Efficient Synchronization of Linux Memory Regions over a Network: A Comparative Study and Implementation (Notes)

A user-friendly approach to application-agnostic state synchronization

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– Complexities when `mmap`ing a region in Go as the GC halts the entire world to collect garbage, but that also stops the NBD server in the same process that tries to satisfy the region being scanned

– Potentially using Rust for this component to cut down on memory complexities and GC latencies

• Pull-Based Memory Synchronization with Migrations

– Plain language description of this approach (like NBD, but two phases to start the device and pull, then only flush the latest changes to minimize downtime)

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– Migration protocol actors (seeders, leechers etc.), phases and state machine

– How the migration API is completely independent of a transport layer

– Switching from the seeder to the leecher state

– Using preemptive pulls and pull heuristics to optimize just like for the mounts

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  - – Migration app state (e.g. TODO list) between two hosts in a universal (underlying memory) manner
  - – Mounting remote file systems as managed mounts and combining the benefits of traditional FUSE mounts (e.g. s3-fuse) with Google Drive-style synchronization
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  - – Streaming video formats like e.g. MP4 that don't support streaming due to indexes/compression
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- Conclusion

  - – Summary of the different approaches, and how the new solutions might make it possible to use memory as the universal access format
  - – Further research recommendations (e.g. `ublk`)

3 Content

- Pull-Based Memory Synchronization with `userfaultfd`

    – Page faults occur when a process tries to access a memory region that has not yet been
    mapped into a process' address space

    – By listening to these page faults, we know when a process wants to access a specific piece
    of memory

    – We can use this to then pull the chunk of memory from a remote, map it to the address on
    which the page fault occured, thus only fetching data when it is required

    – Usually, handling page faults is something that the kernel does

    – In our case, we want to handle page faults in userspace

    – In the past, this used to be possible by handling the `SIGSEGV` signal in the process

    – In our case however, we can use a recent system called `userfaultfd` to do this in a more
    elegant way (available since kernel 4.11)

    – `userfaultfd` allows handling these page faults in userspace

    – Implementing this in Go was quite tricky, and it involves using `unsafe`

    – We can use the `syscall` and `unix` packages to interact with `ioctl` etc.

    – We can use the `ioctl` syscall to get a file descriptor to the `userfaultfd` API,
    and then register the API to handle any faults on the region (code snippet from
    https://github.com/loopholelabs/userfaultfd-go/blob/master/pkg/mapper/register.go#L15)

    – The region that should be handled can be allocated with e.g. `mmap`

    – Once we have the file descriptor for the `userfaultfd` API, we need to transfer this file
    descriptor to a process that should respond with the chunks of memory to be put into the
    faulting address

    – Passing file descriptors between processes is possible by using a UNIX socket (code snippet
    from https://github.com/loopholelabs/userfaultfd-go/blob/master/pkg/transfer/unix.go)

    – Once we have received the socket we need to register the handler for the API to use

    – If the handler receives an address that has faulted, it responds with the `UFFDIO_COPY`
    `ioctl` and a pointer to the chunk of memory that should be used on the file descriptor
    (code snippet from https://github.com/loopholelabs/userfaultfd-go/blob/master/pkg/mapper/handler.go

    – A big benefit of using `userfaultfd` and the pull method is that we are able to sim-
    plify the backend of the entire system down to a `io.ReaderAt` (code snippet from
    https://pkg.go.dev/io#ReaderAt)

    – That means we can use almost any `io.ReaderAt` as a backend for a `userfaultfd-go`
    registered object

    – We know that access will always be aligned to 4 KB chunks/the system page size, so we
    can assume a chunk size on the server based on that

- For the first example, we can return a random pattern in the backend (code snippet from https://github.com/loopholelabs/userfaultfd-go/blob/master/cmd/userfaultfd-go-example-abc/main.go) - this shows a great way of exposing truly arbitrary information into a byte slice without having to pre-compute everything or changing the application
- Since a file is a valid `io.ReaderAt`, we can also use a file as the backend directly, creating a system that essentially allows for mounting a (remote) file into memory (code snippet from https://github.com/loopholelabs/userfaultfd-go/blob/master/cmd/userfaultfd-go-example-file/main.go)
- Similarly so, we can use it map a remote object from S3 into memory, and access only the chunks of it that we actually require (which in the case of S3 is achieved with HTTP range requests) (code snippet from https://github.com/loopholelabs/userfaultfd-go/blob/master/cmd/userfaultfd-go-example-s3/main.go)
- As we can see, using `userfaultfd` we are able to map almost any object into memory
- This approach is very clean and has comparatively little overhead, but also has significant architecture-related problems that limit its uses
- The first big problem is only being able to catch page faults - that means we can only ever respond the first time a chunk of memory gets accessed, all future requests will return the memory directly from RAM on the destination host
- This prevents us from using this approach for remote resources that update over
- Also prevents us from using it for things that might have concurrent writers/shared resources, since there would be no way of updating the conflicting section
- Essentially makes this system only usable for a read-only "mount" of a remote resource, not really synchronization
- Also prevents pulling chunks before they are being accessed without layers of indirection
- The `userfaultfd` API socket is also synchronous, so each chunk needs to be sent one after the other, meaning that it is very vulnerable to long RTT values
- Also means that the initial latency will be at minimum the RTT to the remote source, and (without caching) so will be each future request
- The biggest problem however: All of these drawbacks mean that in real-life usecases, the maximum throughput, even if a local process handles page faults on a modern computer, is ~50MB/s
- Benchmark: Sensitivity of `userfaultfd` to network latency and throughput
- In summary, while this approach is interesting and very idiomatic to Go, for most data, esp. larger datasets and in high-latency scenarios/in WAN, we need a better solution

- Push-Based Memory Synchronization with mmap and Hashing

  - This approach tries to improve on `userfaultfd` by switching to push-based synchronization method

- Instead of reacting to page faults, this one a file to track changes to a memory region
- By synchronizing the file representing the memory region between two systems, we can effectively synchronize the memory region itself
- In Linux, swap space allows Linux to move chunks of memory to disk or other swap partition if the fast speed of RAM is not needed ("paging out")
- Similarly to this, Linux can also load missing chunks from a disk
- This works similarly to how `userfaultfd` handled page faults, except this time it doesn't need to go through user space, which can make it much faster
- We can do this by using `mmap`, which allows us to map a file into memory
- By default, `mmap` doesn't write changes from a file back into memory, no matter if the file descriptor passed to it would allow it to or not
- We can however add the `MAP_SHARED` flag; this tells the kernel to write back changes to the memory region to the corresponding regions of the backing file
- Linux caches reads to such a backing file, so only the first page fault would be answered by fetching from disk, just like with `userfaultfd`
- The same applies to writes; similar to how files need to be `sync`ed in order for them to be written to disks, `mmap`ed regions need to be `msync`ed in order to flush changes to the backing file
- In order to synchronize changes to the region between hosts by syncing the underlying file, we need to have the changes actually be represented in the file, which is why `msync` is critical
- For files, you can use `O_DIRECT` to skip this kernel caching if your process already does caching on its own, but this flag is ignored by the `mmap`
- Usually, one would use `inotify` to watch changes to a file
- `inotify` allows applications to register handlers on a file's events, e.g. `WRITE` or `SYNC`. This allows for efficient file synchronization, and is used by many file synchronization tools
- It is also possible to filter only the events that we need to sync the writes, making it the perfect choice for this use case
- For technical reasons however (mostly because the file is represented by a memory region), Linux doesn't fire these events for `mmap`ed files though, so we can't use it
- The next best option are two: Either polling for file attribute changes (e.g. last write), or by continously hashing the file to check if it has changed
- Polling on its own has a lot of downsides, like it adding a guaranteed minimum latency by virtue of having to wait for the next polling cycle
- This negatively impacts a maximum allowed downtime scenario, where the overhead of polling can make or break a system
- Hashing the entire file is also a naturally IO- and CPU-intensive process because the entire file needs to be read at some point

