Storing the Cardano ledger state on disk: requirements for high performance backend

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Changelog

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Contents

1 Executive summary

The project to reduce the Cardano node's memory use (known informally as "UTxO HD"[1]) has taken the approach of building an interim solution (MVP) as a major step towards the complete solution.

The interim (MVP) solution:

1. is largely complete (at the time of writing);
2. moves approximately half of the ledger state to disk (the UTxO itself); and
3. uses an adequate low performance on-disk storage backend (based on LMDB) without support for comprehensive I/O fault testing.

The MVP is suitable for deployment as an interim solution:

- It reduces the node's memory use by approximately 40%, from 13Gb to 8Gb.
- It increases the node's blockchain synchronisation time by approximately 25%, from approximately 21 to 26 hours. Some regression in synchronisation time was expected. A regression of 25% is not ideal but has been deemed acceptable.

The MVP will not remain suitable indefinitely however.

- The node's performance and memory use will degrade as the UTxO scales with more users.
- The MVP cannot *simultaneously* meet all of the performance targets from the business requirements, even at the minimum 'threshold' level.

Fundamentally, Cardano *cannot scale* to its intended number of users (e.g. Bitcoin or Ethereum size) without completing the project to satisfy the various business requirements.

It is recommended that the project continue to the complete solution, which will involve:

1. moving the remaining large parts of the ledger state to disk; and
2. implementing and integrating a high performance on-disk storage backend with support for comprehensive I/O fault testing.

These two parts of the project are both substantial: they are likely to take several months each with a small team. They can run concurrently or sequentially, with some efficiency savings if done sequentially but taking longer overall. The implementation of the high performance on-disk storage backend can be done as an 'arms length' activity and thus could be outsourced. All other parts will at require significant work from the existing ledger and consensus teams, though with the possibility of extra help.

[1]Connoisseurs of bad jargon may be interested to note that this term is a double misnomer. UTxO HD refers to moving the UTxO to the hard disk, however the the UTxO is only half of the ledger state that the project aims to deal with, and the UTxO cannot be stored on a hard disk because spinning hard disks are far too slow to meet the minimum performance requirements.

The focus of this document is on the improved on-disk storage backend, but the other half of the project should be kept in mind. The improved on-disk storage backend is intended to have two main benefits:

1. it should enable the node to meet its performance and scaling targets, which will allow Cardano to scale to many more users while remaining within reasonable memory limits;
2. it should restore the comprehensive I/O fault testing for the consensus layer which would assure the continued robustness of the node to I/O errors and silent disk corruption.

2 Risks to the status quo

There are a number of risks if the MVP remains as the status quo

- As the number of users and wallets increases, the node's memory use (RAM) will also increase because the large stake related tables are still kept in memory.

  The solution is to move the remaining stake tables to disk. See Section 5.1 for details.

- The time taken for the node to synchronise will degrade as the size of the UTxO grows beyond what can fit in memory (i.e. with more use and more users). It can be expected to degrade to the point where the node does not meet its threshold (i.e. minimum) business requirement targets for the combination of memory use, UTxO size and synchronisation performance.

  The solution is to implement and integrate a higher performance on-disk backend. See Section 5.2 and Section 13.7 for details.

- A compromise in the MVP is that the node can no longer be comprehensively tested for being robust against disk I/O errors and disk corruption. Over time, without the ability to test, this is likely to lead to a lack of robustness and hence more frequent problems for node users, user dissatisfaction and increased support load.

  The solution is to implement and integrate a new on-disk backend that can use the existing I/O fault testing framework, restoring the ability of the consensus layer as a whole to be tested. See Section 14 for details.

- There is an existing security risk to do with switching between chain forks sufficiently quickly to meet Ouroboros Praos security assumptions. It is not always possible to switch between different chain forks as quickly as the Ouroboros Praos security analysis assumes. The risk arising as a consequence of failing to meet this assumption is unfortunately difficult to quantify. It is clear however that a regression in synchronisation speed corresponds to switching forks more slowly, which increases the risk. The MVP has a 25% regression in synchronisation speed and thus a similar regression is expected in the time to switch forks. As noted above this is expected to get worse as the UTxO continues to grow. The consequences and severity of this risk are still being analysed by the Ouroboros researchers.

  Though the risk is hard to quantify, it is clear that the risk can be mitigated by improving the synchronisation speed. Part of that involves integrating a new on-disk backend that will not regress further as the UTxO grows. Another part would be to improve synchronisation speed by taking advantage of CPU and I/O parallelism. See Sections 8.4 and 16.2 for details.

3 Summary of benefits

The improved on-disk storage backend is intended to have three main benefits.

1. It should achieve substantially higher throughput for crucial operations, while also using less memory and scaling to much bigger on-disk tables.

   This would have the following benefits.

   - It should enable Cardano to scale to a much larger UTxO size – comparable with that of Bitcoin – and thus scale to many more users.
   - It should stop the current trend of node operators having to use ever more capable and expense hardware or VMs with more and more memory as the size of the UTxO grows. Indeed it should allow operations to use cheaper VMs compared to what is currently the case.
   - It should enable the current node's consensus layer to achieve faster blockchain synchronisation times than with the existing low-performance backend.
   - It should achieve faster chain replay and revalidation times.
   - It should enable the node to meet its 'middle' performance targets with the minimum required hardware and the 'stretch' targets with higher performance SSD hardware.
   - It should avoid the additional regression in synchronisation (and replay and revalidation) times that is anticipated with the existing low-performance backend as the UTxO continues to grow.
   - It should help to mitigate Ouroboros Praos security risks associated with the time to switch blockchain forks.
   - It would be necessary for the future Ouroboros Leios (aka Ouroboros with input endorsers) in order to achieve its TPS performance goals.

2. It should unlock the opportunity to move the remaining large parts of the ledger state to disk without causing new performance problems such as stalls at the epoch boundary. It should support the additional operations required by the ledger for its stake related tables, such as cheap table snapshots and merges.

3. It should restore the comprehensive I/O fault testing for the consensus layer that had existed prior to the introduction of the low-performance on-disk storage backend. This would assure the continued robustness of the node to I/O errors and silent disk corruption.

4 Project history

The analysis in the original design document for the project to store the ledger state on disk [Wilson and Coutts, April 2021] concluded that a high performance backend would be necessary to achieve the stated business requirement of 200 TPS [Wilson and Coutts, April 2021, Sections 3.1, 5.7], while keeping the time to synchronise the blockchain within reasonable limits.

4.1 Original recommendations

The key recommendations in the original design document [Wilson and Coutts, April 2021, Section 9] were:

1. The use of a pipelined style of interface between the consensus and disk backend. This is to provide the option later to use pipeline style concurrency to take full advantage of a high performance disk backend.
2. The use of an in-Haskell implementation of the on-disk data structure to preserve the investment in the consensus testing infrastructure which assures that the node remains robust in the presence of disk I/O failures.
3. To try the existing `haskey` B+ tree implementation as the basis for an interim solution, and to develop a LSM tree implementation as an eventual solution. The proposal of two implementations was recommended as a way to balance the time to develop a first working version in the short term with the need to meet the given performance targets in the longer term.
4. That it will be necessary eventually to add support for parallel I/O to scale to higher blockchain TPS targets while maintaining acceptable bulk sync times.

4.2 Highlights

The key highlights of the history of the development so far are these.

The project proceeded with detailed design [Coutts and Wilson, November 2021] and prototyping of the interface between the consensus and storage disk backend, followed by a development and integration effort towards a MVP (Minimal Viable Product) milestone. The goal for the MVP was to move the UTxO from memory to disk, but not the other large parts of the ledger state. Moving the remainder is intended to be done after the MVP.

The actual development followed the initial recommendations. In particular the pipelined interface style was prototyped and has been integrated in the current MVP. The `haskey` B+ tree library was tried out as the basis for a backend but it was found to be too slow to be practical, even for the interim performance goals. Instead a backend based on the LMDB C library was developed and has been integrated into the current MVP.

5 Project status and steps to completion

The current MVP moves the UTxO from being in memory to being on disk, which for the current mainnet reduces the memory footprint of the node by approximately 40% (from approximately 13Gb to 8Gb). This memory saving comes at the cost of increased blockchain synchronisation times. For the current mainnet, this synchronisation slowdown is approximately 25% (from approximately 21 to 26 hours) which is deemed acceptable from a technical perspective (though not ideal).

After the MVP, there are two major pieces of work to complete the project.

1. The remaining large parts of the ledger state must be moved to disk. This is required to get the node's memory use down further and to allow the blockchain to scale to larger ledger states (i.e. more users).
2. A higher performance on-disk backend is needed, with support for I/O fault testing. This is required to meet the business requirement for TPS while keeping the synchronisation times acceptable, and to assure the continued robustness of the node to I/O faults.

5.1 The single-table design shortcut

One of the shortcuts in the MVP was to move only the UTxO to disk and to avoid the need to support table snapshots[2]. This allowed the MVP to use a single-table design without snapshot support, which is considerably simpler than a multi-table design with support for snapshots. The original prototype did cover multiple tables and snapshots, but this was simplified for the MVP. The compromise for this simpler design is that the full memory savings are not realised: the large parts of the ledger state other than the UTxO remain in memory. Moving the stake-related tables to disk will however require the multi-table design with snapshot support (as described by Coutts and Wilson [November 2021]).

The other large parts of the ledger state are the stake-related tables:

- a map of stake credential to delegation choice;
- a map of stake credential to reward balance;
- a map of stake credential to stake (i.e. the distribution by stake address);
- snapshots of the three tables above; and
- a map of stake credential to reward payout for the current epoch.

Another shortcut in the MVP was that almost no changes were needed in the ledger or the ledger/consensus interface. This is related to the single-table design compromise. A full multi-table design with snapshots will require support in the ledger and changes in the ledger/consensus interface.

The details of the changes required to the ledger and ledger/consensus interface are out of scope for this document.

5.2 The LMDB backend shortcut

The LMDB disk backend provides acceptable performance for the current throughput of the Cardano mainnet, given the current scale of the Cardano ledger state. It is not a bottleneck to the current mainnet TPS, and causes an acceptable – approximately 25% – slowdown in synchronisation time compared to in-memory storage.

The LMDB backend will however limit the ability to scale the ledger state size and scale the TPS while keeping the synchronisation times acceptable. Indeed, as the ledger state increases, with more use of the system and more users of the system, the synchronisation times will regress. While using the LMDB backend it will not be possible to (simultaneously) meet more than the 'threshold' business requirement targets for system TPS, ledger state size and synchronisation time.

Furthermore, the LMDB backend, being based on the LMDB C library, has the unfortunate consequence that it cannot use the existing consensus testing infrastructure for robustness in the presence of disk I/O failures. This has the overall consequence that the consensus layer, when using this backend, would no longer have the assurance that it is robust in the presence of disk I/O failures. See Section 14 for details.

[2] In this context table snapshots refers to the ability for the ledger to ask for snapshots of individual tables for the ledger to access those snapshots as read-only tables. This is as opposed to the consensus layer taking table snapshots as part of making a checkpoint of the ledger state (to resume from on startup).

5.3 The I/O pipelined concurrency shortcut

The interface between the consensus and disk backends uses the 'pipelined' style. This interface was designed to be *capable* of high throughput, *when used in a pipelined way*. The current MVP takes a shortcut however by only using the interface in a *simple serial way*.

Using it in a pipelined way would mean that multiple batches of reads are executed concurrently. The shortcut in the MVP is a reasonable one because the LMDB backend used in the MVP does not provide any performance benefit when used concurrently, because the LMDB backend is serial[3].

To take full advantage of a higher performance backend later will require further development in the consensus layer to use pipeline style concurrency.

5.4 The monoidal update shortcut

A feature that was not required and not built for the MVP is support for 'monoidal' update operations in the disk backend. One of the large maps mentioned above – the map of stake credential to stake – will require update operations as frequently as updates to the UTxO mapping itself. This is because the stake associated with each stake address will need to be adjusted as a result of transactions moving Ada funds (and thus stake) between addresses. A naive implementation of this would require performing a lookup to find the current stake, followed by an insert with the new adjusted stake. Such an implementation would be bad for performance because it would double the number of lookup operations that need to be performed, and lookups are known to be the performance bottleneck.

An alternative implementation is to perform an update operation that adds a stake change (positive or negative) to the stake – without needing to know what the total stake was. Some database libraries support such an update operation with considerably better performance than the combination of a lookup and an insert. Indeed some write-optimised database libraries support update with similar performance to insert or delete.

The LMDB library does not support monoidal updates, however their use for the stake distribution table is likely to be essential to move the stake distribution to disk while still meeting the node's performance targets. See Section 7 for details.

6 Business requirements for performance and hardware support

The business requirements, including targets for performance and resource use, were agreed at the start of the project [Wilson and Coutts, April 2021, Section 3].

These requirements only cover the existing Cardano system based on Ouroboros Praos. See Section 9 for a discussion of Ouroboros Leios.

There are several relevant targets and minimum hardware constraints:

- Table 1, ledger state size targets: the number of UTxO entries and registered stake addresses that must be supported. For reference, Bitcoin currently has approximately 84 million UTxO entries.
- Table 2, transaction rate (TPS) targets: the average sustained transactions per second on the blockchain.

[3] In principle LMDB can do parallel I/O for reads but it is designed for a multi-client use case, and adapting a single client to use this would incur code complexity costs and performance overheads. See Section 13.7.

Target (millions)	UTxO entries	Stake addresses
Threshold	10	2
Middle	50	10
Stretch	100	20

Table 1: Ledger state size targets.

