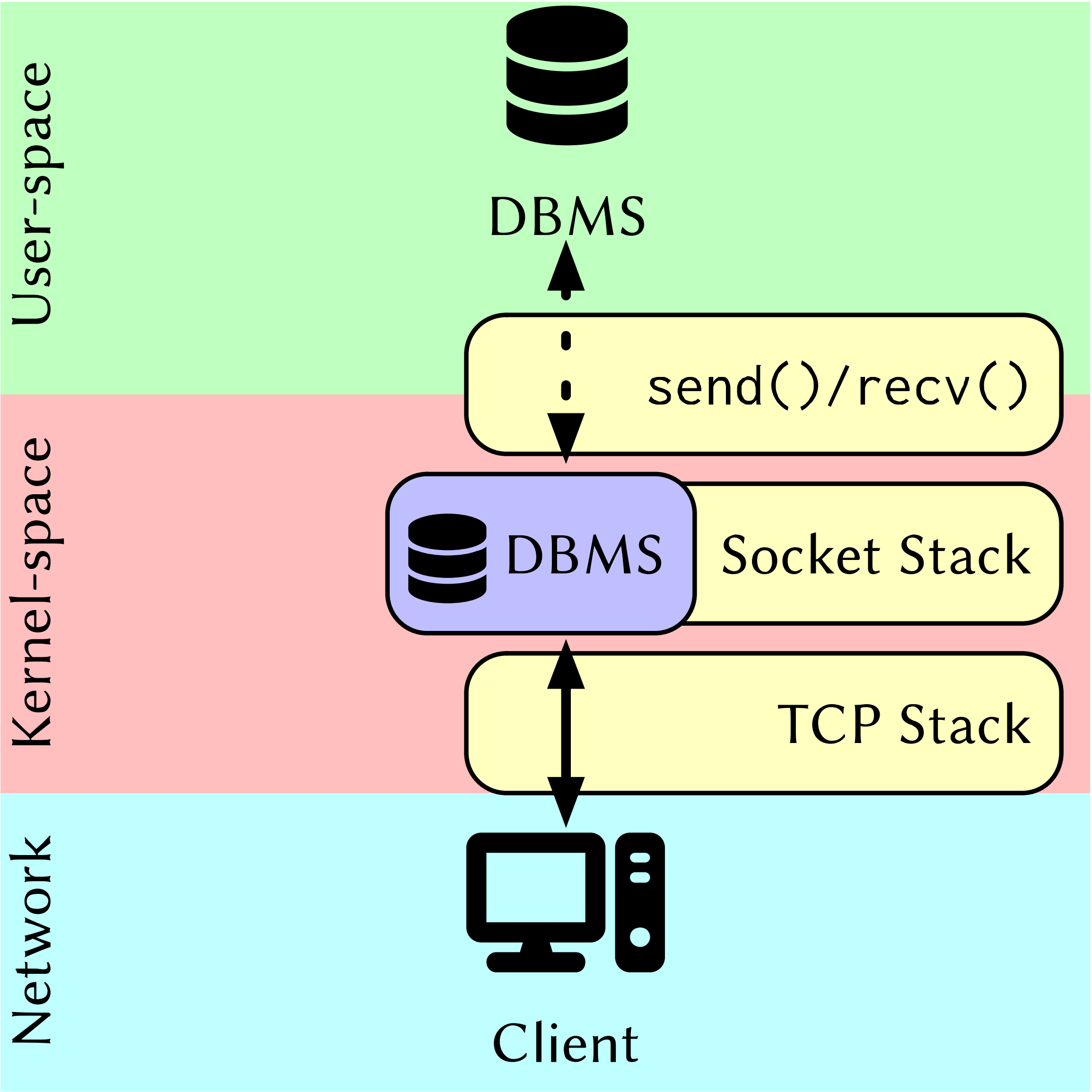
User-Bypass



User-space DBMS

User-Bypass

CMU·DB



User-bypass DBMS

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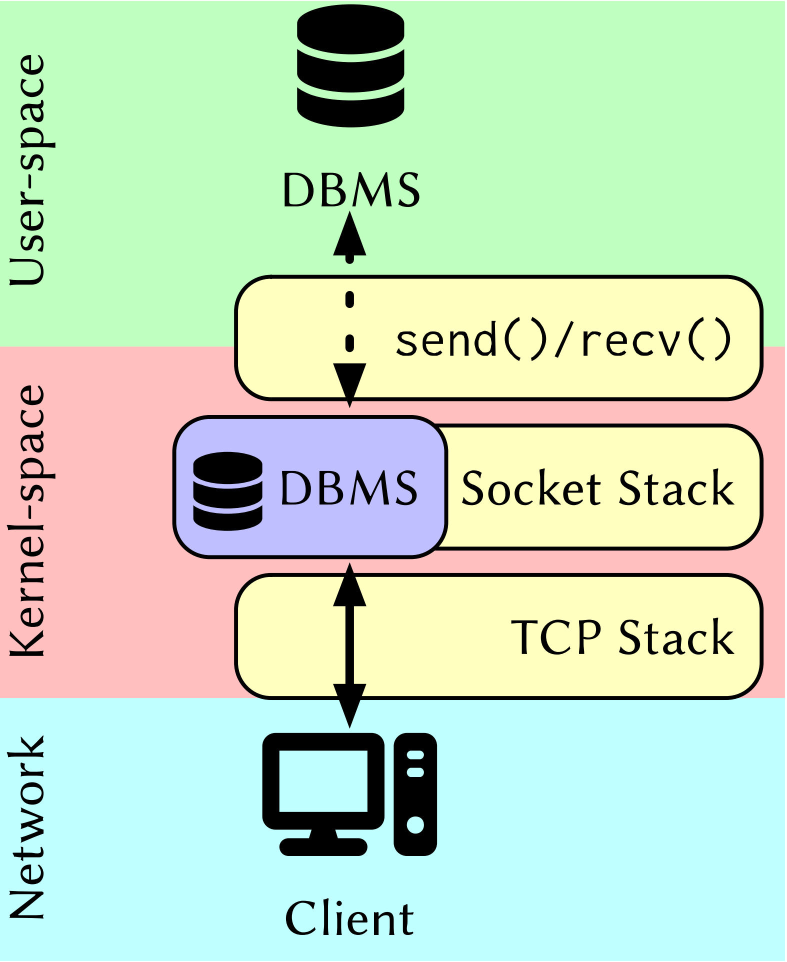
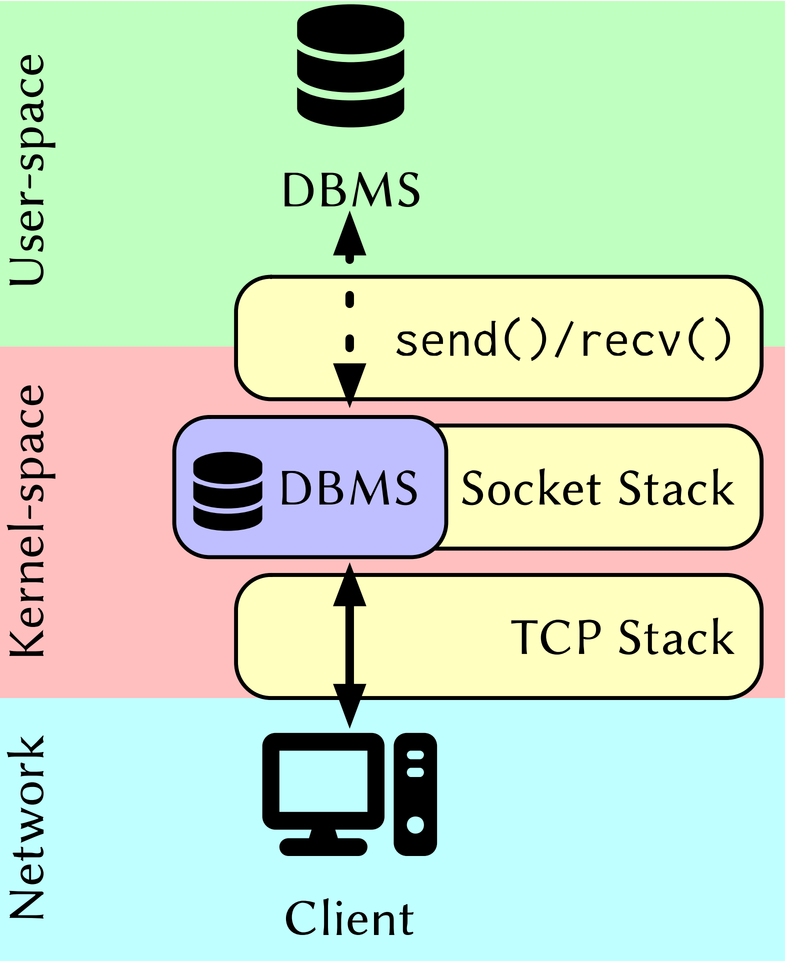


User-bypass DBMS

User-Bypass

- Don’t pull DBMS data to user-space, push DBMS logic to kernel-space



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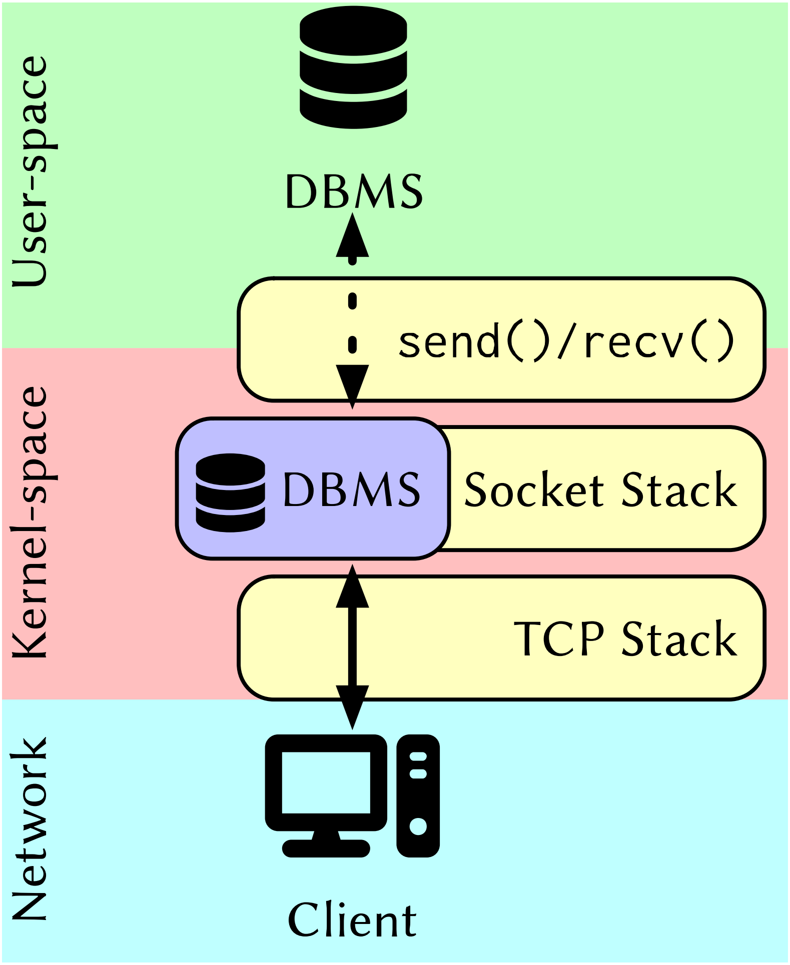
- Avoid copying buffers, scheduling user threads, and system call overhead