- Still, polling & hashing is probably the only reliable way of detecting changes to a file
- When picking algorithms for this hashing process, the most important metric to consider is the throughput with which it can compute hashes, as well as the change of collisions
- Benchmark: Performance of different Go hashing algorithms for detecting writes
- Instead of hashing the entire file, then syncing the entire file, we can want to really sync only the parts of the file that have changed between two polling iterations
- We can do this by opening up the file multiple times, then hashing individual offsets, and aggregating the chunks that have changed
- If the underlying hashing algorithm is CPU-bound, this also allows for better concurrent processing
- Increases the initial latency/overhead by having to open up multiple file descriptors
- Benchmark: Hashing the chunks individually vs. hashing the entire file
- But this can not only increase the speed of each individual polling tick, it can also drastically decrease the amount of data that needs to be transferred since only the delta needs to be synchronized
- Hashing and/or syncing individual chunks that have changed is a common practice
- The probably most popular tool for file synchronization like this is rsync
- When the delta-transfer algorithm for rsync is active, it computes the difference between the local and the remote file, and then synchronizes the changes
- The delta sync algorithm first does file block division
- The file on the destination is divided into fixed-size blocks
- For each block in the destination, a weak and fast checksum is calculated
- The checksums are sent over to the source
- On the source, the same checksum calculation process is run, and compared against the checksums that were sent over (matching block identification)
- Once the changed blocks are known, the source sends over the offset of each block and the changed block's data to the destination
- When a block is received, the destination writes the chunk to the specified offset, reconstructing the file
- Once one polling interval is done, the process begins again
- We have implemented a simple TCP-based protocol for this delta synchronization, just like rsync's delta synchronization algorithm (code snippet from https://github.com/loopholelabs/darkmagyk/ orchestrator/main.go#L1337-L1411 etc.)
- For this protocol specifically, we send the changed file's name as the first message when starting the synchronization, but a simple multiplexing system could easily be implemented by sending a file ID with each message
- Similarly to `userfaultfd`, this system also has limitations
- While `userfaultfd` was only able to catch reads, this system is only able to catch writes

to the file

– Essentially this system is write-only, and it is very inefficient to add hosts to the network later on

– As a result, if there are many possible destinations to migrate state too, a star-based architecture with a central forwarding hub can be used

– The static topology of this approach can be used to only ever require hashing on one of the destinations and the source instead of all of them

– This way, we only need to push the changes to one component (the hub), instead of having to push them to each destination on their own

– The hub simply forwards the messages to all the other destinations

– Benchmark: Throughput of this custom synchronization protocol vs. rsync (which hashes entire files)

- Push-Pull Memory Synchronization with a FUSE

   – Since the push method requires polling and is very CPU and I/O intensive, and `userfaultfd-go` has too low of a throughput, a better solution is needed

   – What if we could still get the events for the writes and reads without having to use `userfaultfd-go` or hashing?

   – We can create a custom file system in Linux and load it as a kernel module

   – This file system could then intercept reads/writes to/from the mmaped region, making it possible to respond to them with a custom backend

   – But such a system would need to run in the kernel directly, which leads to a lot of potential drawbacks

   – While it is possible to write kernel modules with Rust instead of C these days, a lot of problems remain

   – Kernel modules aren't portable; they are built for a specific kernel, which makes them hard to distribute to users

   – A kernel file system is able to skip having to go through user space and thus save on context switching, but that will also mean that it will run in the kernel address space, making for a poor level of isolation

   – Iterating on a kernel module is much harder than iterating on a program running in user space

   – If we want the user to be able to provide their own backends from/to which to pull/push, that will still require communication between user space and the kernel

   – So while adding this implementation in the kernel would be possible, it would also be very complex

   – In order to implement file systems in user space, we can use the FUSE API

   – Here, a user space program registers itself with the FUSE kernel module

- – This program provides callbacks for the file system operations, e.g. for `open`, `read`, `write` etc.
- – When the user performs a file system operation on a mounted FUSE file system, the kernel module will send a request for the operation to the user space program, which can then reply with a response, which the FUSE kernel module will then return to the user
- – This makes it much easier to create a file system compared to writing it in the kernel, as it can run in user space
- – It is also much safer as no custom kernel module is required and an error in the FUSE or the backend can't crash the entire kernel
- – Unlike a file system implemented as a kernel module, this layer of indirection makes the file system portable, since it only needs to communicate with the FUSE module
- – It is possible to use even very complex and at first view non-compatible backends as a FUSE file system's backend
- – By using a file system abstraction API like `afero.Fs`, we can separate the FUSE implementation from the actual file system structure, making it unit testable and making it possible to add caching in user space (code snippet from https://github.com/pojntfx/stfs/blob/main/pkg/fs/fil
- – It is possible to map any `afero.Fs` to a FUSE backend, so it would be possible to switch between different file system backends without having to write FUSE-specific (code snippet from https://github.com/JakWai01/sile-fystem/blob/main/pkg/filesystem/fs.go)
- – For example, STFS used a tape drive as the backend, which is not random access, but instead append-only and linear (https://github.com/pojntfx/stfs/blob/main/pkg/operations/update.go)
- – By using an on-disk index and access optimizations, the resulting file system was still performant enough to be used, and supported almost all features required for the average user
- – FUSE does however also have downsides
- – It operates in user space, which means that it needs to do context switching
- – Some advanced features aren't available for a FUSE
- – The overhead of FUSE (and implementing a completely custom file system) for synchronizing memory is still significant
- – If possible, the optimal solution would be to not expose a full file system to track changes, but rather a single file
- – As a result of this, the significant implementation overhead of such a file system led to it not being chosen

- Pull-Based Memory Synchronization with NBD

  - – As hinted at before, a better API would be able to catch reads/writes to a single `mmap`ed file instead of having to implement a complete file system
  - – It does however not have to be an actual file, a block device also works

