Violin: A Framework for Extensible Block-level Storage

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Abstract

Storage virtualization is becoming more and more important due to the increasing gap between application requirements and the limited functionality offered by storage systems. In this work we propose *Violin*, a virtualization framework that allows easy extensions of *block-level* storage stacks. *Violin* allows developers to provide new virtualization functions and storage administrators to combine these functions in storage hierarchies with rich semantics. *Violin* makes it easy to develop such new functions by providing support for (i) hierarchy awareness and arbitrary mapping of blocks between virtual devices, (ii) explicit control over both the request and completion path of I/O requests, and (iii) persistent metadata management.

To demonstrate the effectiveness of our approach we evaluate *Violin* in three ways: (i) We loosely compare the complexity of providing new virtual modules in *Violin* with the traditional approach of writing monolithic drivers. In many cases, adding new modules is a matter of recompiling existing user-level code that provides the required functionality. (ii) We show how simple modules in *Violin* can be combined in more complex hierarchies. We demonstrate hierarchies with advanced virtualization semantics that are difficult to implement with monolithic drivers. (iii) We use various benchmarks to examine the overheads introduced by *Violin* in the common I/O path. We find that *Violin* modules perform within 10% of the corresponding monolithic Linux drivers.

1 Introduction

Scalable storage systems are starting to be built with commodity storage nodes [11] connected by storage area networks (SANs) [23]. In such systems, each storage node provides a large amount of storage (in the order of a few TBytes) that is available to application servers. Since different applications need access to the same physical storage, the storage system needs to satisfy diverse application needs. To address this problem, storage systems provide virtual volumes that map to physical devices (storage virtualization).

The quality of virtualization mechanisms provided by a storage system affects storage management complexity and storage efficiency, both of which are important problems of modern storage systems. Storage virtualization may occur either at the filesystem or at the block level. Although both approaches are currently being used, our work addresses virtualization issues at the block-level. Storage virtualization at the filesystem level has mainly appeared in the form of extensible filesystems [14, 30, 32]. However, we argue that the importance of block-level virtualization is increasing for two reasons. First, certain virtualization functions, such as compression or encryption, maybe simpler to implement and may perform better with unstructured fixed blocks rather than variable-sized files. Second, block-level storage systems are evolving from simple disks and fixed controllers to powerful storage nodes [1, 10, 11] that offer block-level storage to multiple applications over a storage area network [23, 22]. In such systems, block-level storage extensions can exploit the processing capacity of the storage nodes, where filesystems (running on the servers) cannot.

Over time and with the evolution of storage technology, there has been a number of virtualization features, e.g. volume management functions, RAID, snapshots, that moved from higher system layers to the block level.

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However, current block-level systems offer predefined virtualization semantics, such as virtual volumes mapped to an aggregation of disks or RAID levels. In this category belong both research prototypes [3, 7, 9, 19, 25] as well as commercial products [5, 6, 13, 27, 28]. In all these cases the storage administrator can switch on or off various features at the volume level. However, there is no support for extending the I/O protocol stack by providing new functionality, such as snapshots, encryption, compression, or content hash computation. Moreover, it is not possible to combine existing and new functions in a flexible manner.

In this paper we propose, implement, and evaluate *Violin* (Virtual I/O Layer INtegration) that addresses these issues. *Violin* is a virtual I/O framework for commodity storage nodes that replaces their current block-level I/O stack with an improved I/O hierarchy that allows for (i) easy extension of the storage hierarchy with new mechanisms and (ii) flexible combining of these mechanisms to create modular hierarchies with rich semantics.

Although our approach shares similarities with work in modular and extensible filesystems [12, 14, 30, 32] and network protocol stacks [18, 20, 24, 26], existing techniques from these areas are not applicable to block-level storage virtualization. In all cases, the notion of a hierarchy is employed to describe the structure of the system. However, compared to extensible filesystems, block-level systems operate at a different granularity, with no information about the relationships of blocks. Moreover, metadata needs to be maintained at the block level and there are stringent performance requirements. Compared to extensible network stacks, block-level storage virtualization shares similar performance and modularity goals. However, they are fundamentally different in that protocol stacks are essentially stateless (except for configuration information) and packets are ephemeral, whereas storage blocks and their associated metadata need to persist.

The main contribution of *Violin* is that it significantly reduces the effort to introduce new functionality in the block I/O stack of a commodity storage node and to provide users with virtual volumes that satisfy diverse needs. To achieve this *Violin* allows storage administrators to create arbitrary, acyclic graphs of virtual devices, each adding to the functionality of the successor devices in the graph. In each hierarchy, blocks of each virtual device can be mapped in arbitrary ways to the successor devices, enabling advanced storage functions, such as dynamic relocation of blocks. *Violin* provides virtual devices with full access to both the request and completion paths of I/Os allowing for easy implementation of synchronous and asynchronous I/O. Supporting asynchronous I/O is important for performance reasons, but also raises significant challenges when implemented in real systems. Finally, *Violin* deals with metadata persistence for the full hierarchy, offloading the related complexity from individual virtual devices.

We implement *Violin* as a block device driver under Linux. To demonstrate the effectiveness of our approach in extending the I/O hierarchy we implement various virtual modules as dynamically loadable kernel devices that bind to *Violin*'s API. We also provide simple user level tools that are able to perform on-line fine-grain configuration, control, and monitoring of arbitrary hierarchies of instances of these modules.

We evaluate the effectiveness of our approach in three areas: ease of development, flexibility, and performance. In the first area we are able to quickly prototype modules for RAID (0, 1, 5), versioning, partitioning and aggregation, MD5 hashing, and encryption. In many cases, writing a new module is just a matter of recompiling existing user-level library code. Overall, using *Violin* encourages the development of simple virtual modules that can later be combined to more complex hierarchies. Regarding flexibility, we are able to easily configure I/O hierarchies that combine the functionality of multiple layers and provide complex high-level semantics that are difficult to achieve otherwise. Finally, we use Postmark and Bonnie++ to examine the overhead that *Violin* introduces over traditional block-level I/O hierarchies. We find that overall, internal modules perform within 10% (throughput) of their native Linux block-driver counterparts.

The rest of the paper is organized as follows. Sections 2 and 3 present the design and implementation of *Violin*, emphasizing the main components and introducing various implementation issues. Section 4 presents our results, while Section 5 discusses related work. Finally, Section 6 discusses limitations and future work and Section 7 draws our conclusions.

2 System Architecture

Violin is a virtual I/O framework that provides support for easy and incremental extensions to I/O hierarchies and a highly configurable virtualization stack that combines basic storage layers in rich virtual I/O hierarchies.

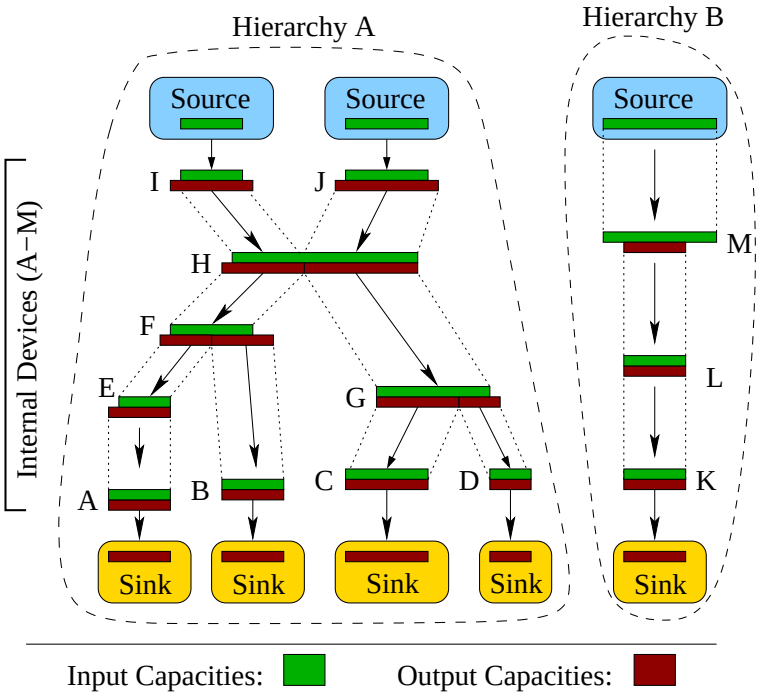


Figure 1: *Violin*'s virtual device graph.

There are three basic components in the architecture of *Violin*:

- *Virtualization semantics and mappings:* virtual device dependencies, transparent translation between mapped address spaces, and hierarchy awareness.
- *I/O request path:* I/O request flow through the system and synchronous or asynchronous operation.
- *State persistence:* model and necessary support for persistent metadata management.

