Making Memory Management Extensible With Filesystems

Abstract

New memory technologies like CXL promise diverse memory configurations such as tiered memory, far memory, and processing in memory. Operating systems must be modified to support these new hardware configurations for applications to make use of them. While many parts of operating systems are extensible, memory management remains monolithic in most systems, making it cumbersome to add support for a diverse set of new memory policies and mechanisms.

Rather than creating a whole new extensible interface for memory managers, we propose to instead use the memory management callbacks provided by the Linux virtual file system (VFS) to write memory managers, called file system memory managers (FSMMs). Memory is allocated by creating and mapping a file in an FSMM's mount directory and freed by deleting the file. Use of an FSMM is transparent to applications. We call this system *Extensible Memory Management* (EMM).

Using EMM, we created a diverse set of standalone memory managers for tiered memory, contiguous allocations, and memory bandwidth allocation, each comprising 500-1500 lines of code. Unlike current approaches that require custom kernels, with EMM, an FSMM can be compiled separately from the kernel and loaded dynamically when needed. We measure the overhead of using filesystems for memory management and found the overhead to be less than 8% when allocating a single page, and less than 0.1% when allocating as little as 128 pages. FSMMs perform competitively with kernel implementations, and sometimes better due to simpler implementations.

1 Introduction

For decades, the memory hierarchy of computer systems was fixed as processor caches, backed by byte addressable and volatile main memory, which itself may be backed by block level nonvolatile storage. However, new hardware technologies, such as huge local memories, nonvolatile byte addressable memories, and CXL-attached far memory, have emerged in recent years that change the traditional memory hierarchy. These hardware technologies have inspired a myriad of systems research for memory management extensions like contiguous allocation [5], tiered memory [20, 33, 38] and disaggregated memory [26, 41]. Linux developers have implemented tightly integrated support for the most available technologies, such as NUMA zones and transparent huge pages as part of the monolithic kernel memory management subsystem.

As the number of new hardware mechanisms grows, and the set of desirable mechanisms and policies grow, more people seek to modify the Linux kernel's memory management subsystem to implement these systems. For example, Meta's TPP kernel patch made changes to the NUMA and page reclamation policies to implement a tiered memory system [33] with changes to 22 kernel files. However, Linux's memory management subsystem makes it more difficult to add software support for new memory hardware: it is monolithic, and functionality is distributed across dozens of files, many of which require modification for each extension. In addition to ensuring that their code changes are correct, engineers must also ensure that their changes do not break existing MM functionality. Finally, engineers either must work to get changes upstreamed to the mainline kernel, or take on maintenance of their own fork for the lifetime of the system. In comparison, file systems and storage can be extended through the VFS and block layers, drivers through standardized driver interfaces, networking through protocols, and there is recent interest in extensible scheduling [9]. These components can all be implemented as standalone components without modifying core kernel code. In fact, Linux's MM subsystem stands out as one of the few major hardware-management subsystems in the kernel that is not easily extensible.

With an increase in memory system diversity and heterogeneity, we believe that operating system memory management *must be made extensible* to cope with the rapid increase in demand. We have four goals for an extensibility interface for MM.

1. **Expressiveness**: an extensibility interface must allow expression of a wide variety of MM behavior.
2. **Transparency**: unmodified applications should be able to use MM extensions.
3. **Control**: advanced applications need to specify memory behavior for specific regions, a la `madvise`.
4. **Non-invasive**: in order to ease adoption, the implementation should not require extensive changes to the existing MM code.

Instead of creating a brand new extensibility interface for MM from scratch, we propose *leveraging the extensibility and MM functionality already provided by the VFS layer*. Developers write MM extensions as file systems, which we call *filesystem memory managers* (FSMMs), and implement the MM functionality in the callbacks provided by the VFS layer. Memory is allocated by creating a file in the FSMM's mount directory and then mapping that file. Memory is freed by unmapping and deleting the memory file. We call this system extensible memory management (EMM).

The callback functions provided by the VFS layer allow FSMMs to control how MM events, such as page faults, are handled, providing sufficient **expressiveness** for a wide variety of FSMMs. For **transparency**, we add a small shim layer to the kernel's memory management system that transparently translates MM system calls like *mmap* into file operations by creating memory-backed files and assigning allocation requests to specific files. Our goal of **control** is achieved as a consequence of basing our system on filesystems, which provide a convenient naming mechanism for different MM implementations. Applications can manually create and map files in the mount directory of the FSMM that provides the functionality desired for a specific memory region. Most importantly, because our approach builds on existing VFS callbacks, it is **non-invasive** and requires adding only the shim layer to make the system transpartent to applications.

The overhead EMM adds to an individual MM operations is 8% in the worst case scenario of single-page sized allocations and fractions of a percent in the common case of multi-page sized allocations. We have used EMM to implement memory managers for tiered memory, bandwidth expansion, and contiguous allocations. Each of those memory managers are implemented as standalone kernel modules without additions to the monolithic kernel MM subsystem.

2 Motivation and Related Work

Memory has become a dominant factor in system performance, which has lead to a multitude of hardware approaches to improve performance, all of which require operating system support. With larger memory sizes, there has been work on improving huge pages [25, 29, 35] and NUMA policies [3]. Fast RDMA networks inspired a renewed interest in remote/disaggregated memory for clusters [15, 32]. Byte-addressable non-volatile memories and high bandwidth memories spur research into tiered memory systems where frequently accessed data is placed in local memory and less frequently accessed memory is stored in slower memory [4, 11, 20, 38, 40]. CXL's memory expansion capabilities also prompt research for tiered memory systems [33] as well as for systems that pool memory between machines [26]. Researchers have also proposed hardware that requires MM changes, such as a TLB that caches contiguous VA to PA translations of arbitrary sizes [22], or a hardware to support dissagregated memory [16].

Problem. Implementing these extensions to support new memory hardware generally requires extensions to operating system memory management policies and mechanisms to support new tradeoffs (e.g., near vs far memory, small vs large pages) and mechanisms (migration for NUMA, compaction for large pages). Such changes are often difficult to make: They require intimate knowledge of the MM system to know all of the places in the code that need to be changed, in addition to knowledge of complex data structures and locking patterns. Unlike many parts of Linux and other OS kernels, the MM subsystem is generally monolithic and lacks extensibility.