- In Linux, block devices are (typically storage) devices that support reading/writing fixed chunks (blocks) of data
- We can mmap a block device in the same way that we can mmap a file
- Similarly to how a file system can be implemented in a kernel module, a block device is typically implemented as a kernel module/in kernel space
- However, the same security, portability and developer experience issues as with the former also apply here
- Instead of implementing a FUSE to solve this, we can create a NBD (network block device) server that can be used by the kernel NBD module similarly to how the process that connected to the FUSE kernel module functioned
- The difference between a FUSE and NBD is that a NBD server doesn't provide a file system
- A NBD server provides the storage device that (typically) hosts a file system, which means that the interface for it is much, much simpler
- The implementation overhead of a NBD server's backend is much more similar to how `userfaultfd-go` works, rather than a FUSE
- NBD uses a protocol to communicate between a server (provided by user space) and a client (provided by the NBD kernel module)
- The protocol can run over WAN, but is really mostly meant for LAN or localhost usage
- It has two phases: Handshake and transmission
- There are two actors in the protocol: One or multiple clients, the server and the virtual concept of an export
- When the client connects to the server, the server sends a greeting message with the server's flags
- The client responds with its own flags and an export name (a single NBD server can expose multiple devices) to use
- The server sends the export's size and other metadata, after which the client acknowledges the received data and the handshake is complete
- After the handshake, the client and server start exchanging commands and replies
- A command can be any of the basic operations needed to access a block device, e.g. read, write or flush
- Depending on the command, it can also contain data (such as the chunk to be written), offsets, lengths and more
- Replies can contain an error, success value or data depending on the reply's type
- NBD is however limited in some respects; the maximum message size is 32 MB, but the maximum block/chunk size supported by the kernel is just 4096 KB, making it a suboptimal protocol to run over WAN, esp. in high latency scenarios
- The protocol also allows for listing exports, making it possible to e.g. list multiple memory regions on a single server

- NBD is an older protocol with multiple different handshake versions and legacy features
- Since the purpose of NBD in this use case is minimal and both the server and the client are typically controlled, it makes sense to only implement the latest recommended versions and the baseline feature set
- The baseline feature set requires no TLS, the latest "fixed newstyle" handshake, the ability to list and choose an export, as well as the read, write and disc(onnect) commands and replies
- As such, the protocol is very simple to implement
- With this simplicity however also come some drawbacks: NBD is less suited for use cases where the backing device behaves very differently from a random-access store device, like for example a tape drive, since it is not possible to work with high-level abstractions such as files or directories
- This is, for the narrow memory synchronization use case, however more of a feature than a bug
- Due to the lack of pre-existing libraries, a new pure Go NBD library was implemented
- This library does not rely on CGo/a pre-existing C library, meaning that a lot of context switching can be skipped
- The backend interface for `go-nbd` is very simple and only requires four methods: `ReadAt`, `WriteAt`, `Size` and `Sync`
- A good example backend that maps well to a block device is the file backend (code snippet from https://github.com/pojntfx/go-nbd/blob/main/pkg/backend/file.go)
- The key difference here to the way backends were designed in `userfaultfd-go` is that they can also handle writes
- `go-nbd` exposes a `Handle` function to support multiple users without depending on a specific transport layer (code snippet from https://github.com/pojntfx/go-nbd/blob/main/pkg/server/nbd.go)
- This means that systems that are peer-to-peer (e.g. WebRTC), and thus don't provide a TCP-style `accept` syscall can still be used easily
- It also allows for easily hosting NBD and other services on the same TCP socket
- The server encodes/decodes messages with the `binary` package (code snippet from https://github.com/pojntfx/go-nbd/blob/main/pkg/server/nbd.go#L73-L76)
- To make it easier to parse, the headers and other structured messages are modeled as Go structs (code snippet from https://github.com/pojntfx/go-nbd/blob/main/pkg/protocol/negotiation.go)
- The handshake is implemented using a simple for loop, which either returns on error or breaks
- The actual transmission phase is done similarly, by reading in a header, switching on the message type and reading/sending the relevant data/reply
- The server is completely in user space, there are no kernel components involved here

- The NBD client however is implemented by using the kernel NBD client
- In order to use it, one needs to find a free NBD device first
- NBD devices are pre-created by the NBD kernel module and more can be specified with the `nbds_max` parameter
- In order to find a free one, we can either specify it directly, or check whether we can find a NBD device with zero size in `sysfs` (code snippet from https://github.com/pojntfx/r3map/blob/main/pkg,
- Relevant `ioctl` numbers depend on the kernel and are extracted using `CGo` (code snippet from https://github.com/pojntfx/go-nbd/blob/main/pkg/ioctl/negotiation_cgo.go)
- The handshake for the NBD client is negotiated in user space by the Go program
- Simple for loop, basically the same as for the server (code snippet from https://github.com/pojntfx/go-nbd/blob/main/pkg/client/nbd.go#L221-L288)
- After the metadata for the export has been fetched in the handshake, the kernel NBD client is configured using `ioctl`s (code snippet from https://github.com/pojntfx/go-nbd/blob/main/pkg/client/nbd.go#L290-L328)
- The `DO_IT` syscall never returns, meaning that an external system must be used to detect whether the device is actually ready
- Two ways of detecting whether the device is ready: By polling `sysfs` for the size parameter, or by using `udev`
- `udev` manages devices in Linux
- When a device becomes available, the kernel sends a `udev` event, which we can subscribe to and use as a reliable and idiomatic way of waiting for the ready state (code snippet from https://github.com/pojntfx/go-nbd/blob/main/pkg/client/nbd.go#L104C10-L138)
- In reality however, polling `sysfs` directly can be faster than subscribing to the `udev` event, so we give the user the option to switch between both options (code snippet from https://github.com/pojntfx/go-nbd/blob/main/pkg/client/nbd.go#L140-L178)
- When `open`ing the block device that the client has connected to, usually the kernel does provide a caching mechanism and thus requires `sync` to flush changes
- By using `O_DIRECT` however, it is possible to skip the kernel caching layer and write all changes directly to the NBD client/server
- This is particularly useful if both the client and server are on the local system, and if the amount of time spent on `sync`ing should be as small as possible
- It does however require reads and writes on the device node to be aligned to the system's page size, which is possible to implement with a client-side chunking system but does require application-specific code
- NBD is a battle-tested solution for this with fairly good performance, but in the future a more lean implemenation called `ublk` could also be used
- `ublk` uses `io_uring`, which means that it could potentially allow for much faster concurrent access

