NATIONAL TECHNICAL UNIVERSITY OF ATHENS
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Efficient file sharing between host and unikernel

DIPLOMA THESIS

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Professor, NTUA

Athens, October 2020

National Technical University of Athens
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Abstract

Cloud computing is the dominant approach to compute infrastructure, established on the technology of virtualization. As the cloud expands, efficient utilization of its compute resources by software becomes imperative. One solution towards that are *unikernels*, operating system kernels specialized to run a single application, sparing resources compared to a general-purpose kernel. Efficient access from virtualized guests to the underlying host's resources is a substantial challenge in virtualization. In this aspect, *virtio* has been a significant contribution, as a specification of paravirtual devices enabling efficient usage of the host's resources. For host-guest file sharing, *virtio-fs* has been proposed, as a virtio device offering guest access to a file system directory on the host, providing high performance and local file system semantics.

This thesis is concerned with the implementation and evaluation of virtio-fs in the context of the OSvunikernel. We demonstrate that combining the two offers great benefits, both with regard to performance achieved, which is comparable to local file systems, and the operational aspect in a cloud context. Moreover, the above are carried out fully within the open-source project behind the unikernel we based our work on. This way, the resulting product gains practical value, being a useful contribution to the project, thus achieving a pivotal, non-technical goal. Furthermore, we explore how open-source software projects and the communities around them work, as we become active members of one.

Keywords

virtualization, cloud, file system, unikernel, virtio, OSv, virtio-fs, QEMU

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Moreover, I owe a big thank you to the people in the OSv and virtio-fs communities for their support, their guidance and their time, but more importantly for their openness, their spirit and work which sparked this contribution.

Finally, those I am most grateful for are my family and friends, who always stand on my side, bear with and support me and without whom nothing could be accomplished.

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Chapter 1

Introduction

1.1 Motivation

1.1.1 Why unikernels

This past decade, we have witnessed the domination of the cloud computing model. The latter has become a cornerstone in many application fields, enabling previously impractical architectures, for a growing number of users. Its broad adoption has also led to a need for managing compute infrastructure of unprecedented scale. The technology behind cloud in its current form is that of virtualization: "curving" multiple, virtual, machines out of a single host system, at will.

Despite the changes brought about by the advent of cloud computing, the conventional slices of the software stack (the operating system being a stark example) have been minimally affected by it. Thus, this part of infrastructure is dominated by general-purpose OS's, like Linux, carrying decades-old design decisions and legacy. This is undoubtedly an indication of the difficulty involved in their implementation, as well as the value contained in current systems, accumulated over a long series of improvements.

A combination of factors makes it obvious that general-purpose operating systems are not the optimal solution for modern application requirements. These factors include the transition from physical to virtual machines, invalidating the assumption of exclusive ownership over the underlying hardware resources. Another contributing element is the rapid bridging of the gap between I/O and processing performance, rendering prohibitive the involvement of the OS in a high-performance application's data path, as backed by the growing popularity of frameworks like [3, 9]. Finally, the large scale of the infrastructure at hand, as mentioned above, amplifies the need for optimized efficiency, since sub-optimum operation bears huge costs.

Unikernels are a notable proposal for substituting conventional operating systems in guests, when those are used to run only a single application. Those result from

merging an application with all supporting elements it requires (typically offered by an OS), in the form of libraries, in a common address space. The executable images produced are run as virtual machines, achieving higher efficiency due to their reduced size (thus faster transport and startup [28], as well as lower storage space requirements), lower memory requirements and more performant system operations, e.g. due to the elimination of mode switches and a simplified security model.

1.1.2 Why shared file system and virtio-fs

Typically, file systems are local, implemented over block devices, inside an operating system kernel. There are cases though which benefit from sharing a common file system across several machines. One such case is that of virtualization, where host and guest share a file system (usually one pre-existing on the host). One example of how useful this can be are virtual machines that get reconfigured by the host, while another one is found in short-lived virtual machines which read input or configuration data and write output data to a common file system.

Virtio-fs is a recent effort in the field of shared file systems, the first one built to target virtualization environments exclusively. This specialization allows it to have no dependency on network protocols or (virtual) network infrastructure, resulting in lower requirements for a guest utilizing it, in addition to improved performance and local file system semantics [41]. What plays an important role in achieving these is the use of a shared memory area between the host and the guest, where file contents are mapped, the so called DAX (Direct Access) window.