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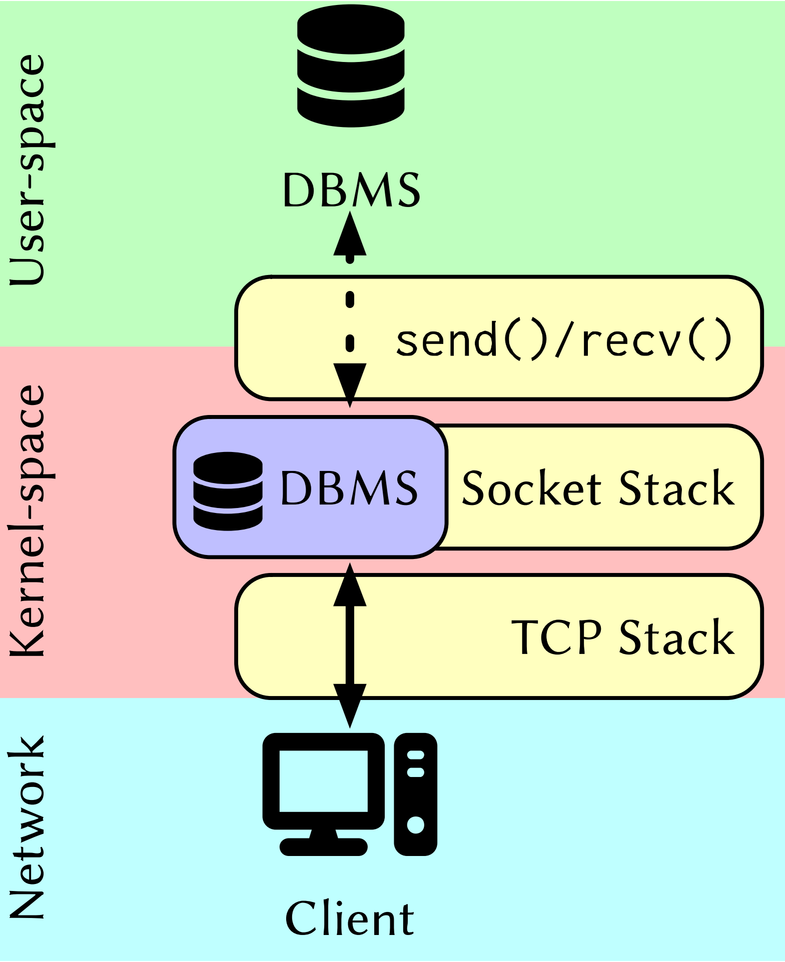
Brian N. Bershad et al. Extensibility, Safety and Performance in the SPIN Operating System. *SOSP*. 1995.

Greg Ganger et al. Fast and flexible application-level networking on exokernel systems. *ACM Trans. Comput. Syst*. 2002.

Margo I. Seltzer et al. Dealing with Disaster: Surviving Misbehaved Kernel Extensions. *OSDI*. 1996.



User-bypass DBMS

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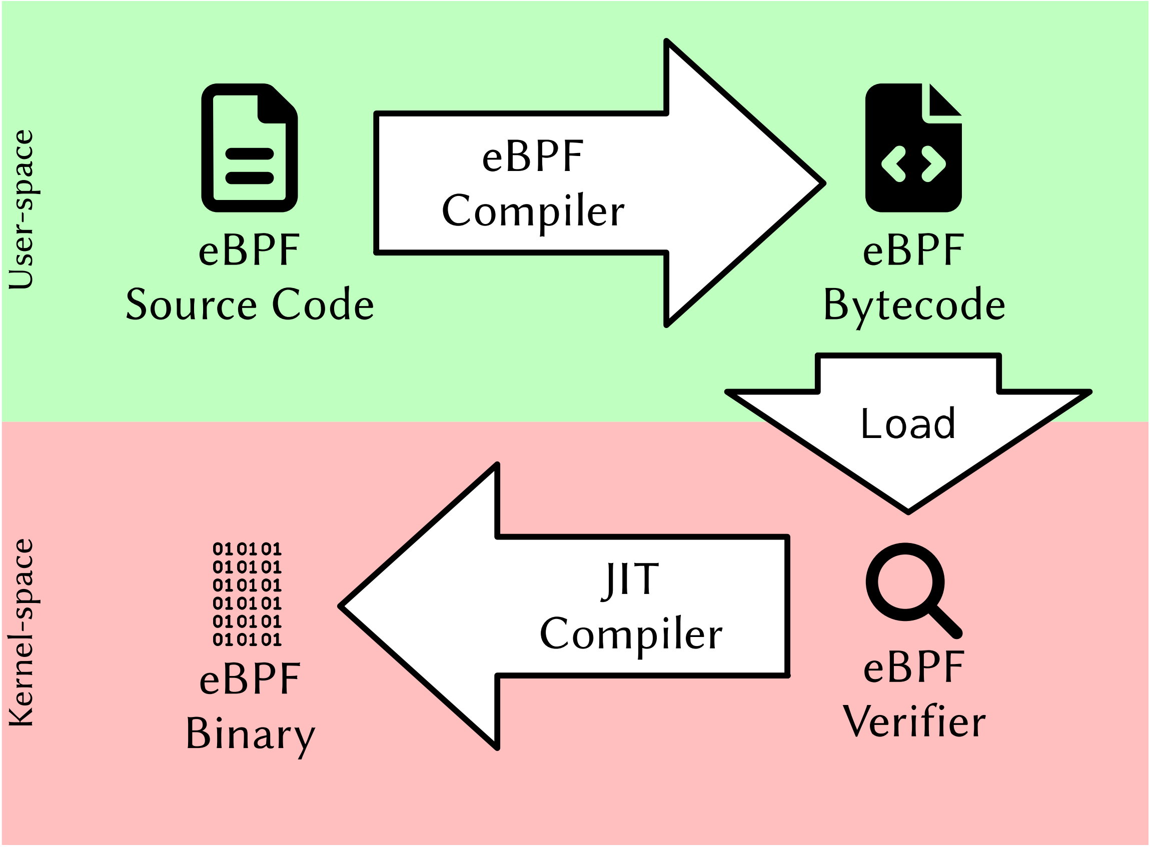

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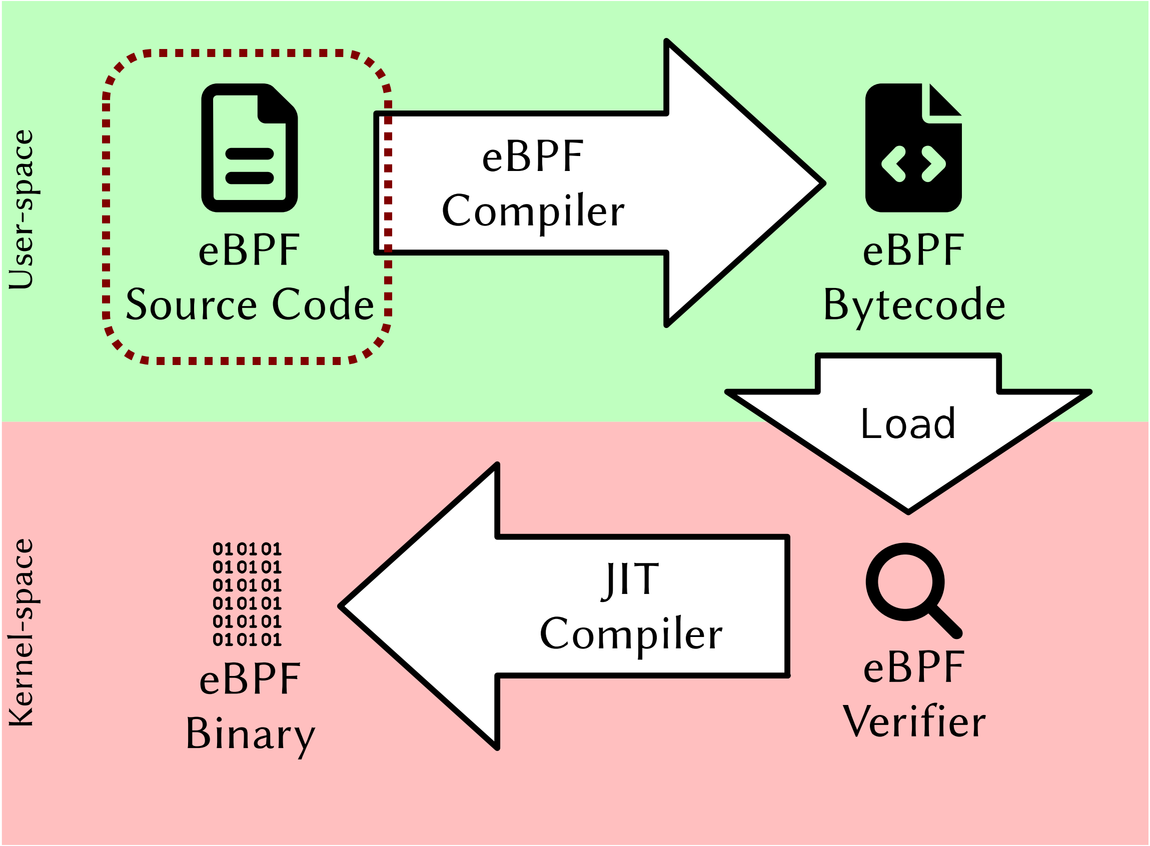