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- It is similar to NBD; it also uses a user space server to provide the block device backend, and a kernel `ublk` driver that creates `/dev`/`ublkb*` devices
- Unlike as it is the case for the NBD kernel module, which uses a rather slow UNIX or TCP socket to communicate, `ublk` is able to use `io_uring` pass-through commands
- The `io_uring` architecture promises lower latency and better throughput
- Because it is however still experimental and docs are lacking, NBD was chosen
- Another option of implementing a block device is BUSE (block devices in user space)
- BUSE is similar to FUSE in nature, and similarly to it has a kernel and user space server component
- Similarly to `ublk` however, BUSE is experimental
- Client libraries in Go are also experimental, preventing it from being used as easily as NBD
- Similarly so, a CUSE could be implemented (char device in user space)
- CUSE is a very flexible way of defining a char (and thus block) device, but also lacks documentation
- The interface being exposed by CUSE is more complicated than that of e.g. NBD, but allows for interesting features such as custom `ioctl`s (code snippet from https://github.com/pojntfx/webpipe/blob/main/pkg/cuse/device.go#L3-L15)
- The only way of implementing it without too much overhead however is CGo, which comes with its own overhead
- It also requires calling Go closures from C code, which is complicated (code snippet from https://github.com/pojntfx/webpipe/blob/main/pkg/cuse/bindings.go#L79-L132)
- Implementing closures is possible by using the `userdata` parameter in the CUSE C API (code snippet from https://github.com/pojntfx/webpipe/blob/main/pkg/cuse/cuse.c#L20-L22)
- To fully use it, it needs to first resolve a Go callback in C, and then call it with a pointer to the method's struct in user data, effectively allowing for the use of closures (code snippet from https://github.com/pojntfx/webpipe/blob/main/pkg/cuse/bindings.go#L134-L162)
- Even with this however, it is hard to implement even a simple backend, and the CGo overhead is a significant drawback (code snippet from https://github.com/pojntfx/webpipe/blob/main/pkg/de
- The last alternative to NBD devices would be to extend the kernel with a new construct that allows for essentially a virtual file to be `mmap`ed, not a block device
- This could use a custom protocol that is optimized for this use case instead of a full block device
- Because of the extensive setup required to implement such a system however, and the possibility of `ublk` providing a performant alternative in the future, going forward with NBD was chosen for now

- Push-Pull Memory Synchronization with Mounts

- Usually, the NBD server and client don't run on the same system
- NBD was originally designed to used as a LAN protocol to access a remote hard disk
- As mentioned before, NBD can run over WAN, but is not designed for this
- The biggest problem with running NBD over a public network, even if TLS is enabled is latency
- Individual chunks would only be fetched to the local system as they are being accessed, adding a guaranteed minimum latency of at least the RTT
- Instead of directly connecting a client to a remote server, we add a layer of indirection, called a `Mount` that consists of both a client and a server, both running on the local system
- We then connect the server to the backend with an API that is better suited for WAN usage
- This also makes it possible to implement smart pull/push strategies instead of simply directly writing to/from the network ("managed mounts")
- The server and client are connected by creating a connected UNIX socket pair (code snippet from https://github.com/pojntfx/r3map/blob/main/pkg/mount/path_direct.go#L59-L62)
- By building on this basic direct mount, we can add a file (code snippet from https://github.com/pojntfx/r3m and slice (code snippet from https://github.com/pojntfx/r3map/blob/main/pkg/mount/slice_direct.go) mount API, which allows for easy usage and integration with `sync`/`msync` respectively
- Using the `mmap`/slice approach has a few benefits
- First, it makes it possible to use the byte slice directly as though it were a byte slice allocated by `make`, except its transparently mapped to the (remote) backend
- `mmap`/the byte slices also swaps out the syscall-based file interface with a random access one, which allows for faster concurrent reads from the underlying backend
- Alternatively, it would also be possible to format the server's backend or the block device using standard file system tools
- When the device then becomes ready, it can be mounted to a directory on the system
- This way it is possible to `mmap` one or multiple files on the mounted file system instead of `mmap`ing the block device directly
- This allows for handling multiple remote regions using a single server, and thus saving on initialization time and overhead
- Using a proper file system however does introduce both storage overhead and complexity, which is why e.g. the FUSE approach was not chosen
- The simplest form of the mount API is the direct mount API
- This API simply swaps out NBD for a transport-independent RPC framework, but does not do additional optimizations
- It has two simple actors: A client and a server, with only the server providing methods to be called (code snippet from https://github.com/pojntfx/r3map/blob/main/pkg/services/backend.go#L14-L19)

- The protocol as such is stateless, as there is only a simple remote read/write interface (add state machine and sequence diagram here)
- One additional layer that needs to be implemented however is proper chunking support
- While we can specify a chunk size for the NBD client in the form of a block size, we can only go up to 4 KB chunks
- For scenarios where the RTT between the backend and server is large, it might make sense to use a much larger chunk size for the actual networked transfers
- Many backends also have constraints that prevent them from functioning without a specific chunk size or aligned offsets, such as using e.g. tape drives, which require setting a block size and work best when these chunks are multiple MBs instead of KBs
- Even if there are no constraints on chunking on the backend side (e.g. when a file is used as the backend), it might make sense to limit the maximum supported message size between the client and server to prevent DoS attacks by forcing the backend to allocate large chunks of memory to satisfy requests, which requires a chunking system to work
- In order to implement the chunking system, we can use a abstraction layer that allows us to create a pipeline of readers/writers - the `ReadWriterAt`, combining an `io.ReaderAt` and a `io.WriterAt`
- This way, we can forward the `Size` and `Sync` syscalls directly to the underlying backend, but wrap a backend's `ReadAt` and `WriteAt` methods in a pipeline of other `ReadWriterAt`s
- One such `ReadWriterAt` is the `ArbitraryReadWriterAt` (code snippet from https://github.com/pojntfx/r3map/blob/main/pkg/chunks/arbitrary_rwat.go)
- It allows breaking down a larger data stream into smaller chunks
- In `ReadAt`, it calculates the index of the chunk that the offset falls into and the position within the offsets
- It then reads the entire chunk from the backend into a buffer, copies the necessary portion of the buffer into the input slice, and repeats the process until all requested data is read
- Similarly for the writer, it calculates the chunk's index and offset
- If an entire chunk is being written to, it bypasses the chunking system, and writes it directly to not have to unnecessarily copy the data twice
- If only parts of a chunk need to be written, it first reads the complete chunk into a buffer, modifies the buffer with the data that has changed, and writes the entire chunk back, until all data has been written
- This simple implementation can be used to allow for writing data of arbitrary length at arbitrary offsets, even if the backend only supports a few chunks
- In addition to this chunking system, there is also a `ChunkedReadWriterAt`, which ensures that the limits concerning the maximum size supported by the backend and the actual chunks are being respected