1.2 Goals

This work aims to explore the possibilities offered by virtio-fs in a unikernel context. Specifically, we choose OSv and extend its existing, elementary virtio-fs implementation by adding read-only support for the DAX window as well as support for booting off of a virtio-fs file system. These render its use practical across a multitude of cases. Moreover, we evaluate our implementation's performance compared to that of an array of other file systems, in various representative scenarios.

Our goals though extend to non-technical ones, having to do with the free / open source model of software development. Since both projects involved use this model, we consider it an opportunity and a moral obligation for all of our work on OSv to be contributed back to the project. This way, other users may benefit from it, extending its value beyond the academic plain, while the respective project communities gain a new, active member.

1.3 Related work

In the years since the introduction of MirageOS [29], a plethora of unikernel frameworks have made their appearance, forming a diverse ecosystem. Some of them, beyond OSv are RumpRun [36], IncludeOS [6], HermitCore [26], and HermiTux [33], ukl [35], Toro [10] and Nanos [7].

The main pre-existing alternative to virtio-fs is VirtFS [23] which is based on the 9P network protocol [1]. Virtio-fs is still a young project, under active development, so there are relatively few implementations available. On the host side, apart from its main implementation in QEMU [40], there exists a complete implementation of it in cloud-hypervisor [18], an alternative virtiofsd implementation named memfsd from the nabla containers community [32] and an implementation for firecracker [14] which has not been accepted by the project for now. On the guest side, apart from the reference implementation in Linux [39], there is an implementation in Toro (a Pascal unikernel) [10], as well as another for Windows [42].

1.4 Thesis structure

A thorough description of the technical background of this thesis, from cloud use cases to the supporting technologies of virtio-fs is included in the second chapter. The third chapter concerns the specifics of the implementation of our extensions to OSv, followed by its evaluation, describing the methodology and examining the results in the fourth chapter. Finally, the fifth chapter contains a brief review in addition to directions for future work.

Chapter 2

Background

2.1 Cloud computing

Cloud computing is a model of providing computing resources as a service, which is now very well established. At its core, it makes concentrated, shared compute resources available on demand, via the network. These resources are owned and controlled by a cloud service provider and made available remotely to users - clients who thus achieve lower up front cost computing infrastructure, flexibility, scalability, reduced deployment times and simplified infrastructure administration [43].

We can distinguish three primary cloud service models, through which the underlying resources are offered, as shown in fig. 2.1 [31]:

Infrastructure-as-a-Service (IaaS) which provides compute, storage and networking resources, such as virtual machines, storage drives, virtual networks and load balancers. This model offers the lowest level of abstraction but the greatest flexibility to the users.

Platform-as-a-Service (PaaS) where the users are able to develop their applications, assuming the "environment" in which those will be executed. Fundamentally, this model provides a higher level service, in the sense that they are not burdened with managing components such as the operating system or runtime system, allowing them to focus on the application instead.

Software-as-a-Service (SaaS) presenting the highest level of abstraction from the infrastructure. According to this model, the users are granted access to applications which are fully managed by the provider, from the underlying infrastructure to the configuration of the application itself. Examples of this are email services, project management and office suite applications such as document and spreadsheet editors.

One model which emerged more recently, attracting a lot of user attention is the so called serverless or Function-as-a-Service (FaaS). This resembles PaaS (it