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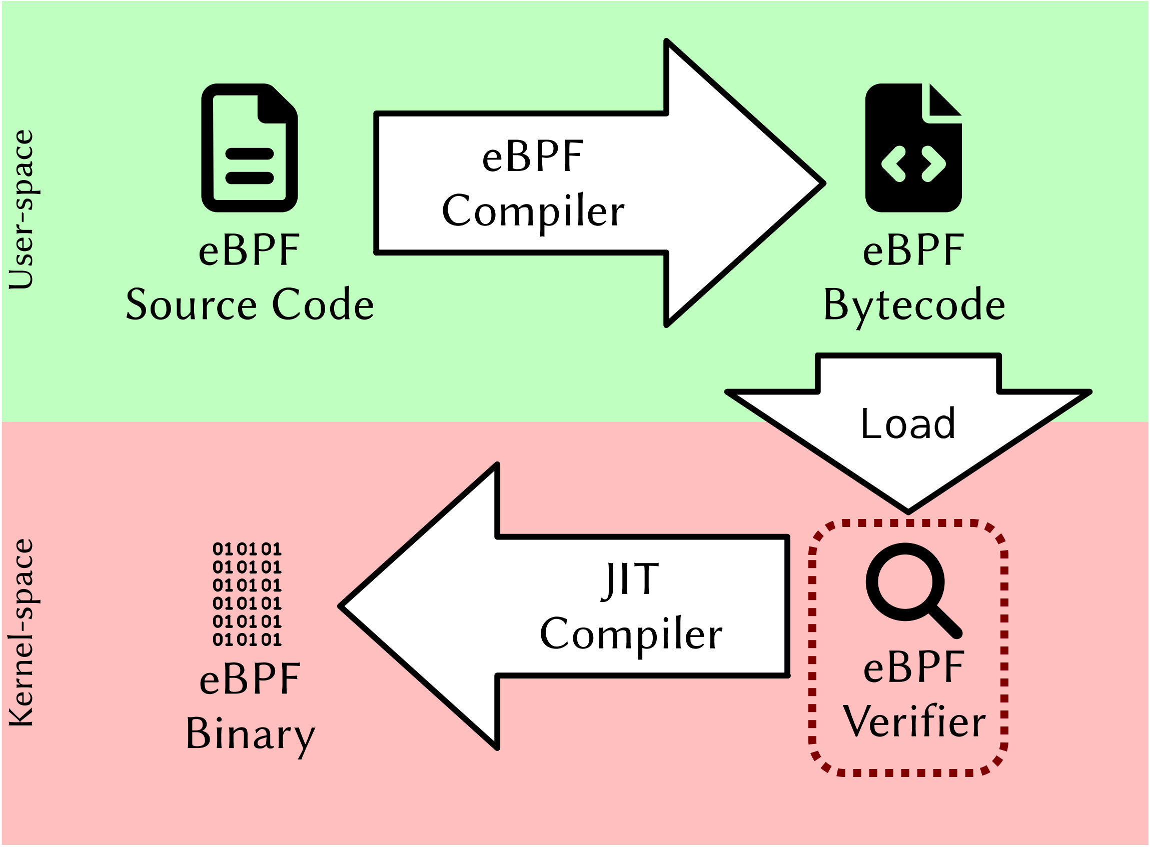
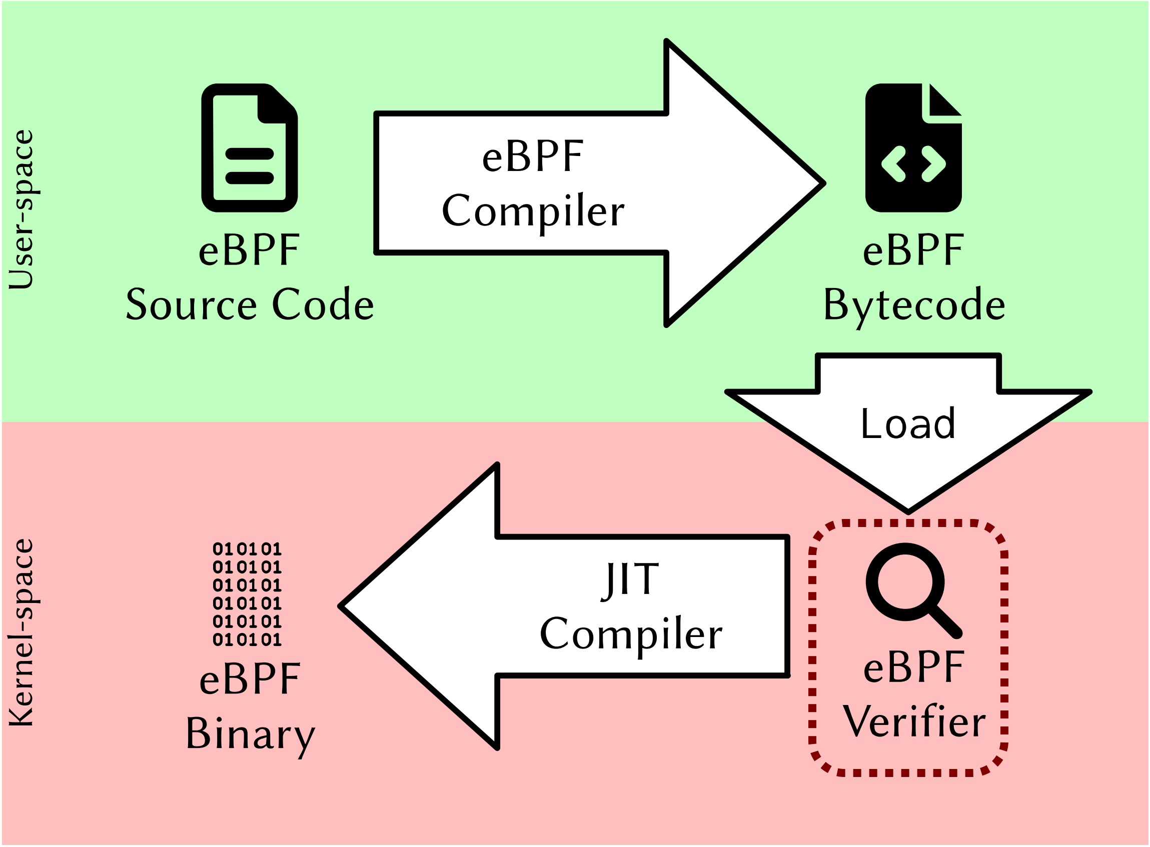


extended Berkeley Packet Filter

- Safe, event-driven programs in kernel-space

- Write in C and compile to eBPF

- Verifier constraints:
    - # instructions, boundedness, memory safety, limited API



eBPF Environment

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- Attach to user-space or kernel-space hooks
  - User-space ⇒ “new system call”
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- eBPF maps: kernel-resident data structures
  - Key-value interface
  - Hash tables, stacks/queues, arrays, etc.

eBPF in the Wild

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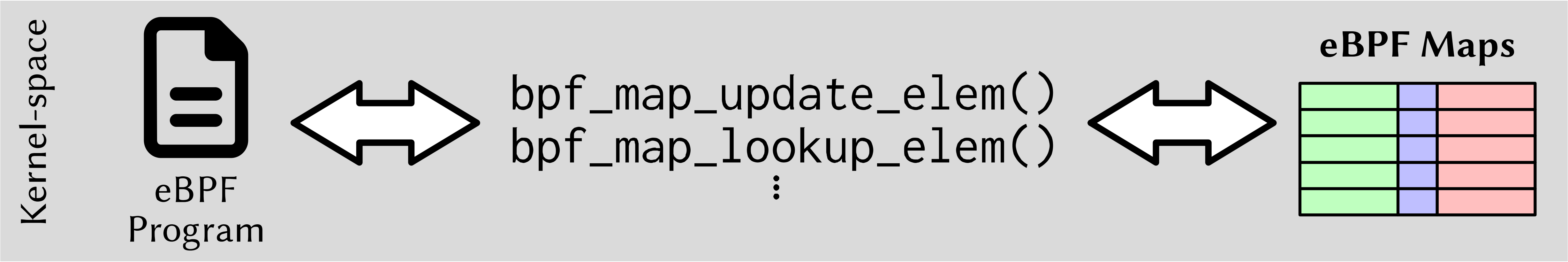
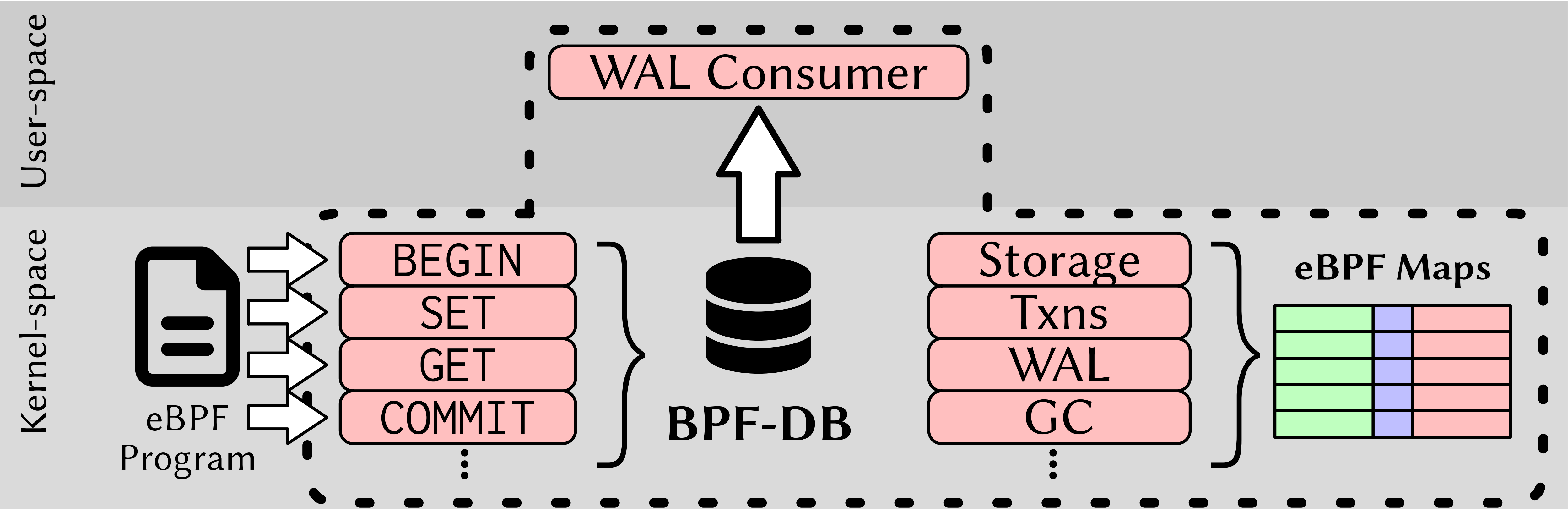
eBPF DBMS



```
bpf_map_update_elem()
bpf_map_lookup_elem()
⋮
```

eBPF DBMS


User-space
WAL Consumer
Kernel-space
eBPF Program
BEGIN
SET
GET
COMMIT
BPF-DB
Storage
Txns
WAL
GC
eBPF Maps

The Verifier Strikes Back

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- User-bypass programs limited to 1M eBPF instructions

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- User-bypass programs limited to 1M *verified* eBPF instructions
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- Tail-calling between eBPF programs (up to 32) helps

BPF-DB Goals

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- Design and implement BPF-DB with traditional DBMS components and features (e.g., ACID transactions)

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- Decompose DBMS components using continuation passing style to satisfy eBPF verifier

- Developers build rich applications using BPF-DB as their backing store (e.g., RocksDB for eBPF)

GET Tail-Calls

“GET foo”

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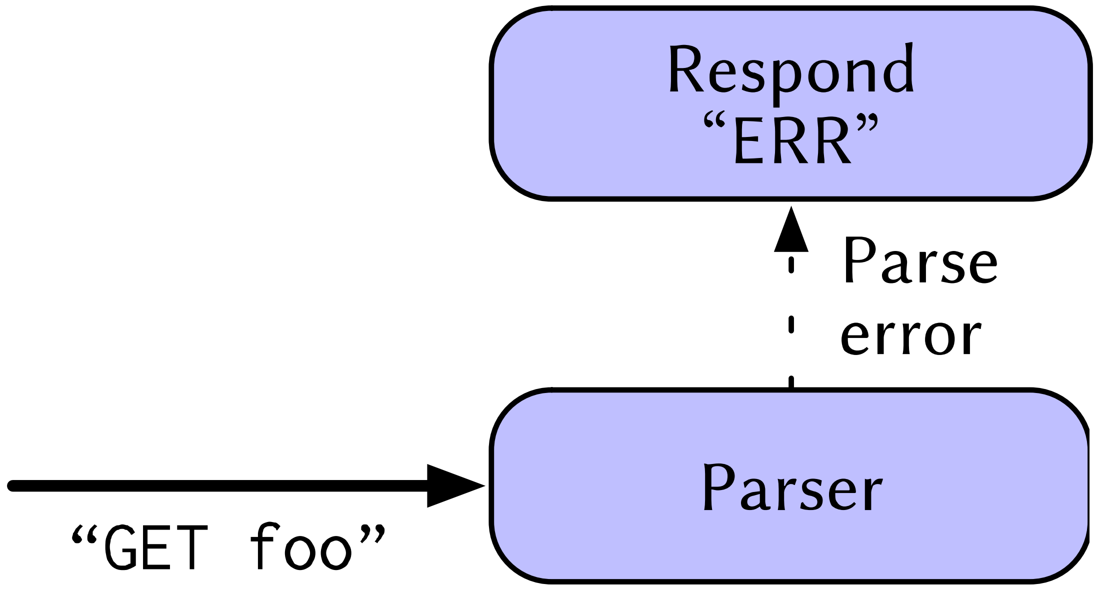