Target	TPS
Threshold	20
Middle	50
Stretch	200

Table 2: Transaction rate targets

Target	faster than real time	hours to sync 1 year
Threshold	100×	88.0 hours
Stretch	1000×	8.8 hours

Table 3: Synchronisation speed targets

Target	Gb
Threshold	8
Middle	4
Stretch	2

Table 4: Memory use constraints

Random 4k reads	IOPS
Queue depth 1	10,000
Queue depth 32	100,000

Table 5: Disk performance constraints

- Table 3, synchronisation speed targets: how fast the node can synchronise the blockchain. These targets are expressed in terms of how much faster synchronisation should be than real time. It makes sense to consider it this way, rather than the total time to synchronise the whole chain because the total depends on how long the chain is, which is constantly increasing.
- Table 4, memory use constraints: the amount of memory (RAM) the node is permitted to use. This also implies a minimum hardware requirement.
- Table 5, disk performance constraints: the minimum hardware specification that the node is expected to run on, while meeting its other targets.

  In particular the machine the node is expected to run on must include an SSD capable of the given minimum random read performance (IOPS). In practice this must be an NVMe SSD because SATA SSDs top out at around 90k IOPS, which itself is often not achievable in practice due to the various overheads.

Many of these are expressed as three targets: 'threshold', 'middle' and 'stretch'. The threshold is the minimum acceptable, corresponding for example to a minimum viable product. The middle target is in some sense the primary target, and stretch target is a goal that would be useful to the business if it were achieved, but it is accepted that it may be impractical or too costly to achieve.

The performance goals and hardware constraints are in tension with each other, so it is important to consider them as a whole. For example it is easy to achieve low memory use if the ledger state remains small, or easy to achieve fast synchronisation if the average TPS on the chain is low. It is harder to achieve all the targets simultaneously, particularly all of the middle or stretch targets.

7 Requirements arising from moving the stake-related tables to disk

As discussed in Section 5.1, the remaining large parts of the ledger state must be moved to disk. All of the remaining large parts of the ledger state are mappings related to stake. Moving these to disk will increase the number of I/O operations that the consensus layer needs to perform, and this must be accounted for in relation to the performance targets. In addition, as we will see in this section, the use of the stake related tables will require some additional efficient operations in the disk backend in order to meet performance targets and avoid 'stalls' in the operation of the node.

Recall (from Section 5.1) the list of stake related mappings:

1. a map of stake credential to delegation choice;
2. a map of stake credential to reward balance;
3. a map of stake credential to stake (i.e. the distribution by stake address);
4. snapshots of the three tables above; and
5. a map of stake credential to reward payout for the current epoch.

7.1 Maintaining stake distributions

There are two stake distributions used in the ledger, and the Voltaire governance extension will add a third:

1. the stake distribution aggregated by stake address (or more precisely by stake credential);
2. the stake distribution aggregated by stake pool;
3. the stake distribution aggregated by stake 'DRep' for Voltaire;

These are all aggregations of the UTxO, which has the ada (and thus stake) for each UTxO entry.

7.2 Maintaining the stake distribution by stake address

The stake distribution aggregated by stake address is relatively straightforward to compute: each UTxO entry directly contains the stake credential that it is associated with. This makes aggregating by stake credential relatively efficient because all the information is directly available. The computation can either be done as a bulk computation, based on a snapshot of the UTxO, or it can be done in a continuous transaction-by-transaction basis to maintain a 'live' stake distribution.

The bulk computation approach would work by doing a linear scan of the UTxO snapshot, accumulating and aggregating into a target table keyed on the stake credential. This bulk computation would need to be spread out over the epoch to avoid too much work at any one point. In principle this is straightforward because the computation works as a single linear pass over the UTxO, so this could be sliced up into an appropriate number of steps.

The continuous incremental approach would work by computing the *change* in stake for each transaction: the reduction in stake for the stake credential associated with each input consumed, and the increase in stake for the stake credential associated with each output created.

It is important to note that, in general, both of these methods involve multiple *update* operations to the stake associated with a single stake credential. In the bulk approach there will be, in general, many UTxO entries associated with a single stake credential, and these will be encountered at different points during the linear scan of the UTxO. So each UTxO entry processed will involve an addition to the stake of the corresponding stake credential. The continuous incremental approach is explicitly based on changes in stake, which corresponds to an update operation.

An update operation can be implemented as a lookup followed by an insert, however disk lookups – at least uncached lookups – inevitably cost at least one disk read. As we will see in Section 13, disk reads (or IOPS) are a limiting factor for overall throughput. Some database libraries support such an update operation with considerably better performance than the combination of a lookup and an insert. Indeed some write-optimised database libraries support update with similar performance to insert or delete. This is because a large batch of insert, delete or update operations can be combined into a single disk write: as many as will fit into a disk page.

Thus either way the stake distribution is computed, the implementation will benefit greatly from having an efficient update operation that does not involve a lookup.

The bulk method would cost one sequential lookup and one random update per UTxO entry. The continuous method would cost one random update per transaction input and per transaction output. Neither would require expensive random lookup. The cost of the two methods are not directly comparable: one is proportional to the total size of the UTxO while the other is proportional to the transaction rate, which is the rate of change of the UTxO. Both methods are acceptable in terms of the IOPS they need, so the choice can be made based on design complexity and other considerations.

7.3 Unified or split stake distribution

Logically the stake distribution is the aggregation of the stake from the UTxO and stake from reward account balances. There is a design choice for the representation: to keep them together or separated. If separated, then operations that consult the stake distribution have to combine results from both parts, but if combined then the operations that change the reward balances (withdrawals and reward payouts) have to modify the stake distribution mapping.

7.4 Maintaining the stake distribution by stake pool or DRep

There are also two approaches to computing the stake distribution aggregated by stake pool (or by DRep): bulk or continuous.

The bulk method involves a simultaneous linear scan (aka a join) of (snapshots of) the stake distribution by stake credential and a scan of the mapping of stake credential to stake pool delegation choice. For each pair of stake and stake pool delegation choice, an entry is accumulated into an in-memory mapping of stake pool to stake. If the reward balances are kept separate to the UTxO stake distribution then an additional linear scan of (a snapshot of) the mapping reward balances is needed. The method is exactly the same for the stake distribution by DRep, but utilising the DRep delegation choice.

The continuous method involves computing the changes in stake arising from each transaction. This is much like the method for continuously computing the stake distribution by stake credential. The difference is that each stake credential needs to be looked up in the delegation choice mapping to find the corresponding stake pool, with the result accumulated into an in-memory mapping of stake pool to stake. Again, the method is the same for the stake distribution by DRep.

The cost of the bulk method is two sequential lookups per registered stake credential. The cost of the continuous method is one random lookup per transaction input and output. Sequential lookups are cheap, but random lookups require an IOOP unless there is a very effective cache. If the lookups could not be cached then the continuous method is very expensive: it would *triple* the number of random read IOPS required for processing each transaction. As we discuss in

Section 13, random read IOPS are a resource that is a bottleneck to throughput. So tripling the number required can be expected to reduce throughput by the same factor.

Whether the delegation maps can be cached effectively is in principle knowable, based on an analysis of the chain. Without doing a full analysis, a back of the envelope analysis makes it appear unlikely. If we take the stretch target of 20M stake addresses, and consider caching that 10% of these, that would take approximately 0.5Gb of memory (stored on the heap, including heap overheads). This would rely on 10% of stake addresses accounting for at least 90% of all transactions for the caching to be effective, which seems like a strong assumption. And 0.5Gb of memory is itself a significant fraction of the target for the memory available of 8Gb down to 2Gb for the stretch target. It seems much safer to rely on an uncached strategy.

Thus for performance, it is highly desirable to use the bulk method to compute the stake distribution by by stake pool or by DRep.

7.5 Table snapshots

One of the operations that the ledger performs with some of its stake related tables is to take a snapshot of a table. In particular, the stake distribution by stake credential, the delegation choices have to have snapshots taken at the epoch boundary.

A snapshot of a table means that a (logical) new snapshot table is created that is an exact copy of the original table at the point of the snapshot, and that the snapshot table does not change even as the original table is subsequently changed after the snapshot is taken.

In the current LMDB backend this is supported – but supported inefficiently. It works by making a complete copy of the files that make up the table, which costs $\mathcal{O}(n)$ time, $\mathcal{O}(n)$ disk IOPS and $\mathcal{O}(n)$ disk storage space. This would be bad because it would cause stalls in block processing at the epoch boundary.

More sophisticated disk data structures and database libraries can support taking persistent snapshots in $\mathcal{O}(\log n)$ time, $\mathcal{O}(\log n)$ disk IOPS and $\mathcal{O}(\log n)$ disk storage space. Such disk data structures typically work by using an append only or copy-on-write design, where existing data is not modified. In such a design it then becomes cheap to keep a reference to an existing state of the data structure.

This should be a required feature for the new on-disk backend to enable the node to avoid stalls at the epoch boundary.

7.6 Ledger state snapshots

The consensus layer needs, from time to time, to take a snapshot of the whole ledger state. This is done in order to provide points from which the node can resume after being shut down. This give rise to the same requirement as in Section 7.5 but for a different purpose.

As mentioned above, the current LMDB backend can support table snapshots but at the cost of $\mathcal{O}(n)$ time, IOPS and disk space. While this is not synchronised with the epoch boundary, it does nevertheless cause stalls in block processing at arbitrary points during the epoch. The duration of these stalls will grow with the size of the UTxO, and would grow further when the remaining stake related tables are moved to disk.

Thus the new on-disk backend should support $\mathcal{O}(\log n)$ table snapshots to enable the node to avoid stalls at arbitrary points during the epoch.

7.7 Updating stake rewards

One of the important and costly operations that the ledger performs is to compute the rewards for each stake address each epoch, and to credit the per-epoch rewards into each reward account at the end of each epoch.

The ledger computes the rewards in a bulk incremental style, involving linear passes over large tables such as the stake distribution by stake credential. It currently accumulates the computed rewards into a large in-memory mapping, and at the epoch boundary it applies the computed rewards to the mapping of reward account balances.

The latter operation of applying the rewards is currently $\mathcal{O}(n)$ in the number of register stake addresses (with their corresponding reward accounts). This is not ideal because it creates a pause in block processing at the epoch boundary. It is currently not too costly in absolute terms because it works on in-memory data structures, and the scale of the ledger state is not yet extreme.

A disk based version of this approach could work similarly, though there is an opportunity for improvement. The computed rewards could be incrementally written into a temporary on-disk rewards table. The challenge is to avoid a costly operation at the epoch boundary when the rewards need to be combined with the live reward accounts. An $\mathcal{O}(n)$ algorithm involving disk tables can be expected to have much worse constant factors than an in-memory version, and of course the n value is expected to grow as the system grows in use. Recall from Table 1 that the stretch target for n – the number of stake addresses – is anticipating at least a $10\times$ growth.

To avoid stalls at the epoch boundary, the per-epoch reward table must be combined with the live reward balances table promptly. This suggests we could afford an operation that takes at most $\mathcal{O}(\log n)$ time. On the face of it, updating the balance of n accounts in $\mathcal{O}(\log n)$ time seems hard, but it is in principle possible with an appropriate choice of on-disk data structure. To achieve such an $\mathcal{O}(\log n)$ merge without continuously degrading the lookup performance, it is acceptable to impose a constraint that such merges not be done too frequently. This is acceptable in our use case because rewards are only paid out every epoch, which is five days. The rebalancing of the on-disk data structure after the merge can be spread out over those five days.

This merge operation should be a required feature for the new on-disk backend to enable the node to avoid stalls at the epoch boundary.

8 Reevaluating the synchronisation speed requirement

The original business requirement for synchronisation speed was relatively simplistic, being based only on the time users need to wait to synchronise the whole blockchain. There are other more technical constraints, and the Mithril project has made significant progress since the business requirements were agreed. So a more detailed analysis is warranted.

8.1 Mithril

It is reasonable to reevaluate the business requirement for synchronisation time given the prospect that in future Mithril may become part of the standard solution for blockchain synchronisation for a large class of users.

Let us assume a future in which Mithril fully achieves its design goals and is widely deployed. Mithril allows a node to synchronise the blockchain by establishing trust in a snapshot at a recent point on the blockchain, downloading the ledger state for that snapshot and then synchronising the remaining part of the chain in the usual way.

It is anticipated that there will be Mithril snapshots every five days. So this bounds the amount of chain that would need to be synchronised in the usual way after fetching the snapshot. Reevaluating the original targets in the context of synchronising just five days gives us

Target	faster than real time	time to sync 5 days of chain
Threshold	100×	72.0 minutes
Stretch	1000×	7.2 minutes

Whether these values are reasonable is of course a business decision and depends on user expectation. It is worth noting that Mithril is likely to raise user expectations, so it may come as rather a disappointment to Mithril users if they still need to wait over an hour even after the snapshot has been verified and downloaded. This suggests that a target in the range of 100x — 1000x may still be reasonable, even with Mithril.

It is of course possible to change the frequency of Mithril snapshots, but there is a significant cost to creating and storing snapshots so it is unlikely that it would make sense for snapshots to be much more frequent than every five days.

8.2 Replay and Revalidation

There are other operations the node performs, beyond full synchronisation of the blockchain: chain replay and revalidation.

Blockchain revalidation is the process of fully validating a local blockchain. This is similar to full synchronisation but where the chain blocks do not need to be downloaded because they are already present locally. This involves all the validation checks, including crypto checks and running scripts.

Blockchain replay is the process of reconstructing the ledger state from the blockchain, on the assumption that the blockchain has previously been validated. It avoids running scripts and crypto checks.

