Safe and Efficient Remote Application Code Execution on Disaggregated NVM Storage with eBPF

Kornilios Kourtis† Animesh Trivedi‡ Nikolas Ioannou§
†Independent researcher ‡Vrije Universiteit (VU), Amsterdam §IBM Research, Zurich

Abstract
With rapid improvements in NVM storage devices, the performance bottleneck is gradually shifting to the network, thus giving rise to the notion of “data movement wall”. To reduce the amount of data movement over the network, researchers have proposed near-data computing by shipping operations and compute-extensions closer to storage devices. However, running arbitrary, user-provided extensions in a shared, disaggregated storage environment presents multiple challenges regarding safety, isolation, and performance. Instead of approaching this problem from scratch, in this work we make a case for leveraging the Linux kernel eBPF framework to program disaggregated NVM storage devices. eBPF offers a safe, verifiable, and high-performance way of executing untrusted, user-defined code in a shared runtime. In this paper, we describe our experiences building a first prototype that supports remote operations on storage using eBPF, discuss the limitations of our approach, and directions for addressing them.

1 Introduction
NVM disaggregation over network (e.g., NVMoF) offers a number of advantages including better utilization and independent scaling of compute and storage [34]. To meet the performance and capacity demands, the underlying storage has innovated rapidly in the mediums, interfaces, and packaging (multiple parallel banks and channels) to push the performance of NVM devices to the near-memory performance in a short span of time [46, 57, 58]. In contrast, the connecting network (or, in general, the link technologies, e.g., PCIe, Ethernet, Fiber Channel) performance is improving at a slower pace. For example, a modern storage device can read upwards of 10-15 GB/sec [51] which exceeds the bandwidth of a 100 Gbps network link (or a PCIe Gen 3 x8 link). This performance gap between a storage device and its access network creates a “data movement wall”, which is shifting the performance bottleneck from storage to network [27, 37].

Naturally, there are many optimization opportunities to reduce the pressure on the network by pushing operations closer to the storage [35]. For example, read-modify-write operations (e.g., incrementing a counter in a key-value store) can be implemented with a single (instead of two) network request(s), while database queries can be partially offloaded to the storage to save bandwidth and energy [17, 28, 32]. These opportunities are widely acknowledged, leading to attempts to exploit them either for local [11, 52] or remote [27, 37] storage. Shipping compute to storage is not novel in itself and has a long history [1, 29, 50], but existing approaches focus on specific operations and applications, and in most cases operate above the block layer. A disaggregated block service, however, is meant to serve different applications. Each application has its own requirements, storage layouts, and implementation nuances that make it difficult to come up with specific operations that can serve all applications equally well.

In this paper, we explore using eBPF to solve the aforementioned challenges. The original BPF (BSD Packet
Filter) [40] was developed for implementing user-specific packet filters that could be safely and efficiently executed in the kernel, avoiding the need to copy all packets from kernel to user-space [39]. Based on this, Linux has developed its own variant called eBPF [12, 20, 56] that is used for a plethora of purposes.  

Why eBPF: eBPF is a good fit for three key reasons. First, unlike being tied to a single domain, the eBPF VM has emerged as an expressive and the de facto way for user-space to push generic code into the Linux kernel, and is used in numerous applications: executing user-defined code in the network data-path before a packet enters the kernel network stack [9, 63], traffic control [8], tracing [24], enhancing Linux security [31], and writing safe kernel/hypervisor extensions [2]. Second, to ensure safe execution, the eBPF framework includes a verifier to check correct and bounded execution of extensions. Performance is delivered by using a JIT facility for compiling eBPF code into native (x86_64, ARM) code. Lastly, eBPF is available now, and is relatively mature and battle tested. Its wide adoption has resulted in a rich ecosystem of compilers, tools, and implementations that can be reused in other contexts [7, 18, 26, 48], in addition to the Linux kernel implementation.  