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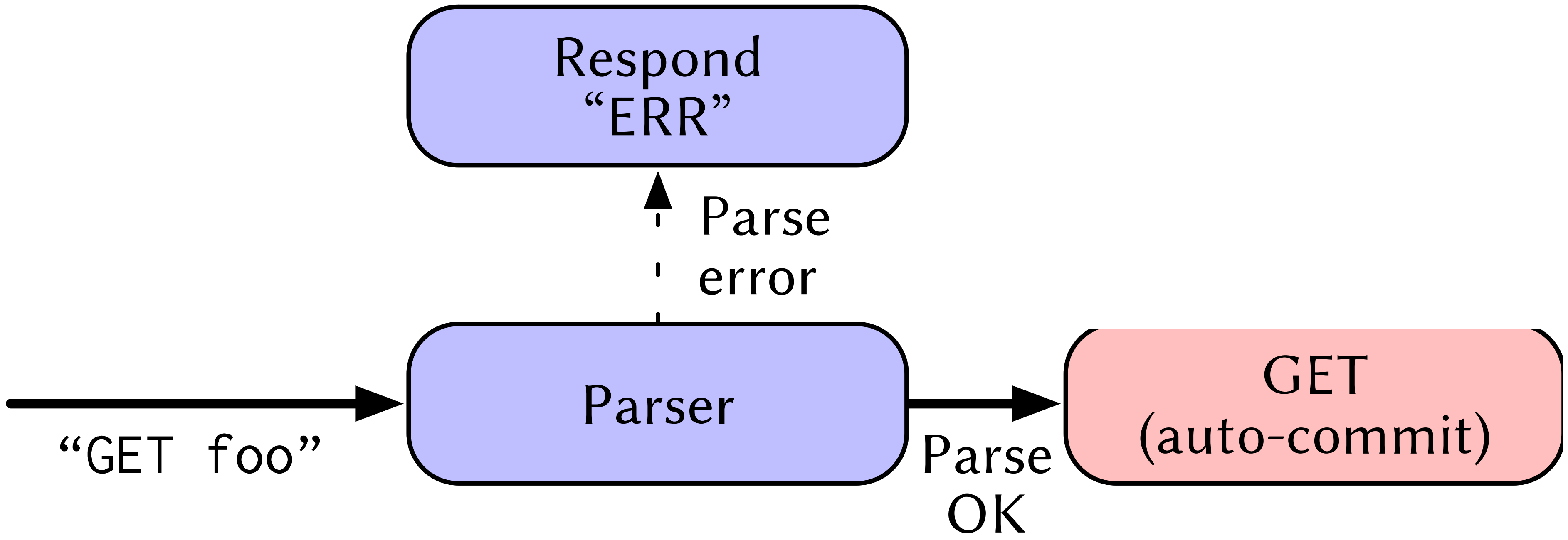


Respond “ERR”

Parse error

“GET foo”

Parser

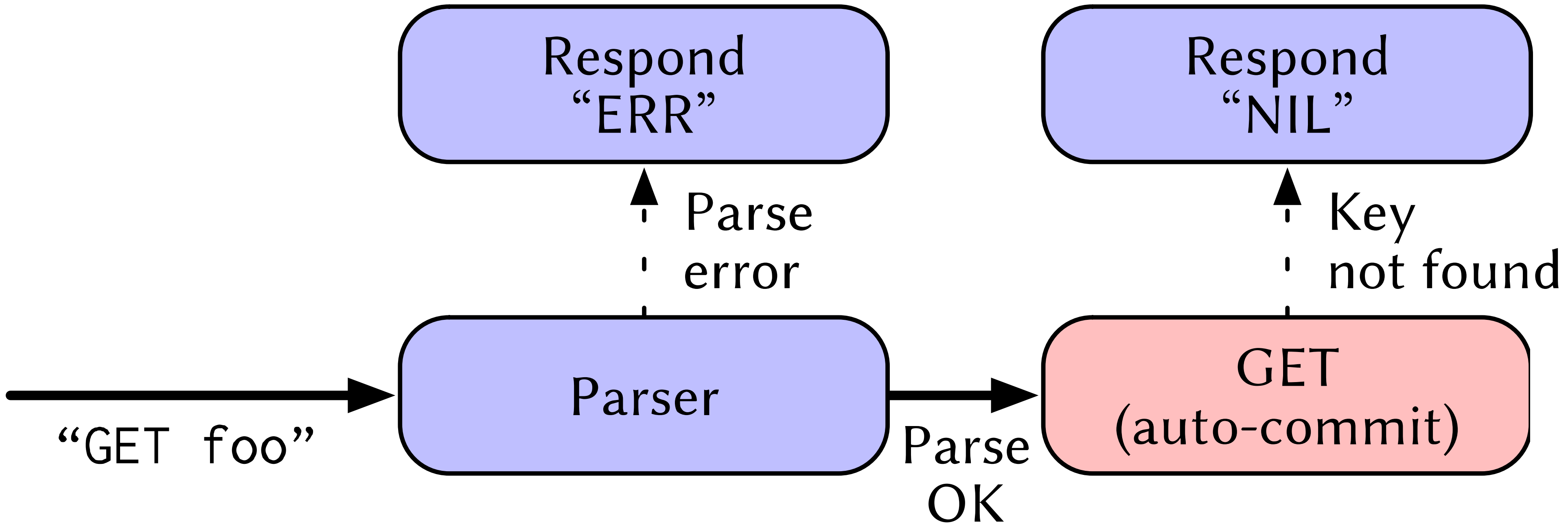
Parse OK

GET (auto-commit)

Context

Key:	“foo”
Value:	

GET Tail-Calls



Respond “ERR”

Respond “NIL”

Parse error

Key not found

“GET foo”

Parser

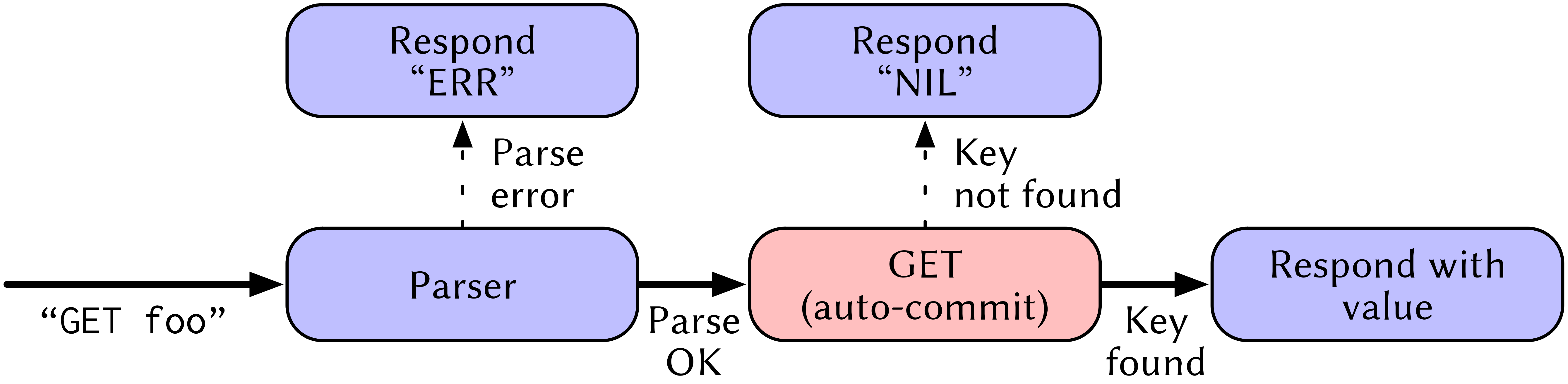
Parse OK

GET (auto-commit)

Context

Key:	“foo”
Value:	

GET Tail-Calls



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Key found

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Context

Key:	“foo”
Value:	“bar”

Storage Management

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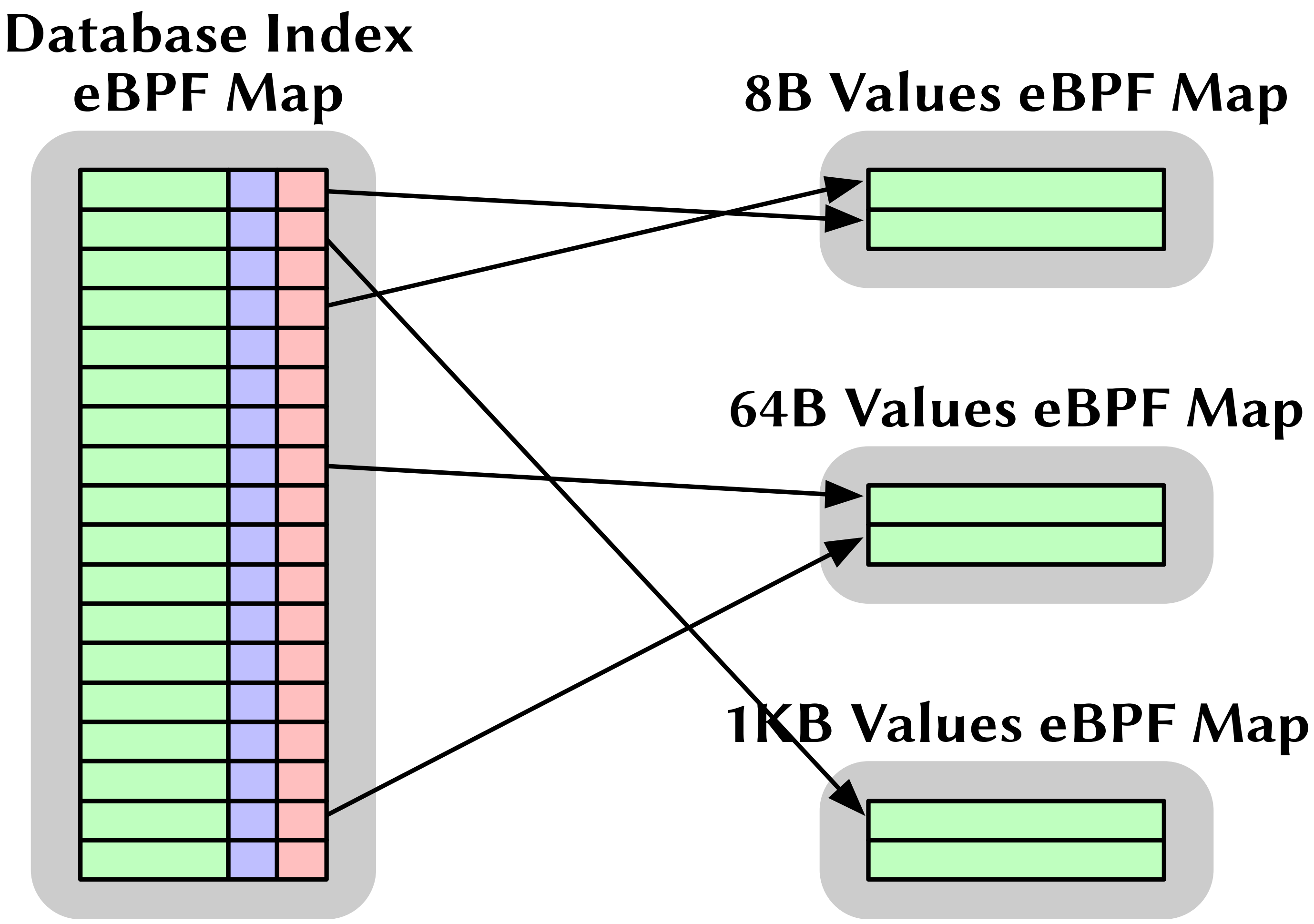