Blockchain revalidation is triggered upon node startup if certain kinds of file corruption are detected in the files that store the blocks. This can take a very long time, but occurs rarely.

Blockchain replay is performed every time the node starts up. The node replays from the most recent ledger snapshot. So the performance of replay directly affects the node startup time. The frequency of ledger snapshots can be adjusted, but making them too frequent also has a performance cost.

Furthermore, a full chain replay – from the beginning of the chain – is triggered upon startup if the ledger snapshot files are corrupted or for a format migration for the ledger snapshots. The migration strategy for the ledger state snapshot format is simple and robust: just reconstruct the ledger state in the new format from the full chain. The ledger state snapshot format is changed in new node releases from time to time.

So a full replay is performed each time a user upgrades the node, when the new node has a format migration. The original targets in Table 3 are relevant for considering how long users will have to wait.

It is possible to change the design to use 'proper' migrations, but at the cost of additional initial development effort and ongoing maintenance and testing effort. Having proper migrations eliminates the replay use case but not the revalidation use case, so it is not a total solution.

8.3 Blockchain data consumers

Chain replay is also performed by various clients of the node that consume or transform blockchain data. Some node clients are only interested in data stored on the chain, but much interesting data comes from the ledger state, such as reward payouts. To get access to this data, node clients maintain a ledger state. Once the ledger state is too large to fit in memory, they will also need to use the disk based storage. Most such clients also want to be able to replay the chain reasonably quickly.

8.4 Blockchain fork switching

The Ouroboros Praos algorithm has a performance requirement that a newly created chain can be diffused and adopted by all other (honest) nodes within Δ slots. For the current Cardano mainnet the Δ parameter is 5 slots, which is 5 seconds. This requirement in Ouroboros holds *irrespective* of the length of the chain. The typical case is relaying and adopting a chain that is one block longer than the current chain for a node, so only a single block needs to be transmitted and validated. In atypical cases however a node may need to switch between forks that are 10s, 100s of blocks different, which means transmitting and validating that number of blocks within Δ slots. Clearly in general it is not possible to diffuse $\mathcal{O}(n)$ blocks within $\mathcal{O}(1)$ time. The question however is at what threshold length is it acceptable to no longer be able to diffuse the chain within Δ slots.

At the time of writing, the Ouroboros researchers have not agreed a specific threshold, but they suggest that it is reasonable to expect that such a threshold would be of the same order of magnitude as the number of blocks that we recommended to exchanges and other merchants to wait for a transaction to become stable.

The intuition of the argument is that if users ought to wait X blocks to achieve transaction stability, then the system should also be able to meet its own security-related deadlines for forks up to X blocks long. It is after all the same event – a fork of length X blocks – and so has the same probability. Thus one cannot dismiss not meeting the deadline as unimportant due to being a relatively rare event, given the importance of the same rare event for users' transaction stability. Furthermore, it is a correlated event: one that happens to a large fraction of the honest nodes at the same time, whereas the assumption for the acceptable usual random loss and delay is that it is independent for each node.

Table 6 gives the recommendation to exchanges and other merchants for how many blocks to wait for transaction stability[4]. Note that for even relatively optimistic assumptions, the number of blocks to wait is on the order of 100.

Adversarial stake	$p = 0.1\%$	$p = 0.01\%$
5%	67	73
10%	102	112
15%	154	169
20%	239	261
25%	391	428
30%	709	776
35%	1553	1698

Table 6: Number of blocks to wait to achieve a probability of failure $< p$

[4]One can observe in practice that long forks are less common than the numbers in the table would suggest, but it is also likely that in practice there is approximately zero adversarial stake. We – of course – cannot design a system on the assumption of very low adversarial stake. One of the primary selling points of Ouroboros over other algorithms is resistance up to a 50% adversary, compared to the 33% in many competing algorithms.

For comparison, Table 7 gives the correspondence between the two original synchronisation speed targets and the fork length that could be adopted within that time. This is a best case analysis because it does not take account of latency and multiple hops in the network. The real numbers are likely to be lower. For example, if we can sync 100× faster than real time, then (crudely) in 5 seconds we can sync 500 seconds worth of chain, which is 25 blocks, given that block production is on average one block every 20 seconds.

Target	faster than real time	fork length switch within Δ slots
Threshold	100×	25 blocks
Stretch	1000×	250 blocks

Table 7: The length of a blockchain fork that could be adopted within Δ slots.

What we can see is that for the stretch target of 1000×, we might be able to achieve fork switches within Δ slots corresponding to a 20% adversary from Table 6, but at 100× we would not even get to the 5% level.

Again, this suggests that a target in the range of 100x — 1000x may be reasonable.

9 Requirements arising from Ouroboros Leios

Ouroboros Leios is still in the research and development phase and no specific business requirements have yet been agreed. Nevertheless we can make reasonable suggestions for what these requirements might be.

Coutts et al. [November 2022] describe the Ouroboros Leios design in detail. The significant point for the requirements of the disk backend is that Leios is intended to allow substantially higher transaction throughput, i.e. TPS. While this has not yet been quantified into a concrete target, it is hoped that the design may be capable of 200 – 1000 TPS. It is important therefore that the I/O subsystem not be a bottleneck that would make this infeasible.

It is expected that a high performance configuration of Leios would involve quite high minimum requirements for hardware and network capabilities. Correspondingly it is expected that only a subset of users would run full nodes. In particular most wallet users would not run full nodes. The "heavyweight" users of the system would run full nodes, such as: SPOs, exchanges, merchants, light wallet backends and other services.

This means we can expect that the minimum hardware requirements would correspond to a typical server class machine with a server class network connection, rather than to a typical end user machine such as a laptop with consumer class broadband. This would include a high performance SSD. It is probably reasonable to assume that, by the time Leios is deployed, SSDs capable of around 1 million IOPS (for 4k random reads at maximum queue depth) will be widely available from mainstream cloud computing services.

Given these considerations some plausible targets for Ouroboros Leios are given in Table 8.

9.1 Additional feature requirements

Ouroboros Leios, like Praos, relies on having straightforward access to multiple versions of the ledger state, one for each of the last K blocks. This is discussed in more detail for Praos in Section 17.1. For Leios, this remains the case and indeed access to older versions is even more common and frequent because in Leios input blocks can be validated in the context of the ledger state of *any* recent ranking block.

Target	Value	Unit
Ledger state size target	100M	UTxO entries
Transaction rate target	1000	TPS
Synchronisation speed target	100–1000	$\times$ faster than real time
Memory use constraint	32	Gb RAM
Disk performance constraints	1M	IOPS for 4k random read at max QD

Table 8: Plausible (order of magnitude) targets for Ouroboros Leios

The existing design, discussed in Section 17.1, keeps only a single version of the ledger state on disk but involves keeping in memory all the *changes* to the ledger state for the last K blocks. For the (relatively low, 7 TPS) throughput of the existing system, the memory use of keeping the changes in memory is expected to be approximately 50Mb, which is acceptable. At the expected TPS for Leios however (1000 TPS or more) that would grow to around 7Gb or more, which is a significant fraction of the total memory assumed to be available to the node[5].

An alternative design would avoid keeping in memory all the changes from the last K blocks, but it would require additional non-standard functionality from the disk backend, specifically the ability to have multiple writable versions of the database available at once. This feature is not available in any common 'off the shelf' database libraries. It would be an additional requirement on a new disk backend. Section 17.3 discusses this idea in more detail.

10 A quantitative method to assess I/O performance feasibility

Before embarking on building a new on-disk table component and moving more tables to disk, it behoves us to assess whether the business requirements for performance are feasible. The original report [Wilson and Coutts, April 2021] assessed feasibility using approximate 'back of the envelope' calculations. At this stage of the project it makes sense to reassess with a higher degree of precision – albeit still using reasonable approximations.

In principle we can make an approximate *quantitative* assessment of the feasibility of the business requirements on performance. It is clear from back-of-the-envelope calculations that the I/O resource is the crucial limiting factor to the overall performance. We will therefore limit the scope of our assessment to I/O resources, and to approximate limits on memory. We will not consider CPU resources.

To do an approximate quantitative assessment of I/O performance feasibility we need:

1. the approximate quantity of table operations per second implied by the business requirements; and
2. some approximation of the relationship between table operations and I/O operations.

The method is then to use these

1. to establish an approximation of the I/O operations per second (IOPS) implied by the business requirements; and
2. to check if the IOPS required is comfortably within the performance capabilities of the minimum disk hardware.

[5]A Leios node can already be expected to be relatively memory hungry, so this would translate into higher system requirements and higher SPO and user costs. Furthermore, 7Gb of frequently churning heap data will have significant GC CPU time costs and limit CPU parallelism scalability.

An on-disk table component provides table operations (LOOKUP, INSERT, DELETE etc.) and implements them in terms of disk I/O operations. The design and implementation of the on-disk table component determines the quantity of disk operations that can be expected for a given *workload* – i.e. the quantity and mix of table operations.

There is some sense of circularity to this problem: we want to establish requirements for the on-disk table component while leaving as much design flexibility as possible, but we also want to know that it is feasible to meet our business goals, which requires some assumptions about the performance of a hypothetical on-disk table component. In reality there is a clear trade-off in the design (and tuning) space for disk data structures (a point we will discuss further in Section 12.1). This means we can pick a point in the design space that suits our workload and memory constraints (while making other reasonable conservative assumptions) and be reasonably confident that it will be possible to realise an implementation for that point in the design space. We can then use the expected performance numbers for that point in the design space to check the feasibility of the performance requirements.

We can also evaluate multiple points in the design space. Such an assessment can tell us whether certain designs are feasible or necessary. For example it should be possible to determine if taking advantage of parallel I/O is necessary to meet some of the targets. This is very useful to avoid unnecessary development effort by using the simplest design that will meet the requirements.

The next three sections follow the the assessment method set out above. Readers interested in the conclusions but not the methodology can skip over Sections 11 and 12 and review the conclusions in Section 13.

In Section 11 we count the table operations that will be required, for both the UTxO table (as in the MVP) and for the stake-related tables. In Section 12 we review reasonable approximations of the cost of table operations in terms of I/O operations, and use that to establish an approximations the number of I/O operations required. In Section 13 we get to the conclusions: establishing which combinations of targets are feasible, a few design options that are necessary to achieve some of those combinations, and some design options we considered but discarded on performance grounds.

11 A quantitative assessment of the required table operations

11.1 Table operations required for the UTxO

Let us review the table operations arising from having just the UTxO on disk. This corresponds to the current MVP. The table operations arise from processing transactions, which modifies the UTxO, and from taking snapshots of the whole ledger state, which includes the UTxO.

As part of processing each (valid) transaction:

- tx inputs must be looked up in the UTxO;
- tx outputs must be added to the UTxO; and
- tx inputs must be deleted from the UTxO.

In addition, each time the consensus layer creates a checkpoint of the ledger state, it has to do a SNAPSHOT operation on the UTxO table.

For table operations, this gives us

- LOOKUP: 1 per tx input
- DELETE: 1 per tx input

- INSERT: 1 per tx output
- SNAPSHOT: 1 per checkpoint

In order to count all the operations on a common basis we will count operations per second – when running in real time rather than syncing. For operations that are not done on a per transaction basis, we will need appropriate factors to put them on a per-second basis. Our formula therefore requires parameters for tx inputs and outputs per second. We will use seconds per checkpoint, since checkpoints are infrequent.

Formula parameters:

- $|txin|$: the number of transaction inputs per second
- $|txout|$: the number of transaction outputs per second
- $|checkpoint|$: the number of seconds between checkpoints

The overall count of operations per second for the UTxO table is thus

$$\begin{aligned} & |txin|\ \text{LOOKUP}_{\text{utxo}} \\ + & |txin|\ \text{DELETE}_{\text{utxo}} \\ + & |txout|\ \text{INSERT}_{\text{utxo}} \\ + & \frac{1}{|checkpoint|}\ \text{SNAPSHOT}_{\text{utxo}} \end{aligned} \tag{1}$$

11.2 Table operations required for the stake related tables

Recall, from Section 5.1, that the list of stake-related mappings are:

1. a map of stake credential to delegation choice;
2. a map of stake credential to reward balance;
3. a map of stake credential to stake (i.e. the distribution by stake address);
4. snapshots of the three tables above; and
5. a map of stake credential to reward payout for the current epoch.

We will make a number of assumptions:

- that the stake distribution by stake credential is maintained by the continuous method (see Section 7.2);
- that the stake distribution by stake pool and by DRep is computed by the bulk method (see Section 7.4);
- that the bulk computation of the stake distribution by stake pool and by DRep is spread out evenly across the whole epoch;
- that reward account balances and the the UTxO stake distribution are kept separately (see Section 7.3);
- that although the computation of rewards is actually spread over $\frac{2}{5}$ of the epoch, we will approximate by pretending it is spread over the whole epoch. The assumption is that this makes an insignificant difference to peak I/O operations per second, and better reflects the aggregate I/O operations for the limiting syncing case.

Formula parameters

- $|txin|$: the number of transaction inputs per second
- $|txout|$: the number of transaction outputs per second
- $|checkpoint|$: the number of seconds between checkpoints
- $|register|$: the number of stake address registrations per second
- $|deregister|$: the number of stake address deregistrations per second
- $|delegate|$: the number of changes of stake address delegation per second
- $|withdraw|$: the number of reward withdrawals per second
- $|stake|$: the number of registered stake addresses
- *sync*: the synchronisation speed factor (i.e. with 1 being real time).

We use operations per second as the common basis, so to account for bulk operations that are spread out over the whole or part of the epoch, we also need a constant for the number of seconds per epoch:

- *epochsec*: the number of seconds per epoch: $60 \times 60 \times 24 \times 5 = 432000$.