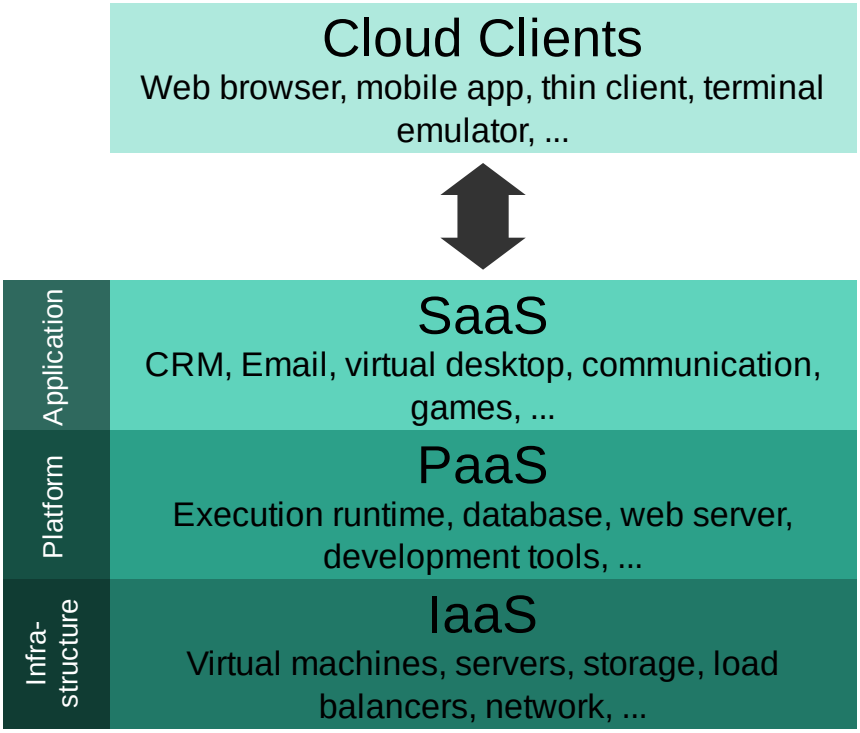


Figure 2.1: Cloud service models. Source Wikimedia Commons.

could be considered part of it, or an evolved form), since as the name suggests, it completely takes away the duty of server management from the users. The emphasized technical aspects include automatic scalability from zero as well as instant reaction to load fluctuations thanks to rapid startup and termination of application instances [5]. One of the drawbacks of serverless is that only some applications fit this model, allowing them to benefit from the above [17, 19].

2.2 Virtualization

The technology at the foundation of the cloud is that of virtualization. This adds an abstraction layer over the physical compute infrastructure, enabling the mapping of one (typically large) physical machine (host) to more, smaller virtual machines (guests), created, modified, moved and deleted dynamically through software [44].

Regarding the requirements for software running as guest, we discern two cases:

Full virtualization where the guest is not aware of running inside a virtual machine. This way, no changes are required for software written for physical machines to execute in virtual ones.

Paravirtualization where the guest is modified specifically for execution in a virtual machine.

Virtualization has been around for decades prior to the advent of the cloud. One decisive point for the realization of the latter was the addition of hardware support for it in the x86 architecture, which led to its efficient use, without high demands from software [13]. Unto that point, virtualization on this highly popular architecture relied upon paravirtualization techniques.

The responsibility for accomplishing virtualization lies with the hypervisor or virtual machine monitor (VMM). This is usually software running on the host, with elevated privileges. Its tasks include starting the virtual machines and emulating the operations not permitted to them, mainly interacting with the system's devices. The latter is normally implemented through the "trap and emulate" technique, where some instructions during the virtual machine's execution cause CPU traps, transferring control to the hypervisor code. That in turn checks and executes the guest's operation, eventually returning control back where it had stopped. This mechanism grants the hypervisor full control over the (virtual) device model of the virtual machine [45].

Hypervisors are classified in two primary categories (fig. 2.2) [34]:

Type 1 which execute directly on top of the physical machine, assuming complete control over it, in addition to managing the virtual machines. Usually these hypervisors depend on a special-purpose guest, running with elevated privileges, to manage the machine's devices, having the necessary drivers. The best known, free software such hypervisor is Xen [15].

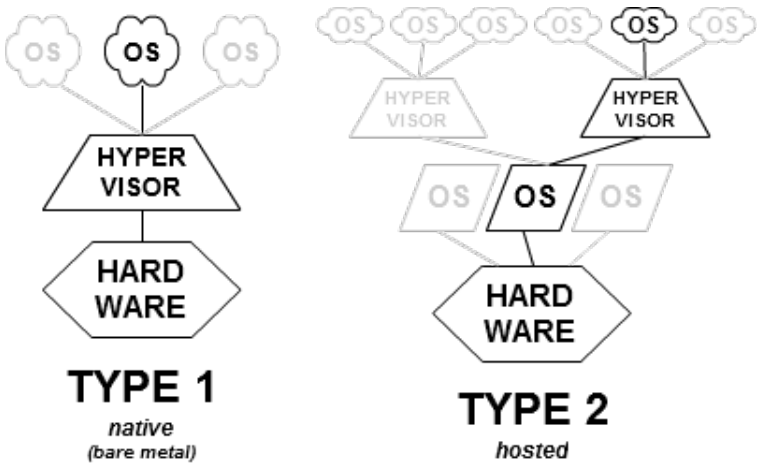


Figure 2.2: Hypervisor types. Source Wikimedia Commons.