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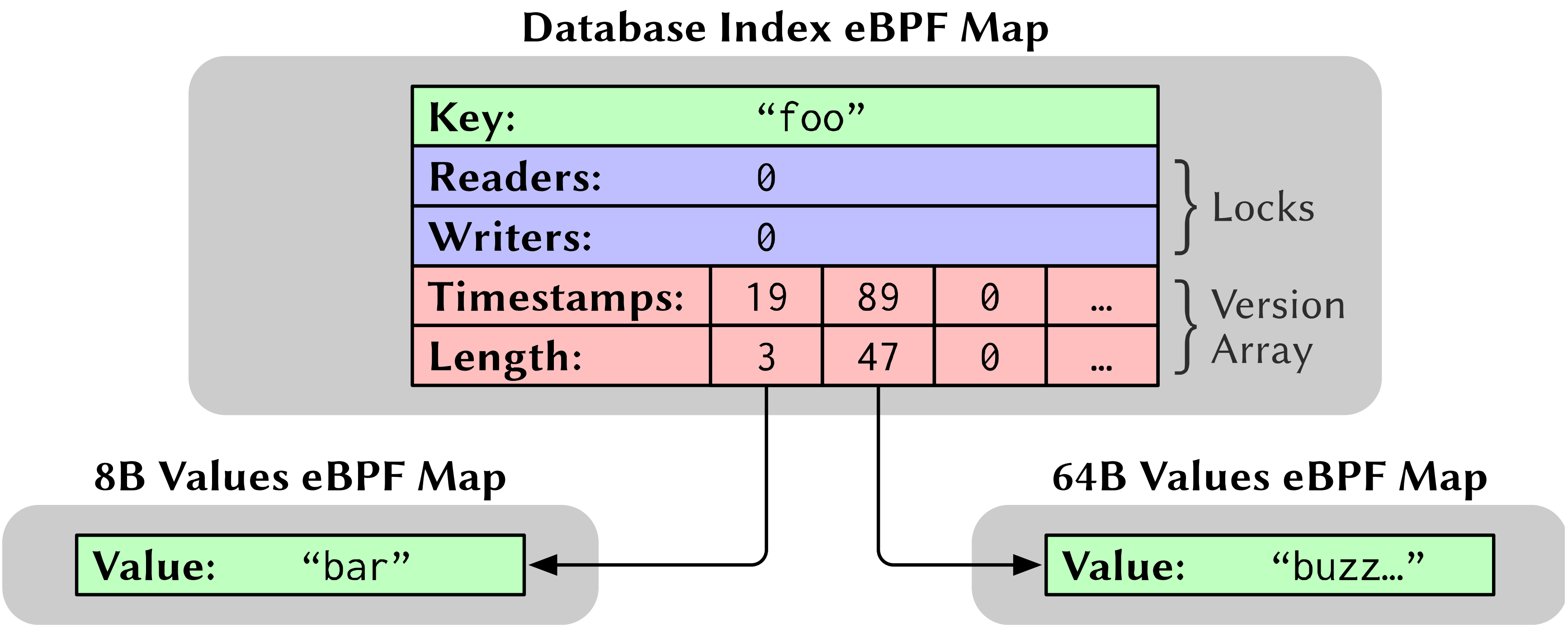


Database Index eBPF Map

Key:	"foo"			
Readers:	0			
Writers:	0			
Timestamps:	19	89	0	…
Length:	3	47	0	…

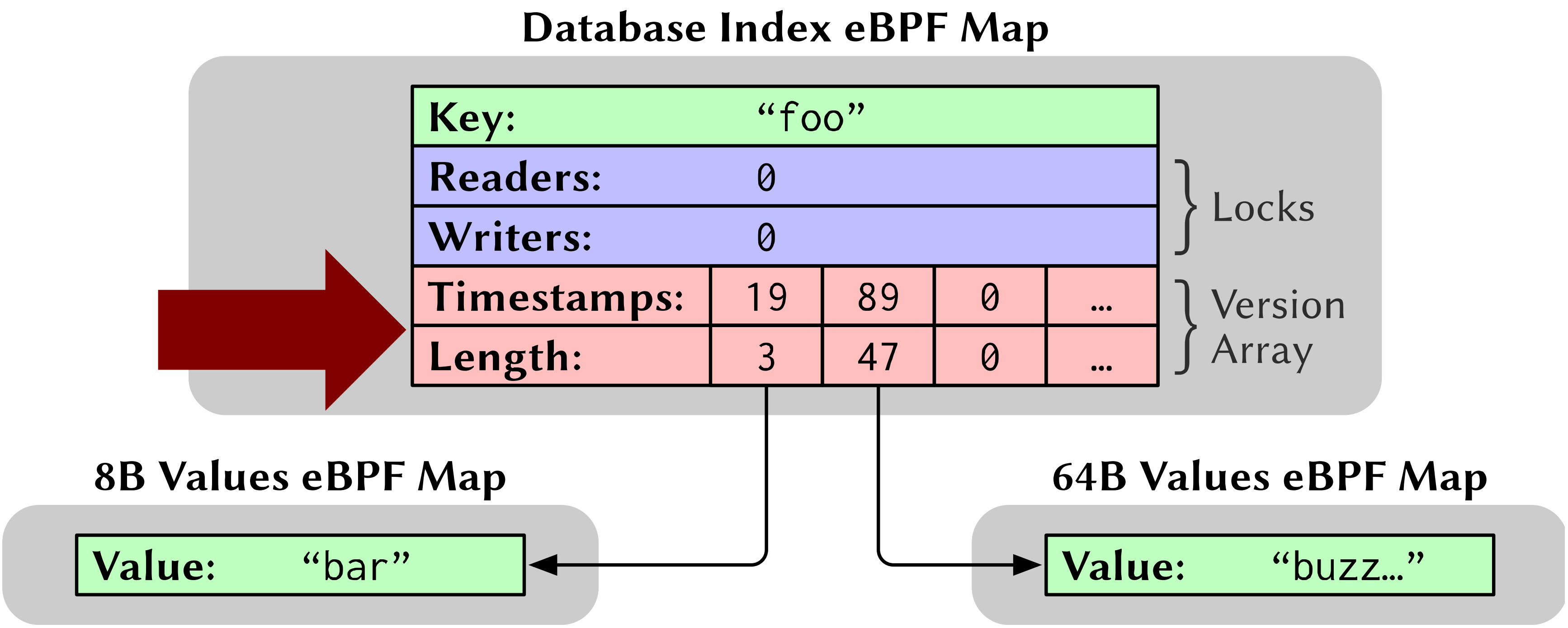
8B Values eBPF Map

Value: "bar"

64B Values eBPF Map

Value: "buzz…"

Storage Management



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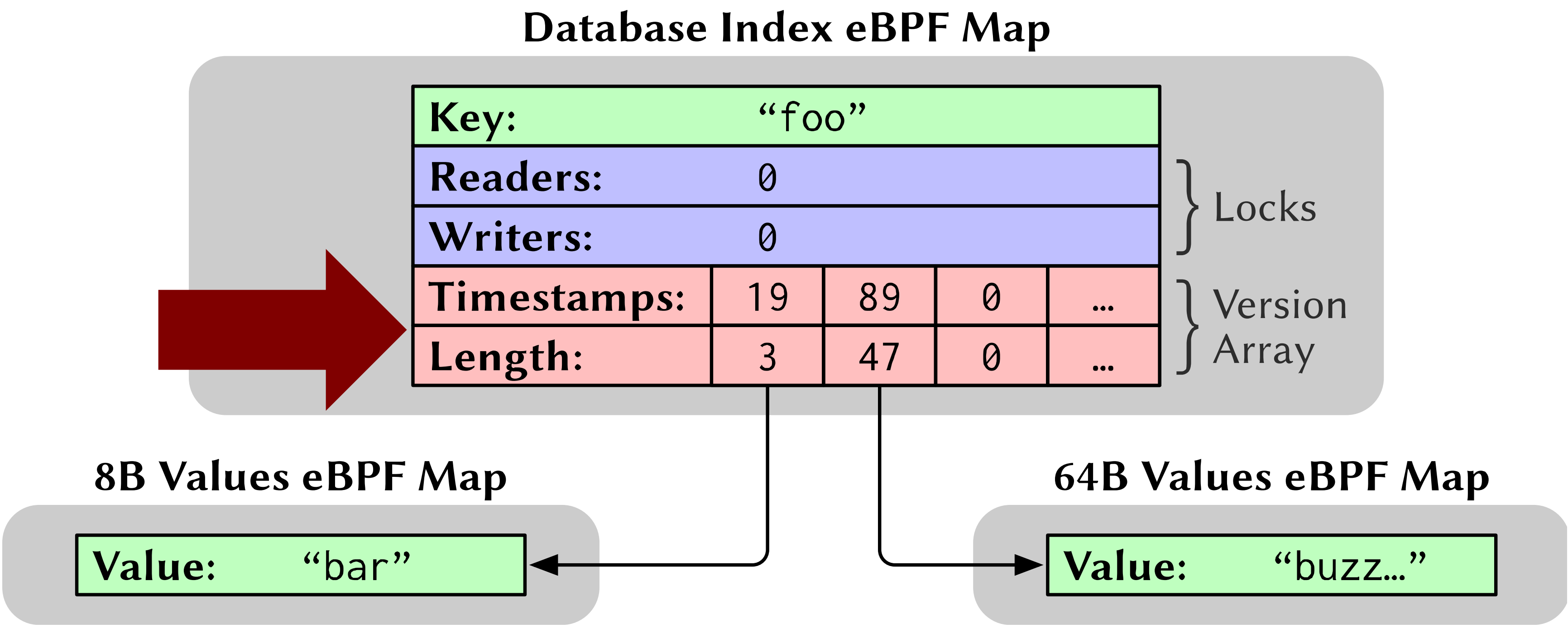
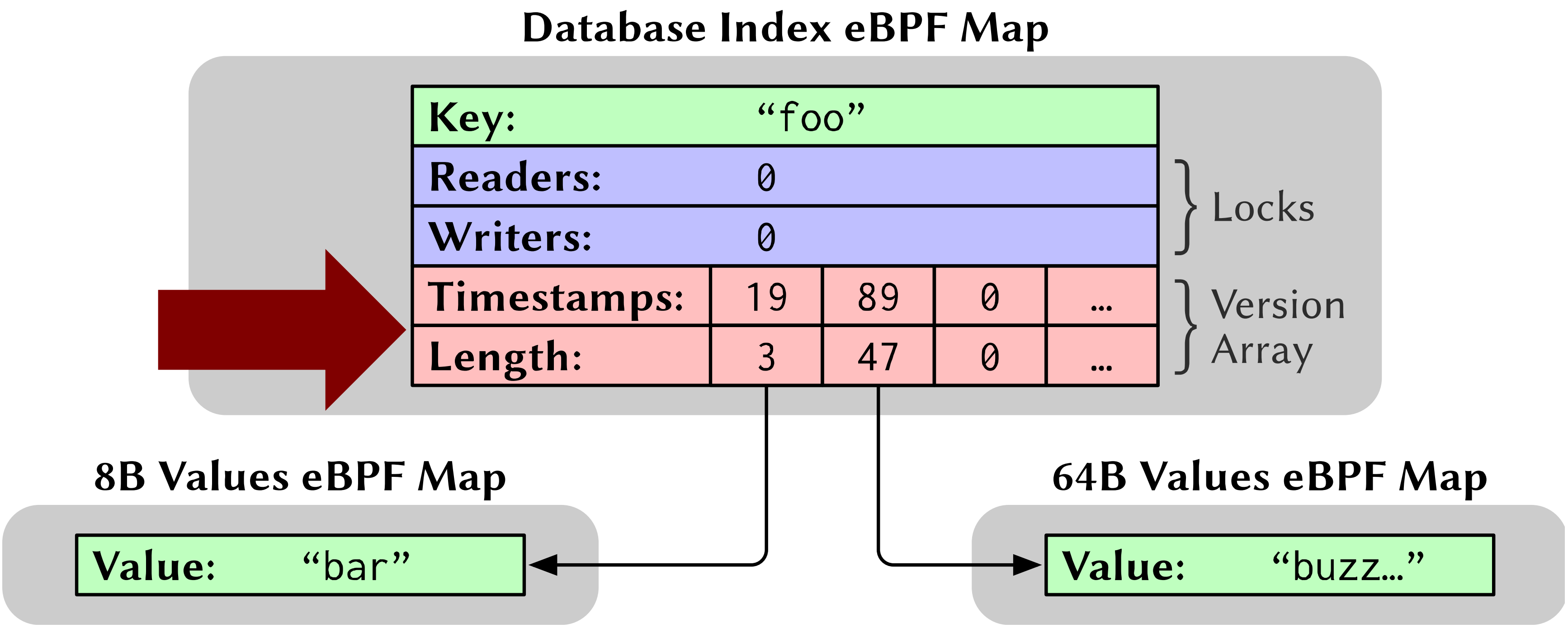
- Bounded, unordered version arrays