Initially we will count operations per second for the system operating in real time, as opposed to when synchronising faster than real time. Thus we will omit the *sync* parameter for now, but it will be a common factor for every term.

We review the use of each of the mappings listed above.

1. The mapping of stake credential to delegation choice is consulted and updated when users register or deregister a stake address and when users change their delegation choice. The mapping needs to be scanned linearly twice per epoch to compute the stake distribution aggregated by stake pool.

$$\begin{aligned} & |register|\ \textsc{lookup}_{\text{stake}} \\ + & |register|\ \textsc{insert}_{\text{stake}} \\ + & |deregister|\ \textsc{lookup}_{\text{stake}} \\ + & |deregister|\ \textsc{delete}_{\text{stake}} \\ + & |delegate|\ \textsc{lookup}_{\text{stake}} \\ + & |delegate|\ \textsc{insert}_{\text{stake}} \\ + & \frac{2}{epochsec}\ \textsc{scan}_{\text{stake}} \end{aligned} \tag{2}$$

2. The mapping of stake credential to reward balance is updated when users register a stake address and is consulted and updated when users deregister a stake address, or withdraw rewards. The mapping needs to be scanned linearly once per epoch to compute the stake distribution aggregated by stake pool.

$$
\begin{aligned}
&|\mathit{register}|\ \textsc{insert}_{\text{stake}} \\
+\ &|\mathit{deregister}|\ \textsc{lookup}_{\text{stake}} \\
+\ &|\mathit{deregister}|\ \textsc{delete}_{\text{stake}} \\
+\ &|\mathit{withdraw}|\ \textsc{lookup}_{\text{stake}} \\
+\ &|\mathit{withdraw}|\ \textsc{insert}_{\text{stake}} \\
+\ &\frac{1}{\mathit{epochsec}}\ \textsc{scan}_{\text{stake}}
\end{aligned} \tag{3}
$$

3. The mapping of stake credential to stake needs to be updated when users register or deregister a stake address. It also needs to be updated for every input and output in each transaction. The mapping needs to be scanned linearly once per epoch to compute the stake distribution aggregated by stake pool.

$$
\begin{aligned}
&|\mathit{register}|\ \textsc{insert}_{\text{stake}} \\
+\ &|\mathit{deregister}|\ \textsc{delete}_{\text{stake}} \\
+\ &|\mathit{txin}|\ \textsc{update}_{\text{stake}} \\
+\ &|\mathit{txout}|\ \textsc{update}_{\text{stake}} \\
+\ &\frac{1}{\mathit{epochsec}}\ \textsc{scan}_{\text{stake}}
\end{aligned} \tag{4}
$$

4. The three snapshot tables will be constructed once each per epoch.

$$
\frac{3}{\mathit{epochsec}}\ \textsc{snapshot}_{\text{stake}} \tag{5}
$$

5. The mapping of stake credential to reward payout is updated while aggregating the rewards for the epoch. It will require an update for each registered stake address each epoch. It also needs to be merged into the mapping of stake credential to reward balance on the epoch boundary.

$$
\begin{aligned}
&\frac{|\mathit{stake}|}{\mathit{epochsec}}\ \textsc{update}_{\text{stake}} \\
+\ &\frac{1}{\mathit{epochsec}}\ \textsc{merge}_{\text{stake}}
\end{aligned} \tag{6}
$$

11.3 Total table operations required

Combining the operation counts for both the UTxO and the stake-related tables gives us the following formula.

$$\begin{aligned}
&|txin|\ \textsc{lookup}_{\text{utxo}} \\
+\ &|txin|\ \textsc{delete}_{\text{utxo}} \\
+\ &|txout|\ \textsc{insert}_{\text{utxo}} \\
+\ &(|txin| + |txout|)\ \textsc{update}_{\text{stake}}
\end{aligned} \tag{7}$$

$$\begin{aligned}
+\ &\frac{|stake|}{epochsec}\ \textsc{update}_{\text{stake}} \\
+\ &\frac{4}{epochsec}\ \textsc{scan}_{\text{stake}}
\end{aligned} \tag{8}$$

$$\begin{aligned}
+\ &(|register| + 2|deregister| + |delegate| + |withdraw|)\ \textsc{lookup}_{\text{stake}} \\
+\ &(3|register| + |delegate| + |withdraw|)\ \textsc{insert}_{\text{stake}} \\
+\ &3|deregister|\ \textsc{delete}_{\text{stake}}
\end{aligned} \tag{9}$$

$$\begin{aligned}
+\ &\frac{1}{|checkpoint}|\ \textsc{snapshot}_{\text{utxo}} \\
+\ &\frac{3}{epochsec}\ \textsc{snapshot}_{\text{stake}} \\
+\ &\frac{1}{epochsec}\ \textsc{merge}_{\text{stake}}
\end{aligned} \tag{10}$$

To make sense of this formula there are several points to keep in mind.

- The number of transaction inputs and outputs is expected to be large in comparison to the number of stake address (de)registrations and changes of delegation choice.
- Reward withdrawals are expected to be relatively infrequent compared to transaction inputs, though more frequent than other stake address operations. In some sense they can be bundled with transaction inputs since they have the same cost (a LOOKUP and an INSERT), and are semantically similar alternatives to each other.
- For a 'back of the envelope' approximation we can therefore ignore the cost contribution of Equation (9).
- The formula does not directly express an overall cost, because the cost is expressed in terms of I/O operations and that depends on the disk data structure design. The formula does however tell us something about cost if we make plausible assumptions about the disk data structure.
- We have already established in Sections 7.5 and 7.7 that the SNAPSHOT and MERGE operations must have at most $\mathcal{O}(\log n)$ cost to avoid unacceptable stalls. We can therefore ignore the cost contribution of Equation (10).
- Thus for a 'back of the envelope' approximation we need only consider Equations (7) and (8).

Overall this confirms the intuition that the UTxO lookups of transaction inputs is the dominant cost, with the major secondary costs being to update the UTxO and the stake distribution, plus some linear scans of the stake-related tables.

12 A quantitative assessment of the required I/O operations

12.1 The choice of read-optimised or write-optimised disk data structures

In the design of disk data structures, there is a trade-off between the performance of read operations (e.g. LOOKUP), the performance of update operations (e.g. INSERT and DELETE), and the amount of main memory required. Athanassoulis et al. [2016] provide a detailed discussion of this trade-off, which they describe as the 'RUM conjecture' (RUM for Read, Update, Memory). Specifically, the RUM conjecture is that one can optimise for two of the aspects, at the cost of the third aspect.

This trade-off gives rise to three main classes of disk data structure: *read optimised*, *write optimised* and *space optimised*. These designs optimise towards minimising the cost of one aspect at the expense of higher cost of one or both of the other aspects. The choice of which class to use depends on the workload and memory constraints. For read heavy workloads, the overall cost is lower when using a read-optimised design, and similarly write heavy workloads will have a lower cost when using a write-optimised design.

When selecting a disk data structure, in addition to understanding the workload it is important to keep in mind the amount of memory that can be made available. The RUM conjecture is that one can optimise for *two* of the three aspects. In particular, in principle one can get good read and write performance at the cost of using plenty of memory. The amount of memory should be understood relative to the size of the data to be stored.

Recall the data size and memory requirements from Tables 1 and 4: the biggest table is the UTxO table at up to 100 million entries for the stretch target, and 2Gb for the stretch target for memory. Of course the memory constraint is for the whole node, so the memory available for individual tables must be considerably less: on the order of a few 100s of megabytes. If we were to use around 100Mb–200Mb of memory for a table with 100 million entries, this gives us around 8–16 bits of memory per key. Perhaps somewhat surprisingly, this puts us into the category of a relatively memory-rich database (though obviously it is not enough to use an in-memory design). We can use this to our advantage, for example to mitigate the cost of reads in a write-optimised disk data structure.

12.2 Approximate I/O operations for read-optimised disk tables

For read-optimised disk data structure a very common choice are B+ trees. For example these are what are used by LMDB, and the default table types for PostgreSQL and SQLite. B+ trees are widely branching trees, with the size of the tree nodes designed to fit the disk page size (typically 4k). The leaf nodes contain key value pairs and the interior nodes contain key ranges.

For table such as the UTxO with our target of 100 million entries, we must assume that the last level of the tree cannot fit into memory. We can however optimistically assume that all but the last level of the tree *can* fit in memory. For 100 million entries with 34 byte keys and 60 byte values, the interior node of the tree would take on the order of 150 Mb of memory, which is reasonable given our overall memory targets of 2-8Gb (see Table 4). Given these assumptions, a LOOKUP will need one random disk page read.

The algorithm to modify the B+ tree has to modify a node at each tree level up to the root. If all but the last level of the tree are cached in memory then typically only one disk page will need to be written[6] (either a new page for a copy-on-write (COW) design or modifying an existing page for an in-place update design). It will also require reading the disk page that is to be modified, to include all the other unchanged table entries on the target page. Thus, with these assumptions,

[6]This assumes no prompt durability, which indeed we do not need.

an INSERT or DELETE will need one random disk read and one disk write (either a random write for an in-place update design or a sequential write for a COW design).

In short, a reasonable approximation is that for the largest table (the UTxO) the LOOKUP operation would cost 1 I/O operation, and that the INSERT and DELETE operations will each cost 2 I/O operations (which are sequentially dependent). The cost for other smaller tables could be less.

Standard B+ trees[7] do not support an efficient UPDATE: it requires a lookup followed by an insert. The page read for the insert can be reused for the insert, so the UPDATE will cost 2 I/O operations.

A linear scan of a B+ tree involves traversing every leaf node. The IO cost of this depends on the number of key value pairs that can be stored in each node. Each key value pair is however only in one page, so there is very little read amplification: only that caused by per-node representation overheads and underfull nodes. We can approximate the SCAN I/O operation cost by the number of key value pairs in the table times the key value pairs per disk page size, divided by 0.75 to account for nodes being $\frac{3}{4}$ full on average.

In short, a reasonable approximation (for a table with the properties of the UTxO) is as follows:

$$\begin{aligned} \text{LOOKUP} &= 1 \quad \text{I/O ops} \\ \text{INSERT} &= 2 \quad \text{I/O ops} \\ \text{DELETE} &= 2 \quad \text{I/O ops} \\ \text{UPDATE} &= 2 \quad \text{I/O ops} \\ \text{SCAN} &= \frac{4}{3}\ \text{tableentries}\ \frac{\text{entrybytes}}{\text{pagebytes}} \quad \text{I/O ops} \end{aligned} \tag{11}$$

The cost for other smaller tables could be less, but we will use this as an approximation.

12.3 Approximate I/O operations for write-optimised disk tables

A common choice for write-optimised disk data structures are log structured merge (LSM) trees. These are used for example by Cassandra, by LevelDB and its derivative RocksDB. LSMs use multiple sorted runs of key-value pairs, with updates being written sequentially to new runs, and older runs are merged from time to time. This minimises the cost of writing updates, with the trade-off that lookups may have to probe multiple runs. With enough memory, the lookup cost can be mitigated by using large Bloom filters to avoid probing most runs most of the time.

The algorithm to look up a key involves consulting the in-memory Bloom filter for every run, and then – for those runs in which the Bloom filter indicates that the key may be found – using an in-memory index to find the disk page containing the key value pair, which is then read. Assuming no caching of the runs themselves, the I/O cost of a lookup is one plus the false positive rate for the Bloom filters combined. For a table of 100 million 100 byte entries, a cumulative size of 150Mb for Bloom filters could give false positive rates as low as 1-2%. The false positive rate is very sensitive to the Bloom filters size, for example at 100Mb the rate could be around 20% while for 200Mb the rate could be less than 0.5%. Fortunately, the order of magnitude of the memory size is very reasonable for our targets (UTxO size and memory available).

The algorithm to insert or delete an entry is initially to append a record of the insertion or deletion into an in-memory buffer. When this buffer grows large enough, it is written to disk as

[7] By contrast, B^ϵ do support efficient UPDATE but, perhaps unsurprisingly, B^ϵ are a write-optimised variation of the general B+ tree idea.

a new sorted run. This in turn will eventually trigger other runs to be merged together. Since many updates can be included into a single disk page (assuming smaller key value pairs), the cost per insert or delete operation can be well less than a single disk write, though the cost of merging runs later will multiply this by a small factor. The overall cost of updates in terms of I/O operations is not trivial to calculate. Dayan et al. [2017] provide the calculation, and a helpful online calculator[8]. This suggests that well-tuned state-of-the-art[9] LSMs could achieve updates costing approximately 0.1 I/O operations for a table of 100 million 100 byte entries.

LSM trees can also support and efficient UPDATE operation: the operation is appended to the in-memory buffer in the usual way. When merging runs, any matching values are combined using the table's monoidal operator. This means the cost of UPDATE can be approximately the same as for INSERT or DELETE.

A linear scan of a LSM tree involves merging every run and resolving updates such as inserts and deletes. This of course requires reading the disk pages for every run. Due to the delayed resolution of updates during run merges, the total size of all the runs is larger than the size of the logical data in the table. How much so depends on the LSM merge strategy. For the parameters used to get the I/O operations numbers above (tiering with size ratio of 4), this would result in the physical size being around 1.3× to 1.4× the logical size. Thus we can approximate the SCAN I/O operations cost by the number of key value pairs per disk page size, times 1.4.