– This is particularly useful when the client is expected to do the chunking, and the server simply checks that the chunking system's chunk size is respected
– In order to check if a read or write is valid, it checks whether a read is done to an offset multiple of the chunk size, and whether the length of the slice of data to read/write is the chunk size (code snippet from https://github.com/pojntfx/r3map/blob/main/pkg/chunks/chunked_rwat.go)
– It is possible to do the chunking in two places; on the mount API's side, and on the (potentially remote) backend's side
– Doing the chunking on the backend's side is usually much faster than on the mount API's side, as writes with lengths smaller than the chunk size will mean that the remote chunk needs to be fetched first, significantly increasing the latency esp. in scenarios with high RTT
– Benchmark: Local vs. remote chunking
– While these systems already allow for some optimizations over simply using the NBD protocol over WAN, they still mean that chunks will only be fetched as they are being needed, which means that there still is a guaranteed minimum downtime
– In order to improve on this, a more advanced API (the managed mount API) was created
– A field that tries to optimize for this use case is live migration of VMs
– Live migration refers to moving a virtual machine, its state and connected devices from one host to another with as little downtime as possible
– There are two types of such migration algorithms; pre-copy and post-copy migration
– Pre-copy migration works by copying data from the source to the destination as the VM continues to run (or in the case of a generic migration, app/other state continues being written to)
– First, the initial state of the VM's memory is copied to the destination
– If, during the push, chunks are being modified, they are being marked as dirty
– These dirty chunks are being copied over to the destination until the number of remaining chunks is small enough to satisfy a maximum downtime criteria
– Once this is the case, the VM is suspended on the source, and the remaining chunks are synced over to destination
– Once the transfer is complete, the VM is resumed on the destination
– This process is helpful since the VM is always available in full on either the source or the destination, and it is resilient to a network outage occurring during the synchronization
– If the VM (or app etc.) is however changing too many chunks on the source during the migration, the maximum acceptable downtime criteria might never get reached, and the maximum acceptable downtime is also somewhat limited by the available RTT
– An alternative to pre-copy migration
– In this approach, the VM is immediately suspended on the source, moved to the destination with only a minimal set of chunks

- After the VM has been moved to the destination, it is resumed
- If the VM tries to access a chunk on the destination, a page fault is raised, and the missing page is fetched from the source, and the VM continues to execute
- The benefit of post-copy migration is that it does not require re-transmitting dirty chunks to the destination before the maximum tolerable downtime is reached
- The big drawback of post-copy migration is that it can result in longer migration times, because the chunks need to be fetched from the network on-demand, which is very latency/RTT-sensitive
- For the managed mount API, both paradigms were implemented
- The managed mount API is primarily intended as an API for reading from a remote resource and then syncing changes back to it however, not migrating a resource between two hosts
- The migration API (will be discussed later) is a more well-optimized version for this use case
- The pre-copy API is implemented in the form of preemptive pulls based on another `ReaderAt`
- The `Puller` component asynchronously pulls chunks in the background (code snipped from https://github.com/pojntfx/r3map/blob/main/pkg/chunks/puller.go)
- It allows passing in a pull heuristic function, which it uses to determine which chunks should be pulled in which order
- Many applications commonly access certain bits of data first
- If a resource should be available locally as quickly as possible, then using the correct pull heuristic can help a lot
- For example, if the data pulled consists of a header, then using a pull heuristic that pulls these header chunks first can be of help
- If a file system is being synchronized, and the superblocks of the file system are being stored in a known pattern, the pull heuristic can be used to fetch these superblocks first
- If a format like MP4, which has an index, is used then said index can be fetched first, be accessed first and during the time needed to parse the index, the remaining data can be pulled in the background
- After sorting the chunks, the puller starts a fixed number of worker threads in the background, each of which ask for a chunk to pull
- Note that the puller itself does not copy to/from a destination; this use case is handled by a separate component
- It simply reads from the provided `ReaderAt`, which is then expected to handle the actual copying on its own
- The actual copy logic is provided by the `SyncedReadWriterAt` instead
- This component takes both a remote reader and a local `ReadWriterAt`
- If a chunk is read, e.g. by the puller component calling `ReadAt`, it is tracked and market

as remote by adding it to a local map

– The chunk is then read from the remote reader and written to the local `ReadWriterAt`
, and is then marked as locally available, so that on the second read it is fetched locally
directly

– A callback is then called which can be used to monitor the pull process

– Note that if it is used in a pipeline with the `Puller`, this also means that if a chunk which
hasn't been fetched asynchronously yet will be scheduled to be pulled immediately

– WriteAt also starts by tracking a chunk, but then immediately marks the chunk as available
locally no matter whether it has been pulled before

– The combination of the `SyncedReadWriterAt` and the `Puller` component imple-
ments the pull post-copy system in a modular and testable way

– Unlike the usual way of only fetching chunks when they are available however, this system
also allows fetching them pre-emptively, gaining some benefits of pre-copy migration, too

– Using this `Puller` interface, it is possible to implement a read-only managed mount

– This is very similar the `rr`+ prefetching mechanism from "Remote Regions" (reference
atc18-aguilera)

– In order to also be able to write back however, it needs to have a push system as well

– This push system is being started in parallel with the pull system

– It also takes a local and a remote `ReadWriterAt`

– Chunks that have changed/are pushable are marked with `MarkOffsetPushable` (code
snippet from https://github.com/pojntfx/r3map/blob/main/pkg/mount/path_managed.go#L171C24-
L185)

– This integrates with the callbacks supplied by the syncer, which ensures that we don't
sync back changes that have been pulled but not modified, only the ones that have been
changed locally

– Once opened, the pusher starts a new goroutine in the background which calls `Sync` in a
set recurring interval (code snippet from https://github.com/pojntfx/r3map/blob/main/pkg/chunks/push

– Once sync is called by this background worker system or manually, it launches workers in
the background

– These workers all wait for a chunk to handle

– Once a worker receives a chunk, it reads it from the local `ReadWriter`, and copies it to
the remote

– Safe access is ensures by individually locking each chunk

– The pusher also serves as a step in the `ReadWriterAt` pipeline

– In order to do this, it exposes `ReadAt` and `WriteAt`

– `ReadAt` is a simple proxy, while `WriteAt` also marks a chunk as pushable (since it mu-
tates data) before writing to the local `ReadWriterAt`

– For the direct mount, the NBD server was directly connected to the remote, while in this

setup a pipeline of pullers, pushers, a syncer and an `ArbitraryReadWriter` is used
(graphic of the four systems and how they are connected to each other vs. how the direct
mounts work)