Storage Management

- Bounded, unordered version arrays

- Cooperative GC on SET



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Key: "foo"

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Locks

Timestamps: 19 | 89 | 0 | …

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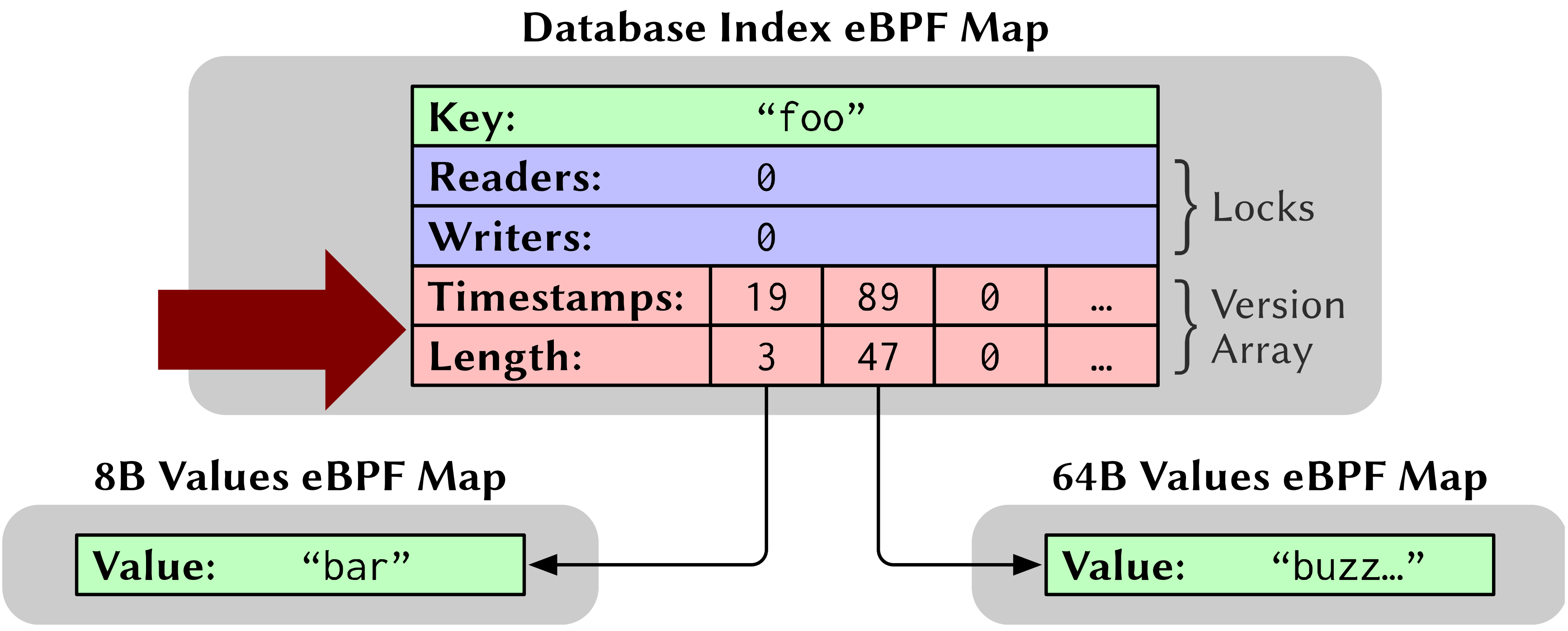
Storage Management

- Bounded, unordered version arrays

- Cooperative GC on SET

- Database contents separate from DBMS logic



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Aakash Goel et al. Fast Database Restarts at Facebook. *SIGMOD*. 2014.

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- Challenges:
  - Restrictive atomic primitives
  - Boundedness limits spinning
  - eBPF program execution cannot yield

Transaction Management

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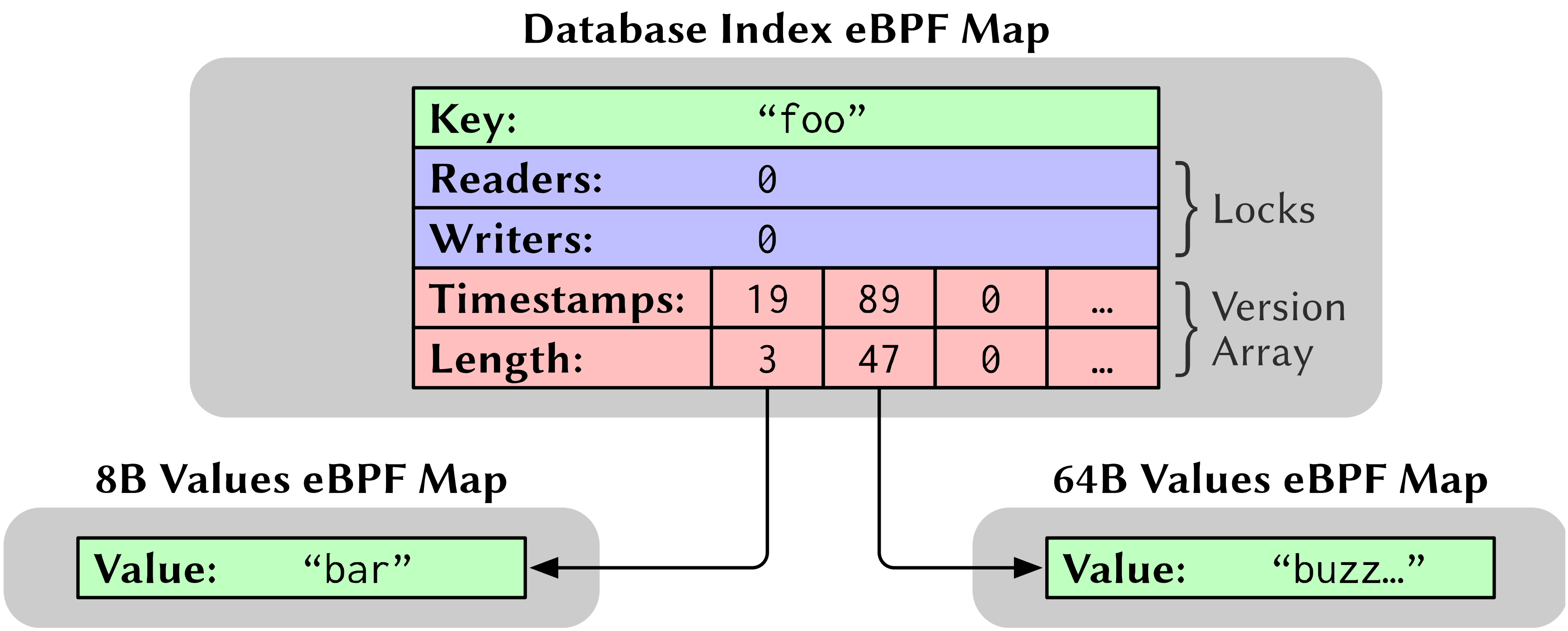

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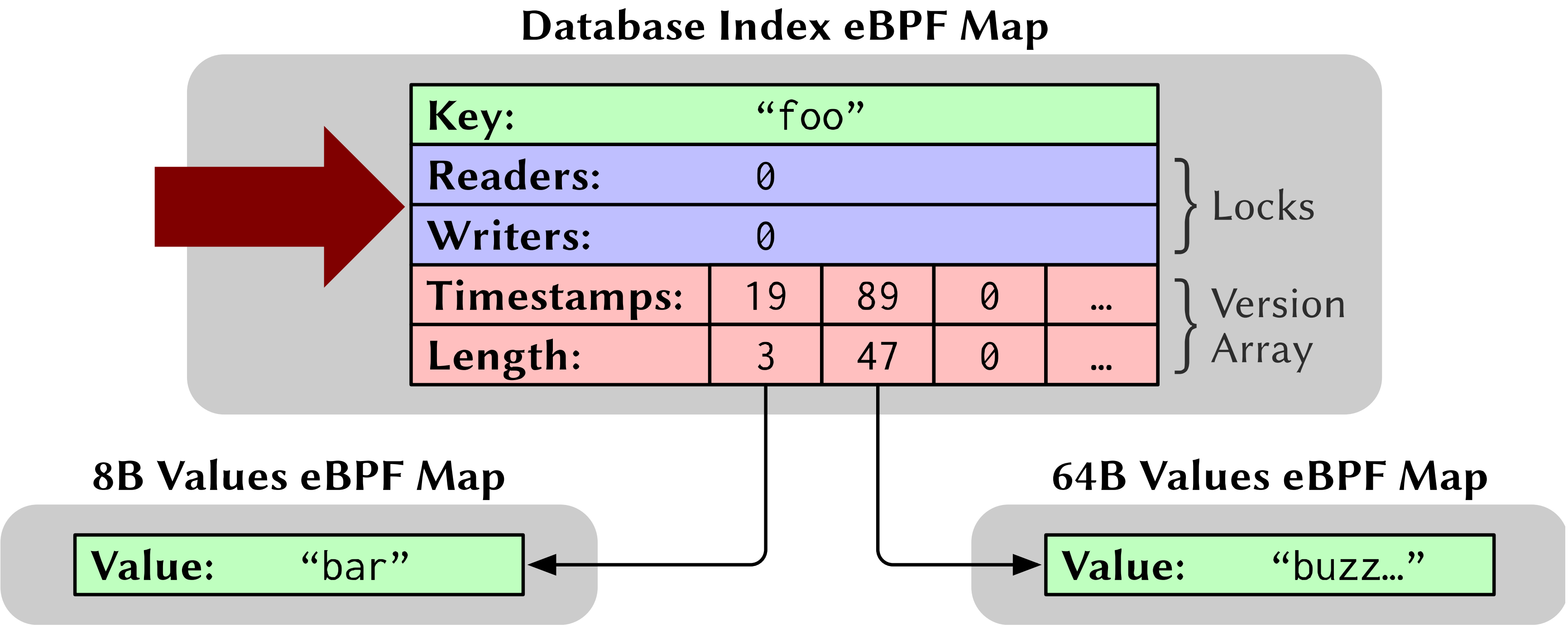

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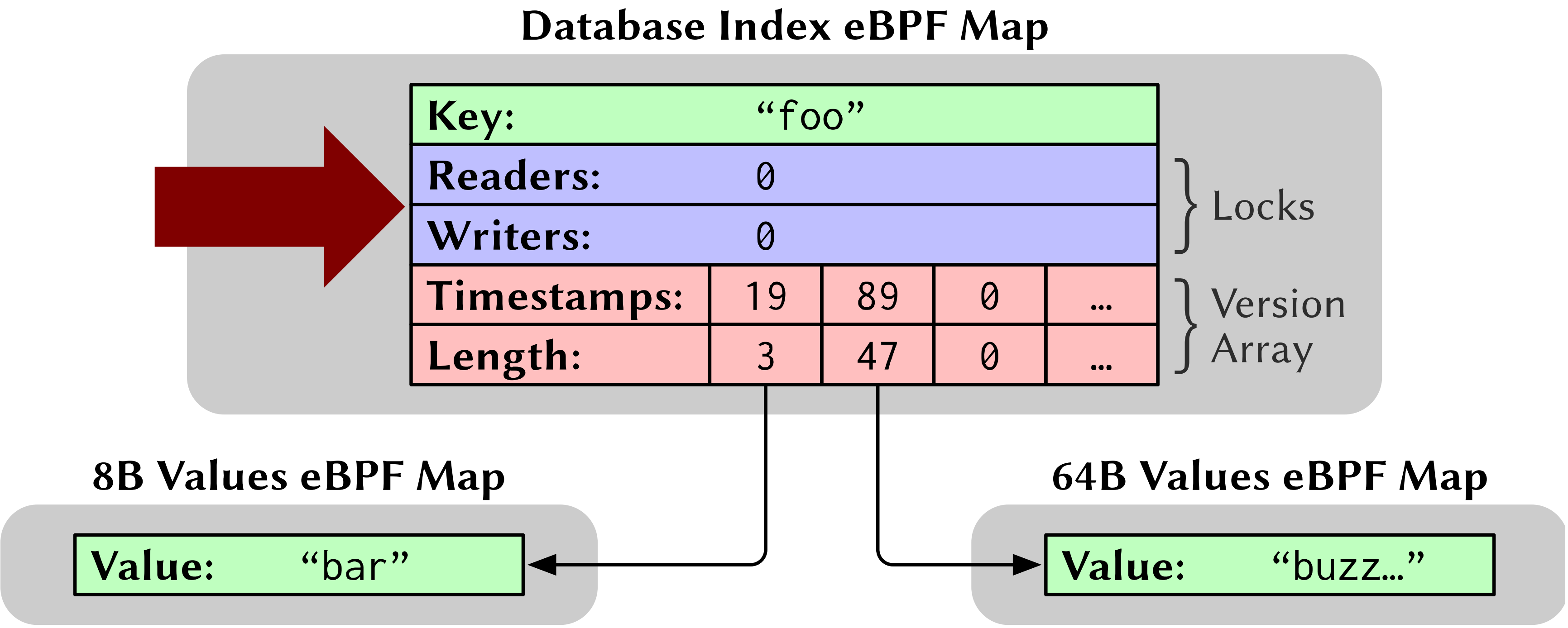
Transaction Management