Our approach is in contrast to a clean slate approach of implementing such a facility from scratch (using proof-carrying code [43], software fault isolation (SFI) [61], or safe language extensions like Rust [37]). Indeed, we believe that if we had undertaken the latter, we would have reached a fundamentally different design. Starting from eBPF, however, is a more pragmatic approach because it allows us to reuse a lot of the existing infrastructure and benefit from the community built around it.

Potential Gains: To motivate our work, we estimate the I/O operation overhead for doing two key operations over remote data: (i) increment a numerical value and (ii) performing a binary search over a 1 TiB sorted array of 8B values. We measure the TCP round trip time of a small message (64B) over a 10GbE network using `netperf` (41.9 µs), and use that to account for network I/O operations. We measure the read and write latency (5.6 and 8.0 µs, respectively) of an 3DXP NVMe drive, and use that to account for the read and write latency of storage I/O operations. Fig 1 illustrates the expected performance of these two operations when only accounting for I/O operations, not taking into account any data processing or contention. Offloading the remote numerical increment operation can reduce the latency by 43% (Fig 1a), due to halving the network operations required. Offloading a binary search over 1 TiB of sorted 8B values (237 values) to the disaggregated storage provides even higher benefits, reducing latency by 86% compared to performing this operation remotely (Fig 1b). This large expected speedup can be attributed to the reduction of network operations from 37 down to 1.

In summary, reducing the network round trips helps to reduce the pressure on the network, thus improving an application performance. In this paper, we tackle this performance improvement problem by using eBPF to ship to and safely execute code (which we call `appcode`) on shared, disaggregated NVM devices.

2 eBPF Primer

Toolchain: While it is possible to write eBPF directly in bytecode, the clang compiler includes a backend for generating eBPF from C code. Each eBPF program is defined as a function that takes a context (ctx) argument and returns an integer value. The type of ctx depends on the type of the eBPF program (e.g., packet filtering or
Within the area that the eBPF code can access. Without
valid boundaries of the \texttt{ctx} structure, eBPF code
may also access data outside of the \texttt{ctx} structure (e.g.,
raw network packet data), but the verifier needs to ensure
that the accesses are valid. This works by having fields
of \texttt{ctx} designating valid regions. In the example of Listing 1,
the region is within \texttt{ctx->data} and \texttt{ctx->data_end}.\footnote{There is also another region the code is allowed to access: \texttt{ctx->data\_meta, ctx->data}, but we ignore this in the rest of the paper for sake of brevity.} The check in line 5 ensures that the Ethernet packet header is
within the area that the \texttt{eth} field of \texttt{ctx} occupies.
Without that check, the verifier would fail to validate the code on
line 7 since it cannot tell that this is indeed a valid access.

Second, the execution time of eBPF code is bounded
so that other applications will not be denied service. The
verifier ensures that the eBPF function will return in a
reasonable amount of time by ensuring that there are no
back-edges in the control flow graph (disallowing loops),
and that both the number of total instructions but also the
maximum number of instructions for any given control
flow path are bounded.

eBPF code is also allowed to invoke a number of helper
functions \cite{19}. These functions are provided by the
system as a way to implement functionality that is not possible
to implement within eBPF itself, such as interacting
with other subsystems.

\begin{verbatim}
int ipv4(struct xdp_md *ctx) {
  void *data_end = (void *)\((\text{long})\)ctx->data_end;
  void *data = (void *)\((\text{long})\)ctx->data;
  struct ethhdr *eth = data;
  if (data + \text{sizeof}(\text{struct}) > data_end)
    return XDP\_DROP;
  if (eth->h\_proto == htons(ETH\_P\_IP))
    return XDP\_PASS;
  return XDP\_DROP;
}
\end{verbatim}

Listing 1: C eBPF code example

Listing 2: Code sketch of task serving a client

\begin{verbatim}
while (true) {
  recv(req); // receive request
  ty = req->type // request type
  if (ty == READ) {
    // read blocks from device
    rep = do\_read(req);
  } else if (ty == WRITE) {
    // write blocks to the device
    rep = do\_write(req);
  } else if (ty >= AC\_BASE && ty < AC\_MAX) {
    appcode = appcode\_table[ty - AC\_BASE];
    rep = appcode(req);
  } else rep = error();
  send(rep); // send reply
}
\end{verbatim}