Next we discuss each of these components in detail.

2.1 Virtualization Semantics

A virtual storage hierarchy is generally represented by a *directed acyclic graph* (DAG). In this graph, the vertices or nodes represent virtual devices. The directed edges between nodes signify *device dependencies* and *control flow* through I/O requests. Control in *Violin* flows from higher to lower layers. This arises from the traditional view of the block-level device as a dumb passive device. Each virtual device in the DAG is operated by a virtualization module that implements desired functionality. Virtual devices that provide the same functionality are handled by different instances of the same module. From now on, we will use the terms module (instance) and device interchangeably.

Figure 1 shows an example of such a device graph. Nodes are represented with horizontal bars illustrating the mappings of their address spaces and they are connected with directed vertices. There are three kinds of nodes and accordingly three kinds of I/O modules in the architecture:

- *Source nodes* that do not have incoming edges and are top-level devices that *initiate I/O requests* in the storage hierarchy. The requests are initiated by external kernel components such as file systems or other block-level storage applications. Each of the source devices has an external name, e.g. an entry in /dev for Unix systems.
- *Sink* nodes that do not have outgoing edges and correspond to bottom-level virtual devices. Sink nodes sit on top of other kernel block-level drivers, such as hardware disk drivers and, in practice, are the final recipients of I/O requests.

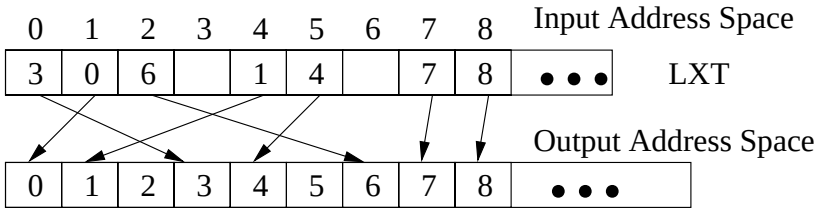


Figure 2: The LXT address translation table.

- *Internal* nodes that have both incoming and outgoing edges and provide virtualization functions.

Internal nodes in a hierarchy are not visible to external drivers, kernel components, or user applications.

A *virtual hierarchy* is defined as a set of connected nodes in the device graph that do not have links to nodes outside the hierarchy. A hierarchy within a device graph is a self-contained sub-graph that can be configured and managed independently of other hierarchies in the same system. Hierarchies in *Violin* are objects that are explicitly created before adding virtual devices (nodes).

To manage devices and hierarchies, users may specify the following operations on the device graph:

- Create a new internal, source, or sink node and link it to the appropriate nodes, depending on its type. The DAG is created in a bottom-up fashion to guarantee that an I/O sink will always exist for any I/O path.
- Delete a node from the graph. A node may be deleted only if its input devices have been deleted (top-down).
- Change an edge in the graph, i.e. remap a device.

Violin uses the above generic DAG representation to model its hierarchies. A hierarchy in *Violin* is constructed with simple user-level tools implementing the above graph operations and linking the source and sink nodes to external OS block devices. Currently, the storage administrator has to specify the exact order in which virtual devices will be combined. The user-level tools can also be used online, during system operation to modify or extend I/O hierarchies. However, it is the administrator's responsibility to maintain data consistency while performing online structural changes to a hierarchy.

Violin checks the integrity of a hierarchy at creation time and each time it is reconstructed. Checking for integrity includes various simple rules, such as the presence of cycles in the hierarchy graph and lack of input or output edges in internal nodes. Creating hierarchies and checking dependencies reduces the complexity of each *Violin* module.

2.1.1 Dynamic Block Mapping and Allocation

Nodes in a hierarchy graph do not simply show output dependencies from one device to another but rather map between block address spaces of these devices. As can be seen in Figure 1, a storage device in the system represents a specific storage capacity and a block address space, while the I/O path in the graph represents a series of translations between block address spaces. *Violin* provides transparent and persistent translation between device address spaces in virtual hierarchies.

Devices in a virtual hierarchy may have widely different requirements for mapping semantics. Some devices, such as RAID-0, use simple mapping semantics. In RAID-0 blocks are mapped statically between the input and output devices. There are, however, modules that require more complex mappings. For instance, providing snapshots at the block level, requires arbitrary translations and dynamic block remappings [8]. Similarly, volume managers [25] require arbitrary block mappings to support volume resizing and data migration between devices. Another use of arbitrary mappings is to change the device allocation policy, for instance, to a log-structured policy. The Logical Disk [4] uses dynamic block remapping for this purpose. *Violin* supports dynamic block mapping through a logical-to-physical block address translation table (LXT). Figure 2 shows an example of such an LXT mapping between the input and output address spaces of a device.

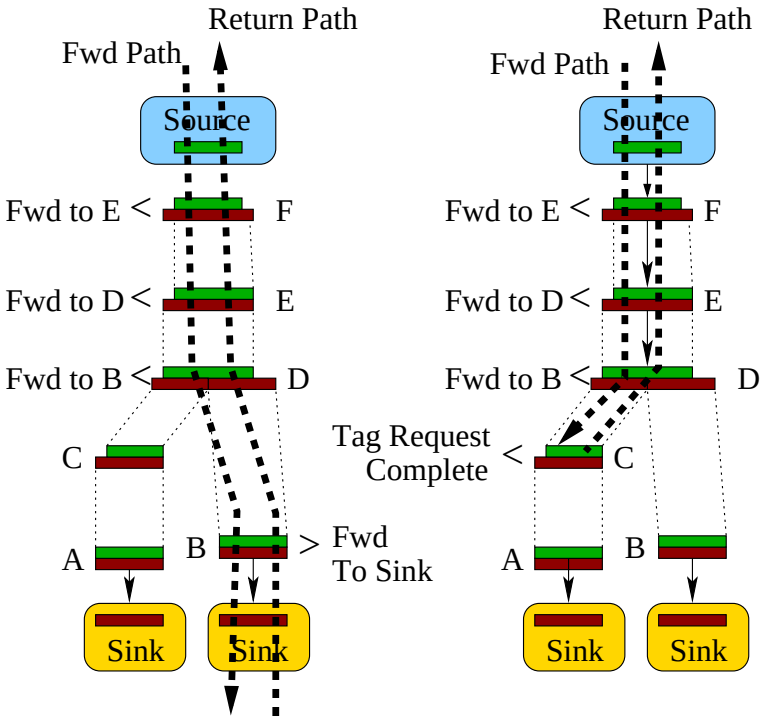


Figure 3: Example of request flows (dashed lines) through devices. Forward paths are directed downwards, while return paths upwards.

An issue with support arbitrary mappings is the size of LXT persistent objects, which can become quite large, depending on the capacity and block size of a device. Keeping such objects in memory can increase memory footprint substantially. *Violin* offers two solutions: First, it supports an internal block size (extent size) for its devices, which is independent of the OS device block size. The extent size is specified by each module when an LXT is allocated. Increasing the extent size can greatly reduce the size of the LXT. For example, the LXT of a 1 TByte device with 32-bit extent addressing and 4 KByte extent size would require 1 GByte of memory to be cached. By increasing the extent size to 32 KBytes, we achieve a reduction of the required metadata to less than 130 MBytes. Second, *Violin* provides the capability to explicitly load and unload persistent metadata to and from memory, as explained in Section 2.3.

2.2 *Violin* I/O Request Path

The second significant aspect of *Violin* is how the I/O request path works. *Violin* is both reentrant as well as it supports synchronous and asynchronous requests. Thus, I/O requests never block in the framework, unless a driver module has explicitly requested it. In this manner, *Violin* offers both synchronous and asynchronous I/O semantics to internal modules that can choose which ones to use. Moreover, since *Violin* is reentrant, it runs in the issuers context for each request issued from the kernel. Thus, many requests may proceed concurrently in the framework, each in a different context.

A generic virtual storage framework must support two types of I/O requests:

- *External requests* are initiated by the kernel, enter the framework through the source devices, traverse a hierarchy through internal nodes usually until they reach a sink nodes and then return back up the same path to the top of the stack.
- *Internal requests* generated from internal devices as a response to an external request. Consider for example a RAID-5 module that needs to write parity blocks. The RAID-5 device in this case generates an internal write request to the parity device, becoming the source device of the request. Internal requests are indistinguishable from external ones for all modules and are handled in the same manner.