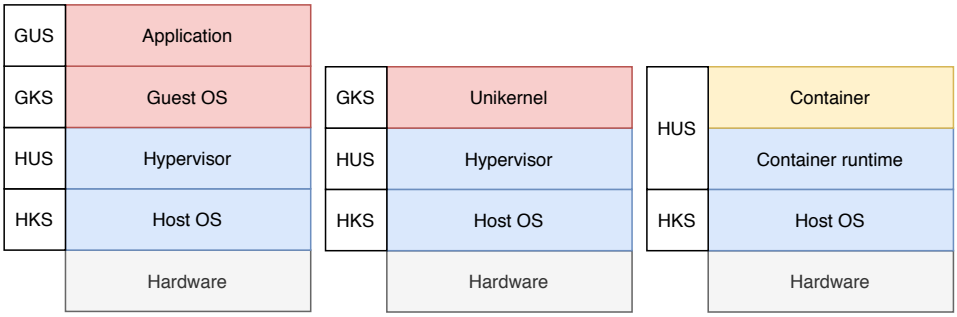
Type 2 which execute as part of a typical operating system, only in charge of starting and monitoring the virtual machines, while the host is managed by the operating system as usual. In this category it is customary for every guest to be a regular process from the host's perspective. The most popular free software representative of this category is QEMU [16] (usually in combination with KVM [24] to provide hardware acceleration).

2.3 Unikernels

In the common virtualization use case, the software supporting an application can be viewed as (see fig. 2.3a):

- On the host (kernel space) runs a general-purpose operating system with direct access to the physical machine's resources and assuming responsibility over them.
- On the host (typically user space) also runs the hypervisor, assuming the duty of managing the virtual machines which correspond to the system.
- On the guest (kernel space) again runs an instance of a general-purpose operating system. This is responsible for the resources allocated to the virtual machine by the hypervisor.
- On the guest (user space) runs the application, frequently in conjunction with components like third-party libraries and runtime systems.

Ths software stack contains duplication and high complexity, two elements commonly at fault for problems such as sub-optimal resource usage, reduced performance due



(a) Typical VM (b) Unikernel (c) Container

Figure 2.3: Comparison between "classic" virtual machine arrangement, unikernel and container, with a type 2 hypervisor. Where HKS=Host Kernel Space, HUS=Host User Space, GKS=Guest Kernel Space and GUS=Guest User Space.

to overheads (e.g. mode switches) in the overall system operation and security hazards due to the software's size, of which a good part is unnecessary (e.g. guest drivers).

A modern attempt at rectifying the above problem are unikernels [29]. These are executable machine images comprising of an application bundled with all necessary dependencies for its execution, from the likes of libraries and runtime systems to network stacks and device drivers. All of these are situated in a common, flat address space, as seen in fig. 2.3b. Unikernels are thus special-purpose kernels, built to run a single application in a virtual machine, considering that virtual machines are regularly employed to serve just a single application.

Unikernels are established on the older idea of library operating systems, which were introduced with the innovative at the time and very relevant today exokernels [20]. In a library operating system the majority of the functionalities traditionally offered as part of a monolithic kernel (e.g. file systems and networking) are extracted from it, becoming independent elements in the form of libraries which accompany an application. This rearrangement grants the application the liberty of choosing which of these elements in requires, as well as which implementation of each it prefers. Therefore, the application can optimize its operation through said choices, but at the same time is burdened with this extra duty.

A big hurdle in implementing unikernels is the diversity of devices and consequently drivers necessary to operate them. This is overcome thanks to the hypervisors' device model, encompassing few, common and well documented devices. Another obstacle is the complexity associated with matching the various components together to create the final executable image. There are numerous solutions proposed to this, each forming a "unikernel framework". Virtually all of those are free software projects, each providing a set of libraries for inclusion by the user applications, as well as the tools necessary for building the images. Each

of these frameworks typically takes one of two principal approaches:

- Clean-slate, providing custom APIs. In this case, both library and application code is written in the same programming language. A major downside to this approach is that the applications need to be written from scratch in the language and using the API of the respective framework.
- Compatible, providing standard interfaces (e.g. POSIX), which allows running existing applications with minimum to no modifications, independently of any programming language (binary compatibility). In this case, the biggest tradeoff is the commitment to legacy interfaces, often hindering taking full advantage of the unikernel potential.