3  eBPF-powered Disaggregated NVM Storage Service Design

A disaggregated storage service provides different clients
with storage devices over the network via a protocol such as
NVMoF \cite{44}, AoE \cite{14}, iSCSI, or NBD \cite{42}. Clients
connect to a given device, and after they are authenticated
and authorized, they can issue block-level commands (e.g.,
\texttt{READ} or \texttt{WRITE}) to it. We built a prototype to explore
using eBPF for a disaggregated NVM storage service,
which we briefly describe next. While our ideas are not
necessarily tied to this design, we include it because it
allows for a more concrete discussion. The service serves
requests over the network from multiple clients by issuing
appropriate commands to storage devices. Listing 2
(ignoring lines 10–12) shows a code sketch for a task that
serves a client, issuing appropriate (e.g., \texttt{read} or \texttt{write})
commands to the storage. When an IO operation (e.g.,
\texttt{recv, read, write, or send}) is issued, the task switches to
the scheduler. When the results of the requested IO operation
become available, the task will become runnable, and
eventually be scheduled. To avoid the performance limitations of synchronous IO \cite{4,30}, we perform asynchronous
IO using collaboratively scheduled user-space tasks, as in
our previous work \cite{36}. The tasks are written so that they
do not hold the CPU for a long time, allowing other tasks
to run and other clients to be served. Moreover, using
appropriate algorithms in the scheduler, QoS policies can
be implemented, but this is beyond the scope of this work.

3.1 Supporting eBPF appcode

In our design, the eBPF verification and execution runs in
the storage service instead of the kernel. To this end, we
ported the Linux kernel eBPF infrastructure to user-space,
and used it to build our prototype.

We use NBD in our prototype because it is simple
(request and reply headers are shown in Listing 3). To
support the eBPF appcode, we piggyback on NBD by
overloading the request type, and allow users to register different appcodes and then invoke them by setting the proper request type (Listing 2, lines 10–12).

The appcode’s argument (ctxt) in our prototype includes: a handle to the storage device (e.g., file descriptor); data from the request header (from, len, and type); and data pointers (data and data_end) to the payload of the request. The len field contains the size of the payload, while the from field, which normally contains the operation offset in the storage device, can be used arbitrarily by the appcode. The payload data are also arbitrarily interpreted by the appcode. The return value of the appcode is placed in the error field of the reply, while the appcode can also specify an area in the data region to be sent as payload to the reply.

The appcode may use the following eBPF functions: data_realloc(s), which resizes the data area between data and data_end to be s bytes, potentially allocating a new area and copying data; io_read(dev_off, data_off, s), which reads s bytes from an offset in the device (dev_off) and places them in ctxt->data + data_off; and io_write(dev_off, data_off, s), that operates similarly to the read operation, but writes data.

Using the above approach, it is possible to support remote operations on disaggregated storage. Next, we describe two example use-cases: implementing read-modify operations for a KV store, and SQL filter offloading.

### 3.2 Example: remote increment operation

Many data stores (e.g., key-value stores) support read-modify (e.g., increment) operations [41, 49]. Implementing a read-modify operation in a traditional disaggregated storage service requires two network requests. Using our appcode facility we can perform the read-modify operation in the storage server, requiring a single network request, reducing the latency and network traffic.

We consider a key-value store as a concrete use case, with an in-memory hash table index. Each hash table entry includes a key fingerprint, the storage location of the full key-value record, and the size of the record. The format of the key-value record in storage is as follows: (key length, value length, key, value). Increasing an integer value (with the same endianness as the host) requires: i) fetching the key-value record from storage, ii) comparing the full key of the request with the key of the record, iii) increasing the value by one, assuming the keys match, and iv) writing the record back to storage.