- For a read-only scenario, the `Pusher` step is simply skipped (code snippet from
  https://github.com/pojntfx/r3map/blob/main/pkg/mount/path_managed.go#L142-
  L169)
- If no background pulls are enabled, the creation of the `Puller` is simply skipped (code
  snippet from https://github.com/pojntfx/r3map/blob/main/pkg/mount/path_managed.go#L187-
  L222)
- This setup allows pulling from the remote `ReadWriterAt` before the NBD device is open
- This means that we can start pulling in the background as the NBD client and server are still
  starting (code snippet from https://github.com/pojntfx/r3map/blob/main/pkg/mount/path_managed.go
  L272)
- These two components typically start fairly quickly, but can still take multiple ms
- Often, it takes as long as one RTT, so parallelizing this startup process can significantly
  reduce the initial latency and pre-emptively pull quite a bit of data
- Benchmark: Parallelizing startups and pulling n MBs as the device starts
- Using this benchmark and simple interface also makes the entire system very testable
- In the tests, a memory reader or file can be used as the local or remote `ReaderWriterAt`
  s and then a simple table-driven test can be used (code snippet from https://github.com/pojntfx/r3map/blo
- With all of these components in place, the managed mounts API serves as a fast and effi-
  cient option to access almost any remote resource in memory
- Similarly to how the direct mounts API used the basic path mount to build the file and
  `mmap` interfaces, the managed mount builds on this interface in order to provide the same
  interfaces
- It is however a bit more complicated for the lifecycle to work
- For example, in order to allow for a `Sync()` API, e.g. the `msync` on the `mmap`ed file must
  happen before `Sync()` is called on the syncer
- This is done through a hooks system (code snippet from https://github.com/pojntfx/r3map/blob/main/pkg
  L37)
- The same hooks system is also used to implement the correct lifecycle when `Close`ing
  the mount
- While the managed mounts API mostly works, there are some issues with it being imple-
  mented in Go
- This is mostly due to deadlocking issues; if the GC tries to release memory, it has to stop
  the world
- If the `mmap` API is used, it is possible that the GC tries to manage the underlying slice, or
  tries to release memory as data is being copied from the mount

- Because the NBD server that provides the byte slice is also running in the same process, this causes a deadlock as the server that provides the backend for the mount is also frozen (https://github.com/pojntfx/r3map/blob/main/pkg/mount/slice_managed.go#L70-L93)
- A workaround for this is to lock the mmaped region into memory, but this will also cause all chunks to be fetched, which leads to a high Open() latency
- This is fixable by simply starting the server in separate thread, and then mmaping
- Issues like this however are hard to fix, and point to Go potentially not being the correct language to use for this part of the system
- In the future, using a language without a GC (such as Rust) could provide a good alternative
- While the current API is Go-specific, it could also be exposed through a different interface to make it usable in Go
- A similar approach was made in RegionFS (reference atc18-aguilera)
- RegionFS is implemented as a kernel module, but it is functionally similar to how this API exposes a NBD device for memory interaction
- In RegionFS, the regions file system is mounted to a path, which then exposes regions as virtual files
- Instead of using a custom configuration (such as configuring the amount of pushers to make a mount read-only), such an approach makes it possible to use chmod on the virtual file for a memory region to set permissions
- By using standard utilities like open and chmod, this API usable from different programming languages with ease
- Unlike the managed mounts API however, the system proposed in Remote Regions is mostly intended for private usecases with a limited amount of hosts and in LAN, with low-RTT connections
- It is also not designed to be used for a potential migration scenarios, which the modular approach of r3map allows for
- While Remote Regions' file system approach does allow for authorization based on permissions, it doesn't specify how authentication could work
- In terms of the wire protocol, Remote Regions also seems to target mostly LAN with protocols like RDMA comm modules, while r3map targets mostly WAN with a pluggable transport protocol interface

- Pull-Based Memory Synchronization with Migrations

  - We have now implemented a managed mounts API
  - This API allows for efficient access to a remote resource through memory
  - It is however not well suited for a migration scenario
  - For migrations, more optimization is needed to minimize the maximum acceptable downtime

- The flexible architecture of the `ReadWriterAt` components allow the reuse of lots of code for both use cases
- For the migration, the process is split into two distinct phases
- The same preemptive background pulls and parallelized device/syncer startup can be used, but the push process is dropped
- The two phases allow pulling the majority of the data first, and only finalize the move later with the remaining data
- This is inspired by the pre-copy approach to VM live migration, but also allows for some of the benefits of the post-copy approach as we'll see later
- Why is this useful? A constraint for the mount-based API that we haven't mentioned before is that it doesn't allow safe concurrent access of a resource by two readers or writers at the same time
- This poses a problem for migration, where the downtime is what should be optimized for, as the VM or app that is writing to the source device would need to be suspended before the transfer could begin
- This adds very significant latency, which is a problem
- The mount API was also designed in such a way as to make it hard to share a resource this way
- The remote backend for example API doesn't itself provide a mount to access the underlying data, which further complicates migration by not implementing a migration lifecycle
- To fix this, the migration API defines two new actors: The seeder and the leecher
- The seeder represents a resource that can be migrated from/a host that exposes a migratable resource
- The leecher represents a client that wants to migrate a resource to itself
- Initially, the protocol starts by running an application with the application's state on the seeder's mount
- When a leecher connects to the seeder, the seeder starts tracking any writes to it's mount
- The leecher starts pulling chunks from the seeder to it's local backend
- Once the leecher has received a satisfactory level of locally available chunks, it as the seeder to finalize, which then causes the seeder to stop the remote app, `msync`/flushes the drive, and returns the chunks that were changed between it started tracking and finalizing
- The leecher then marks these chunks as remote, immediately resumes the VM, and queues them to be pulled immediately
- By splitting the migration into these two distinct phases, the overhead of having to start the device on the leecher can be skipped and additional app initialization that doesn't depend on the app's state (e.g. memory allocation, connecting to databases, loading models etc.) can be performed before the application needs to be suspended

- This solution combines both the pre-copy algorithm (by pulling the chunks from the seeder ahead of time) and the post-copy algorithm (by resolving dirty chunks from the seeder after the VM has been migrated) into one coherent protocol (add state machine diagram here)
- This way, the maximum tolerable downtime can be drastically reduced, and dirty chunks don't need to be re-transmitted multiple times
- Effectively, it drops the maximum guaranteed downtime to the time it takes to `msync` the seeder's app state, the RTT and, if they are being accessed immediately, how long it takes to fetch the chunks that were written in between starting to track and finalize
- To achieve this, the seeder defines a simple read-only API with the familiar `ReadAt` methods, but also new APIs such as returning dirty chunks from `Sync` and adding a `Track` method (code snippet from https://github.com/pojntfx/r3map/blob/main/pkg/services/seeder.go#L15-L21)
- Unlike the remote backend, a seeder also exposes a mount through a path, file or byte slice, so that as the migration is happening, the underlying data can still be accessed by the application
- The tracking aspect is implemented in the same modular and composable way as the syncer etc. - by using a `TrackingReadWriterAt` that is connected to the seeder's `ReadWriterAt` pipeline (graphic of the pipeline here)
- Once activated by `Track`, the tracker intercepts all `WriteAt` calls and adds them to a local de-duplicated store (code snippet from https://github.com/pojntfx/r3map/blob/main/pkg/chunks/tra L40)
- When `Sync` is called, the changed chunks are returned and the de-duplicated store is cleared
- A benefit of the protocol being defined in such a way that only the client ever calls an RPC, not the other way around, is that the transport layer/RPC system is completely interchangeable
- This works by returning a simple abstract `service` utility struct struct from `Open` (code snippet from https://github.com/pojntfx/r3map/blob/main/pkg/services/seeder.go)
- This abstract struct can then be used as the backend for any RPC framework, e.g. for gRPC (code snippet https://github.com/pojntfx/r3map/blob/main/pkg/services/seeder_grpc.go)
- The leecher then takes this abstract API as an argument
- As soon as the leecher is opened, it calls track on the seeder, and in parallel starts the device (code snippet from https://github.com/pojntfx/r3map/blob/main/pkg/migration/path_leecher.go#L1 L203)
- The leecher introduces a new component, the `LockableReadWriterAt`, into its internal pipeline (add graphic of the internal pipeline)
- This component simply blocks all read and write operations to/from the NBD device until