- Strict MV2PL



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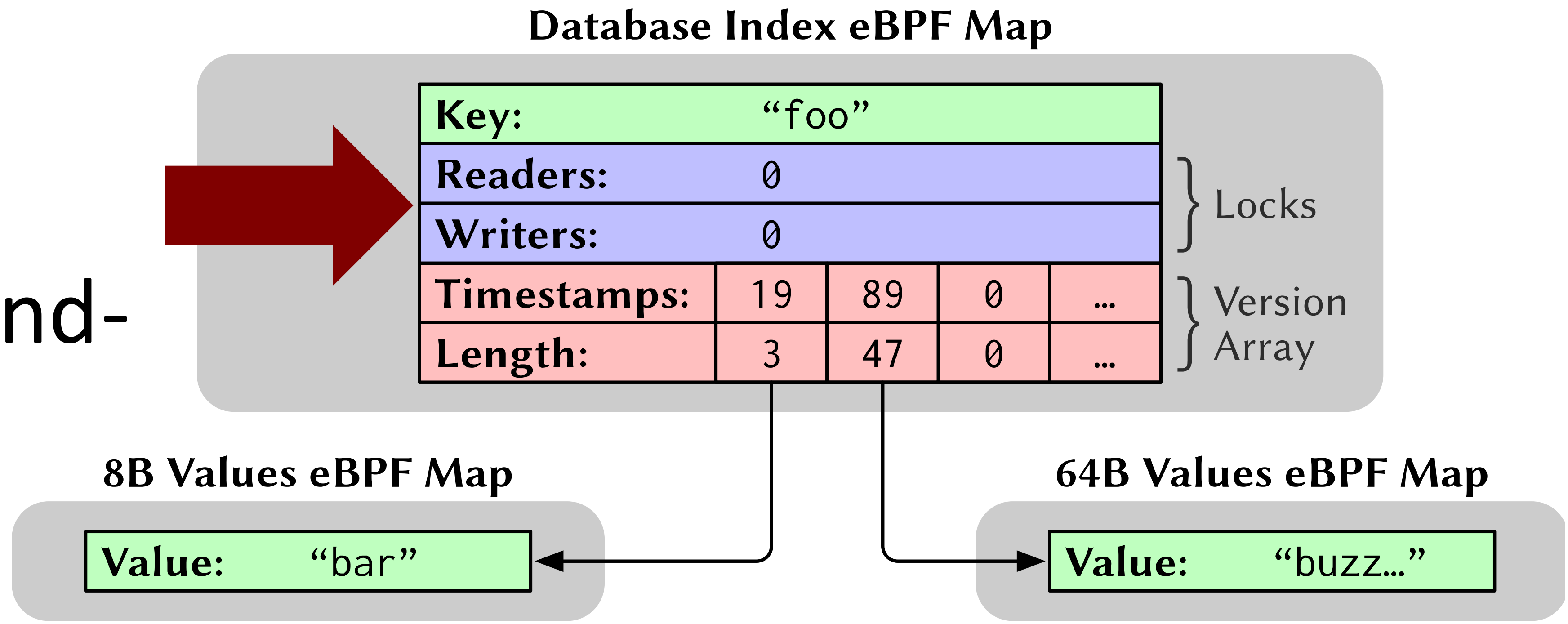

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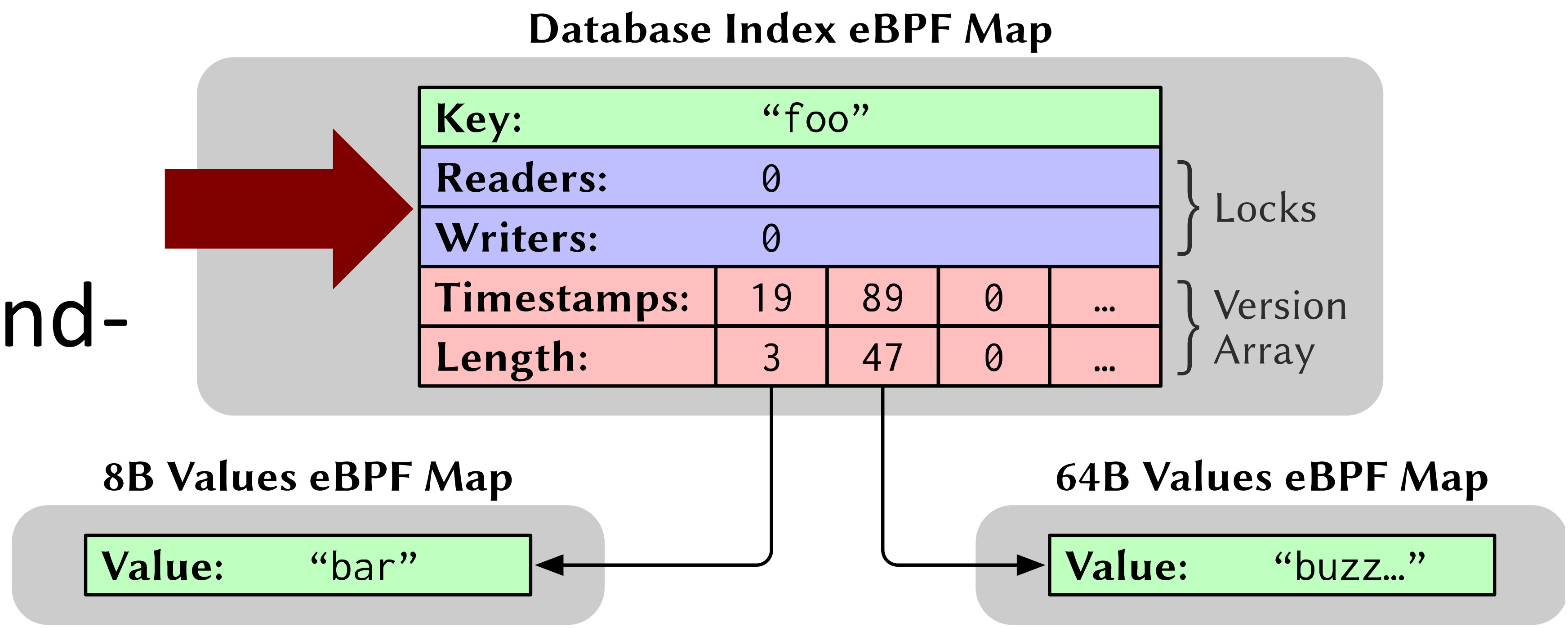
Yingjun Wu et al. An Empirical Evaluation of In-Memory Multi-Version Concurrency Control. *VLDB*. 2017.

Transaction Management

- Strict MV2PL
- No-wait instead of wound-wait or wait-die
- Read-only optimizations



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Write-Ahead Logging

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- Challenges:
  - eBPF programs cannot initiate disk access
  - Database contents are stored in kernel-resident data