An example of the complicated and tangled MM code in the Linux kernel is transparent huge pages [2]. The implementation of transparent huge pages is spread across 18 files in the Linux memory-management subsystem (MM). This code touches a wide range of MM components, such as page fault handling, physical memory allocation, page table management, etc. Additionally, because transparent huge page policies are distributed throughout the MM subsystem, there is an increased likelihood of pathological long latency behavior [29]. Another example is Meta's Transparent Page Placement (TPP [33]), which modifies the NUMA system to support tiered memory. Despite leveraging the existing NUMA code to handle complicated operations like page migration, the authors still modified 22 files in their implementation [31].

Table 1 lists the breadth of changes a selection of recent projects to support better memory management made to the kernel to implement their designs. We organize these changes into sections that represent the core responsibilities of a memory management system: virtual memory management, physical memory management, and translation (e.g., page table management). Adding support for one of these may not be an issue; however, with new memory hardware, we expect there will be many different memory configurations that will need kernel support. Each addition to the monolithic MM subsystem will add to its complexity, making it harder to maintain and expand upon in the future. As such, an extensible interface for MM is imperative to sustain the innovation the boom in new memory hardware promises to bring.

System	Target Hardware	Virtual MM	Physical MM	Translation
TPP [33]	Tiered Memory	N/A	Memory placement decisions. Page migration	Page table updates after migration
Leap [32]	Disaggregated Memory	N/A	Prefetch swapped out pages	N/A
Mitosis [3]	NUMA	N/A	N/A	Replicate and migrate page tables
Range Translations [22]	Range TLB	N/A	Physically contiguous allocation	Manage range based translation table
DVM [18]	Direct Mapping	Make virtual addresses = physical	Physically contiguous allocation	Identity mapping between VA and PA
ASAP [30]	Prefetched Address Translation	N/A	N/A	Page table allocated contiguously

Table 1: Research projects that extend the MM system, and how they extend virtual MM, physical MM, and translation.

Prior work. The interest in extensible MM is not new. In the late 90s, several systems have explored this problem [7,24,37,39]. However, the mechanisms for extensibility in these systems only focus on application-specific paging policies, rather than extensibility for other MM responsibilities. Likewise, microkernel systems [19,23,27,37] and Exokernels [13,17] move much or all of memory management out of the kernel to user-mode where it can be extended or replaced. However, these strategies are maximally invasive, as they require whole new kernel designs that make adoption difficult.

More recent work, like HeMem, extend MM by implementing a user library that overloads MM functions like `mmap` using `LD_PRELOAD` [38]. This approach allows extensions to be self contained inside of a library and transparent to the target application, but it lacks the control and information available to a kernel solution, and does not support policies that span multiple applications.

Inspiration. To guide our design of an extensible MM system, we looked at other extensible subsystems. In particular, with the VFS layer, a developer can create a new filesystem by implementing callback functions provided by the VFS layer to perform generic filesystem operations such as open, read, write, etc. Implementations that do not need to modify standard behavior rely on general helper functions, such as `generic_file_open` and `generic_get_unmapped_area` and can implement only a subset of the interface This greatly simplifies the engineering effort of creating a new filesystem because an engineer only needs to focus on their implementation without having to implement or modify more general filesystem code. As a result, Linux has around 50 filesystem implementations in-tree thanks to the VFS layer. In contrast, Windows has a much lower-level extension interface for file systems [10] and many fewer file system options.

Many filesystems support memory mapping files to an application's memory space, and the VFS layer has callbacks for MM operations, such as page faults, to support this. Linux kernel developers have taken advantage of this in that past for memory management. When support for huge pages was first being discussed, a requirement was that adding support could not overly complicate the existing MM code [28]. This requirement motivated the design of HugeTLBFS, a filesystem-based memory allocator that allows applications to manually allocate huge pages. Because HugeTLBFS is written as a filesystem using VFS, the core of its code is kept in a small set of standalone files. Only a small amount of changes needed to be made to Linux's core MM code, which is what allowed it to be added to the Linux kernel several years before transparent huge pages were supported.

The idea of implementing HugeTLBFS as a filesystem is treated as a one-off solution, and to our knowledge has not been considered again for other systems. It is also not a completely standalone solution. Minor changes have been made to the monolithic MM code to support its use. However, the success of HugeTLBFS as a deployable huge-page mechanism points to a potential solution to extensibility: use the power of the VFS as an extension mechanism to support richer memory management mechanisms and policies and more varied memory configurations.

In order to make VFS a viable extension mechanism for MM, we need to add a layer between the MM syscalls Linux provides and the filesystems that provide the hardware- and policy-specific implementations of those operations for transparency.

3 Design and Implementation

We have the following goals for an extension interface for MM:

1. **Expressiveness**: The extension interface must be able to express a wide variety of MM behavior needed to support modern hardware, such as physical memory allocation, virtual address allocation, and translation management.

2. **Transparency**: A user can change the MM behavior of

an application from the default without modifying the application's source.

3. **Control**: Sophisticated applications can select different MM behavior on different data structures at the same time by explicitly choosing a memory manager for an allocation.

4. **Non-invasive**: The implementation of the extension interface must not overly complicate the existing MM code. Given the existing complexity of OS kernels, we prefer a non-invasive design over a maximally expressive design, so not all extensions may be implementable.

We designed an MM extension interface called *extensible memory management* (EMM) that meets these goals by leveraging the MM capabilities that already exist in the VFS layer. In this design, memory managers are written as filesystems called filesystem memory managers (FSMM) that implement VFS callback related to MM behavior (e.g. `page_fault`). Mounting an FSMM onto the system enables it for use. An FSMM can be mounted anywhere on the file path, and our practice is to have one global mount directory accessible by all users for each FSMM. Memory is allocated by creating and mapping files in the mount directory of an FSMM. We create the *EMM translation layer* that transparently replaces an application's dynamic anonymous memory allocations with allocations using a default FSMM. After mapping, applications access data with ordinary load/store operations. Applications can also choose which memory manager to use by selecting the mount directory in which to create a files. This enables them to choose the FSMM for specific data structures, similar to the use of HugeTLBFS.