       `Finalize` has been called (code snippet from https://github.com/pojntfx/r3map/blob/main/pkg/chunks
       L37)

- This is required because otherwise stale data (since `Finalize` did not yet mark the changed chunks) could have poisoned the cache on the e.g. mmaped device
- Once the leecher has started the device, it sets up a syncer (code snippet from https://github.com/pojntfx/r3map/blob/main/pkg/migration/path_leecher.go#L214-L252)
- A callback can be used to monitor the pull process (code snippet from https://github.com/pojntfx/r3map/b migration-benchmark/main.go#L544-L548)
- As described before, after a satisfactory local availability level has been reached, `Finalize` can be called
- `Finalize` then calls `Sync()` on the remote, marks the changed chunks as re- mote, and schedules them also be pulled in the background (code snippet from https://github.com/pojntfx/r3map/blob/main/pkg/migration/path_leecher.go#L257-L280)
- As an additional measure aside from the lockable `ReadWriterAt` to make accessing the path/file/slice too early harder, only `Finalize` returns the managed object, so that the happy path can less easily lead to deadlocks
- After a leecher has successfully reached 100% local availability, it calls `Close` on the seeder and disconnects the leecher from the seeder, causing both to shut down (code snippet from https://github.com/pojntfx/r3map/blob/main/cmd/r3map-migration-benchmark-server/main.go#L137)
- Once the leecher has exited, a seeder can be started, to allow for migrating from the desti- nation to another destination again
- A interesting question to ask with the two-step migration API is when to start the finaliza- tion step
- As is visible from the migration API protocol state machine showed beforehand, the final- ization stage is critical and hard or impossible to recover from depending on the imple- mentation
- While for the memory sync on its own, one could just call `Finalize` multiple times to restart it
- But since `Finalize` needs to return a list of dirty chunks, it requires the VM or app on the source device to be suspended before `Finalize` can return
- While not necessarily the case, such a suspend operation is not idempotent (since it might not just be a suspension that is required, but also a shutdown of dependencies etc.)
- "Reducing Virtual Machine Live Migration Overhead via Workload Analysis" provides an interesting analysis of options on how this decision of when to migrate can be made
- While being designed mostly for use with virtual machines, it could serve as a basis for

other applications or migration scenarios, too

– The proposed method identifies workload cycles of VMs and uses this information to postpone the migration if doing so is beneficial

– This works by analyzing cyclic patters that can unnecessarily delay a VM's migration, and identifies optimal cycles to migrate VMs in from this information

– For the VM use case, such cycles could for example be the GC of a large application triggering a lot of changes to the VMs memory etc.

– If a migration is proposed, the system checks for whether it is currently in a beneficial cycle to migrate in in which case it lets the migration proceed; otherwise, it postpones it until the next cycle

– The algorithm uses a Bayesian classifier to identify a favorable or unfavorable cycle

– Compared to the alternative, which is usually waiting for a significant percentage of the chunks that were not changed before tracking started to be synced first, this can potentially yield a lot of improvements

– The paper has found an improvement of up to 74% in terms of live migration time/downtime and 43% in terms of the amount of data transferred over the network

– While such a system was not implemented for r3map, using r3map with such a system would certainly be possible

– With these results in mind, it is interesting to look at how the migration API performs compared to the single-phase mount API

– Benchmark: Maximum acceptable downtime for a migration scenario with the Managed Mount API vs the Migration API

• Optimizing Mounts and Migrations

– Compared to existing remote mount and migration solutions, r3map is a bit special

– As mentioned before, most systems are designed for scenarios where such resources are accessible in a high-bandwidth, low-latency LAN

– This means that some assumptions concerning security, authentication, authorization and scalability were made that can not be made here

– For example encryption; while for a LAN deployment scenario it is probably assumed that there are no bad actors in the subnet, the same can not be said for WAN

– While depending on e.g. TLS etc. for the migration could have been an option, r3map should still be useful for LAN migration use cases, too, which is why it was made to be completely transport-agnostic

– This makes adding encryption very simple

- E.g. for LAN, the same assumptions that are being made in existing systems can be made, and fast latency-sensitive protocols like the SCSI RDMA protocol (SRP) or a bespoke protocol can be used

- For WAN, a standard internet protocol like TLS over TCP or QUIC can be used instead, which will allow for migration over the public internet, too

- For RPC frameworks with exchangeable transport layers such as dudirekta (will be explained later), this also allows for unique migration or mount scenarios in NATed environments over WebRTC data channels, which would be very hard to implement with more traditional setups

- Similarly so, authentication and authorization can be implemented in many ways

- While for migration in LAN, the typical approach of simply trusting the local subnet can be used, for public deployments mTLS certificates or even higher-level protocols such as OIDC can be used depending on the transport layer chosen

- For WAN specifically, new protocols such as QUIC allow tight integration with TLS for authentication and encryption

- While less relevant for the migration use case (since connections can be established ahead of time), for the mount use case the initial remote `ReadAt` requests' latency is an important metric since it strongly correlates with the total latency

- QUIC has a way to establish 0-RTT TLS, which can save one or multiple RTTs and thus significantly reduce this overhead, and handle authentication in the same step

- Another optimization that has been made to support this WAN deployment scenario is the pull-only architecture

- Usually, a pre-copy system pushes changes to the destination in the migration API

- This however makes such a system hard to use in a scenario where NATs exist, or a scenario in which the network might have an outage during the migration

- With a pull-only system emulating the pre-copy setup, the client can simply keep track of which chunks it still needs to pull itself, so if there is a network outage, it can just resume pulling like before, which would be much harder to implement with a push system as the server would have to track this state for multiple clients and handle the lifecycle there

- The pull-only system also means that unlike the push system that was implemented for the hash-based synchronization, a central forwarding hub is not necessary

- In the push-based system for the hash-based solution, the topology had to be static/all destinations would have to have received the changes made to the remote app's memory since it was started

- In order to cut down on unnecessary duplicate data transmissions, a central forwarding hub was implemented

- This central forwarding hub does however add additional latency, which can be removed completely with the migration protocol's P2P, pull-only algorithm

- In WAN, where latency is high, the ability to fetch chunks concurrently is very important

- Without concurrent background pulls, latency adds up very quickly as every memory request would have at least the RTT as latency

- The first prerequisite for supporting this is that the remote backend has to be able to read from multiple regions without locking the backend globally

- For the file backend for example, this is not the case, as the lock needs to be acquired for the entire file before an offset can be accessed (code snippet from https://github.com/pojntfx/go-nbd/blob/main/pkg/backend/file.go#L17-L25)