I/O requests in *Violin* move from source to sink nodes through some path in a virtual hierarchy, as shown in Figure 3. Sink devices are connected to external block devices in the kernel, so after a request reaches a sink device it is forwarded to an external device. When multiple output nodes exist, routing decisions are taken at every node (device), according to its mapping semantics. Virtual devices can control requests beyond simple forwarding. When a device receives an I/O request it can make four control decisions and set corresponding control tags on a request:

- *"Error Tag"*: There was an error with this request. Erroneous requests are returned through the stack to the issuer with an error code.
- *"Forward Tag"*: The request should be forwarded to an output device. In this case, the target device and block address must also be indicated. Forwarding occurs to the direction of one of the output graph vertices.
- *"Return Control Path Tag"*: The device needs return path control of the request. Some devices need to know when an asynchronous I/O request has completed and need control of its return path (Figure 3). For instance, an encryption module, requires access to the return path of a read request, because data needs to be decrypted after it is read from the sink devices. However, many modules do not need return path control. If no modules in a path through the hierarchy request return path control, the request is merely redirected to another kernel device outside the framework (e.g. the disk driver) and returned directly to the issuer application, bypassing the framework's control. If, however, some module requests return path control, the framework must gain control of the request when it completes in another kernel device. In *Violin*'s Linux implementation, the driver sets an asynchronous callback on the request to gain control of it when it completes. When the callback receives the completed request, it passes it back up through the module stack in the reverse manner, calling the *pop I/O handlers* (described later in the API Section 2.4). Errors in the return path are handled in a similar manner as in the forward (request) path.
- *"Complete Tag"*: The request is completed by this device. Consider the example of a caching module in the hierarchy. A caching device is able to service requests either from its cache or from the lower-level devices. If a requested data block is found in the cache, the device loads the data in the request buffer and sets the "complete" tag. The completed request is not forwarded deeper in the hierarchy, but returns from this point upwards to the issuer as shown at the right of Figure 3 for device C. If the return control path tag is set, the framework passes control to the devices in the stack that have requested it. Using this control tag, an internal device essentially becomes an "internal sink" device.

A final issue with I/O requests flowing through the framework, is dependencies between requests. For instance, there are cases where a module requires an external request to wait for one or more internal requests to complete. The mechanism for dependent requests operates as follows: when an internal request X is issued (asynchronously) it may register a dependence to another request Y and a callback function. Requests X, Y are processed concurrently and if X completes first, it is queued until Y completes. X is resumed by the callback function of Y. This mechanism supports arbitrary dependencies among multiple requests.

2.3 State Persistence

Violin supports metadata management facilities. the three main issues associated with metadata management are: facilitating the use of persistent metadata, reducing memory footprint, and providing consistency guarantees.

Persistent metadata: In *Violin*, modules can allocate and manage persistent metadata objects of varying sizes using the API summarized in Figure 4. To allocate a metadata object, a module calls `vl_persistent_alloc()` using a unique object ID and its size, as it would allocate memory.

Modules access metadata directly in memory, as any other data structure. However, since device metadata are loaded dynamically when the device in initialized, pointers may not point to the right location. There are two methods for addressing this issue: (i) disallow pointers in metadata accesses and (ii) always force loading of metadata to the same address. Since the latter can be a problem for large metadata objects and in our experience the former is not overly restrictive, in our current design we disallow pointers in metadata objects.

```
void *vl_persistent_obj_alloc(int oid,int size);
void *vl_persistent_obj_[un]load(int oid);
void vl_persistent_obj_flush(int oid);
void vl_persistent_obj_free(int oid);
```

Figure 4: *Violin* API for metadata management.

However, this issue requires further investigation and is left for future work. When a module needs to destroy a persistent object it calls the `vl_persistent_free()` function.

By default, when a virtual device is created in *Violin*, the system stores its metadata in the same output address space as the data. Alternatively, the user may specify explicitly a metadata device that will be used for storing persistent metadata for the new virtual device. This can be very useful when metadata devices are required to have stronger semantics compared to regular data devices.

Violin's metadata manager automatically synchronizes dirty metadata from memory to stable storage in an asynchronous manner. The metadata manager uses a separate kernel thread to write to the appropriate device metadata that are loaded in memory. The user can also flush a metadata object explicitly with the `vl_persistent_flush()` call.

Internally, each metadata object is represented with an object descriptor, which is modified only by allocation/deallocation calls. During these calls metadata object descriptors are stored in a small index in the beginning of the metadata device. A pointer to the metadata header index is stored with each virtual device in the virtual hierarchy. Thus, when the virtual hierarchy is being loaded and recreated, *Violin* reads the device metadata and loads it to memory.

Reducing memory footprint: This is important for large metadata objects that may consume a large amount of main memory or incur large amounts of I/O during saving to the metadata device. For this reason, *Violin* provides API calls for explicitly loading and unloading metadata to and from memory within each module (Figure 4). Another possible solution, is to transparently swap metadata to stable storage. This solution is necessary for extremely large devices, where the size of the required metadata can sometimes exceed the available memory of a machine. Since it is not clear whether such modules actually need to be implemented (this is not the case in all modules we have examined), *Violin* does not support this feature yet.

Violin retains a small amount of internal metadata that represent the hierarchy structure and are necessary to reconstruct the device graph. Each graph node and edge requires a pointer, which amounts to a few bytes per virtual device, but depends on the complexity of the device graph. The hierarchy metadata is saved in each physical device (i.e. with a hardware device driver) within a hierarchy. For this purpose, *Violin* reserves a superblock of a few KBytes in every physical device of a hierarchy. A complete hierarchy configuration can thus be loaded from the superblock of any physical device that belongs to the hierarchy.

In summary, each module needs to allocate its own metadata, and in the common case, where metadata can be kept in memory, it does not need to perform any other operation. The framework will maintain metadata persistent and will reload the metadata from disk each time the virtual device is loaded, which significantly simplifies metadata management in individual modules.

Metadata consistency: In the event of system failures, where a portion of the in-memory metadata may be lost or partially written, application and/or *Violin* state may be corrupted. Using these two categories of corruption we can define the following levels of metadata consistency[2]:

1. *Lazy-update consistency,* that is, metadata are synchronized on disk overwriting the older version metadata every few seconds. This means that if a failure occurs between or during updates of metadata then metadata may be left inconsistent on-disk and *Violin* may not be able to recover, that is its internal state will be inconsistent. In this case, there would be a need for a *Violin*-level recovery procedure, which however, we

[2] *Violin* supports the first form of metadata consistency and we are currently implementing the second and third form. We expect that all three forms of consistency will be available for the final version of this paper.

```
-> initialize (_device_t *dev, ...);
-> open  (_device_t *dev,void *data);
-> close (_device_t *dev,void *data);
-> read_push  (_device_t *dev, ...);
-> read_pop   (_device_t *dev, ...);
-> write_push (_device_t *dev, ...);
-> write_pop  (_device_t *dev, ...);
-> ioctl  (_device_t *dev, int cmd, ...);
-> resize (_device_t *dev, int new_size);
-> device_info (_device_t *dev, ...);
```

Figure 5: API methods for *Violin*'s I/O modules.

do not provide. If stronger guarantees are required then one of the next forms of consistency may be used instead.

2. *Shadow-update consistency*, where we use two metadata copies on disk and maintain at least one of the two consistent at all times using a two-phase commit process. If during an update the set that is currently being written becomes inconsistent due to a failure, *Violin* uses the second copy to recover. In this case, it is guaranteed that *Violin* will recover the device hierarchy and all its persistent objects and will be able to service I/O requests. However, some application data may be corrupted. This approach is similar to the behavior of today's, simple block level systems that can always recover (almost trivially) since they are mostly stateless.
3. *Atomic versioned-metadata consistency,* where a modified versioning layer [8] is placed over physical devices at the bottom of a hierarchy. This layer guarantees that after a failure, the system will be able to see a previous, consistent version of data and metadata. Thus, this is equivalent to a rollback to a previous point in time. In *Violin* this can be achieved by using a versioning layer at the leaves of a hierarchy[3].

2.4 Module API

The interface provided by kernels for block I/O is fairly low-level. A block device driver has the role of servicing block I/O `read` and `write` requests. Block requests adhere to the simple block I/O API, where every request is denoted as a tuple of `(block device,read/write,block number,block size,data)`. In Linux, this API involves many tedious and error prone tasks such as I/O request queue management, locking and synchronization of the I/O request queues, buffer management, translating block addresses and interfacing with the buffer cache and the VM subsystem.