3.1 EMM Overview

Figure 1 EMM is composed of the *EMM translation layer* (described in Section 3.2) and one or more FSMMs. The user assigns each process a default FSMM (or none) to use on process startup.

In EMM, the process's syscall interface to MM operations, like the `mmap` and `munmap` system calls remain unchanged. However, with EMM, whenever an process allocates memory by calling `mmap` with the `MAP_ANON` flag or `brk`, or unmaps memory by calling `munmap`, the MM operation is forwarded to the EMM translation layer transparently to the process (1A). Then, the EMM translation layer assigns the allocation to a file in the mount directory of the process's default FSMM when mapping memory or deletes memory in the file(s) mapped to the memory range when unmapping memory (1B). We call these files *EMM files*. From there, the VFS Layer invokes the process's default FSMM, which does whatever processing it needs to do to handle the allocation (1C). Finally, the FSMM either allocates the physical memory for the request if `mmap` was called with the `MAP_POPULATE` flag, or frees the physical memory associated with the deleted files if `munmap` was called (1D).

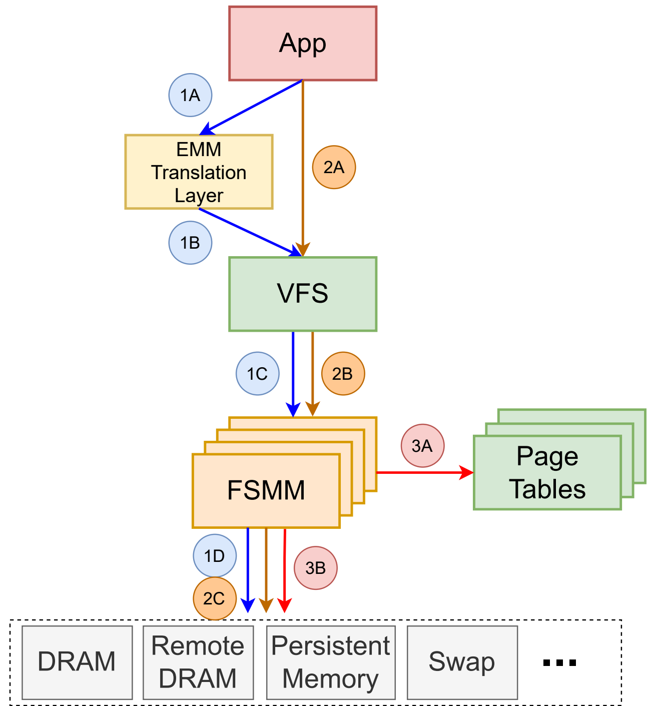

Figure 1: The overall architecture of EMM.

After a call to `mmap`, the process can read and write to the mapped memory region as it normally would. If the physical memory for the region has not already been populated, the first access will trigger a page fault. Because the faulted memory region is associated with a file, the kernel's page fault handler forwards the fault to the VFS (2A). The VFS, in turn, invokes the page fault handler of the FSMM the faulted memory region belongs to (2B). Finally, the FSMM allocates physical memory to handle the fault (2C).

FSMM operation is not limited to synchronous invocations by the VFS layer. As a part of the kernel, FSMMs can spawn kernel threads to perform asynchronous work. For example, a tiered memory system can monitor the hotness of pages by periodically sampling page table access bits inside of an asynchronous thread (3A). With that information, the FSMM thread migrates pages itself, without the prodding of the VFS layer or user applications (3B).

The transparency provided by the EMM translation layer is important for the ease of use of EMM; however, some applications may want to have more control over the MM behavior of special memory regions. For example, a latency-sensitive application running on a tiered memory system may want a critical data structure to always remain in local memory, regardless of the default MM policy used for the rest of the address space. The application can control allocation by cre-

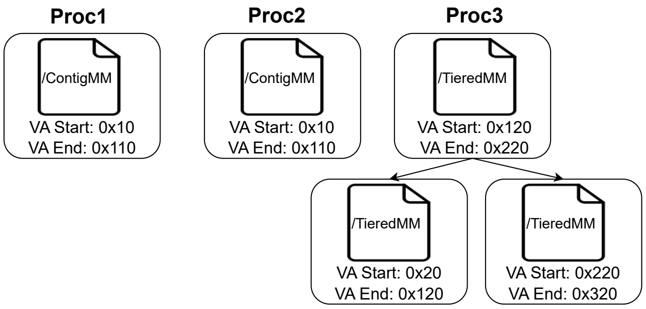

Figure 2: Example of EMM file trees inside of EMM translation layer.

ating and mapping a file in the mount directory of the FSMM that provides the desired functionality for the special region. When doing this, the application takes on the responsibilities of the EMM translation layer for the region. For example, it must create temporary files so they are automatically deleted on process termination, and also set the logical size of the file to at least the desired size of the memory area before mapping, using the `ftruncate` system call. This only sets the logical size of the file, and does not allocate physical memory.

The core Linux MM system still plays an important role in EMM. It still manages the kernel's private memory and the page cache. Additionally, memory for the stack and BSS/data sections of a process are still the responsibility of the core MM system because having them managed by EMM would have significantly increased the invasiveness of the system since they are not allocated via `mmap` or `brk`.

3.2 EMM Translation Layer

The EMM translation layer is the mechanism for transparency in EMM. For each process, it maintains a tree of open EMM files called an *EMM file tree*. When a process calls `mmap` with the `MAP_ANON` flag or `brk`, the kernel invokes the EMM translation layer. It calls the `get_unmapped_area` callback of the application's default FSMM to get the virtual address range for the allocation. Then, the kernel asks the EMM translation layer for a file in the default FSMM to map and the page offset to map it to. The EMM translation layer searches the process's file tree for an existing file that can satisfy the request. If no such file exists, the EMM translation layer creates a new unnamed temporary file and assigns it a compliant virtual address range.

A process's file tree is implemented with the kernel's maple tree implementation and contains every EMM file being used by the process. An example of EMM file trees inside of the EMM translation layer is shown in Figure 2. Each entry of the file tree contains a pointer to an EMM file and virtual address range the file can be mapped to. EMM files are quite large (discussed below) so many EMM file trees only contain one or two entries, but we do not limit the number of entries an EMM file tree can have. Entries are indexed by the start address of their virtual address range.