- For high-latency scenarios, this can quickly become a bottleneck

- While there are many ways to solve this, one is to use the directory backend

- Instead of using just one backing file, the directory backend is a chunked backend that uses a directory with one file for each chunk instead of a global file

- This means that the directory backend can lock each file individually, speeding up concurrent access

- This also applies to writes, where even concurrent writes to different chunks can be done at the same time as they are all backed by a separate file

- The directory backend keeps track of these chunks by using an internal map of locks (code snippet from https://github.com/pojntfx/r3map/blob/main/pkg/backend/directory.go#L22-L24)

- When a chunk is first accessed, a new file is created for the chunk (code snipped from https://github.com/pojntfx/r3map/blob/main/pkg/backend/directory.go#L77-L94)

- If the chunk is being read, the file is also truncated to one chunk length

- Since this could easily exhaust the number of maximum allowed file descriptors for a process, a check is added (code snippet from https://github.com/pojntfx/r3map/blob/main/pkg/backend/L75)

- If the maximum allowed number of open files is exceeded, the first file is closed and removed from the map, causing it to be reopened on a subsequent read

- These optimizations add an initial overhead to operations, but can significantly improve the pull speed in scenarios where the backing disk is slow or the latency is high

- Benchmark: File vs. directory backend performance

- Another aspect that plays an important role in performance for real-life deployments is the choice of RPC framework and transport protocol

- As mentioned before, both the mount and the migration APIs are transport-independent

- A simple RPC framework to use is dudirekta

- Dudirekta is reflection-based, which makes it very simple to use to iterate on the protocol quickly

- To use it, a simple wrapper struct with the needed RPC methods is created (code snippet from https://github.com/pojntfx/r3map/blob/main/pkg/services/backend.go#L41-L61)

- This wrapper struct simply calls the backend (or seeder etc.) functions

- The wrapper struct is then passed as the local function struct into a registry, which creates the RPC server (code snippet from https://github.com/pojntfx/r3map/blob/main/cmd/r3map-mount-benchmark-server/main.go#L146-L166)

- When the transport protocol, in this case TCP, `accept`s a client it is linked to the registry (code snippet from https://github.com/pojntfx/r3map/blob/main/cmd/r3map-mount-benchmark-server/main.go#L198-L200)

- The used protocol is very simple (code snippet from https://github.com/pojntfx/dudirekta#protocol)

- If an RPC, such as `ReadAt`, is called, it is looked up via reflection and validated (code snippet from https://github.com/pojntfx/dudirekta/blob/main/pkg/rpc/registry.go#L323-L357)

- The arguments, which have been supplied as JSON, are then unmarshalled into their native types, and the local wrapper struct's method is called in a new goroutine (code snippet from https://github.com/pojntfx/dudirekta/blob/main/pkg/rpc/registry.go#L417-L521)

- This allows for one important feature: Concurrent RPC calls

- Many simple RPC frameworks only support one RPC call at a time, because no demuxing is implemented

- For example, when dRPC (https://github.com/storj/drpc) was used, drastic performance issues were noted compared to gRPC etc., because no support for concurrent RPCs was implemented

- To use a RPC backend on the destination side, the wrapper struct's remote representation is used (code snippet from https://github.com/pojntfx/r3map/blob/main/pkg/services/backend.go#L14-L19)

- For the destination site, the remote representation's fields are iterated over, and replaced by functions which marshal and unmarshal the function calls into the dudirekta JSON protocol (code snippet from https://github.com/pojntfx/dudirekta/blob/main/pkg/rpc/registry.go#L228-L269)

- To do this, the arguments are marshalled into JSON, and a unique call ID is generated (code snippet from https://github.com/pojntfx/dudirekta/blob/main/pkg/rpc/registry.go#L109-L130)

- Once the remote has responded with a message containing the unique call ID, it unmarshalls the arguments, and returns (code snippet from https://github.com/pojntfx/dudirekta/blob/main/pk L217)

- This makes both calling RPCs and defining them completely transparent to the user

- Since dudirekta has a few limitations (such as the fact that slices are passed as copies, not references, and that context needs to be provided), the resulting remote struct can't be used directly

- To work around this, the standard go−nbd backend interface is implemented for the remote representation, creating a universally reusable, generic RPC backend wrapper (code snippet from https://github.com/pojntfx/r3map/blob/main/pkg/backend/rpc.go)

- The same backend implementation is also done for the seeder protocol (code snippet from https://github.com/pojntfx/r3map/blob/main/pkg/services/seeder.go)

- While the dudirekta RPC serves as a good reference implementation of the basic RPC protocol, it does not scale particularly well

- This mostly stems from two aspects of how it is designed

- JSON(L) is used for the wire format, which while simple and easy to analyze, is slow to marshal and unmarshal

- Dudirekta supports defining functions on both the client and the server

- This is very useful for implementing e.g. a pre-copy protocol where the source pushes chunks to the destination by simply calling a RPC on the destination

- Usually, RPCs don't support exposing or calling RPCs on the client, too, only on the server

- This would mean that in order to implement a pre-copy protocol with pushes, the destination would have to be dialable from the source

- In a LAN scenario, this is easy to implement, but in WAN it is complicated and requires authentication of both the client and the server

- Dudirekta fixes this by making the protocol itself bi-directional (example and code snippet from https://github.com/pojntfx/dudirekta/tree/main#1-define-local-functions)

- In addition to this, dudirekta works over any `io.ReadWriter`

- This does however come at the cost of not being able to do connection pooling, since each client `dial`ing the server would mean that the server could not reference the multiple client connections as one composite client without changes to the protocol

- While implementing such a pooling mechanism in the future could be interesting, it turned out to not be necessary thanks to the pull-based pre-copy solution described earlier

- Instead, only calling RPCs exposed on the server from the client is the only requirement for an RPC framework, and other, more optimized RPC frameworks can already offer this

- Dudirekta uses reflection to make the RPCs essentially almost transparent to use

- By switching to a well-defined protocol with a DSL instead, we can gain further benefits from not having to use reflection and generating code instead

- Analyzing the gRPC backend and how it differs from dudirekta

- Analyzing the fRPC backend and how it differs from gRPC

- Connecting polling and/or concurrent RPCs

- Benchmark: Latency till first n chunks *and* throughput for dudirekta, gRPC and fRPC backends (how they are affected by having/not having connection polling and/or concurrent RPCs)

- Benchmark: Effect of tuning the amount of push/pull workers in high-latency scenarios

- Analyzing the Redis backend

- Analyzing the S3 backend (empty chunks etc.)

- Analyzing the Cassandra backend (migrations etc.)

- Benchmark: These three backends on localhost and on remote hosts, where they could be of use

- Effects of slow disks/memory on local backends, and why direct mounts can outperform managed mounts in tests on localhosts

- Benchmark: Latency and throughput of all benchmarks on localhost and in a realistic latency and throughput scenario

- Looking back at all options and comparing ease of implementation, CPU load and network traffic between them