Violin provides to its modules high-level API calls, that intuitively support its hierarchy model and hide the complexity of kernel programming. The author of a module must set up a *module object,* which consists of a small set of variables with the attributes of the implemented module and a set of methods or API functions that can be seen in Figure 5. The variables of the module object in our current implementation include various static pieces of information about each module, such as the module name and id, the minimum and maximum number of output nodes supported by the device, and the number of non-read and write (ioctl) operations supported by the module. The role of each method prototype is:

- `initialize()` is called once, the first time a virtual device is created to allocate and initialize persistent metadata and module data structures for this device (i.e. a module instance). Note that since *Violin* retains state in persistent objects, this method will not be called when a hierarchy is loaded, since device state is also loaded.
- `open(), close()` are called when a virtual device is loaded or unloaded during the construction of hierarchy. The module writer can use the `close()` call to perform garbage collection and unlink the binded kernel modules from the framework code.

[3]Given our current implementation of versioning though, we need to modify it so that its own metadata are handled differently in this particular case.

- `read(), write()` handle I/O requests passed to a virtual device. Each has two methods `push` or `pop` that represent the different I/O paths. `Push` handlers are called in the forward path, while `pop` handlers are called in the return path (if requested). These API methods are higher-level compared to their kernel counterparts and do not require complex I/O buffer management and I/O queue management.
- `ioctl()` handles custom commands and events in a module, in case direct access to it is required. This is used in some of our modules, for example to explicitly trigger a snapshot capture event in the versioning module.
- `resize()` is an optional method that specifies a new size for an output virtual device. When this method is called in a virtual device, it means that one of its output devices has changed size as specified and thus, the virtual device has to adjust all internal module metadata appropriately.
- `device_info()` is used to export runtime device information in human or machine readable form.

The main difference of this API with the classic block driver API in Unix systems is the distinct push and pop methods for read and write operations, versus two in the classic API. This is a key feature of *Violin*'s API. Asynchronous behavior stems from using these call to avoid blocking on I/O requests, even when a device needs control of the I/O completion path, as discussed in Section 2.2.

3 System Implementation

We have implemented *Violin* as a block device driver in the Linux 2.4 kernel accompanied by a set of simple user-level management tools. Our prototype implements fully the I/O path model described in Section 2.4. A central issue with the *Violin* driver is the implementation of its asynchronous API on Linux. Next, we explain how I/O requests are processed in Linux block device drivers and then describe *Violin*'s implementation.

3.1 I/O Request Processing in Linux

The Linux kernel uses an *I/O request* structure to schedule I/O operations to block devices. Every block device driver has an *I/O request queue*, containing all the I/O operations intended for this block device. Requests are placed in this queue by the kernel function `make_request_fn()`. This function can be overridden by a block driver's own implementation. Requests are removed from the queue and processed with the *strategy* or *request* function of a block driver. When a request is complete, the driver releases the I/O request structure back to the kernel after tagging it as successful or erroneous. If a released request is not appropriately tagged or the data is not correct, the kernel may crash.

Thus, there are two ways of processing I/O requests in a Linux device driver. First, a device driver can use a request queue as above where the kernel places requests and the *strategy* driver function removes and processes them. This approach is used by most hardware block devices. Second, a driver may override the `make_request_fn()` kernel function with its own and thus, gain control of every one of its I/O requests before it is placed in the request queue. This mode of operation is more appropriate for virtual I/O drivers. In this mode, the driver does not use an I/O request queue, but rather *redirects* requests to other block devices. This is the mode of operation used by many virtual I/O drivers, such as LVM and MD. When a new I/O request arrives, the device driver performs simple modifications to the I/O request structure, such as modifying the device ID and/or the block address and returns the request to the kernel that will redirect it to the new device ID.

3.2 *Violin* I/O path

Violin uses the method of replacing the `make_requ- est_fn()` call and operates asynchronously without blocking inside this function. For every external I/O request received through the `make_request_fn()` call, *Violin*'s device driver traverses the hierarchy path and calls the necessary module I/O handlers (`read_push()` or `write_push()` depending on the type of request). The I/O path traversal for a write request can be seen in Figure 6.

The difference in the case of a read request is that the `read_*()` handlers are called instead of the `write_*()` ones. Each handler performs its function on the incoming request (modifying its address, data, or both) and

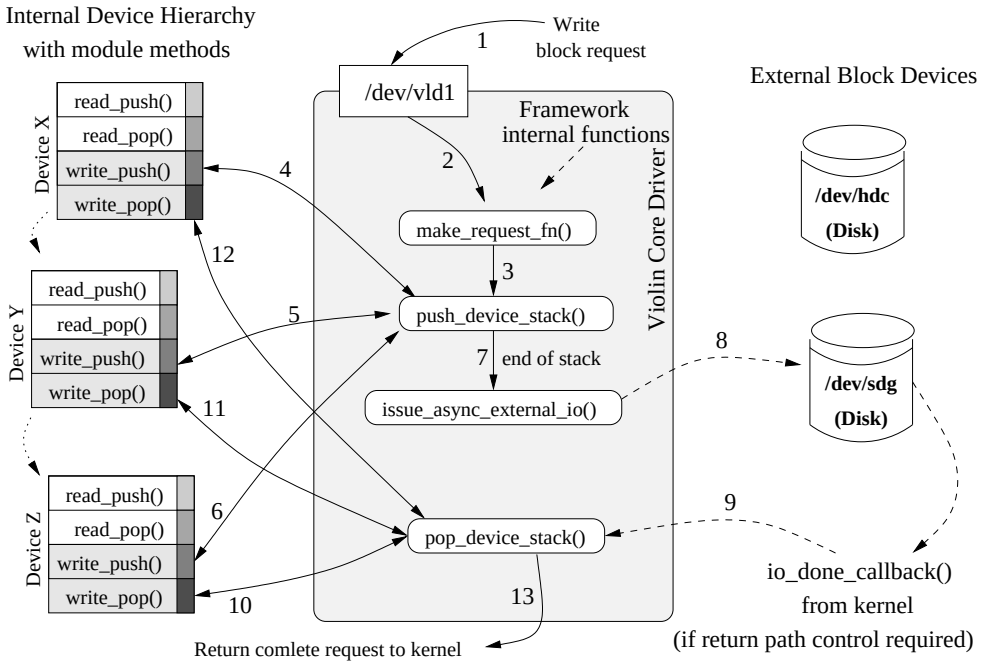


Figure 6: Path of a write request in *Violin*.

then returns control to the `push_device_stack()` function indicating the next device in the path from one of its dependent (or lower) devices, marked with outward arrows. Thus, the `push_device_stack()` function passes the request through all the devices in the path. When the request reaches an exit node, the driver issues an asynchronous request to the kernel to perform the actual physical I/O to another kernel driver (e.g. the disk driver). When return path control is needed, the driver uses callback functions that Linux attaches to I/O buffers. Using these callbacks the driver is able to regain control of the I/O requests when they complete in another driver's context and perform all necessary post-processing.

A Linux-specific issue that *Violin*'s kernel driver must deal with, is the data modifications that certain modules perform (e.g. encryption). The request descriptors received by the kernel, contain pointers to a memory page with the data mapped by higher kernel layers, such as the filesystem. This happens for avoiding copies between I/O buffers. While the request is in progress, the memory page remains available for read access to these higher layers. Thus, modification of the data on the original memory page results in the corruption of the filesystem and buffer cache buffers. Unfortunately, the Linux kernel does not provide a mechanism to ensure exclusive access to system buffers. To resolve this problem with data-modifying modules, we have to create a copy of the buffer where we can modify the data. However, this occurs only when requests pass through data-modifying modules.

Finally, *Violin* can be loaded at runtime as a kernel module. *Violin* modules are implemented as separate Linux modules that are loaded on demand. However, they are not full Linux device drivers themselves but require the framework. Upon loading, each module registers with the core framework driver, binding its methods to internal *module objects* as shown in Figure 7.

4 Experimental Results

In this section we evaluate the effectiveness of *Violin* in three areas: ease of development, flexibility and performance.

4.1 Ease of Development

Measuring development effort is a hard task, since there exist no widely accepted metrics for it. We attempt to quantify the development effort by looking at the code size reduction that we can achieve by using *Violin*.