The naive approach to managing the EMM files would be to have a one-to-one mapping between memory allocations and EMM files. However, there are several issues with this approach. First, creating and opening a new file is expensive, taking about 2-3x the time of a call to `mmap` for anonymous memory. Second, if adjacent memory areas are mapped to different files, the kernel is unable to put those areas in the same VMA structure. This is costly, as allocating a new VMA adds overhead to the `mmap` call, similar to creating and opening a file, and more VMAs makes it more expensive for the kernel to traverse the VMA tree in the future. Additionally, if the process makes many allocations, it is possible to reach the kernel limit of 2^{16} VMAs per process.

The EMM translation layer instead shares EMM files across multiple allocations and organizes the allocations within the file to increase the likelihood that they can reside in the same VMA. Other than being in the same file, two memory regions can only be placed in the same VMA if: their permissions are the same, their virtual addresses are contiguous, and the areas they map in they file are contiguous. The EMM translation layer does not have control over the first two. The permissions are determined by the caller of `mmap`, and the virtual addresses are controlled by the FSMM, though existing implementations of `get_unmapped_area` provided by the kernel, like `generic_get_unmapped_area_topdown`, provide virtual contiguity. However, the EMM translation layer can control where allocations reside in a file.

When a new EMM file is created, the EMM translation layer sets its logical size to large value (128GB in our implementation) so it can fit many allocations while allocating from the top down. Setting the logical size of a file simply modifies the file's directory entry metadata, so setting the logical size of a file to a large value is no more expensive than setting it to a smaller value. In order to ensure that allocations maintain the same relative placement inside the file as they do in virtual memory, the EMM translation layer associates each file with a virtual address range of equal size to the file. When the EMM translation layer is asked to provide an EMM file for a new allocation, it searches through the process's file tree for a file such that the allocation is wholly within the file's virtual address range. If such a file is found, the EMM translation layer returns it for the allocation to map. The EMM translation layer assigns the allocation an offset into the file equal to the allocation's start address subtracted by the start of the file's virtual address range. The EMM translation layer does not need to track which regions of a EMM file are allocated because `get_unmapped_area` implementations cannot allocate overlapping virtual address regions.

If a suitable file is not found, the EMM translation layer creates a new one. The virtual address range of the new file is determined by the virtual address of the allocation and whether the allocation is done via `brk` or `mmap`. If the allocation was done by brk, the start of the file's virtual address range is set to the start address of the allocation because brk grows the address space upwards. If the allocation was done by mmap, the end of the file's virtual address range is set to the end address of the allocation because mmap typically grows the address space downwards.

When a process calls munmap, the EMM translation layer searches the process's EMM file tree and punches a hole into each file that overlaps with the range of addresses being unmapped by calling fallocate with the FALLOC_FL_PUNCH_HOLE flag on the files. Similarly, when a process terminates, the EMM translation layer traverses each entry of the process's file tree and deletes each file. These two actions signal to the corresponding FSMM that physical memory should be freed.

We integrate the EMM translation layer into the kernel, but an alternative implementation would be to create it as a userspace library that intercepts processes's calls to MM related glibc functions via LD_PRELOAD, similar to the implementation of HeMem [38]. We chose to pursue a kernel solution because a userspace implementation would incur the overheads of crossing the kernel boundary for each file operation in addition to the MM system calls. Additionally, while unlikely, applications can invoke MM system calls directly rather than going through the glibc functions, bypassing a userspace solution. For these reasons, we believe the kernel implementation is a more robust design, despite the need for modest kernel changes.

3.3 FSMM Design

An FSMM can be implemented with only a subset of the callbacks provided by the VFS layer. A list of particularly important callbacks are listed in Table 2. With these interfaces, an FSMM is able to control how virtual addresses are allocated (get_unmapped_area), how physical memory is allocated (page_fault and fallocate), and how physical memory is freed (free_inode and fallocate). An FSMM can also be signalled when a file is mapped for the first time (mmap).

In addition to the interfaces from the VFS layer, FSMMs have access to interfaces available to other kernel subsystems because they themselves are parts of the kernel. They can allocate physical pages directly by statically reserving memory at boot time, or can dynamically allocate and free physical memory by calling the alloc_pages and put_page kernel functions. FSMMs can also traverse process VMA trees and modify page tables.

Because the core of their implementation is done as callback functions, FSMMs can be written as completely standalone pieces of software, like most filesystems. In fact, an FSMM can be created as an independent kernel module that is compiled and loaded seperately from the main kernel.

3.3.1 Virtual Memory Management

The primary way an FSMM controls the virtual addresses of an allocation is via the get_unmapped_area VFS callback. The get_unmapped_area callback passes the length of the allocation, the mmap flags it was called with, and an address hint provided by the caller to the FSMM. Then, the FSMM finds a suitable virtual memory region in the caller's address space that satisfies the input parameters as well as the FSMM's design goals. For example, an FSMM implementing devirtualized memory [18] would have the virtual addresses be equal to the physical addresses allocated for the allocation. FSMMs could also use virtual addresses to encode information about the allocations as in OVC [6]. In order to minimize the overhead of the EMM translation layer, implementations of get_unmapped_area should allocate virtual addresses contiguously and grow the address space downward to allow for VMA merging (as detailed in Section 3.2).

FSMMs that are not particular about virtual addresses selection can point the get_unmapped_area callback to existing helper functions in the kernel, like generic_get_unmapped_area_topdown and thp_get_unmapped_area.

3.3.2 Physical Memory Management

There are two ways an FSMM is alerted that a process needs physical memory: the page_fault VFS callback and the fallocate VFS callback. The kernel invokes page_fault callback during a page fault and gives the FSMM the address the triggered the fault. The fallocate callback, which is used to tell filesystems to preallocate disk space for a file, is invoked by the EMM translation layer when mmap is called with the MAP_POPULATE flag and gives the FSMM the memory range to allocate memory for. In both callbacks, the FSMM can make decisions such as where the physical memory should be allocated from and whether or not to use huge pages.