We implemented this operation in our prototype. The key-value store runs on the client of the storage service, and invokes the appcode that performs the increment. The from field of the request includes the storage address of the key-value record, while the payload includes the record size and the full key. The appcode uses data_realloc() and io_read() to make space and read the key-value record using the storage address and the record size. Then it compares the key of the record with the key in the payload, and if they do not match, it returns an appropriate error. Otherwise, it increments the value and uses io_write() to store it. Because eBPF does not support loops, the memory compare operations needs to be unrolled, so our approach can only be applied to keys smaller than a certain size. If the key is larger than this size, the key-value store works as it would have before.

### 3.3 Example: Spark SQL filter offloads

Here, we sketch how Spark SQL filters can be offloaded into an eBPF-enhanced storage service for a “near-device” evaluation. During the query planning phase, Spark generates row filters for selection queries. A filter consists of a group of constraints on the value of columns in a row. For example, in `SELECT * FROM Customers WHERE CustomerID=1`, the equality condition for the CustomerID column is the filter. These filters are then provided to an input data source, where the data are typically stored using Parquet [47] or ORC [45]. We assume a disaggregated block device using one of these data formats to store data.

Many formats maintain metadata segments that contain column information. For example, in Parquet metadata are stored at the end of every data file. Alibis [59], another high-performance format, maintains metadata in a separate file. The metadata contain information about the data such as minimum and maximum values, sorted or not, all nulls or not, etc., that is used to evaluate a filter, as well as the location of the data blocks. These metadata are maintained in blocks of data ranging from 10 to 100MBs. Instead of fetching these blocks to the client, we want to offload this operation to the storage service by shipping appropriate eBPF code. The code will receive parameters that specify the filters and the location of the metadata block. Using this information, the code will read the metadata block, and return the data blocks that the query needs to process (e.g., by considering the minimal and maximum values of a column).
3.4 Limitations and future directions

Trying to implement the above examples (and also a Boyer-Moore string search algorithm [10]) in our prototype, we concluded that even if these operations can be supported in a constrained form with our current approach, the absence of loops in eBPF makes it difficult to support use cases that involve processing large amounts of data. Moreover, we found that the compiler (clang) has a hard time generating code that would pass the verification process with high loop unroll counts.

The above issues are not surprising, since eBPF was not built with data processing in mind. Nevertheless, we believe that this is an important use case which should be supported. In the next paragraphs, we discuss a number of approaches for extending eBPF to address these issues.

Extend eBPF to support loops As eBPF is increasingly used, the inability to verify code with loops has become a noticeable problem. Recent work, for example, aims to allow bounded loops in eBPF [15]. Although such a facility is certainly useful, applications that operate on large amounts of data will still be limited in what they can do. A different approach would be to "teach" the verifier that some eBPF functions (e.g., io_read, io_write, in our case) return the control to the system, so they effectively reset the time the appcode is executing because the system (the task scheduler in our case) may defer execution to other tasks. This, however, requires substantial changes to the verifier, because introducing loops has implications not only for bounding execution time, but also for proving the safety of the code since now register values might be set from multiple dataflow paths. Even though projects like KLEE [33] push the boundaries of what symbolic execution can do, this is still a challenging problem.

Total programs A program is total if it always terminates. It is a well-known theoretical result that it is impossible to prove totality for Turing-complete languages, but there are languages which sacrifice their generality to be able to prove that their programs (assuming they compile) will always terminate. One approach would be to try and incorporate methods from this domain into eBPF to allow for a richer set of computations for eBPF code. This, however, is not sufficient for practical purposes since a program might be guaranteed to terminate, but still take a very long time to terminate. Indeed, the Dhall language which is a configuration language following this approach, identifies this issue in its documentation [22].

High-order functions Another approach is to enrich the execution environment with high-order functions such as map, reduce which may take user-defined functions implemented in eBPF as arguments. This will result in a declarative approach of the remote code to be executed, which allows the run-time system to decide how to exactly execute it. At the same time, the user-defined functions, written in eBPF, are verified for safety in terms of data access and bounded execution times. The challenge with this approach is to determine the proper functions that allow expressing the required programs, while at the same time allowing for an efficient execution by the run-time system. We plan to follow this direction in our future work.