In short, a reasonable approximation (for a table with the properties of the UTxO) is as follows:

$$
\begin{aligned}
\textsc{lookup} &= (1+\epsilon) \quad \text{I/O ops} \\
\textsc{insert} &= 0.1 \quad \text{I/O ops} \\
\textsc{delete} &= 0.1 \quad \text{I/O ops} \\
\textsc{update} &= 0.1 \quad \text{I/O ops} \\
\textsc{scan} &= 1.4 \quad \text{tableentries} \, \frac{\text{entrybytes}}{\text{pagebytes}} \quad \text{I/O ops}
\end{aligned}
\tag{12}
$$

The cost for other smaller tables could be less, but we will use this as an approximation. For numerical evaluation, will assume that $\epsilon = 0.02$, i.e. 2%.

12.4 Data access locality, or the lack thereof

One of the assumptions about the cost of table operations in I/O operations in the previous two sections is that main memory is only used for data structures such as indexes (like the B+ tree interior nodes), and not for any of the values in the tables. One might reasonably wonder if additional memory could be used effectively to cache some of the values in the table, perhaps the most frequently used ones.

As discussed in the original design document, Wilson and Coutts [April 2021] in Sections 5.2 and 5.3, the data access pattern for the UTxO has very little useful locality and thus there is little opportunity to cache data in memory. The summary reasons for this are that the keys are random (as they are cryptographic hashes) and there is relatively weak time-based locality. There is a weak effect that younger UTxO entries are more likely to be used, but this effect is not nearly strong enough to make good use of extra memory as a cache.

For the stake related tables, the situation is similar. They are also keyed on cryptographic hashes. There may be a somewhat stronger time-based locality for stake addresses than for

[8] `http://daslab.seas.harvard.edu/monkey/`

[9] The paper provides an improvement in the false positive rate, and thus lookup cost, compared to the contemporary state of the art.

UTxO entries: some wallets are likely to be much more active than others. As discussed in Section 7.4, it appears unlikely that this effect is strong enough to be useful for a caching strategy.

It is also safer for the long term to make worst-case assumptions about user behaviour. Thus for assessing I/O cost feasibility we do not assume any caching.

12.5 Approximate I/O operations per second (IOPS) required for real time

Following our methodology from Section 10: we need to cast our table operation counts in terms of I/O operations per second. We also need to base it on the parameters relevant for our performance targets: TPS, number of registered stake addresses and synchronisation speed.

Recall from Section 11.3, that we can approximate the count of table operations per second using Equations (7) and (8):

$$\begin{aligned}
& |txin|\ \text{LOOKUP}_{\text{utxo}} \\
+\ & |txin|\ \text{DELETE}_{\text{utxo}} \\
+\ & |txout|\ \text{INSERT}_{\text{utxo}} \\
+\ & (|txin| + |txout|)\ \text{UPDATE}_{\text{stake}} \\
+\ & \frac{|stake|}{epochsec}\ \text{UPDATE}_{\text{stake}} \\
+\ & \frac{4}{epochsec}\ \text{SCAN}_{\text{stake}}
\end{aligned}$$

We can recast the parameters $|txin|$ and $|txout|$ in terms of the TPS, given our standard assumption that TPS refers to small transactions with 2 inputs and 2 outputs:

$$|txin| = |txout| = 2\ tps$$

We can also recast this in terms of I/O operations per second for a read or write optimised design, using Equations (11) and (12). For the read-optimised case we get

$$\begin{aligned}
& 1 \times 2\ tps \\
+\ & 2 \times 2\ tps \\
+\ & 2 \times 2\ tps \\
+\ & 2 \times 4\ tps \\
+\ & 2 \times \frac{|stake|}{epochsec} \\
+\ & \frac{4}{epochsec} \times \frac{4}{3}\frac{|stake|}{40}
\end{aligned} \quad = \quad 18\ tps + \frac{2.13|stake|}{epochsec} \quad \text{IOPS} \tag{13}$$

while the write-optimised case is

$$\begin{aligned}
& 1 \times 2\ tps \\
+\ & 0.1 \times 2\ tps \\
+\ & 0.1 \times 2\ tps \\
+\ & 0.1 \times 4\ tps \\
+\ & 0.1 \times \frac{|stake|}{epochsec} \\
+\ & \frac{4}{epochsec} \times 1.4\frac{|stake|}{40}
\end{aligned} \quad = \quad 2.8\ tps + \frac{0.24|stake|}{epochsec} \quad \text{IOPS} \tag{14}$$

As expected, the write-optimised approach is strictly better than the read-optimised approach for this workload. We will see in Section 13 that this is significant in that it makes the difference between feasible and infeasible for some combinations of targets.

12.6 Approximate I/O operations per second (IOPS) required while syncing

When synchronising the chain, the same work to validate the chain has to be done, but ideally much faster. So the synchronisation speed is a simple factor for the IOPS.

The IOPS for the read-optimised and write-optimised cases are thus

$$sync\left(18\ tps + \frac{2.13|stake|}{epochsec}\right) \quad \text{IOPS} \tag{15}$$

$$sync\left(2.8\ tps + \frac{0.24|stake|}{epochsec}\right) \quad \text{IOPS} \tag{16}$$

Thus the need to synchronise the chain 2 to 3 orders of magnitude faster than real time has a directly corresponding orders-of-magnitude effect on the number of IOPS required. As we shall see, this pushes us up against the limits of I/O hardware capabilities.

13 I/O performance (in)feasibility

Following our methodology from Section 10: having established the approximate number of I/O operations per second (IOPS) that we require, we now check if this is within the performance capabilities of the minimum disk hardware.

In this section we make frequent use of the term *feasible* but it should more properly be understood as *not obviously infeasible* or *plausibly feasible*. The analysis really tells us what is *not* possible because it violates constraints. The analysis does not take into account the details and overheads involved in a full implementation so it cannot be seen as a guarantee that a full implementation meeting certain targets is actually possible. Nevertheless, it is a useful indication.

We evaluate the IOPS required – Equations (15) and (16) above – for multiple combinations of our performance targets. In particular we use the targets for the number of registered stake addresses (Table 1), TPS (Table 2), and synchronisation speed (Table 3). The results are presented in Tables 9 and 10 for the read and write-optimised cases respectively, and re-presented in the form of a bar chart in Figure 1.

The summary conclusions are as follows.

- The threshold targets are *feasible* with the minimum SSD hardware requirement when using the SSD serially (assuming no other bottlenecks), but only for a write-optimised design.
- The middle targets are certainly *infeasible* when using the SSD serially. This is the case for the minimum SSD hardware requirement, but also the case for high-performance SSDs.
- The middle targets are *feasible* with the minimum SSD hardware requirement when using the SSD with maximum I/O parallelism, but only for a write-optimised design.
- the stretch targets are *infeasible* with the minimum SSD hardware requirement, but are *feasible* with high-performance SSDs when using maximum I/O parallelism and a write-optimised design.
- A read-optimised design is *infeasible* for most combinations of targets. It is only *feasible* for the threshold targets only when using parallel I/O.

TPS	Stake addrs	Sync speed	IOPS	≤10k	≤100k	≤1M
threshold: 20 TPS	threshold: 2M	threshold: 100×	37.0k	✖	✔	✔
middle: 50 TPS	middle: 10M	threshold: 100×	95.0k	✖	✔	✔
threshold: 20 TPS	threshold: 2M	stretch: 1000×	370.0k	✖	✖	✔
middle: 50 TPS	middle: 10M	stretch: 1000×	949.3k	✖	✖	✔
stretch: 200 TPS	stretch: 20M	stretch: 1000×	3,699.0k	✖	✖	✖

Table 9: I/O performance feasibility for a read-optimised data store

TPS	Stake addrs	Sync speed	IOPS	≤10k	≤100k	≤1M
threshold: 20 TPS	threshold: 2M	threshold: 100×	5.7k	✔	✔	✔
middle: 50 TPS	middle: 10M	threshold: 100×	14.6k	✖	✔	✔
threshold: 20 TPS	threshold: 2M	stretch: 1000×	57.1k	✖	✔	✔
middle: 50 TPS	middle: 10M	stretch: 1000×	145.6k	✖	✖	✔
stretch: 200 TPS	stretch: 20M	stretch: 1000×	571.1k	✖	✖	✔

Table 10: I/O performance feasibility for a write-optimised data store

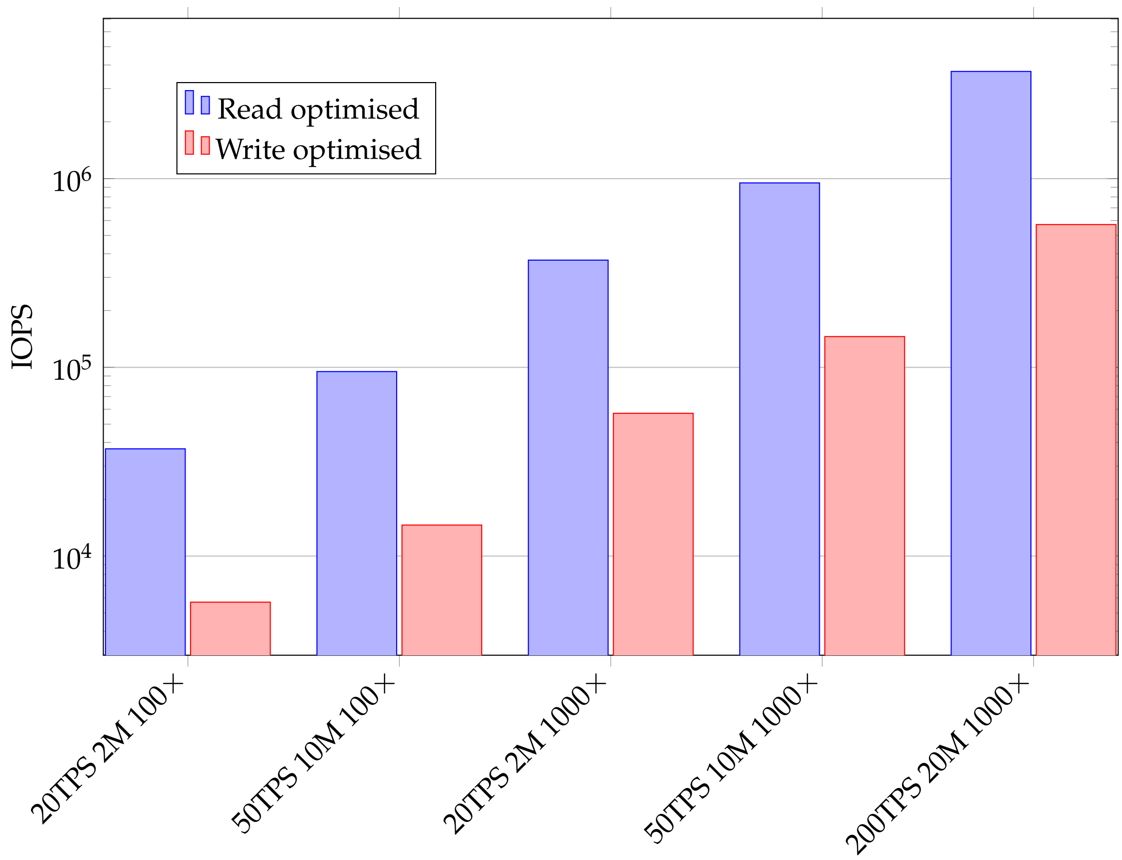


Figure 1: I/O performance feasibility for a read and write-optimised data store

Some explanation of Tables 9 and 10 is in order:

- The first three columns are the targets for TPS, number of stake addresses and synchronisation speed. We use the threshold, middle and stretch targets for TPS (20, 50 and 200), and for stake addresses (2M, 10M, 20M) and we use the threshold and stretch targets for synchronisation speed (100× and 1000×).
- The IOPS column is the number of I/O operations per second required to be able to meet the given combination of targets. These values are the result of evaluating Equations (15) and (16) for the given combination of targets.
- The final three columns indicate whether the required IOPS are within the capabilities of the hardware, for three capability levels:
  - 10k IOPS: the minimum hardware requirement when using serial I/O.
  - 100k IOPS: the minimum hardware requirement when using parallel I/O.
  - 1M IOPS: the capability of state-of-the-art high end SSDs.
- Note that the last column is well beyond our minimum hardware requirements from Table 5 – indeed 10× beyond – but it gives an indication of the headroom to scale with future or server-class hardware.

An alternative presentation of the same data is given in Figure 1. Note in particular that this uses a log axis. Coincidentally the hardware IOPS limits we are interested in correspond to the log axis major grid lines of 10^4, 10^5 and 10^6 respectively, so it is straightforward to see how the IOPS required compares to the IOPS available.

13.1 SSD performance

To assess feasibility we need a sense of typical SSD performance. This is also needed to assess if the minimum hardware requirements (from Table 5) are reasonable.

In addition to SSDs, we will include the performance of spinning disks but only to illustrate that their performance is so poor as to be out of the question.

To make things concrete we look at the example of Samsung SSDs. Samsung manufacture a range of medium to high performance consumer and server SSDs. They helpfully publish rated performance numbers including low and high queue depth. We select a vaguely representative sample of their range, picking 500GB models where possible. For our spinning disk comparison we select a couple models from Western Digital. Western Digital do not consistently publish performance numbers for their disk drives, so some numbers below are taken from 3rd party reviews, or are omitted entirely.

Model	Capacity	Interface type	Comment
WD Blue	1TB	SATA	Mainstream, low cost spinning disk
WD Black	1TB	SATA	‘High performance’ spinning disk
870 QVO	1TB	SATA	Latest gen, high capacity, lower performance
860 PRO	512GB	SATA	Previous gen high performance SATA
960 EVO	512GB	NVMe PCIe 3	Previous gen high performance NVMe
970 EVO Plus	500GB	NVMe PCIe 3	Current gen high performance NVMe
980 PRO	500GB	NVMe PCIe 4	Current gen ultra-high performance NVMe

The random read performance is given at “queue depth 1” and at “queue depth 32”. Queue depth 1 means issuing all I/O operations serially, whereas a high queue depth implies continuously issuing many I/O operations in parallel, so that the hardware it given 32 operations to do at any one time.