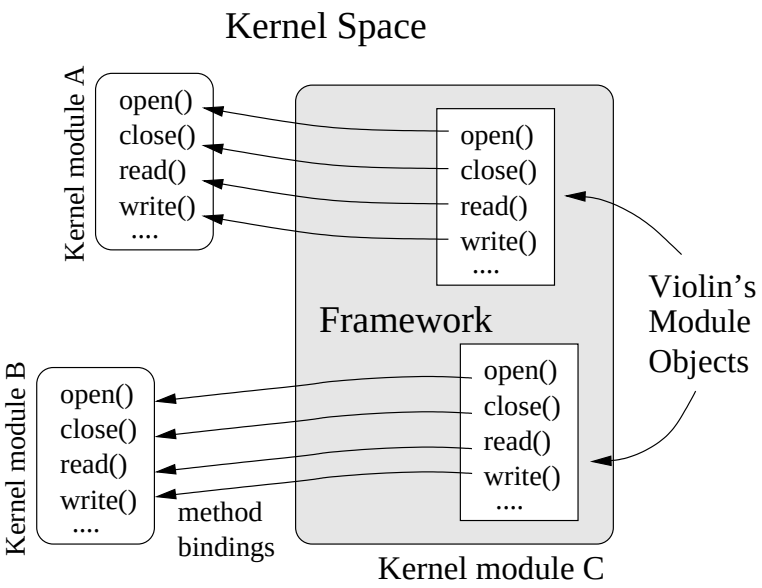


Figure 7: Binding of modules to the *Violin* framework.

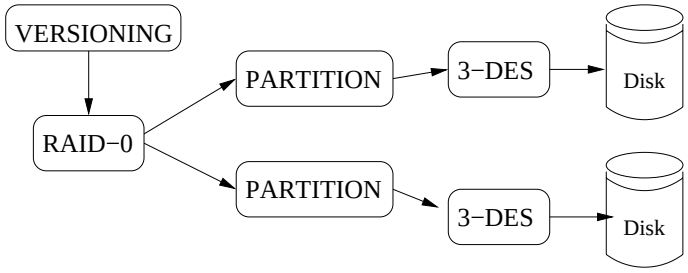
Functions	Number of code lines	
	Linux Driver	*Violin* Module
Violin Framework	12556	–
RAID	11223 (MD)	2430
Partition & Aggregation	5141 (LVM)	1521
Versioning	4770 (Clotho)	809
MD5 Hashing	–	930
Blowfish Encryption	–	806
DES & 3DES	–	1526

Table 1: Linux drivers and *Violin* modules in kernel code lines.

Similar to FiST [32], we use code size as a metric to examine relative complexity. We compare code sizes of various block device drivers that exist for Linux with implementations of these modules under *Violin*:

- **RAID:** Implements RAID levels 0, 1, and 5 for an arbitrary number of devices. Failure detection and recovery is also implemented for levels 1 and 5. Using *Violin*'s ability to synthesize complex hierarchies, this module can be used to create composite RAID levels, such as 1 + 0.
- **Versioning:** Offers on-line snapshot functionality at the block level [8].
- **Partitioning:** Creates a partition on top of another device. It supports partition tables and partition resizing.
- **Aggregation:** Its purpose is to function as a volume group manager. It aggregates many devices into one, either appending each after the other or using striping and allows resizing of the individual or aggregate device. Also, devices can be added or removed and data can be migrated from one device to another.
- **MD5 hashing:** Computes the MD5 fingerprint for each block. Fingerprints are inserted in a hash table and can be queried. Its purpose is to provide the ability for content-based search and facilitates differential compression.
- **Encryption:** Encrypts/decrypts data blocks using the Blowfish, DES or, 3DES algorithms based on a user-specified key.

Table 1 shows the code size for each functional layer implemented as a driver under Linux and as a module under *Violin*. The features implemented in *Violin* modules are close to the features provided by the block drivers under




```
#Create a hierarchy named "voila"
hrc_init /dev/vld voila 32768 1
#Import two disks: /dev/hdb1 and /dev/hdc1
dev_import /dev/vld /dev/hdb1 voila hdb1
dev_import /dev/vld /dev/hdc1 voila hdc1
#Create a 3-DES Encryption Layer on each disk
dev_create /dev/vld DES voila DES_Dev_1 1 hdb1 \
           0 0 0 DES_Dev_1 0
dev_create /dev/vld DES voila DES_Dev_2 1 hdc1 \
           0 0 0 DES_Dev_2 0
#Create two 10 GByte Partitions on top of these
dev_create /dev/vld Partition voila Part_Dev_1 \
           1 DES_Dev_1 -1 300000 0 Part_Dev_1 0
dev_create /dev/vld Partition voila Part_Dev_2 \
           1 DES_Dev_2 -1 300000 0 Part_Dev_2 0
#Create a RAID-0 device on the 2 partitions
dev_create /dev/vld RAID voila RAID0_Dev 2 \
           Part_Dev_1 Part_Dev_2 0 1 0 RAID0_Dev 0
#Create a Versioned device on top
dev_create /dev/vld Versioning voila Version_Dev \
           1 RAID0_Dev 40 0 0 Version_Dev 100000
#Link hierarchy "voila" to /dev/vld1
dev_linkpart /dev/vld voila Version_Dev 1
#Make a filesystem on top
mkfs.ext2 -m 1 /dev/vld1
mount -t ext2 /dev/vld1 /vldisk
```

Figure 8: Example I/O hierarchy with advanced semantics and the script that creates it.

Linux, including LVM. The only exception exists in the MD Linux [3] driver. Our implementation, although it includes code for failure detection and recovery in RAID, does not support the feature of spare disks in a RAID volume. The main reason for not adding this functionality is that we expect it to be handled in a different way in our framework, by composing simpler "spare disk" layers. In our evaluation we consider mainly kernel code and do not report user-level tools. For LVM user-level tools amount to about 14100 lines of code and for *Violin* to about 1700 lines of code.

From Table 1, we see that the size of the *Violin* framework is about 12500 lines of code. Looking at individual modules, in the case of LVM, code length is reduced by a factor of three, while in MD and Versioning the reduction is about a factor of five and six respectively. In MD, more than half of the module code (1300 lines) is copied from MD and is used for fast XOR computation. This piece of code is written mainly in assembly and tests various XOR implementations for speed in order to select the fastest one for each system. If we compute code-length differences without the user-level copied code (i.e. the XOR code), the code difference for the RAID module reaches an order of magnitude.

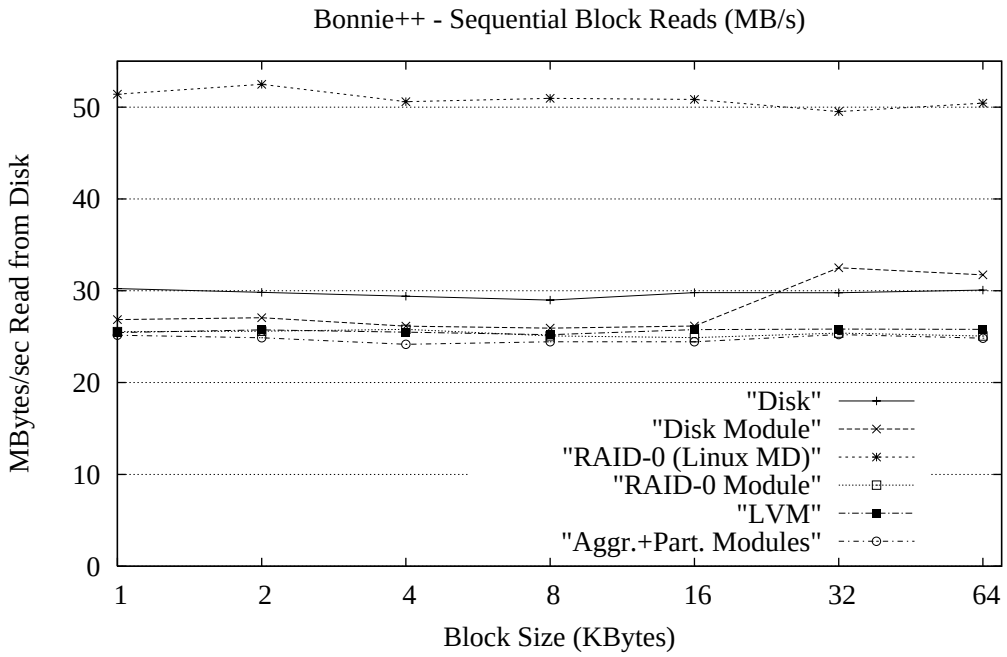


Figure 9: Bonnie performance results for sequential read.

Clearly code size cannot be used as a precise measure of complexity. However, it is an indication of the reduction in effort when implementing new functionality under *Violin*. For the modules we implement, we can attribute the largest code reductions to the high-level module API and to the persistent metadata management support.

To examine how new functionality can be provided under *Violin*, we implement two new modules for which we could not find corresponding Linux drivers: MD5 hashing and DES-type encryption. For each module we use publicly available user-level code. Table 1 shows that MD5 hashing is about 900 lines of code in *Violin* out of which 416 lines are copied from the user-level code. Similarly, our DES encryption module uses about 1180 lines of user-level code, out of a total of 1526 lines. Creating each module was an effort of just a few hours.