Similarly, there are two ways an FSMM is alerted that a process's memory can by freed: the free_inode callback and the fallocate callback when it is called with the FALLOC_FL_PUNCH_HOLE flag. The EMM translation layer invokes the free_inode callback when an EMM file is deleted, which occurs after the process using the file terminates, and tells the FSMM to free all of the physical memory belonging to that file. When a process calls munmap on a region including an EMM file, the EMM translation layer invokes the fallocate callback with the FALLOC_FL_PUNCH_HOLE flag, which gives the FSMM a memory range to free.

Allocating and freeing physical memory is not limited to these callbacks. For example, for a tiered memory FSMM to migrate a page from the local node to the remote node in a kernel thread, it would need to both allocate a page in the remote node and free a page in the local node. Additionally, some FSMMs, such as those used to implement RMM [22] and

Interface	Defined in	Called by	Purpose
`mmap` (callback, not syscall)	`struct file_operations`	mmap syscall	provide VFS a set of functions (`struct vm_operations_struct`) to manage a mapping
`get_unmapped_area`	`struct file_operations`	mmap syscall	allocate virtual address range
`fallocate`	`struct file_operations`	mmap syscall with `MAP_POPULATE` flag / munmap syscall	signal need to allocate / free physical memory
`fault`	`struct vm_operations_struct`	Page fault handler	control the paging behavior of a process
`free_inode`	`struct super_operations`	file deletion code	signal need to free physical memory

Table 2: Interfaces used by FSMMs.

DVM [18], may want to always preallocate physical memory for a region whether or not the region was created with the `MAP_POPULATE` flag. This can be accomplished by allocating physical memory at the same time virtual memory is allocated in the `get_unmapped_area` callback.

FSMMs need to know what parts of EMM files are backed by physical memory and what pages they are backed by so those pages can be freed later. Traditional filesystems solve a similar problem by managing indexing structures that map file offsets to disk blocks. Such a structure is not generally needed in an FSMM because they can walk the the page tables of the processes that map their files to get this information.

An FSMM needs access to physical pages in order to assign them to processes. This access can be granted statically by reserving a chunk of memory at boot time or immediately when the FSMM is mounted. An FSMM can also allocate physical pages dynamically using standard kernel functions like `alloc_pages`. Both strategies have their benefits.

Reserving physical pages statically guarantees that a certain amount memory will be available to an FSMM without having to worry about the memory usage of the rest of the system. It gives the FSMM more control over the memory. For example, a problem that some systems experienced is interference from internal memory fragmentation [29]. By statically reserving a block of pages, an FSMM can guarantee that specific contiguity requirements are met. The control of a static reservation can also help simplify physical page allocation, leading to performance improvements. With statically allocated pages, an FSMM can use data structures other than the kernel's buddy heap, such as a simple free list of base pages for speed, or a tree of free segments for contiguous allocation.

Dynamically reserved pages have the benefits of flexibility. When an FSMM reserves pages dynamically from the kernel, it eliminates concerns of overprovisioning physical pages, taking away resources from the rest of the machine needlessly, or underprovisioning and not having enough pages to satisfy the requests of the applications using it. FSMMs can also respond to kernel memory pressure by registering a "shrinker" callback with the kernel. Shrinkers are typically used by the kernel to tell drivers to free memory by clearing their caches, but FSMMs can use it as a signal that it needs to start returning physical memory to the kernel [8]. Additionally, by using built in kernel functions to allocate pages, the FSMM does not have to implement its own page allocator.

Regardless of whether an FSMM reserves physical pages statically or dynamically, FSMMs will still generally manage physical pages via the kernel `page` and `folio` structures.

3.3.3 Virtual to Physical Translation

FSMMs handle virtual to physical translation by modifying the page tables of the process's using them. Translation in FSMMs are primarily created in the `page_fault` VFS callback. In most cases, this involves simply populating PTEs in the page table, but the `page_fault` callback is also the natural place to implement alternative page tables designs, like those proposed in RMM [22] and Mitosis [3]. Existing kernel helper functions, such as `mk_pte`, which creates a PTE entry from a physical page and access permissions, and `walk_page_range`, which walks a process's page table invoking callbacks provided by the caller for each entry, help FSMMs accomplish these translation tasks. While most translation work occurs in the `page_fault` callback, an FSMM can traverse and edit a process's table at any time. This is useful, for example, to periodically monitor page table access and dirty bits in a kernel thread.

3.4 Discussion

This design satisfies our four goals for an MM extension interface. The VFS layer's support of memory mapped files for traditional filesystems along with MM helper functions available in the kernel provide an **expressive** interface that allow engineers to express a wide variety of MM behaviors (see Section 5). The EMM translation layer allows processes to use EMM **transparently** by translating standard MM functions to file operations in the default FSMM's mount directory. Furthermore, the default FSMM is chosen on process start without any change necessary to application code. If an application wants **control** over the MM behavior of specific memory regions, it can manually create and map files in the mount directory of the FSMM that provides the desired behavior. Finally, piggybacking off of the kernel's longstanding ability to memory map files into a process's address space allows EMM to be **non-invasive** to the existing MM code - only modest changes were needed to invoke the EMM translation layer (see Section 3.5).

Impact on kernel MM With EMM, we envision that most MM policy decisions will be moved inside FSMMs. As such, we believe the role of the core kernel MM subsystem should be providing a sound foundation for the FSMMs to build upon. This includes things it already does well, such as forwarding MM events to FSMMs and doing bookkeeping needed for most MM implementations, such as maintaining the VMA list and creating default page tables. A solid foundation also involves providing useful helper functions to FSMMs for common MM operations, acting as a software library to more easily create FSMMs. Some useful helper functions, like `alloc_pages` for allocating physical memory and `walk_page_range` for walking the page table, are already available to FSMMs. As more FSMMs are written, we believe it will become clear what other helper functions would be useful. Finally, a simple memory manager should remain in the core MM code for the kernel to use, to manage stack and data/BSS segment memory, and to bootstrap the system on startup.