4 Related Work

Pushing computation to storage is not a new idea and has a long history in systems like iDisk [29], Active disks from UCSB [1], and CMU [50]. Later systems like MapReduce [16] and Spark [64] popularized the idea of "shipping code to data" where compute was shipped to co-located data and compute nodes. Systems like YourSQL [28], Ibex [62], and other works [17, 32] explore SQL offloading to smart, programmable storage devices. In this work, we focus on developing a more general approach towards compute offloading, which also includes SQL offloading.

Summarizer offloads parts of computation on wimpy SSD ARM cores by enhancing the NVMe protocol [35]. Willow [52] is a programmable SSD with an attached FPGA. Caribu [27] implements “smart distributed storage with replication” in FPGAs, and provides a key-value interface with a support for iterations with predicates for compute offloading. IBM Netezza and Oracle Exadata also offload parts of the computation close to storage devices. In comparison, our approach focuses on synthesizing safe extensions that can be run in a shared storage environment. Naturally, any hardware accelerator can be used to accelerate the execution of the eBPF code (e.g., eBPF NIC offloading [60]). Splinter [37] is a recently proposed system that uses Rust language features to support the safe execution of user code in a multi-tenant KV store. Broadly speaking, sandboxes and fault isolation research using compiler, language, or runtime systems is another promising avenue [6, 21, 25, 61]. In this work, instead of starting from scratch, we focus on using the existing eBPF framework for developing and executing user-provided compute offloading extensions. Building advanced features in the storage devices like distributed shared log [3], key-value stores [54, 55], higher-level abstractions and re-usable components [13, 38, 53] help to extend the utility of the storage service beyond just storing data. More recently, there is an open discussion on evaluating the suitability of eBPF for block devices on the Linux kernel mailing list as well [5].

5 Discussion Topics

This paper discusses work which is still at early stages. We are fairly confident that the ability to push operations to remote storage is important. Hence, we would be in-
We are less confident that eBPF is best the way to tackle the resulting security trade-offs. We are less confident that eBPF is best the way to tackle this issue, but we do think that it will become increasingly used which means that building on it offers unique benefits. We would be interested in hearing counter-proposals to eBPF for supporting these remote operations, as well as other ways of enhancing eBPF to make it more suitable for data processing.

In our paper we focus on the challenge of safety and generality of using eBPF for remote operations on disaggregated storage. A full system, however, needs to address a number of other issues. We would be very interested in discussing these issues, some of which we mention next. NBD is a simple protocol and we used it as a placeholder, but a practical solution will need to be piggybacked to more complicated protocols such as NVMoF. Furthermore, another interesting question is how offloading to disaggregated storage can be integrated with the rest of the storage stack, and specifically how it can be used on top of a block device or even on top of a file-system. Finally, allowing applications to upload arbitrary code has non-obvious security implications (e.g., it may introduce side channels) and we would need to understand the resulting security trade-offs.

References

[1] Acharya, A., Uysal, M., and Saltz, J. Active disks: Programming model, algorithms and evaluation. In Proceedings of the Eighth International Conference on Architectural Support for Programming Languages and Operating Systems (1998). ASPLOS VIII.

[2] Amit, N., and Wei, M. The design and implementation of hypercalls. In 2018 USENIX Annual Technical Conference (USENIX ATC 18) (Boston, MA, 2018), USENIX Association, pp. 97–112.

[3] Balakrishnan, M., Malkhi, D., Prabhakaran, V., Wobblor, T., Wei, M., and Davis, J. D. CORFU: A shared log design for flash clusters. In Presented as part of the 9th USENIX Symposium on Networked Systems Design and Implementation (NSDI 12) (San Jose, CA, 2012), USENIX, pp. 1–14.

[4] Barroso, L., Marty, M., Patterson, D., and Ranganathan, P. Attack of the killer microseconds. Commun. ACM 60, 4 (2017).