Model	4k reads at QD1	4k reads at QD32	QD32 speedup
WD Blue	–	128 IOPS	–
WB Black	200 IOPS	500 IOPS	2.5×
870 QVO	11,000 IOPS	98,000 IOPS	9×
860 PRO	11,000 IOPS	100,000 IOPS	9×
960 EVO	14,000 IOPS	330,000 IOPS	23×
970 EVO Plus	19,000 IOPS	480,000 IOPS	25×
980 PRO	22,000 IOPS	800,000 IOPS	35×

On the write side, some on-disk data structures are sensitive to random writes, while others rely on sequential writes. The WD Blue model is omitted as the numbers are not readily available.

Model	4k writes at QD1	4k writes at QD32	sequential writes
WB Black	450 IOPS	460 IOPS	176 MB/s
870 QVO	35,000 IOPS	88,000 IOPS	530 MB/s
860 PRO	43,000 IOPS	90,000 IOPS	530 MB/s
960 EVO	50,000 IOPS	330,000 IOPS	1,800 MB/s
970 EVO Plus	60,000 IOPS	550,000 IOPS	3,200 MB/s
980 PRO	60,000 IOPS	1,000,000 IOPS	5,000 MB/s

There are a number of things to note:

- Many of these are relatively high end and expensive SSDs (which in turn require relatively high performance and expensive desktop or server platforms). Minimum system requirements can only be at the lower end of this range.
- There is huge difference between serial and parallel performance: typically a factor of 10 to 20 times.
- Read performance at queue depth 1 has only slightly improved over time.
- Read performance at high queue depths continues to improve from one generation to the next.
- Sequential write performance is even higher than random 4k writes at high queue depth, typically by an extra 40–50%.
- Spinning hard drives have extremely low random access performance, though moderate sequential performance.

Real world performance numbers are less than the manufacturer rated numbers, once practical details like file systems and OS I/O APIs are taken into account. The author has benchmarked a Samsung 960 EVO 250GB model under Linux using the ext4 file system on an encrypted block device, using the `fio` benchmarking tool. While rated by the manufacturer at 330k IOPS for random reads at QD32, the `fio` benchmark shows that at QD32 it achieves around 220k IOPS.

In conclusion, the minimum hardware requirement from Table 5 are reasonable. They are at the lower end of the current generation of SSDs.

13.2 AWS cost of memory vs. IOPS

Most SPOs run their nodes using cloud VM instances or rented physical machines. Not all such instances have access to high IOPS SSDs, so the question arises: is it cheaper to use RAM to keep data in memory, or cheaper to use high IOPS and keep data on disk. We will look at this question in the context of AWS as it is one of the major providers of cloud VMs.

AWS provides hundreds of different types of VM instance, all with different characteristics and price. These instance types provide two main kinds of disk access: all instances support networked EBS volumes, and some have local SSDs (of which some are NVMe while others are older technology). AWS publishes IOPS figures for EBS volumes but not for local SSDs – presumably because it depends on the OS the user chooses. We have not benchmarked any AWS instances for this report but we will assume that the local SSDs marketed as "NVMe" will achieve over 100k IOPS, while we will assume the non-NVMe SSDs achieve less than 100k IOPS – as they are presumably SATA drives.

The cost of EBS volumes with high IOPS is very significant. The cheapest EBS option is the 'gp2' volume type, but it tops out at 16k IOPS. The high performance option is the 'io2' volume type which can provision higher IOPS, but at significant cost. The table below is the current cost for these two EBS volume types.

	EBS 'gp2' $/month	EBS 'io2' $/month
128 GB storage	$ 10	$ 16
3k IOPS	$ 0	$ 195
16k IOPS	$ 80	$ 1,040
32k IOPS	—	$ 2,080
64k IOPS	—	$ 3,552
128k IOPS	—	$ 5,600

By contrast, the cost of AWS instance types with small local SSDs is not significantly more than equivalent EBS-only instances, though the choice of instances with local SSDs is limited. To answer the question of cost of memory vs disk, we should look at the instance types with the cheapest memory, and the cheapest[10] instance types with local NVMe SSDs:

AWS instance	Arch	vCPUs	RAM	Local SSD storage	$/month
x2gd.large	Arm	2	32 GiB	118 GiB NVMe	$120.24
x2gd.xlarge	Arm	4	64 GiB	237 GiB NVMe	$240.48
r6a.xlarge	x86-64	4	32 GiB	EBS Only	$163.30
r6a.2xlarge	x86-64	8	64 GiB	EBS Only	$326.59
m6gd.medium	Arm	1	4 GiB	59 GiB NVMe	$32.54
m6gd.large	Arm	2	8 GiB	118 GiB NVMe	$65.09
m5ad.large	x86-64	2	8 GiB	75 GiB NVMe	$74.16

The first group of instances are the 'cheap memory' ones, assuming the ledger state will fit within 32 or 64 GiB, while the second group are the 'cheap local SSD' options. It is clear that the cheaper option is storing the data on disk than in memory.

Note that each of these instances would also need an EBS volume for non-ledger storage, but these could be the cheaper 'gp2' volumes, without special IOPS requirements. Note that the Arm based instance types are cheaper, but it will take some more time before the node can be fully validated on Arm. So these are indicative of future lower cost options.

13.3 The need for a write-optimised backend

It is clear from Tables 9 and 10 and Figure 1 that a write-optimised disk data structure is necessary to achieve most of the performance targets. Given the write-heavy workload of the

[10] There are hundreds of AWS instance types, with new ones added frequently so it is hard to be sure that the examples chosen are the cheapest available. Consider them as indicative.

UTxO table, it is not surprising that a write-optimised disk data structure will perform better, but the numbers make clear that (when synchronising) this performance advantage is necessary to fit within the hardware constraints.

The original report, Wilson and Coutts [April 2021] Section 8, discusses the primary choices of on-disk data structure: B+ trees (such as LMDB) which are not write-optimised, and LSM trees which are write-optimised. It recommends an initial integration with an existing B+ tree implementation, and recommends an LSM tree implementation to meet the performance targets in the longer term. The original analysis remains valid. A write-optimised disk data structure is necessary to achieve more than the threshold performance targets, and an LSM is a good choice for such a data structure.

13.4 The need for parallel I/O

It is also clear from Tables 9 and 10 and Figure 1 that using parallel I/O is necessary to achieve more than the threshold targets.

The implication for the project is that disk backends, such as LMDB, that use only serial I/O cannot achieve more than the threshold targets, and that to achieve the middle or stretch targets requires a disk backend that can use parallel I/O to effectively take advantage of modern SSDs. Furthermore, a disk backend using parallel I/O effectively may be able to hit the stretch targets, but only when used with higher performance SSD hardware.

This is the same conclusion of the original report, see Wilson and Coutts [April 2021] Sections 5.7, 6.1, 8.1, 8.3 and 9.

13.5 The need for monoidal updates

As discussed in Section 7.2, the operations the ledger needs to perform could make good use of an UPDATE operation, and some write-optimised disk data structures can support UPDATE more efficiently than the combination of a LOOKUP and INSERT.

The question is if this feature is necessary to achieve performance targets. The answer is yes it is necessary, and we can use our quantitative method to demonstrate it.

Recall that starting with Equations (7) and (8) we derived the IOPS cost for the write-optimised case, as Equation (16):

$$sync\left(2.8\ tps + \frac{0.24|stake|}{epochsec}\right) \quad \text{IOPS}$$

This derivation was based on the assumption from Equation (12) that the UPDATE would cost 0.1 IOPS. If we assume instead that UPDATE costs the same as a LOOKUP plus an INSERT then it will cost 1.1 IOPS. With this assumption we would derive the total IOPS cost to be

$$sync\left(6.8\ tps + \frac{1.24|stake|}{epochsec}\right) \quad \text{IOPS}$$

Evaluating these and comparing them in Figure 2, we can see that the lack of an efficient UPDATE not only makes a significant difference, but it makes the difference between hitting or missing targets. Note again that this uses a log axis, so the modest visual differences are large numeric differences.

13.6 The need for other special operations

The existing MVP design makes use of a SNAPSHOT operation, used as part of checkpointing the whole chain and ledger state. The full design with all the stake related tables will have

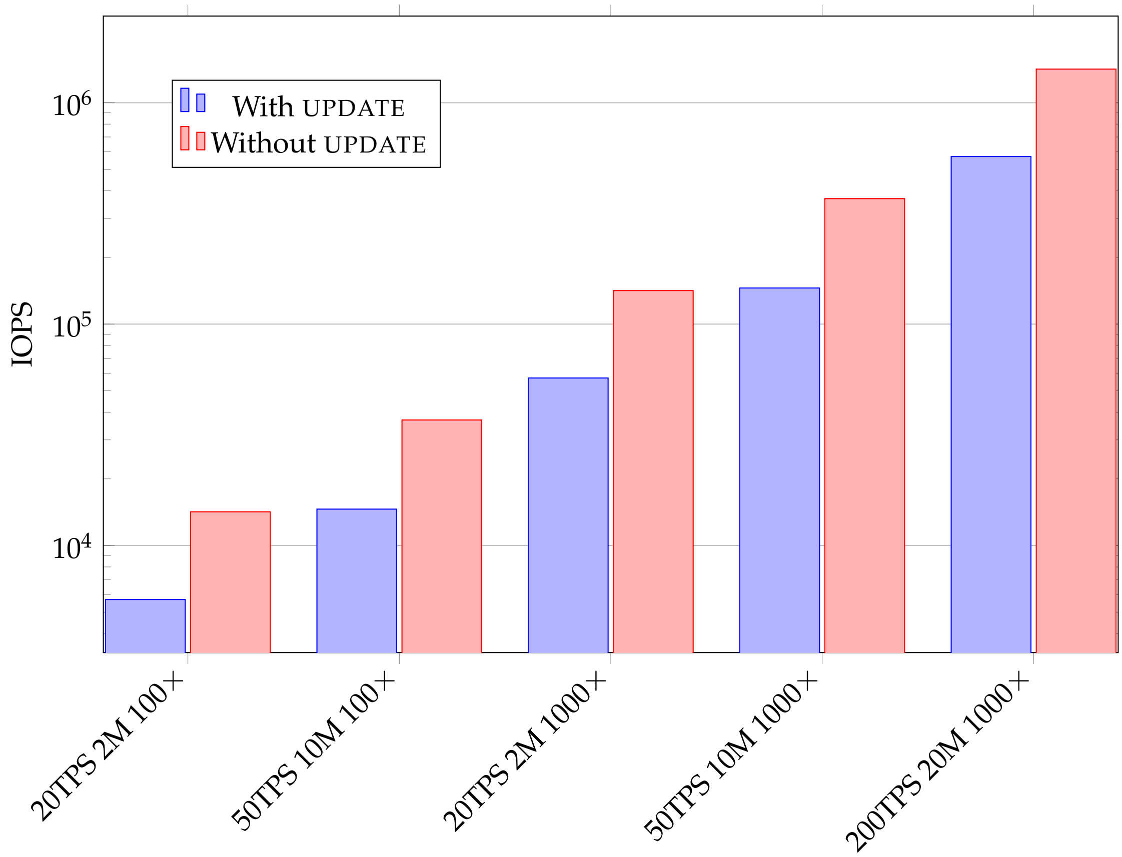


Figure 2: I/O performance with and without an efficient UPDATE operation

additional uses for the SNAPSHOT operation, and additional timing constraints. We established in Section 7.5 that the SNAPSHOT operation must have $\mathcal{O}(\log n)$ cost because any higher cost would cause unacceptable stalls in the operation of the system.

In Section 7.7 we discussed the hard problem of updating the reward account balances at the epoch boundary without causing stalls. The best design idea we have is to require a MERGE operation, which must have at most $\mathcal{O}(\log n)$ cost to avoid unacceptable stalls.

13.7 Infeasibility of using the existing LMDB backend

We have established that to meet performance targets, we need:

- a write-optimised data store,
- good support for parallel I/O,
- support for monoidal updates,
- support for an $\mathcal{O}(\log n)$ SNAPSHOT operation, and
- support for an $\mathcal{O}(\log n)$ MERGE operations.

The LMDB backend has *none* of these characteristics, and is thus not a suitable choice.

Note that in principle, the LMDB library has some support for parallel I/O via its support for concurrent clients operating on independent transactions. Unfortunately this does not fit well with our use case of a single client that wants to perform batches of lookups in parallel. The backend using LMDB could be adapted to use multiple OS threads with an LMDB transaction for each thread and to perform lookups from each thread, but at quite a high implementation complexity cost. This would scale I/O performance to some degree but the overheads of spreading out the requests and collecting the results from the many threads would limit the improvement. The overheads would be proportionally worse for SSDs with higher IOPS, since the overhead per operation is fixed.

It may be helpful to get an intuition of why the LMDB backend was a suitable choice for a MVP, but cannot be a suitable choice for a full implementation that meets the performance targets from the business requirements.