4.2 Flexibility

To demonstrate the flexibility of the proposed framework we show how one can create more complex multi-layered hierarchies by combining simple modules. Providing the same functionality with standard OS mechanisms is much more difficult. In this demonstration, we construct a complex hierarchy of virtual devices over a set of physical devices, adding one layer at a time.

Figure 8 depicts a complex hierarchy and shows the script with which this hierarchy is built in a bottom-up fashion using simple user-level tools. Initially two disks modules are inserted in the hierarchy. Next, a partitioning layer is added, which creates two partitions, one on each disk. Then, a RAID-0 layer creates a striped volume on top of the two partitions. Next, a versioning layer is added on top of the striped volume to provide online snapshots. Finally, a triple-DES encryption layer is added in the hierarchy to encrypt data. While this module can be placed anywhere in the hierarchy, we chose to place it directly above the disks.

Overall, we find that *Violin* simplifies the creation of complex hierarchies that provide advanced functionality, once the corresponding modules are available.

4.3 Performance

To evaluate the impact of *Violin* on system performance we use two well-known I/O benchmarks, Bonnie++ (version 1.03a) [2] and PostMark [16], to quantify sequential block I/O and seek latencies. Bonnie++ is a

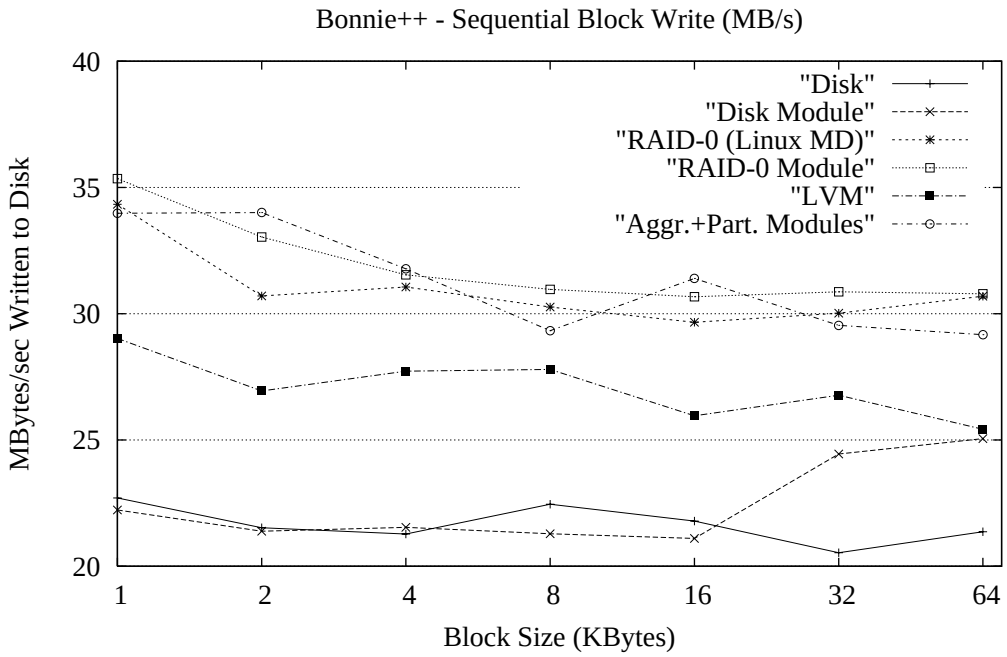


Figure 10: Bonnie performance results for sequential write.

microbenchmark that performs various types of I/O operations and reports basic I/O statistics. PostMark is a synthetic benchmark that emulates the operation of a mail server. Both benchmarks run on top of the Linux Ext2FS filesystem. Reported numbers are averaged over five runs.

The system we use in our evaluation is a commodity x86-based Linux machine, with two AMD Athlon MP 2200+ CPUs, 512 MB RAM, three Western Digital WDC WD800BB-00CAA1 ATA Hard Disks with 80 GB capacity, 2MB cache, and UDMA-100 support. The operating system is Red Hat Linux 9.0, with a 2.4.23 SMP kernel.

First, we examine the performance of single *Violin* modules compared to their Linux driver counterparts. We use three different configurations: raw disk, RAID, and logical volume management. In each configuration we use layers implemented as a block driver under Linux and as modules under *Violin*:

A. The raw Linux disk driver (Disk) vs. a *pass-through* module in *Violin* (Disk Module). The same physical disk partition is used in both cases.

B. The Linux Volume Manager driver (LVM) vs. a dual module setup in *Violin* using the partitioning and aggregation modules (Aggr.+Part. Modules). In the *Violin* setup we use two disks that are initially aggregated into a single resizable striped volume. On top of this large volume we create a 10 GByte partition where the filesystem is created. In LVM we use the same setup. We initialize the same disks into physical volumes, create a volume group consisting of the two disks, and finally create a striped logical volume on top. The size of the stripe block is 64 KBytes in both setups.

C. The Linux MD driver (RAID-0 MD) vs. the *Violin* RAID module (RAID-0 Module). Both modules support RAID levels 0, 1, and 5, however, we choose to measure performance of RAID level 0, which usually offers the highest performance and is the simplest to compare. In both setups we use two disks that are utilized as a single striped volume with a stripe block of 64 KBytes. Note that the system setup in this case is identical to the LVM experiments, with the exception of different software layers being used.

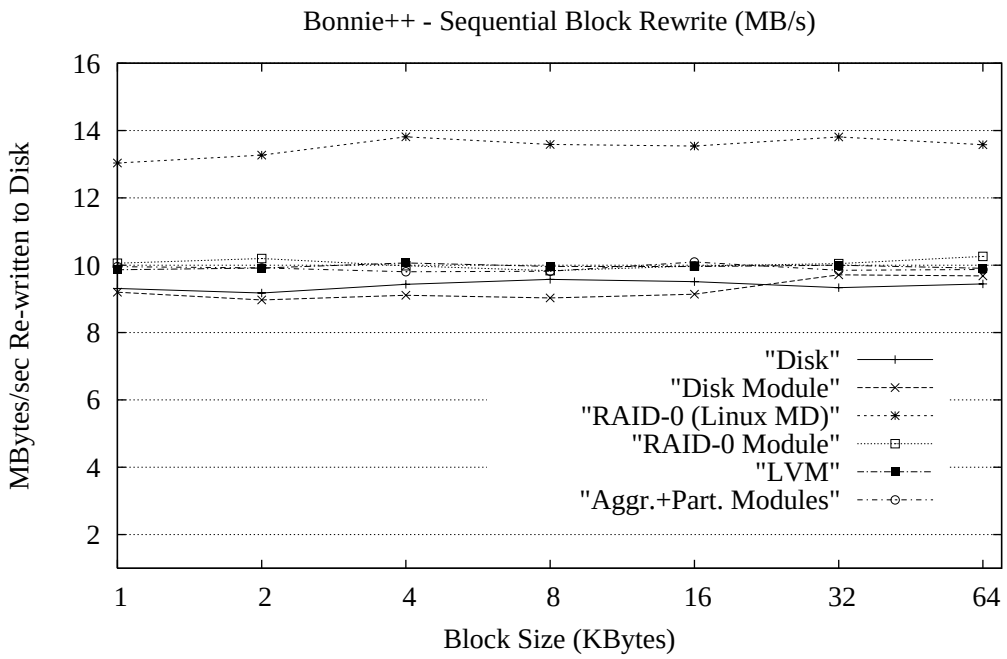


Figure 11: Bonnie performance results for rewrite (read and write).

4.3.1 Bonnie++

Bonnie++ measures sequential I/O throughput and seek latency. The data size we use for sequential I/O is 2 GBytes. We vary block size between 1 and 64 KBytes. Bonnie++ performs the following four tests: (1) *Sequential block write:* A large file is created using the `fwrite()` call. (2) *Block rewrite:* Each block of the file is read with `fread()`, dirtied, and rewritten with `fwrite()`, requiring an `lseek()` operation. (3) *Sequential block read:* The file is read using an `fread()` for every block. (4) *Random seek and read:* Processes running in parallel are performing `lseek()` to random locations in the file and `fread()`ing the corresponding file blocks.