[5] Bates, S. Mailthread on the Linux kernel mailing list, subject:[lsf/mm topic] bpf for block devices. https://lkml.org/lkml/2019/2/7/647.

[6] Bershad, B. N., Savage, S., Pardyak, P., Sirer, E. G., Ficucienski, M. E., Becker, D., Chambers, C., and Eggers, S. Extensibility safety and performance in the spin operating system. In Proceedings of the Fifteenth ACM Symposium on Operating Systems Principles (New York, NY, USA, 1995), SOSP ’95, ACM, pp. 267–283.

[7] Big Switch Networks. Userspace ebpf vm. https://github.com/iovisor/ubpf.

[8] Borkmann, D. BPF programmable classifier and actions for ingress/egress queuing disciplines. http://man7.org/linux/man-pages/man8/tc-bpf.8.html.

[9] Borkmann, D. Making the kernel’s networking data path programmable with BPF and XDP. Open Source Summit North America, 2017. http://sched.ws/hosted_files/ossna2017/da/BPFandXDP.pdf.

[10] Charras, C., and Lecroq, T. Handbook of exact string matching algorithms. 2004.

[11] Cho, S., Park, C., Oh, H., Kim, S., Yi, Y., and Ganger, G. R. Active disk meets flash: A case for intelligent ssds. In Proceedings of the 27th International ACM Conference on International Conference on Supercomputing (New York, NY, USA, 2013), ICS ’13, ACM, pp. 91–102.

[12] BPF and XDP reference guide. https://github.com/cilium/cilium/blob/master/Documentation/bpf.rst.

[13] Coburn, J., Bunker, T., Schwarz, M., Gupta, R., and Swanson, S. From aries to mars: Transaction support for next-generation, solid-state drives. In Proceedings of the Twenty-Fourth ACM Symposium on Operating Systems Principles (New York, NY, USA, 2013), SOSP ’13, ACM, pp. 197–212.

[14] Coile, B., and Hopkins, S. The ATA over ethernet protocol. Tech. rep., Coraid Inc, 2005.

[15] Corbet, J. Bounded loops in BPF programs. https://lwn.net/Articles/773605/.

[16] Dean, J., and Ghemawat, S. Mapreduce: Simplified data processing on large clusters. In Proceedings of the 6th Conference on Symposium on Operating Systems Design & Implementation - Volume 6 (2004), OSDI’04.

[17] Do, J., Kee, Y.-S., Patel, J. M., Park, C., Park, K., and DeWitt, D. J. Query processing on smart SSDs: Opportunities and challenges. SIGMOD ’13.
[18] DPDK (version 18.05): Berkeley packet filter library. https://doc.dpdk.org/guides-18.05/ prog_guide/bpf_lib.html.

[19] Linux eBPF helper functions (version: 5.0). https://git.kernel.org/pub/scm/linux/kernel/git/torvalds/linux.git/tree/include/uapi/linux/bpf.h?h=v5.0#n455.

[20] Linux socket filtering aka berkeley packet filter (BPF). https://www.kernel.org/doc/ Documentation/networking/filter.txt

[21] Geambasu, R., Levy, A. A., Kohno, T., Krishnamurthy, A., and Levy, H. M. Comet: An active distributed key-value store. In Proceedings of the 9th USENIX Conference on Operating Systems Design and Implementation (Berkeley, CA, USA, 2010), OSDI’10, USENIX Association, pp. 323–336.

[22] Gonzalez, G. Dhall safety guarantees: Turing-completeness. https://github.com/dhall-lang/dhall-lang/wiki/Safety-guarantees#turing-completeness.

[23] Gregg, B. Learn ebpf tracing: Tutorial and examples. http://www.brendangregg.com/blog/2019-01-01/learn-ebpf-tracing.html.

[24] Gregg, B. D. Linux Enhanced BPF (eBPF) Tracing Tools. http://www.brendangregg.com/ebpf.html.