Limitations There are some limitations to the design of EMM. The first is the FSMMs are not composable. If, for example, one had an FSMM for huge pages and another for tiered memory, they cannot be "stacked" together to make an FSMM for tiered memory using huge pages. A second limitation is there is no easy way for multiple FSMMs to coordinate with each other. For example, such functionality could be useful to decide which FSMM should be chosen as a victim to swap out pages under memory pressure. Additionally, previous research has shown benefits in extending the MM behavior of kernel processes [21]. Sadly, using EMM on the kernel is not supported as the kernel cannot memory map files. For the same reason, EMM cannot be used to manage page cache memory. Similarly, EMM does not apply to memory in the stack or data/BSS segments because these regions are not allocated with `mmap` or `brk`. However, these memory sections are often much smaller than dynamically allocated regions, so we believe they do not require as much specialized behavior. Finally, an FSMM may not support all the features of Linux anonymous memory, such as the handling of copy-on-write after a process is forked, so allocations or operations may fail for applications that use these.

3.5 Implementation

We implemented EMM in Linux kernel version 6.2. The EMM translation layer was implemented in about 600 lines of code. Changes to the rest of the kernel MM code were minimal; only about 50 lines of code were added to interface with the EMM translation layer where appropriate.

In our implementation, a process's default FSMM is set by writing its mount directory to `/proc/<pid>/EMM_mount_dir`. For our experiments, we use a wrapper application that sets the default FSMM and then calls `execv` to run the desired application.

In addition to the kernel changes to support EMM, we have also implemented four different FSMMs to demonstrate EMM's extension capability. These include a bare-bones FSMM that simply allocates base pages, and FSMMs for tiered memory, bandwidth expansion, and contiguous memory allocation. They are described in more detail in Section 5.

4 Performance Evaluation

EMM, like any other abstraction layer, comes with some level of overhead. The main source of this overhead is in the creation and management on files in the EMM translation layer.

Applications only invoke EMM translation layer when a memory region is mapped/unmapped; subsequent callbacks go directly to the VFS layer. Therefore, to stress the EMM translation layer, we created a microbenchmark that calls the `mmap` system call multiple times in quick succession in one or more threads. We also instrumented the EMM translation layer to measure the time spent managing files when mapping/unmapping a region

All experiments in this paper are run on bare metal Cloudlab [12] c220g1 machines with two Intel E5-2630 v3 8-core CPUs and 128GB of ECC DDR4 RAM spread across two NUMA nodes. We set the CPU scaling governor to `performance`, fixing the clock frequency to 3.2GHz. Due to lack of CXL hardware, we approximate remote memory as memory accesses to the remote NUMA node.

BasicFSMM We implemented a simple bare bones FSMM we call BasicFSMM to measure the minimum cost of an FSMM. When it is first mounted, BasicFSMM pre-reserves the pages it will use for its operation from the kernel and places them in a linked list of free pages. It defers to the kernel to allocate virtual address space. When memory is requested via the `page_fault` or `fallocate` VFS callbacks, it allocates a 4KB base page by popping one from the free list to satisfy the request. When memory is freed, such as via the `free_inode` callback, BasicFSMM places the freed pages back onto the free list. BasicFSMM is implemented in about 550 lines of code. This simple design, while not useful in practice, is helpful for measuring the minimum cost of a FSMM and for understanding the minimal implementation of a FSMM.

EMM translation layer Latency. We first measure how the latency overhead of EMM scales with the size of the allocation compared to base Linux. We configure the microbenchmark to measure the latency of `mmap` with the `MAP_ANON` flag and without the `MAP_POPULATE` flag 100,000 times with allocation sizes ranging from 1 to 128 pages, and measure the latency of calling `munmap` on those regions. We use BasicFSMM for these experiments. Table 3 shows the results.

These results show that time it takes to call `mmap`/`munmap` is near constant as the allocation size varies when using both base Linux and EMM, which is expected because the operation only reserves virtual address space but does not allocate and zero memory. However, calling `mmap` is about 15-20% slower with EMM than with base Linux. Similarly, calling `munmap` is between 30-40% slower than Linux. This overhead comes from the EMM translation layer's work to manage the file tree and locate a file for the allocation. With the `MAP_POPULATE` flag, EMM translation layer (marked as EMM- Populate in Table 3) adds only 8% extra latency to the cost of allocating 1 page, which decrease proportionally with the allocation size, down to 0.1% of the cost of allocating 128 pages. When allocation is included, the overhead introduced by the EMM translation layer is overshadowed by the cost of allocating and zeroing free pages. In fact, EMM with BasicFSMM was between 4-8% faster than Linux at `mmap` with the `MAP_POPULATE` because of its simpler page allocation path. Likewise, BasicFSMM is up time 45% faster than Linux at `munmap` when the memory region is populated because of the simple page freeing path. Results where the microbenchmark touches pages to trigger allocation during a fault, rather than with `MAP_POPULATE`, behave similarly.

We also measure how EMM scales with an increasing number of threads allocating memory at once. We use the same configuration as above, with 1-page allocations while varying the number of threads calling `mmap` from 1 to 32. This stresses the EMM translation layer code walking the process file tree. The overhead of EMM remains between 15-20%, similar to the last experiment, regardless of the number of threads used. This makes sense because the `mmap` system call serializes these requests with the `mmap_lock`.

Extrapolation to applications. Our microbenchmark stresses the performance of the EMM translation layer, but is not representative of how applications use memory, as user-mode heaps typically allocate large chunks of memory infrequently and then satisfy small memory requests from these chunks. To understand real-world behavior, we measured the frequency of `mmap` and `brk` calls made by various applications. These results are listed in Table 4. Calls to `mmap` and `brk` are relatively infrequent, typically less than twice a second, which makes the overhead of EMM translation layer negligible. Furthermore, each call to `mmap`/`brk` typically allocates several thousand pages, amortizing overheads further. The exception to both of these is canneal, which on average makes an allocation of 54 pages twenty times a second for an overhead of a 0.23% (a few microseconds delay per second). Additionally, the cost of allocating tens of physical pages is still enough to further hide overheads.

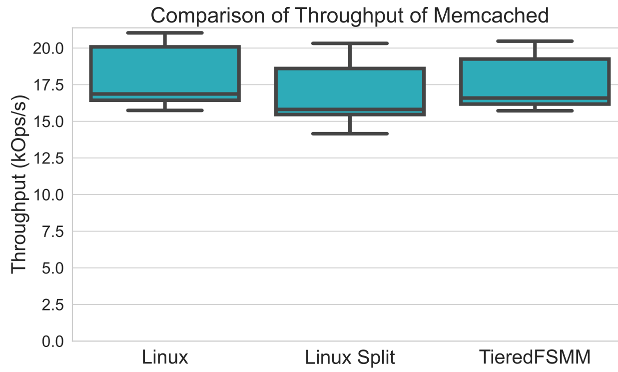

Figure 3: Stem-and-whiskers plot of the average throughput over 50 executions of Memcached driven by YCSB in a read only workload in the Linux, Linux Split, and TieredFSMM configurations.