Figures 9-12 summarize our Bonnie results. The block rewrite and read graphs show that Linux MD performs significantly better than the *Violin RAID* configuration. We attribute this difference to the read-ahead optimizations in MD that aggressively prefetch data from the disk and to MD's optimized I/O buffer management. We expect that similar optimizations are possible within the *Violin* buffer management code, however, they require extensive knowledge and experimentation with the Linux kernel. Also, note that although LVM implements essentially the same (functional) operations as MD, it performs similarly or worse than *Violin*'s modules. Specifically in the write experiments with Bonnie, *Violin*'s RAID and Aggregation modules perform have about 15% higher throughput than LVM. In all other cases, however, *Violin* modules and Linux drivers are within a 10% difference from each other. Finally, in the random seek and read test, since the seek latency is bounded by the high disk seek times, we observe that the curves in all three configurations are almost identical.

4.3.2 Postmark results

PostMark creates a large pool of continually changing files and measures the transaction rates for a workload approximating a large Internet electronic mail server. PostMark generates an initial pool of random text files ranging in size from a configurable low bound to a configurable high bound. Once the pool has been created, a specified number of transactions occurs. Each transaction consists of a pair of smaller transactions: (i) create file or delete file (ii) read file or append file. Each transaction type and its affected files are chosen randomly. When all of the transactions have completed, the remaining active files are deleted.

To evaluate the performance of each configuration, we use four input sizes, by varying two independent param-

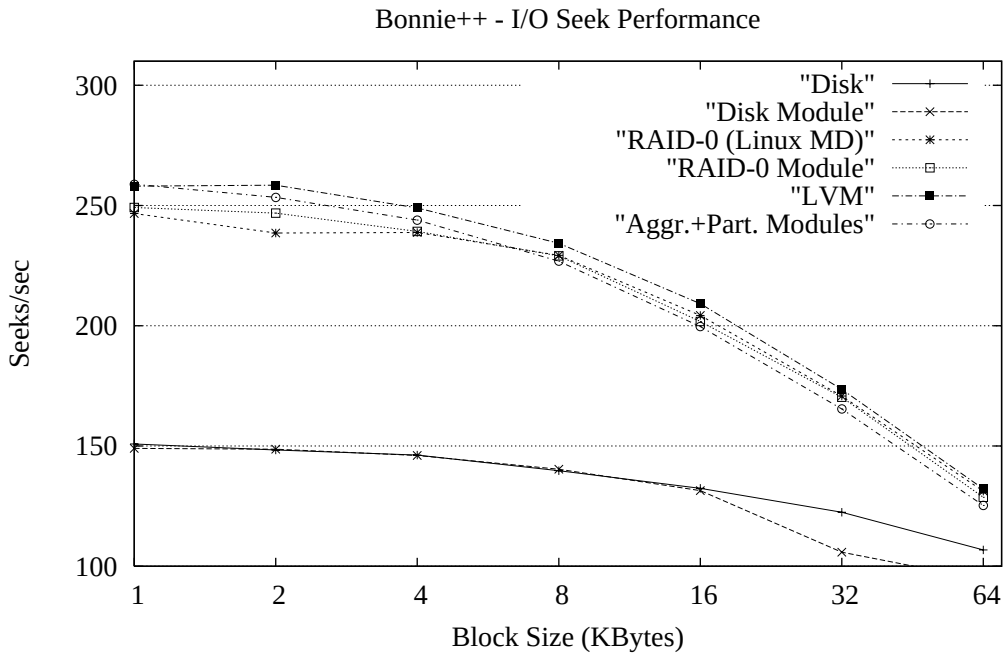


Figure 12: Bonnie performance results for random seeks.

Setup	Initial files	Total Transactions
1	20000	100000
2	20000	200000
3	40000	100000
4	40000	200000

Table 2: PostMark input parameters.

eters: The number of initial files created and the total numbers of transactions. Table 2 shows the values for each postmark experiment. The rest of PostMark's parameters are left to their default values [16]: files range between 500 bytes and 10 KBytes in size, block sizes both for read and write transactions are 512 bytes, and equal biases for read/append and create/delete are used.

Figure 4.3 shows our PostMark results. In each graph and configuration, the solid bars depict the kernel device driver measurements, while the striped bars show the numbers for the framework modules. Also the bars have been grouped according to each system configuration and PostMark experiment. In all cases, there is a small difference between the two system configurations, Linux driver vs. *Violin* module. The kernel module that exhibits the largest difference with its counterpart in the framework is LVM (3.3%). In all other experiments the difference remains below 2%.

4.4 Hierarchy Performance

Finally, for the hierarchy of Figure 8, we evaluate with PostMark the performance of the hierarchy as each module is introduced. Our goal is to provide some intuition on expected system performance with complex configurations. We use a PostMark input of 20K files and 200K transactions. The versioning layer captures a snapshot every 10 minutes during the measurements. Figure 4.4 shows our results as each module is introduced from left to right. The performance of the hierarchy with no modules (*pass-through*) is shown at the first bar. We note that variations in performance as new layers are introduced are fairly small.

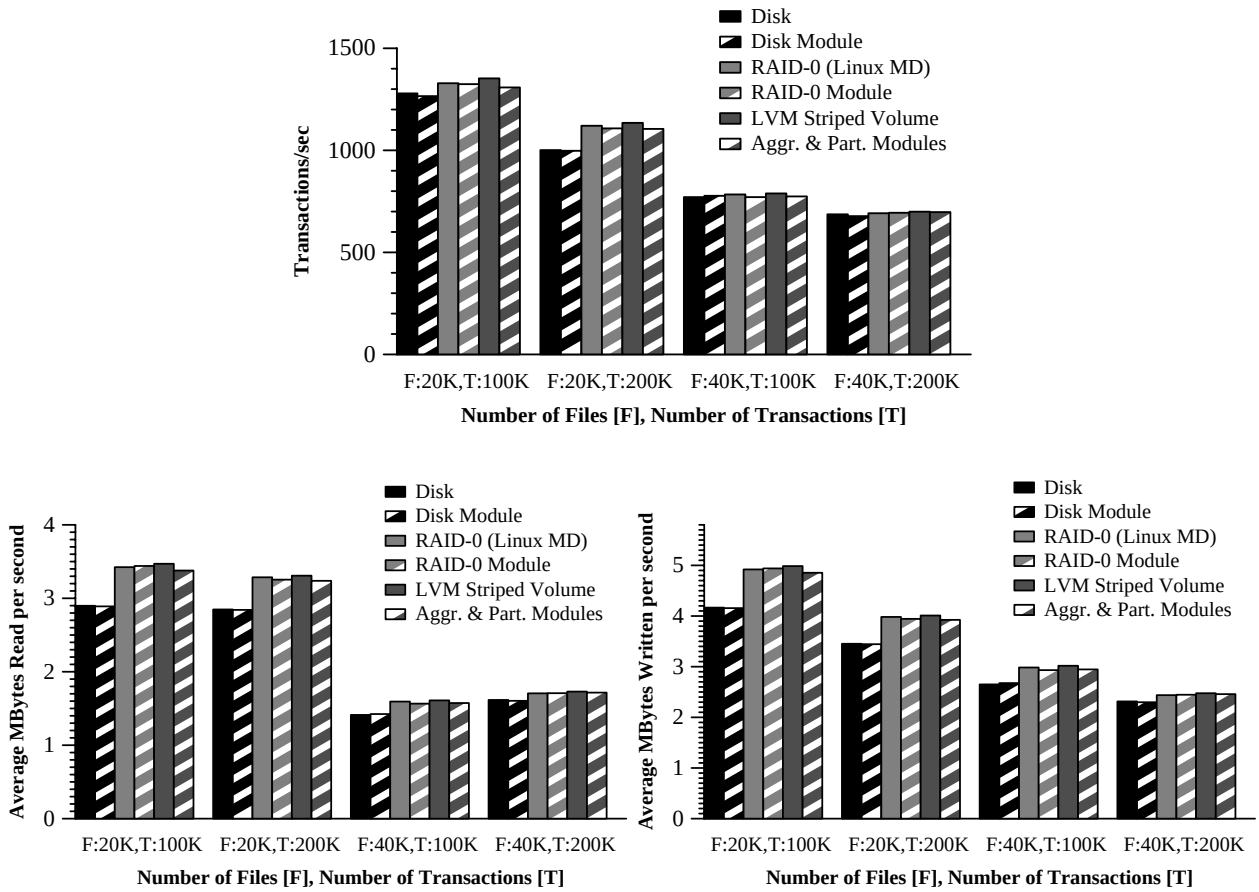


Figure 13: Postmark results (Transactions/sec, Read Throughput and Write Throughput).

5 Related Work

In this section we comment on previous and related work on (a) extensible filesystems, (b) extensible network protocols, and (c) block-level storage virtualization.

Extensible filesystems: Storage extensions can be implemented at various levels in a storage system. The highest level is within the filesystem, where software layers can be combined to implement the desired functionality. The concept of layered filesystems has been explored in previous research.