[25] Gu, B., Yoon, A. S., Bae, D.-H., Jo, I., Lee, J., Yoon, J., Kang, J.-U., Kwon, M., Yoon, C., Cho, S., Jeong, J., and Chang, D. Biscuit: A framework for near-data processing of big data workloads. In Proceedings of the 43rd International Symposium on Computer Architecture (Piscataway, NJ, USA, 2016), ISCA ’16, IEEE Press, pp. 153–165.

[26] IO Visor. BPF compiler collection (BCC). https://github.com/iovisor/bcc.

[27] István, Z., Sidler, D., and Alonso, G. Caribou: Intelligent distributed storage. Proc. VLDB Endow. (2017).

[28] Jo, I., Bae, D.-H., Yoon, A. S., Kang, J.-U., Cho, S., Lee, D. G., and Jeong, J. Yoursql: A high-performance database system leveraging in-storage computing. Proc. VLDB Endow. 9, 12 (Aug. 2016), 924–935.

[29] Keeton, K., Patterson, D. A., and Hellerstein, J. M. A case for intelligent disks (idisks). SIGMOD Rec. 27, 3 (Sept. 1998).

[30] Kegel, D. The c10k problem. http://www.kegel.com/c10k.html, 2014.

[31] Kerrisk, M. Using seccomp to limit the kernel attack surface. Linux Plumbers Conference, 2015. http://man7.org/conf/lpc2015/limiting_kernel_attack_surface_with_seccomp.pdf.

[32] Kim, S., Oh, H., Park, C., Cho, S., Lee, S.-W., and Moon, B. In-storage processing of database scans and joins. Inf. Sci. 327, C (Jan. 2016), 183–200.

[33] KLEE LLVM execution engine. https://klee.github.io/.

[34] Klimovic, A., Kozyrakis, C., Thereska, E., John, B., and Kumar, S. Flash storage disaggregation. In Proceedings of the Eleventh European Conference on Computer Systems (2016), EuroSys ’16.

[35] Koo, G., Matam, K. K., I. T., Narra, H. V. K. G., Li, J., Tseng, H.-W., Swanson, S., and Annavaram, M. Summarizer: Trading communication with computing near storage. MICRO-50 ’17.

[36] Kourtis, K., Ioannou, N., and Koltsidas, I. Reaping the performance of fast NVM storage with udevopt. In 17th USENIX Conference on File and Storage Technologies (FAST 19) (2019).

[37] Kulckarni, C., Moore, S., Naqvi, M., Zhang, T., Ricci, R., and Stutsman, R. Splinter: Bare-metal extensions for multi-tenant low-latency storage. In 13th USENIX Symposium on Operating Systems Design and Implementation (OSDI 18) (Carlsbad, CA, 2018), USENIX Association, pp. 627–643.

[38] MacCormick, J., Murphy, N., Najork, M., Thekkath, C. A., and Zhou, L. Boxwood: Abstractions as the foundation for storage infrastructure. In Proceedings of the 6th Conference on Symposium on Operating Systems Design & Implementation - Volume 6 (Berkeley, CA, USA, 2004), OSDI’04, USENIX Association, pp. 8–8.

[39] McCanne, S., and Jacobson, V. The bsd packet filter: A new architecture for user-level packet capture. In Proceedings of the USENIX Winter 1993 Conference, USENIX’93.

[40] McCanne, S., and Jacobson, V. The bsd packet filter: A new architecture for user-level packet capture. In USENIX winter (1993), vol. 46.
[41] memcached – a distributed memory object caching system. http://www.memcached.org/.

[42] The NBD protocol. https://sourceforge.net/p/nbd/code/ci/master/tree/doc/proto.md.

[43] NECULA, G. C., AND LEE, P. Safe kernel extensions without run-time checking. SIGOPS Operating Systems Review 30 (1996).

[44] NVM EXPRESS WORKGROUP. NVM Express over Fabrics, 2016. Rev. 1.0.

[45] Apache parquet. https://parquet.apache.org/.

[46] Paik, Y. Developing extremely low-latency nvme ssds. Flash Memory Summit, 2017. https://www.flashmemorysummit.com/English/Collaterals/Proceedings/2017/20170809_FA21_Paik.pdf.