Once EMM allocates a physical page and maps it into a process page table, the cost of load and store instructions in those regions will be the same as loads and stores to regions managed by the kernel's default memory manager, as there is no software overhead. Differences in performance at this point occur due to policies and mechanisms of the specific FSMM, such as manipulations of the page table (e.g., clearing access and dirty bits, TLB flushes) or page migration.

5 Case Studies

In addition to the BasicFSMM we implemented three FSMMs inspired by previous works on memory management to show the power of EMM. Unlike their original implementations, each FSMM is a standalone kernel module built and loaded separately from the main kernel.

5.1 Tiered Memory

We have built a tiered memory FSMM based on the design of TPP [33] called TieredFSMM. The goal of TieredFSMM is to place a process's frequently accessed (hot) data in faster local memory, while placing less frequently accessed (cold) data in slower remote memory. It is implemented in about 1500 lines of C code, about a third of which is for debugging and boilerplate for defining a filesystem.

The memory available to TieredFSMM is segregated into local and remote memory pools. These memory pools are reserved statically at boot time for simplicity. Each pool keeps a list of hot pages and a list of cold pages allocated from that pool. Periodically, a kernel thread samples the page table

System	1 page	2 pages	8 pages	32 pages	128 pages
Linux	0.78 / 1.50	0.70 / 1.53	0.71 / 1.54	0.69 / 1.49	0.70 / 1.50
EMM	0.94 / 2.05	0.83 / 1.96	0.83 / 1.99	0.82 / 2.02	0.84 / 2.01
Linux - Populate	2.17 / 2.36	3.16 / 2.55	9.56 / 4.01	35.18 / 9.34	136.99 / 22.50
EMM- Populate	2.08 / 2.50	2.97 / 2.62	8.73 / 3.74	31.52 / 7.28	125.21 / 14.88

Table 3: Average time spent to `mmap`/`munmap` in microseconds.

Application	`mmap` calls	`brk` calls	Average Size (Pages)	Allocation Frequency (Hz)
xz	538	6	22,000	1.2
mcf	47	7	45,000	0.06
cactuBSSN	195	11	8500	0.5
canneal	9	4,691	54	20
Memcached	930	3	17,000	1.8

Table 4: Breakdown of `mmap` and `brk` calls made by applications.

accessed bits of allocated pages and adjusts the hot and cold lists accordingly. Similarly, a kernel thread will periodically monitor the amount of memory available in the local pool. If the available memory is below an administrator defined reclamation threshold, pages from the bottom of the local pool's cold list will be migrated to the remote pool and placed on the top of the remote pool's cold list. If the available memory is above an administrator defined allocation threshold, which is lower than the reclamation threshold, pages from the remote pool's hot list will be migrated to the local pool and placed on top of the local pool's hot list.

When a process using TieredFSMM requests a physical page, it is placed in the local pool if the available memory is above the allocation threshold. Otherwise, it is placed in the remote pool. In both cases, the page is placed on the hot list of the pool it is allocated to. This logic is implemented inside of the VFS `page_fault` callback. TieredFSMM supports mapping 2MB huge pages as well as 4KB base pages. However, we have found that the smaller base pages are more useful for determining hot regions, so we use base pages for our experiments.

We evaluated TieredFSMM with a modified version of the GUPS microbenchmark where 90% of accesses go to a hot region of memory, and the addresses that make up the hot region change partway through execution (originally used with HeMem [38]). We run GUPS with 32GB of data and a hot region size of 8GB, and configure TieredFSMM with 8GB of local memory and 64GB of remote memory, and compare against standard Linux's default NUMA policy with the same local/remote allocation (Linux Split), and standard Linux where all of the workload's memory fits comfortably in local memory (Base Linux). Regrettably, we were unable to get TPP working (and confirmed others experienced similar problems), so we cannot compare it to the performance of TieredFSMM.

Table 5 shows the performance of Linux Split and TieredFSMM relative to the performance of Base Linux. TieredFSMM outperforms Linux Split because it lowers the number

System	Relative Throughput	Remote Access %
Linux Split	70%	20%
TieredFSMM	88%	6.5%

Table 5: Throughput of GUPS as a percentage of Base Linux throughput and the percentage of memory reads going to remote memory. We only measure reads because there is no perf counter for stores that miss the last level cache.

of memory accesses going to remote memory. It does this by identifying the new hot set when the access pattern changes and demotes no longer hot pages to remote memory and migrates the new hot set to local memory. Linux Split on the other hand is hurt by the fact that NUMA's ability to demote memory is limited, leaving no room for the new hot set to enter local memory [33].

We also evaluated TieredFSMM's performance with Memcached using YCSB with a read-only zipfian workload using the same configurations as above. Because the throughput results vary, we ran the experiment fifty times per configuration and report the results in Figure 3. The median throughput when using TieredFSMM is 98% of the median throughput of Base Linux, while Linux Split achieves only 94% of Base Linux. Again, the performance gains of TieredFSMM over Linux Split is due to the number of remote memory accesses. With Linux Split, 57% of memory reads are served by remote memory, compared to less than 0.5% in TieredFSMM.