The size of the UTxO is currently well below the minimum target. Furthermore, the node process is being run on host machines that have plenty of RAM. This combination means that the disk files that make up the UTxO table can be kept wholly in RAM (in the OS page cache), and thus no I/O is needed to perform lookups. The use of the OS page cache does not show up in the measurement of the memory used by the node process, but it is essential for the current good I/O performance. As the UTxO grows, or if the node is run on a machine with less memory, then inevitably the UTxO will no longer fit into the page cache. At this point, the I/O bottleneck will limit performance, as discussed earlier in this section. In particular, the LMDB backend will be limited to the serial I/O limit of SSDs, unless it can be modified to partially take advantage of parallel I/O as described above.

In summary, the LMDB backend can meet the current needs of the chain only because those current needs are well below the minimum targets from the business requirements.

13.8 Table operations and IOPS for other alternative design choices

We have already looked at whether we need a write-optimised design, parallel I/O, and monoidal updates – and it turns out that we need all of them! There are some other design decisions we have mentioned in previous sections that we can evaluate in the same quantitative manner.

13.8.1 Maintaining the stake distribution by stake address

In Section 7.2 we considered two methods of maintaining the stake distribution by stake address: the continuous or bulk method. The continuous method involves one UPDATE operation for each transaction input and output.

$$\begin{aligned} &|txin| \ \text{UPDATE}_{\text{stake}} \\ + &|txout| \ \text{UPDATE}_{\text{stake}} \end{aligned} \tag{17}$$

The bulk method involves a linear scan of the UTxO snapshot, accumulating and aggregating into a target table keyed on the stake credential.

$$\begin{aligned} &\text{SNAPSHOT}_{\text{utxo}} \\ + &\frac{1}{epochsec}\text{SCAN}_{\text{stake}} \\ + &\frac{|stake|}{epochsec}\ \text{UPDATE}_{\text{stake}} \end{aligned} \tag{18}$$

Using these as modifications to the overall operation counts, and then using the I/O cost for a write-optimised design we can re-derive the cost in IOPS. The continuous method is our default design option so we get the same formula as Equation (16)

$$sync\left(2.8\ tps + \frac{0.24|stake|}{epochsec}\right) \quad \text{IOPS}$$

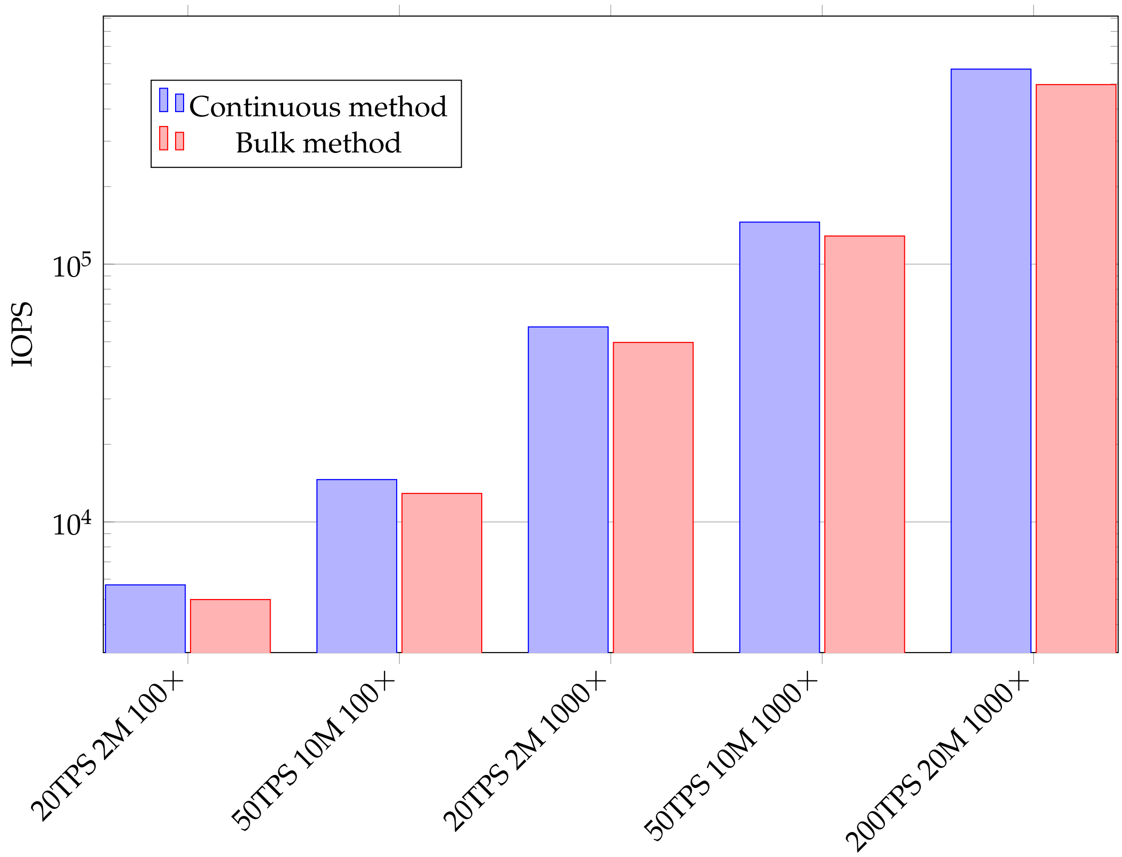


Figure 3: I/O performance for methods of maintaining the stake distribution by stake address

or for the bulk method we get

$$sync \left(2.4 \; tps + \frac{0.375 |stake|}{epochsec} \right) \quad \text{IOPS}$$

As we would expect, this has a lower factor for TPS but a higher factor for the number of stake addresses.

Evaluating these and comparing them in Figure 3, we see that the bulk method does result in fewer IOPS, but that overall the difference is not very significant. It seems reasonable therefore to decide on the basis of code complexity rather than IOPS cost.

13.8.2 Maintaining the stake distribution by stake pool or DRep

In Section 7.4 we considered two methods of maintaining the stake distribution by stake pool (or equivalently by DRep): the continuous or bulk method. The continuous method would extend the continuous method for maintaining the stake distribution by stake address: where additionally each input and output stake credential must be looked up in the mapping of stake credential to delegation choice. Counting only the additional operations, this gives us

$$\begin{aligned} & |txin| \; \text{LOOKUP}_{\text{stake}} \\ + & |txout| \; \text{LOOKUP}_{\text{stake}} \end{aligned} \tag{19}$$

The bulk method involves a scan of the mapping of stake credential to stake and of the mapping of stake credential to delegation choice.

$$\frac{2}{epochsec} \; \text{SCAN}_{\text{stake}} \tag{20}$$

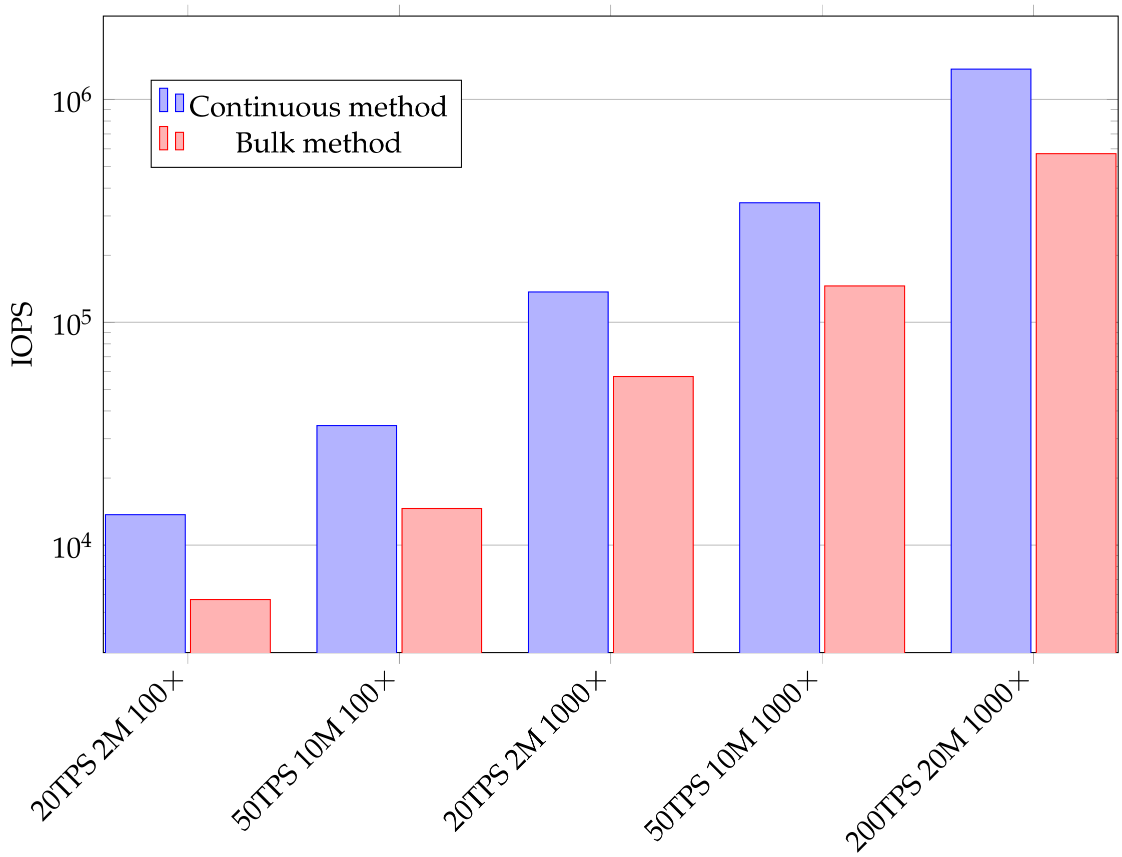


Figure 4: I/O performance for methods of maintaining the stake distribution by DRep

Using these as modifications to the overall operation counts, and then using the I/O cost for a write-optimised design we can re-derive the cost in IOPS. For the continuous method we get

$$sync \left(6.8\ tps + \frac{0.17|stake|}{epochsec}\right) \quad \text{IOPS}$$

while bulk method is our default design option so we get the same formula as Equation (16)

$$sync \left(2.8\ tps + \frac{0.24|stake|}{epochsec}\right) \quad \text{IOPS}$$

As we would expect, the continuous method has a higher factor for TPS but a lower factor for the number of stake addresses.

Evaluating these and comparing them in Figure 4, we see that the continuous method is substantially more expensive, and indeed sufficiently more expensive to make it infeasible to meet several of the targets. Note again that this uses a log axis, so the modest visual differences are large numeric differences.

14 Assuring node robustness in the presence of I/O faults

14.1 The importance of I/O fault testing

Disk I/O errors can and do happen, e.g. due to hardware failures, or power outages. They are not the fault of the code itself, but are an aspect of the environment in which the code runs. Testing for correct behaviour in the presence of I/O faults is notoriously difficult. Such I/O faults happen rarely in practice, so I/O fault testing is usually based on fault simulation or injection.

The benefit of the I/O fault testing should not be underestimated. The original Cardano node deployed at the original Byron Genesis suffered from occasional disk or database corruption which could not be reproduced or diagnosed by the development team, but occurred sufficiently frequently in production with users and exchanges that it created a substantial workload for the support team, and contributed to a poor reputation. In the Shelley re-design, the issue of robustness in the presence of I/O faults and disk corruption was taken seriously. The solution in the Shelley re-design was to develop and use a test framework that can simulate I/O errors and silent disk corruption and check that the node can detect and recover from them. This has proved very successful in practice: such errors and complaints are now almost unheard of and they no longer generate a significant load for the support team.

The I/O fault testing framework however relies on the code under test interacting with the filesystem *only* via a specific API that is provided by the Haskell-based I/O simulation framework. In practice this means it must be written in Haskell[11]. The three original Shelley on-disk components (immutable DB, volatile DB and ledger DB) were all written in the appropriate style (using the simulation framework's filesystem API) to be used with the simulation and I/O fault testing framework. The LMDB backend however relies on the LMDB C library which cannot be practically adjusted to run within the I/O simulation or to use the required filesystem API. Thus overall, when using this backend it is no longer possible to use I/O fault testing for the consensus layer as a whole.

This is the motivation for using an on-disk backend that is written in Haskell, and that uses the consensus's existing I/O simulation and I/O fault testing framework.

14.2 How to test disk components are robust against I/O faults

The basic requirement is that all disk components use the `io-sim` library to allow running in simulation and do all their I/O via the `fs-sim` library API. This allows running the component in simulation with a simulated file system, and allows for the I/O fault injection.

There are two main kinds of I/O fault: 'noisy' and 'silent'. The noisy faults are ones which are reported synchronously, usually as I/O exceptions, such as failure to write to a file or the disk being full. This could also include data corruption detected as part of a read operation (e.g. checking a checksum after reading data). The silent faults are those that do not report a problem at the time the problem occurs, but results in data being lost or corrupted. A primary example is data failing to be persisted to disk due to the machine being turned off, but this could also include undetected hardware faults and bit flips due to cosmic rays.

Running in simulation is necessary but not sufficient. We want to establish some robustness properties. The general property for the consensus layer overall is to treat I/O faults as a truncation of the blockchain. Truncation is obviously not desirable, but it is acceptable if it is infrequent (and not correlated with external events).

The general strategy taken by the consensus layer is to detect errors and upon detecting an error, to shutdown and restart the node. Upon restarting, the strategy is to check carefully for file corruption errors. If any are found then the disk state must be adjusted so that it is the equivalent of a truncation of the blockchain. In particular for the ledger state, the consensus layer strategy is to take occasional snapshots of the ledger state and on startup to restore from

[11]While it is plausible to imagine a C library for disk data structures that only interact with the filesystem via a callback interface that could be implemented by Haskell test code on top of a mock filesystem, in practice production C database libraries are not written in this way.

the most recent non-corrupted snapshot. Any corrupted snapshots are deleted. In the worst case this involves replaying from genesis.