For example, in the first category one finds MirageOS [29] and IncludeOS [6], whereas in the second we note RumpRun [36], OSv [25] and HermiTux [33]. Overall, there are several unikernel frameworks, varying in popularity (with none prevailing), maintenance status (from active to practically abandoned) and origins (academic, corporate-backed or personal projects).

2.3.1 OSv

OSv is a unikernel framework supporting applications written for Linux, while offering its own API which new applications can opt to use [25]. It has been designed with the cloud in mind, in order to accommodate modern applications most often encountered there. The project was started by Cloudius Systems (later ScyllaDB) but lately it has been maintained and enhanced by a small team of volunteers. It is made available under the terms of the BSD software license. Its community makes use of a mailing list[1] for its development: submitting patches, code reviews and general discussion.

Although it is mostly written in C++, also incorporating C code from other projects, this imposes no restriction on the applications it supports, as long as those don't make use of operations that by nature are not applicable in unikernels: system calls in the family of `fork()` and `exec()`. Moreover, it is supported on several hypervisors, including QEMU/KVM, Xen and firecracker [14]. As a general note, it is one of the most advanced unikernels in terms of features, and more heavy-weight as a result of that.

Regarding file systems, OSv offers many choices. First of all, it boasts a complete virtual file system (VFS), based on that of Prex [8]. Beneath that are implementations of various file systems, which can be grouped in two categories:

- Pseudo-file systems, corresponding to those of Linux: devfs, procfs, sysfs and ramfs.

[1] `https://groups.google.com/forum/#!forum/osv-dev`

- Conventional file systems: ZFS (based on FreeBSD's implementation), rofs (custom, read-only file system with simple caching functionality) and NFS (powered by libnfs [27]).

2.3.2 Alternatives

As expected, there have been alternative approaches to the problem of bloat in the virtualized software stack. By far the most popular at this point is that of containers. These belong to the broad class of OS-level virtualization [46] (see fig. 2.3c).

There exist multiple techniques for implementing containers, most of which rely on Linux kernel mechanisms, like cgroups and namespaces, to achieve isolation between separate containers. What's common among all container technologies is that applications running in all containers on the same host share the same kernel instance. One could say that in this case there is a single kernel but many user spaces.

Probably the chief advantage of containers is that they are a lot "lighter" than virtual machines: much lower startup times (compared to a VM with a general-purpose guest), greater flexibility and lower resource usage, resulting in higher density (instances running concurrently on the same physical machine). Their weakest point is that they offer much weaker isolation than virtual machines, due to the common kernel serving them [30].

2.4 Shared file systems

"Classic" file systems are implemented over block devices ("disks") connected via a local system bus. The software comprising them is usually part of an operating system kernel which assumes it is the exclusive user of the file system for as long as that is mounted. This more often than not constitutes a restriction with attempts to lift it since the advent of computer networking, in order to allow concurrent use of a file system by more computers, rendering it shared. The most prevalent and among the oldest representatives of shared file systems is NFS (Network File System) [37], with this class of file systems gaining many new members with the proliferation of distributed systems in recent years.

Virtualization can be viewed as a special case of multiple, interconnected machines: the host and the virtual machines running on it. The demand for a file system shared between them is thus present and in fact very common due to their coexistence on the same physical machine. After all, the host's file system is yet another one of its resources, so it is expected for it to be accessible by the guests.

Most solutions for host-guest shared file systems rely on the existing, network file systems, not differentiating between this case and that of separate hosts. This approach builds of course on the network connection between the parts, fully reusing preexisting solutions. A popular example of shared file system in the context of

virtualization is VirtFS [23] which depends on the 9P protocol [1]. Although the latter is a network protocol, VirtFS does not use the network as its transport layer, granting it improved performance.

It is worth mentioning that in the case of containers access to a file system shared with the host is also in high demand. One way this is accomplished in Docker [2] (by far the most prevalent container runtime) is through bind mounts [11], taking advantage of the common kernel to mount a host directory in the container's file system.

2.5 virtio-fs

The shared memory underlying both host and guests is an element not fully taken advantage of by current shared file systems. Virtio-fs [41] sets out with the goal of changing that. Its differentiating factor is that it is not dependent on the network at the transport layer (using virtio instead), neither at the protocol layer (where it opts for FUSE). These two choices allow for better performance as well as local file system semantics, which manifests e.g. in coherence issues.