Ficus [12, 14], one of the earliest approaches, proposes a filesystem with a stackable layer architecture, where desired functionality is achieved by loading appropriate modules. A later approach [30] proposes layered filesystem implementation by extending the vnode/VFS interface to allow "stacking" vnodes. More recently, FiST [32] uses a high-level specification language and a compiler to produce a filesystem with the desired features. FiST filesystems are built as extensions on top of *baseFS*, a native low-level filesystem. A similar concept was used in the Exokernel [15], an extensible OS that comes with XN, a low-level in-kernel storage system. XN allows users to build library filesystems with their desired features. However, developing library filesystems for the Exokernel requires significant effort and can be as difficult as developing a native monolithic FS for an operating system.

Our work shares similarity with these approaches to the extent that we are also dealing with extensible storage stacks. However, the fact that we work at the block-level requires that our framework, provides different APIs to modules, uses different I/O abstractions for providing its services, and different kernel facilities in its

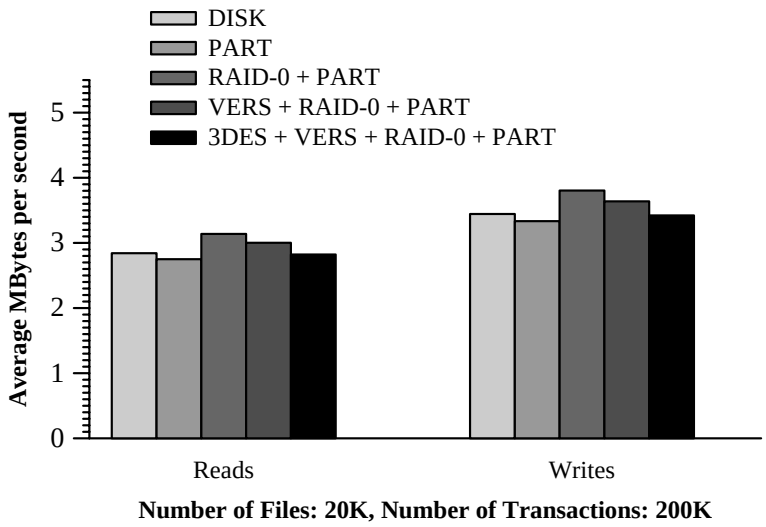


Figure 14: Hierarchy configuration.

implementation. Thus, although the high level concept is similar to extensible filesystems the challenges faced and solutions provided are different.

Extensible network protocols: Our work on storage virtualization bears similarity with frameworks for layered network stacks. The main efforts in this direction are the Click Router [18], X-kernel [24], and Horus [26]. All three approaches aim at building a framework for synthesizing network protocols from simpler elements. They use a graph representation for layering protocols, they envision simple elements in each protocol, and provide mechanisms for combining these simple elements in hierarchies with rich semantics and low performance overhead. Scout [20] is a communication-centric OS, also supporting stackable protocols. The main abstraction of Scout is the I/O paths between data sources and sinks, an idea applicable both to network and storage stacks.

In our work we are interested in providing a similar framework for block-level storage systems. We share the same observation that there is an increased need to extend the functionality of block-level storage (network protocol stacks) and that doing so is a challenging task with many implications on storage (network) infrastructure design. However, the underlying issues in network and storage stacks are different:

- Network stacks distinguish flows of self-contained packets, while storage stacks cannot distinguish flows, but map data from blocks of one device to blocks of another device.
- Network and storage stacks exhibit fundamentally different requirements for *state persistence.* Network stacks do not need to remember where they scheduled every packet in order to recover it at a later time, and thus, do not require extensive metadata. On the other hand, storage stacks must be able to reconstruct the data path for each I/O request passing through the stack, requiring often times large amounts of persistent metadata.
- Send and receive paths in network protocol stacks are fairly independent, whereas in a storage hierarchy there is strong coupling between the request and completion paths for each read and write request. Moreover, an issue not present in network protocol stacks is the the need for asynchronous handling of I/O requests and completions, which introduces additional complexity in the system design and implementation.

Block-level storage virtualization: The most popular virtualization software is volume managers. The two most advanced open-source volume managers currently are EVMS and GEOM. EVMS [7], is a user-level distributed volume manager for Linux. It uses the MD [3] and device-mapper kernel modules to support user-level plugins called *features.* However, it does not offer persistent metadata or block remapping primitives to these plugins. Moreover, EVMS focuses on configuration flexibility with predefined storage semantics (e.g. RAID levels) and does not easily allow generic extensions (e.g. versioning). GEOM [9] is a stackable BIO

subsystem under development for FreeBSD. The concepts behind it GEOM are, to our knowledge, the closest to *Violin*. However, GEOM does not support persistent metadata which, combined with dynamic block mapping are necessary for advanced modules such as versioning [8]. LVM [25] and Vinum [19] are simpler versions of EVMS and GEOM. *Violin* has all the configuration and flexibility features of a volume manager coupled with the ability to write extension modules with arbitrary virtualization semantics.

Besides open-source software, there exist numerous virtualization solutions in the industry. HP OpenView Storage Node Manager [13] helps administrators control, plan, and manage direct-attached and networked storage, acting as a central management console. EMC Enginuity [5], a storage operating environment for high-end storage clusters, employs various techniques to deliver optimized performance, availability and data integrity. Veritas Volume Manager [28] and Veritas File System aim at assisting with online storage management. Similar to other volume managers, physical disks can be grouped into logical volumes to improve disk utilization and eliminate storage-related downtime. Moreover, administrators have the ability to move data between different storage arrays, balance I/O across multiple paths to improve performance, and replicate data to remote sites for higher availability. However, in all cases, the offered virtualization functions are predefined and there do not seem to support extensibility of the I/O stack with new features. For instance, EMC Enginuity currently supports only the following predefined data protection options: RAID-1, Parity RAID (1 parity disk per 3 or 7 data disks), and RAID-5 [6].

RAIDframe [31] enables rapid prototyping and evaluation of RAID architectures, which is similar but narrower than our goals. Also, the authors use a DAG representation for specifying RAID architectures, similar to *Violin*. However, their goal is to evaluate alternatives of certain architectural parameters (encoding, mapping, caching) and not to provide extensible I/O hierarchies with arbitrary virtualization functions.

The latest versions of the Windows OS support an integrated model for building device drivers, the Windows Driver Model (WDM) [21]. This model specifies the runtime support available to writers of device drivers. However, unlike *Violin* for block-level devices, it only provides generic kernel support and does not include functionality specific to storage.

6 Limitations and Future work

Overall, *Violin* provides us with a highly configurable environment to easily experiment with advanced storage functionality. The main limitation of our work is that we have evaluated *Violin* with a specific set of modules. However, we believe that this set is broad enough to demonstrate the benefits of our approach. Further extensions to *Violin* are possible as we gain more experience with its strengths and limitations.

There are two important directions for future work. First, given that we can extend the I/O hierarchy with a rich set of mechanisms, it is important to examine how user requirements can be mapped to these pmechanisms automatically [17]. An interesting aspect on this research direction is to answer the question of how much a system can do in terms of optimizations in this translation process both statically when the virtual I/O hierarchy is built [29], but mostly dynamically during system operation.

Second, it is interesting to examine how *Violin* can be extended to include the network path in virtual hierarchies. Networked storage systems, offer the opportunity to distribute the virtual I/O hierarchy throughout the path from the application to the disk. Exploring the various possibilities and tradeoffs may provide insight on how virtualization functionality should be split among components in storage systems.

7 Conclusions

In this work we design, implement, and evaluate *Violin*, a virtualization framework for block-level disk storage. *Violin* allows easy extensions to the block I/O hierarchy with new mechanisms and flexible combining of these mechanisms to create modular hierarchies with rich semantics.

To demonstrate its effectiveness we implement *Violin* within the Linux operating system and provide numerous I/O modules. We find that *Violin* significantly reduces implementation effort. For instance, in cases where user-level library code is available, new *Violin* modules can be implemented within a few hours. Using a simple user-level tool we create I/O hierarchies that combine the functionality of various modules and provide a set of

features difficult to offer with monolithic block-level drivers. Finally, we use two benchmarks to examine the performance overhead of *Violin* over traditional, monolithic drivers and driver-based hierarchies, and find that *Violin* modules and hierarchies perform within 10% of their counterparts.

Overall, we find that our approach provides adequate support for embedding powerful mechanisms in the storage I/O stack with manageable effort and small performance overhead. We believe that *Violin* is a concrete step towards supporting advanced storage virtualization, reducing storage management overheads and complexity, and building self-managed storage systems.

8 Acknowledgments

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