[47] Apache parquet. https://parquet.apache.org/.

[48] QUENTIN MONNET. Rust virtual machine and jit compiler for ebpf programs. https://github.com/qmonnet/rbpf.

[49] Redis. http://redis.io/.

[50] Riedel, E., Faloutsos, C., Gibson, G. A., and Nagle, D. Active disks for large-scale data processing. Computer 34, 6 (June 2001).

[51] Seagate announces 64tb nvme ssd and new nytro ssds at fms. https://www.storageresview.com/seagate_announces_64tb_nvme_ssd_new_nytro_ssds_at_fms.

[52] Seshadri, S., GaHagan, M., Bhaskaran, S., Bunker, T., De, A., Jin, Y., Liu, Y., and Swanson, S. Willow: A user-programmable SSD. In Proceedings of the 11th USENIX Conference on Operating Systems Design and Implementation (2014), OSDI’14.

[53] Sevilla, M. A., Watkins, N., Jimenez, I., Alvaro, P., Finkelstein, S., LeFevre, J., and Maltzahn, C. Malacology: A programmable storage system. In Proceedings of the Twelfth European Conference on Computer Systems (New York, NY, USA, 2017), EuroSys ’17, ACM, pp. 175–190.

[54] Shen, Z., Chen, F., Jia, Y., and Shao, Z. Optimizing flash-based key-value cache systems. In 8th USENIX Workshop on Hot Topics in Storage and File Systems (HotStorage 16) (Denver, CO, 2016), USENIX Association.

[55] Shen, Z., Chen, F., Jia, Y., and Shao, Z. Dida-cache: A deep integration of device and application for flash based key-value caching. In 15th USENIX Conference on File and Storage Technologies (FAST 17) (Santa Clara, CA, 2017), USENIX Association, pp. 391–405.

[56] Starovoitov, A. BPF – in-kernel virtual machine. Linux Foundation Collaboration Summit, 2015. https://events.linuxfoundation.org/sites/events/files/slides/bpf_collabsummit_2015feb20.pdf.

[57] Strukov, D. B., Snider, G. S., Stewart, D. R., and Williams, R. S. The missing memristor found. Nature 453, 7191 (May 2008), 80–83.

[58] TALLIS, B. The intel Optane SSD DC P4800X (375GB) review: Testing 3D XPoint performance. http://www.anandtech.com/show/11209/intel-optane-ssd-dc-p4800x-review-a-deep-dive-into-3d-xpoint-enterprise-performance, 2017.

[59] Trivedi, A., Stuedi, P., Pfefferle, J., Schuepbach, A., and Metzler, B. Albis: High-performance file format for big data systems. In 2018 USENIX Annual Technical Conference (USENIX ATC 18) (Boston, MA, 2018), USENIX Association, pp. 615–630.

[60] VILJOEN, N. Transparent ebpf offload: Playing nice with the linux kernel. https://www.slideshare.net/Open-NFP/transparent-ebpf-offload-playing-nice-with-the-linux-kernel.

[61] Wabh, R., Lucco, S., Anderson, T. E., and Graham, S. L. Efficient software-based fault isolation. In Proceedings of the Fourteenth ACM Symposium on Operating Systems Principles (New York, NY, USA, 1993), SOSP ’93, ACM, pp. 203–216.

[62] Woods, L., István, Z., and Alonso, G. Ibex: An intelligent storage engine with support for advanced sql offloading. Proc. VLDB Endow. 7, 11 (July 2014), 963–974.

[63] XDP: xpress Data Path. https://www.iovisor.org/technology/xdp.

[64] Zaharia, M., Chowdhury, M., Das, T., Dave, A., Ma, J., McCauley, M., Franklin, M. J., Shenker, S., and Stoica, I. Resilient distributed datasets: A fault-tolerant abstraction for in-memory cluster computing. In Proceedings of the 9th USENIX Conference on Networked Systems Design and Implementation (Berkeley, CA, USA, 2012), NSDI’12, USENIX Association, pp. 2–2.