The existing virtio-fs implementation in QEMU is distinctive in its architecture. Whereas device implementation is usually fully contained inside QEMU, here a significant part is split in the so-called virtiofsd (virtio-fs daemon), a separate process handling all file system operations on the host, while QEMU is left with the task of implementing the virtual device. On one hand, has the merit of higher security, since virtiofsd can be sandboxed with the host's mechanisms (namespaces, seccomp). On the other hand, it is modular, facilitating easy switching between different virtiofsd implementations (e.g. with one backed by a distributed file system instead of the host's local file system). Splitting the implementation in separate processes is made possible by the host-user protocol [12], which evolves the idea of vhost in QEMU [21]. Pushing devices out of the VMM has many advantages and is expected to be favored in the future [22].

2.5.1 Virtio

Virtio is a standard specifying devices exclusively for virtualized environments [38]. It enjoys wide support and is considered the de facto solution to the problem of fragmentation in virtual device models. Offering an efficient and extendable mechanism, it builds on physical device terminology and mechanisms, thus assisting in new support for it and enabling reuse of existing driver code in guests.

The standard consists mainly of two notions:

The transport layer which defines a generic way for device discovery, configuration and normal operation (bidirectional data transfer). The latter is achieved via so-called "virtqueues", relying on the shared memory between guest and hypervisor. The transport layer, initially given an abstract specification, is

specialized by three implementations: PCI bus, memory-mapped I/O (MMIO) and channel I/O (used in cases of the IBM S/390 architecture).

The set of devices which builds on the transport layer to specify for each device the available configuration fields, the number of virtqueues and the messages exchanged over those for its operation.

2.5.2 FUSE

FUSE (Filesystem in Userspace) is a protocol introduced in Linux to enable file system implementations in user space instead of inside the kernel [4]. As made clear in fig. 2.4, the file system operations are carried out by a user space daemon communicating with the kernel according to the protocol via a special character device (`/dev/fuse`). When the kernel receives VFS requests corresponding to a FUSE file system, it forwards them to the appropriate daemon which acts as a backend.

In the context of virtio-fs, FUSE is utilized for communicating the file system requests to the device. Hence its architecture resembles the classic FUSE architecture, with the difference that the client is the guest instead of the kernel, while communication is performed through virtio rather than the FUSE character device. In practice though, virtio-fs and regular FUSE are incompatible because virtio-fs incorporates modifications and extensions to the FUSE protocol. Moreover, the security model differs (it is essentially inverted), with the client (the guest) being untrusted in virtio-fs, whereas in FUSE it is the other way round (by default there is trust in the kernel the daemon is running on). The latter translates in safer request handling in a virtio-fs device backend than in a FUSE backend.

2.5.3 DAX window

For the file read and write operations, FUSE utilizes the FUSE_READ and FUSE_WRITE requests respectively. These involve copying the data and in the case of virtio-fs ensue VM exits. Since these are operations at the core of the data path, it is crucial for them to be optimized. To that end, virtio-fs introduces the DAX window: a "window" of memory shared between the host and the guest where file contents are mapped, providing the guest with direct access on them. This results in skipping the copying (and bypassing the guest page cache in the case of Linux guests), while not every read or write operation implies suspending the virtual machine's execution.

For realizing the DAX window functionality, initially the FUSE protocol is extended with messages for establishing and removing mappings. The guest dispatches these messages to virtiofsd, which carries out all necessary checks and instructs QEMU to eventually perform the actual operation (establishing or removing a mapping). See also fig. 2.5.