5.2 Bandwidth Utilization

SK Hynix recently released the HMSDK library and modified kernel that supports heterogeneous memories [1]. A key feature is interleaving a process's memory across the memory nodes of the machine to maximize the memory bandwidth available to the process. We implemented the same functionality as a FSMM called BWFSMM. With BWFSMM, an administrator sets the allocation weights for each memory node

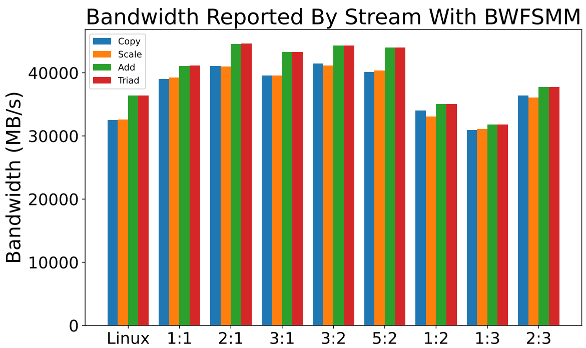

Figure 4: Memory bandwidth results calculated by the STREAM benchmarks with Linux and BWFSMM with different local:remote allocation ratios. 2:1 means 2 pages are allocated to local memory for every 1 page allocated to remote memory.

via a sysfs interface created when BWFSMM is mounted: a local:remote weight ratio of 3:2 indicates 60% of memory should be allocated locally and 40% remotely. When a process requests physical memory, a BWFSMM will allocate a page chosen from one of the available nodes in a round robin fashion, weighted by the provided allocation weights. This allocation is done inside of the `page_fault` and `fallocate` callbacks which use the `alloc_pages_node` kernel function to allocate physical pages dynamically from the desired node. BWFSMM currently only supports allocating base pages, but we plan on adding huge page support. Because of the extensibility of EMM, this prototype bandwidth expanding memory manager was able to be written in a single afternoon.

We test the functionality of BWFSMM by using it as the default FSMM for a version of the STREAM benchmark [34] running with 8 threads to saturate the bandwidth on the local node. The original STREAM benchmark exercises memory bandwidth by accessing global variables, so we modified the benchmark to allocate those variables via `mmap` instead. Figure 4 shows the bandwidth results of running STREAM with Linux and BWFSMM with various local:remote node allocation ratios. BWFSMM with allocation ratios of 1:1, 2:1, 3:1, 3:2, and 2:3 outperform Linux's MM which only allocates to the local node because BWFSMM is able to utilize more bandwidth across the two nodes than it can with the local node alone.

We ran the same experiments with HMSDK to see how BWFSMM compares. In all cases, the results from BWFSMM are within $\pm 3\%$ of the results from HMSDK.

5.3 Contiguous Allocation

Redundant Memory Mappings proposes adding a software "range page table" with a corresponding hardware "range TLB" to CPU translation hardware that caches virtual to physical address mappings of arbitrarily sized memory ranges contiguous in both virtual and physical memory [22]. To increase the effectiveness of the range TLB, the authors modify the MM code to eagerly allocate physical memory when `mmap` is called, rather than lazily allocating physical memory on first use of eachpage. This increases the contiguity of the physical memory, allowing a larger range to be cached in the range TLB. We have implemented these extensions to MM as an FSMM called ContigFSMM.

	% TLB Misses Prevented
mcf	99.78%
cactuBSNN	99.92%
GUPS	99.91%

Table 6: Percentage of an application's TLB misses prevented by using ContigFSMM as the default FSMM, with a 32 entry range TLB

To eagerly allocate a memory region's physical memory, ContigFSMM allocates all of its physical memory inside the `get_unmapped_area` VFS callback. ContigFSMM allocates contiguous blocks of physical pages using the `folio_alloc` kernel function. This design choice simplifies the implementation of ContigFSMM, allowing it to piggyback off of the kernel's existing capability for contiguous allocation rather than creating its own implementation. Since it has already allocated the physical memory at this point, ContigFSMM also populates the relevant page table entries, as well as the entries for the range page table inside of the `get_unmapped_area` callback. The ContigFSMM is implemented in only 479 lines of code.

Because no available hardware implements RMM, we simulate it inside of the kernel with a modified version of BadgerTrap [14] that counts the total number of page table walks that occur in a process along with the number of walks that would have been prevented by a range TLB, as is done by the authors of RMM, in order to test the functionality of ContigFSMM. Table 6 shows the percentage of TLB misses that would be prevented in the selected applications when using ContigFSMM with a 32 entry range TLB compared to just using base pages. ContigFSMM's ability to allocate large regions of physical memory contiguously and populate the novel range tree allows applications to reduce the number of TLB misses they suffer dramatically.

5.4 Discussion

Each of the FSMMs described in this section are able to express complex MM behavior and maintain competitive performance while being implemented as standalone kernel modules. Writing memory managers as kernel modules with EMM helps simplify their implementation. This is shown in Table 7. Systems like TPP, HMSDK, and RMM must spread their im-

System	Files Changed	Lines Changed
TPP [31]	22	471
TieredFSMM	3	1567
HMSDK [1]	9	920
BWFSMM	2	579
RMM [22]	16	546
ContigFSMM	2	479

Table 7: The number of files and lines of code needed to implement FSMMs and the systems they were based on.

plementations across many files and require the implementors to have a good understanding of the complicated code they build their policies on top of. On the other hand, the implementations of TieredFSMM, BWFSMM, and ContigFSMM only span an handful of independent files.

These modular implementations are not always smaller than monolithic additions. TieredFSMM adds 3x more lines of code than the implementation of TPP (2x if you discount boilerplate and debug code) because TieredFSMM implements page migration and hotness tracking itself, while TPP integrates itself into the NUMA subsystem to accomplish those tasks. However, we believe the benefits of writing memory managers as standalone pieces of software that do not further add to the kernel's technical debt outweigh the costs of occasionally re-implementing behavior. Furthermore, better kernel abstractions such as DAMON [36] for hotness tracking could reduce the implementation size.

Part of the reason the FSMM implementations are only hundreds of lines of code is that they do not need to support every standard MM feature of anonymous memory. An FSMM is not required to support huge pages, and the same goes for functionally specific MM features like copy-on-write. As a result, when using an FSMM as an application's default memory manager, it is important to ensure the FSMM supports all of the features the application requires to run.

6 Conclusion

New MM policies are needed to effectively make use of the explosion of new memory hardware in recent years, such as CXL, high bandwidth memories, and persistent memories. However, the kernel MM subsystem's monolithic design makes adding the policies challenging and those additions further complicate the monolith. EMM solves this problem by leveraging the VFS layer's MM capability, allowing memory managers to be written as standalone kernel modules as filesystems (FSMMs). The EMM translation layer allows users to choose the FSMM to use for an application transparently to the application by intercepting MM syscalls and translating them to filesystem operations in the FSMM. The overhead EMM adds to allocating memory ranges between 8% when allocating a single page, and quickly decreases to near zero as the number of pages allocated increases.

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