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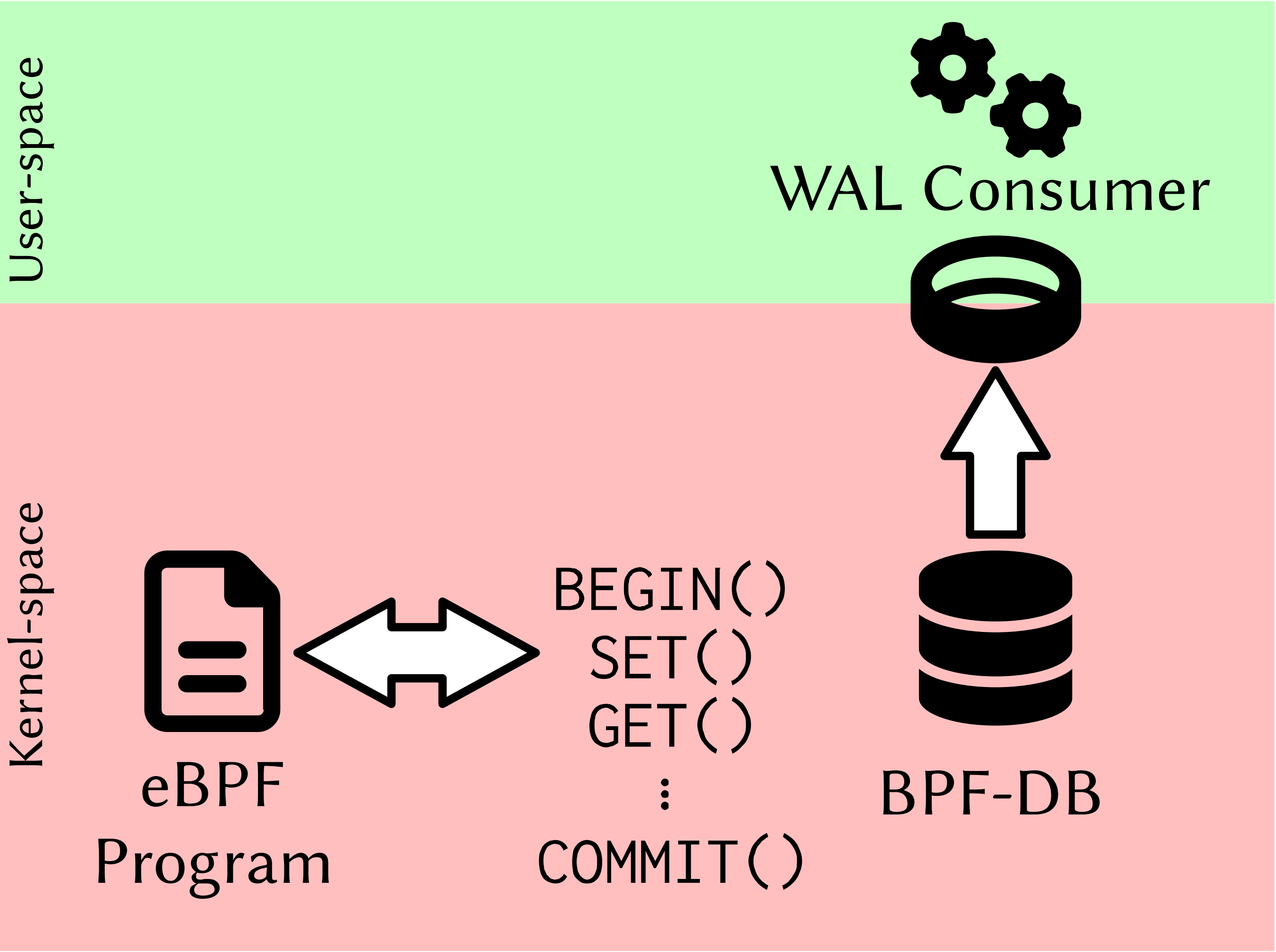
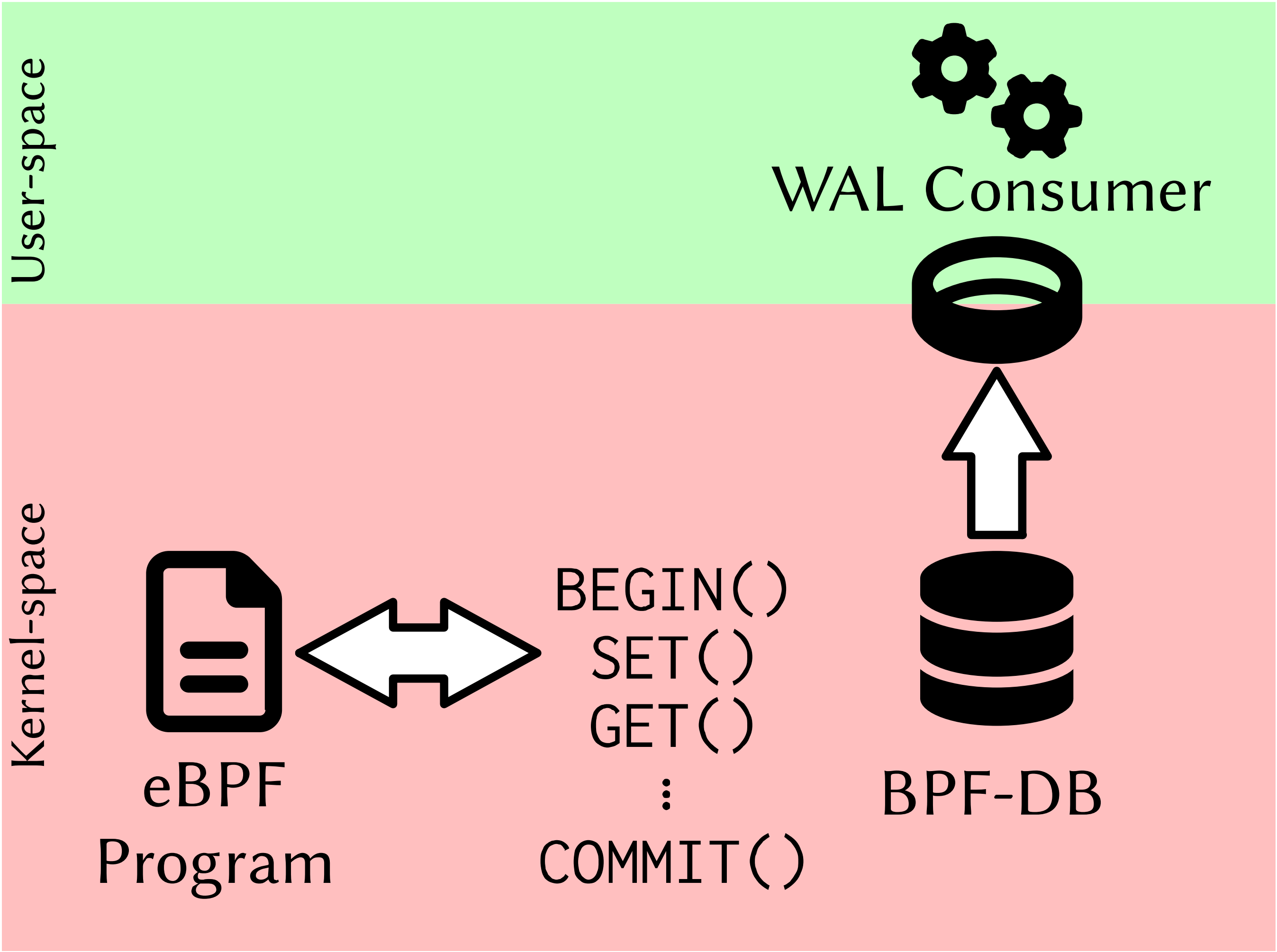


Write-Ahead Logging

- Logical logging via ring buffer to user-space



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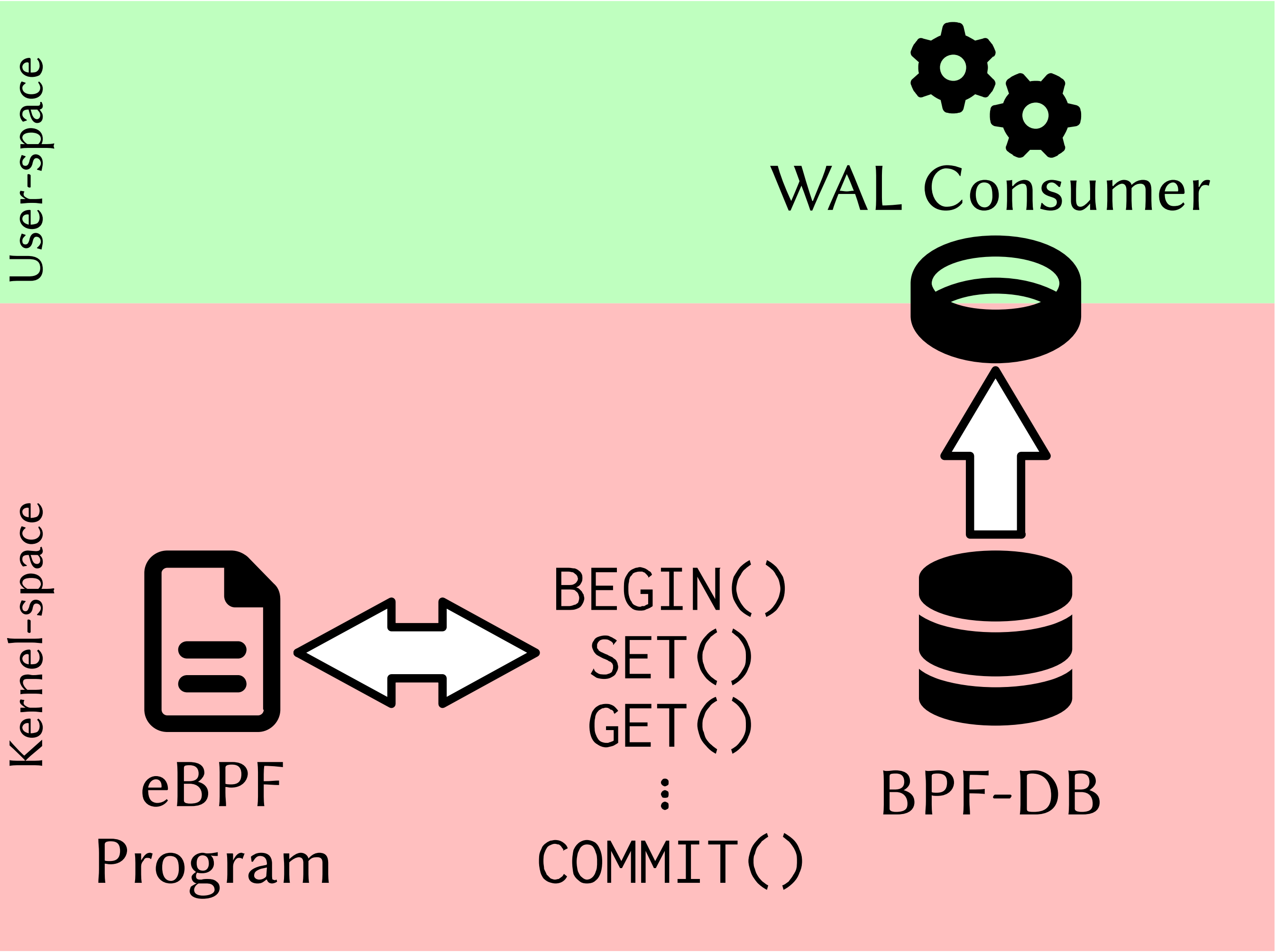
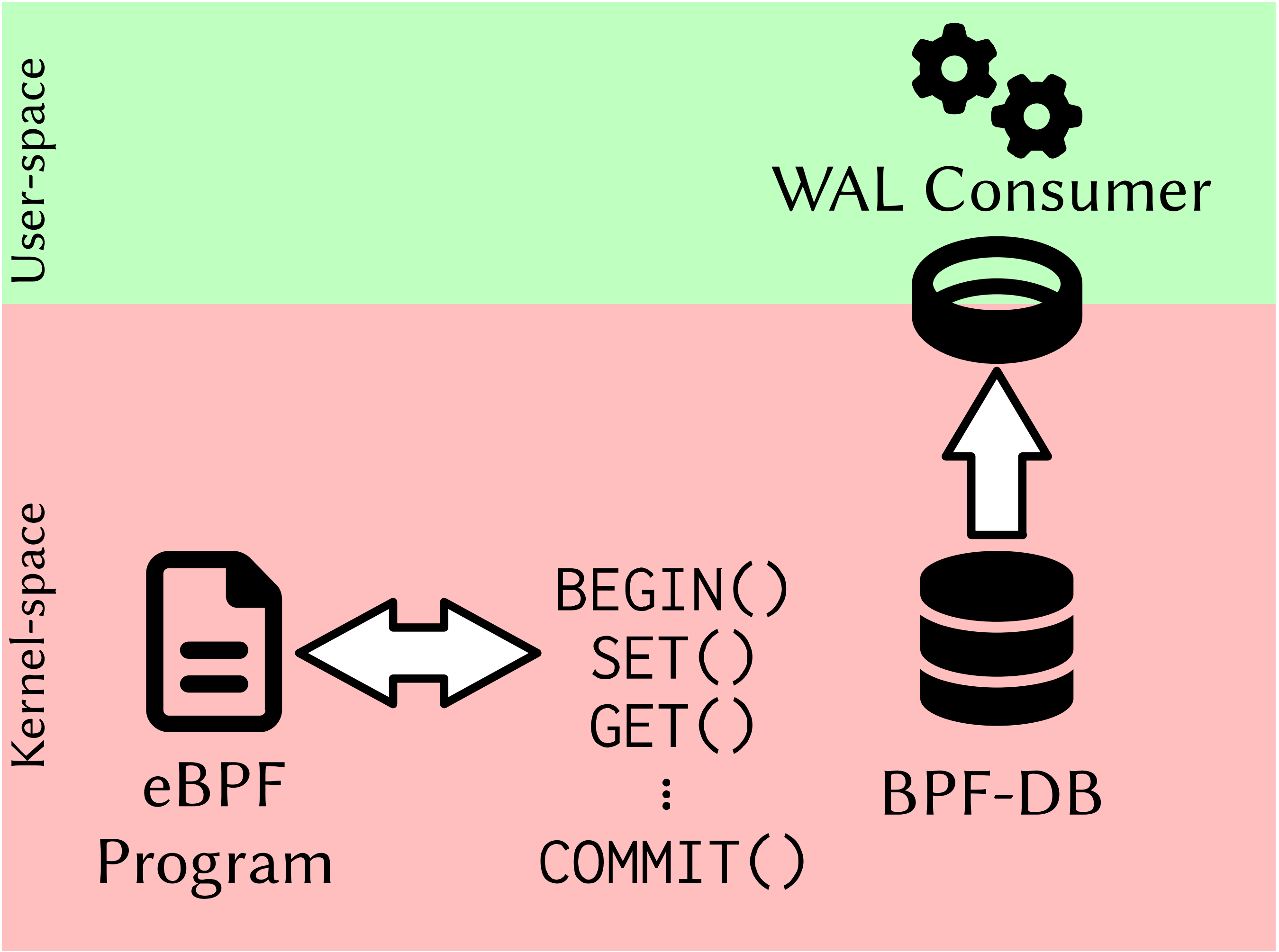


Write-Ahead Logging

- Logical logging via ring buffer to user-space
- User-space can persist on disk or over network
- Checkpointing requires to quiesce the DBMS



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- Adaptation generates a customized DBMS for the client application