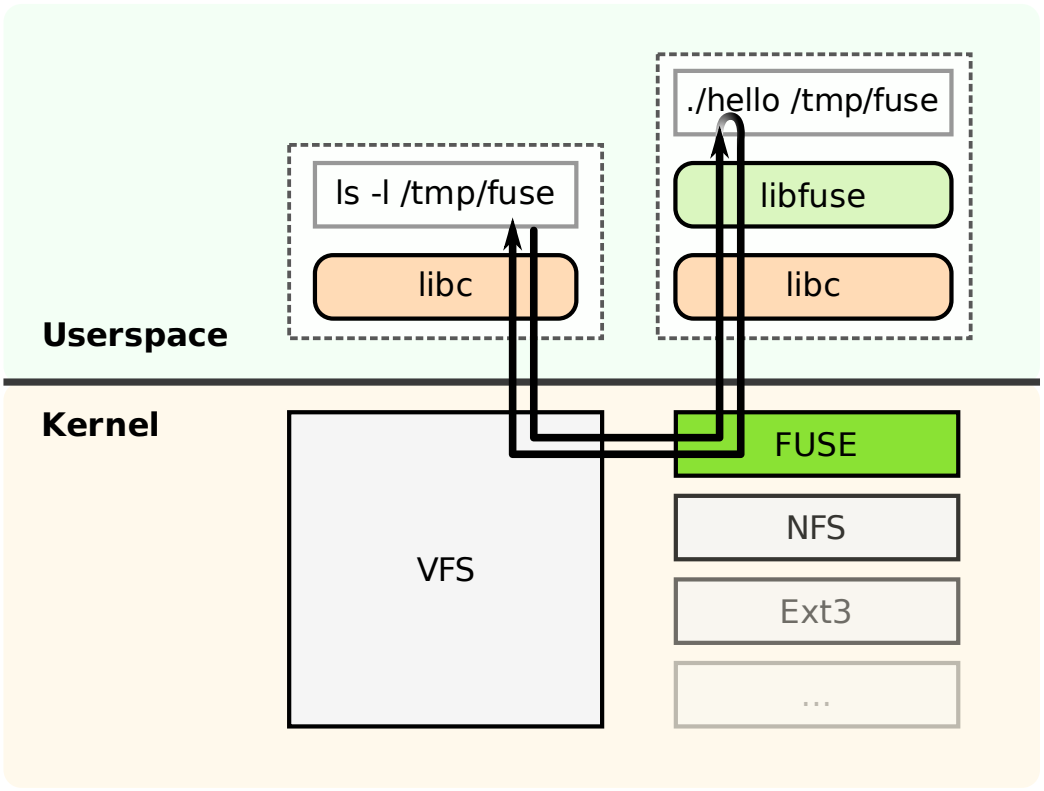


Figure 2.4: FUSE architecture in Linux. By Sven (`https://commons.wikimedia.org/wiki/User:Sven`) licensed under CC-BY-SA 3.0 (`https://creativecommons.org/licenses/by-sa/3.0/legalcode`). Source `https://commons.wikimedia.org/wiki/File:FUSE_structure.svg`.

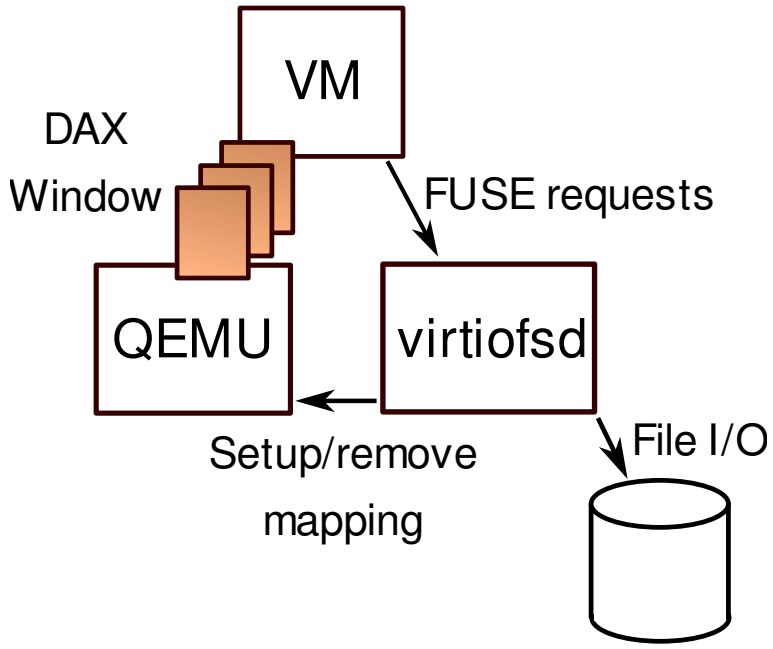


Figure 2.5: DAX window architecture in virtio-fs. By Stefan Hajnoczi (`https://vmsplice.net/`) licensed under CC-BY-SA 4.0 (`https://creativecommons.org/licenses/by-sa/4.0/legalcode`). Source `https://gitlab.com/virtio-fs/virtio-fs.gitlab.io/-/blob/master/architecture.svg`.

Appendix A

FUSE copyright notice

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