It is generally not required nor useful to try to recover directly from individual I/O faults.

Thus for the on-disk table component

- we need to be able to detect and report corruption found during restoration. Being able to detect corruption may require the use of checksums.
- We need to report any 'noisy' I/O faults during normal operation so that the consensus layer can shut down and restart the whole node.
- It is not necessary to detect all silent corruption during normal operation. This is a trade-off: doing so would be expensive and this kind of corruption is rare. The most common kind of corruption is recently written data failing to make it to disk before the process or machine is terminated, and this kind can be detected on restoration.

15 Integrating a new high performance disk backend

A new disk backend that fits the existing interface should be possible to integrate relatively easily – at least for functional correctness. The performance effects are more subtle.

The summary is that,

- for a drop-in replacement disk backend, the consensus layer would benefit from I/O *batching* which provides a limited degree of I/O parallelism and a corresponding performance improvement; but
- to achieve full I/O parallelism, the consensus layer would need to be adapted to take advantage of the pipelined style of the existing interface, to execute multiple batches of I/O reads *concurrently*.

It is also important to distinguish the integration of a new backend from the full exploitation of the new backend, either for performance or the use to support moving the large stake-related tables to disk.

15.1 Fitting the existing interfaces

The interface between the consensus and disk backends uses the 'pipelined' style that was originally recommended and prototyped. This was designed with a high throughput backend in mind. It is therefore expected that a new high throughput backend will be able to fit the existing interface with no changes or minimal changes to the interface.

There are other aspects of integration that will require some work, including

- adjusting the code to initialise the new backend
- integration testing
- performance benchmarking
- integrating with the I/O fault testing framework

The I/O fault testing framework interface will need some small adjustments. The current I/O interface supported by the test simulation includes simple blocking reads on single files. To support a new backend that can perform parallel I/O will require a small extension. This is expected to be an extra interface to perform batches of reads across multiple open files, but still as a blocking operation overall. This should be straightforward to implement in the simulator in terms of sequential operations and aggregation of any I/O faults.

15.2 Extending the existing interfaces for new operations

Part of the requirements for the new backend is new operations to support the ledger when the stake-related tables are moved to disk. These were discussed in detail in Section 7. In particular there is a new MERGE operation and support for monoidal updates. Exposing these new operations will require an extension to the existing API between the backend and consensus layer. This should be a fairly modest amount of work.

15.3 Initial improvement to I/O parallelism by batching

Once the new disk backend is integrated, the consensus layer will benefit from improved I/O parallelism due to batching. This should work without significant additional changes to the consensus layer. It should work with the existing backend API, and the existing use of that API by the consensus layer.

The current design in the MVP is that all the transaction input lookups for all the transactions in a whole block are submitted to the disk backend in a single batch, followed by waiting for the results. A disk backend supporting parallel I/O can take advantage of this batching to submit the reads in parallel. The degree of parallelism is limited by the batch size. The batch size for the consensus layer will be the number of inputs in each block.

The good thing about batching is that it is relatively straightforward to do and to integrate. The performance benefits for reasonable sized batches should be significant.

Batching alone cannot achieve full I/O utilisation however. This is due to the fact that once one batch starts to complete, there is no more I/O work to do for a while, and thus a lost opportunity to utilise the hardware. This is the case even if batches are executed back-to-back sequentially. To fully utilise the hardware, the next batch must be available to start, as soon as the SSD hardware is ready to accept more I/O operations, which is *before* the previous operations fully completes. To utilise this fully requires pipelining. See Section 16.2 for details.

16 Fully exploiting a new disk backend

16.1 Moving the stake related tables to disk

The other half of the overall project is to move the remaining large parts of the ledger state to disk. These are all the stake-related tables. Doing so will take advantage of the new disk backend, in particular new operations and improved performance of existing operations.

This part of the project will require substantial work in the consensus and ledger layers. It will require several changes to the consensus/ledger interface:

- changing to a multi-table design;
- requiring the ledger state to be parameterised by the table type;
- adding support for individual table snapshots;
- adding support for read-only and monoidal table types;
- adding support for table merges;

All but the last item above have been previously explored in the prototype, prior to the MVP.

In the consensus layer it will require:

- introducing and using difference-tracking map types;
- introducing and using difference-tracking monoidal map types;
- tracking of snapshots within the 'changelog';
- routing reads via snapshots to the correct table.

In the ledger layer it will require:

- adapting to all the changes in the consensus/ledger interface;
- moving each of the stake related tables to use the new consensus/ledger interface;
- adapting the bulk incremental algorithms to use the new consensus/ledger interface;
- converting any remaining bulk algorithms to be incremental;
- using the new table merge operation for rewards payout;
- functional testing;
- performance testing, including verifying that there are no I/O related stalls at any point in the epoch.

16.2 A possible approach to I/O pipelining in the consensus layer

Taking advantage of the pipelined style of the interface to the disk backend will require design changes in the consensus layer. This is not necessary for functional integration or for I/O batching, but would be needed to hit the higher performance targets.

One possible design to incorporate pipelining into the existing consensus layer would be to include it into the 'chain db' component. The chain db already uses an asynchronous approach to submitting new blocks: it has a queue of incoming blocks for consideration for chain selection. It may be practical to adjust this so that upon initial submission to the queue, the I/O reads for the block are initiated, with the expectation that – by the time the block is extracted from the queue for validation – the I/O reads have completed. The typical length of the queue may need to be increased to give enough time for the I/O to complete.

A challenge of this approach is that the chain db may need to track the pending or completed reads for a block systematically throughout its volatile db component. This is because blocks are not necessarily added to the chain as soon as they are submitted to the chain db. For example, the chain db supports blocks being submitted out of order (which can happen when blocks are downloaded from multiple independent peers) which means the blocks will only be added later once the 'gaps' are filled.

17 Opportunities with a new disk backend

17.1 Unusual requirements in the management of the ledger state

The consensus layer of Cardano node has some somewhat unusual requirements for how it manages the ledger state – which translates to unusual requirements for storing the ledger state on-disk. These requirements arise from the Ouroboros algorithm and the need to avoid denial of service (DoS) attacks.

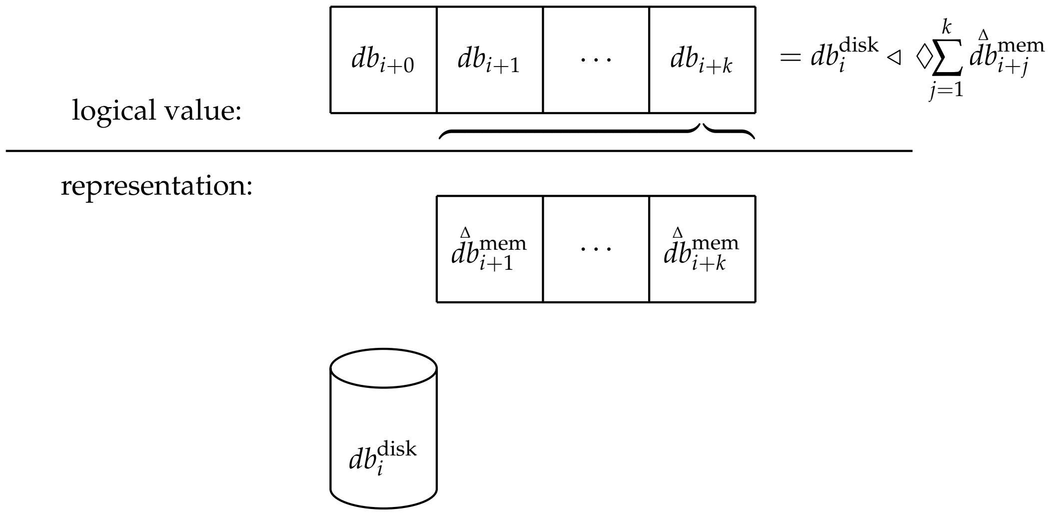
Most applications that use databases only need a *single* value of the database to be available at once. This is not the case for the ledger state managed by the consensus layer. The consensus layer needs many versions of the ledger state to be available at once (with low cost) and it needs to be able to extend (i.e. modify) any of these versions. This arises from the fact that the node needs to be able to evaluate potential chain forks, and to avoid DoS attacks it must be able to do so with reasonable cost.

Kanjalkar et al. [2019] (Section 3, "Attack on Disk") describe a class of potential DoS attacks on PoS blockchains, such as Cardano. We believe our current consensus design avoids this class of attack, but to do so it relies on being able to cheaply obtain and extend the ledger state for any recent block, up to K (2160) blocks back.

In particular, evaluating an alternative chain fork works by first obtaining evidence of a strictly longer chain of valid headers that intersects with the current chain within the last K blocks. Then the block bodies for this chain are downloaded and verified. Verifying the blocks in the chain fork relies on having access to the ledger state on the current chain at point where it intersects with the fork. Then with the ledger state from the intersection point, it must be extended as each block in turn on the fork is validated. Thus not only is read access required for the recent ledger states, but any one of them may need to be extended, without modifying the current ledger state (or the state for any other fork being validated concurrently).

If each of these multiple ledger states were to be stored on disk then the database would need to support multiple *writable* snapshots. This is not a feature that is available in most off-the-shelf database libraries, and not available in the libraries that would otherwise be plausible choices for Cardano. For example, LMDB and RocksDB support multiple read-only snapshots, but not writable ones.

The need to use an off-the-shelf database library for the MVP necessitated a somewhat complex and costly design. Coutts and Wilson [November 2021] describes this design in detail. The summary is that the consensus layer only keeps on disk the ledger state corresponding to a block that is at least K blocks old – which is therefore stable. The ledger states corresponding to all the more recent blocks are maintained in memory using a representation of differences. This allows keeping only a single copy of the ledger state on disk – fitting within the constraints of the LMDB library – while still having access to all the intermediate ledger states, and the ability to extend any one of them in memory.



This design has a complexity cost, and it also has a computational cost:

- The complexity cost translates into initial development time in the MVP and ongoing maintenance cost such as the time for new developers to become familiar with the code-base.

- The performance regression between the prior in-memory design and the new in-memory test backend can be ascribed primarily to the extra costs of managing the sequence of differences. Work has already been carried out to minimise the cost of managing the sequence of differences[12], and further improvements are not expected.

17.2 Opportunities to reduce code complexity

If a new disk backend could directly support multiple writable versions of the database on disk, and if it could do so with reasonable resource cost, then it could enable a simpler consensus design that would eliminate the management of explicit differences and their associated costs.

In the original in-memory design, the consensus layer directly keeps hold of the whole ledger state for each of the last K blocks. This makes access to old versions of the ledger state trivial. The representation uses persistent data structures and thus shares the vast majority of the in-memory data between all these versions. Indeed, one measurement for the mainnet found that the cost of keeping K versions was approximately 1% higher than the cost of keeping a single version. In theory the memory cost is directly related to the rate of change (i.e. TPS) and how many copies are kept (i.e. K).

A disk backend supporting multiple writable versions of the database on disk would allow a design analogous to the original design. The consensus layer would keep hold of database references to the state corresponding to each of the last K blocks. Then any of them are accessible and any can be extended when a chain fork needs to be validated.

17.3 Opportunities to reduce memory use

Furthermore, a new disk backend with support for multiple writable versions could enable a design that uses less memory. In particular, while the design for the MVP needs to keep track of all the differences in the last K blocks in memory, the new design outlined above needs no such tracking of differences.

In the current MVP design, the size of the differences is proportional to the data rate of the chain (which is proportional to block size), times the K (2160) versions that the consensus layer needs access to. For the expected TPS of the current Cardano implementation, this is an acceptable amount of memory.

For Leios however, the TPS is expected to be substantially higher and the memory use would be correspondingly higher. A disk backend that supports multiple writable versions could have a fixed memory use (for its write buffer) rather than it being proportional to the blockchain TPS. This would translate to a significant memory saving.

One must be careful however to account for memory used by the disk backend in the proposed design, otherwise one may be simply shifting memory use from one place to another. In particular, the new design calls for keeping K references to versions of the database. We must account for the memory of these K version references.

It is expected that a new disk backend will maintain a "write buffer" and only flush data to disk when the write buffer is full. By bounding the buffer size, the memory use can be bounded. However each version reference can be expected to have its own write buffer. Even if the write buffer uses a persistent data structure to share values between versions, if K versions are kept then all changes in the last K versions will still have to be kept in memory.

[12]The improvement involved extending the operations on the representation of differences to make them a group rather than just a semi-group, which in turn allowed an improved algorithm for the key difference sequence maintenance operations which are now $\mathcal{O}(1)$ rather than $\mathcal{O}(\log n)$ in the length of the sequence (i.e. K).

To avoid this, we can keep fewer versions, and make the buffers smaller.

Keeping fewer versions Keeping references to fewer versions is possible in principle and indeed an earlier version of the consensus layer for Cardano Shelley did so. The observation is that while we need to be able to get hold of the ledger state for any of the last K blocks, we do not need to store them all if we can compute them within reasonable cost. The early Shelley design only kept the ledger state for every "n'th" block. This feature was not kept because the memory savings for the in-memory design were insignificant, but for an on-disk design the savings could be considerable.

Using smaller write buffers The behaviour of the write buffer is that it accumulates changes to the database and is flushed to disk when it becomes full. This also means it is often empty or nearly empty: immediately after it is flushed. If the consensus layer were to keep the database references after each flush then the memory use would be minimal. It is also worth noting that the frequency of flushes is directly related to the rate of change and the maximum size of the write buffer.

A combined design idea The combination of these two ideas is that the consensus layer could keep occasional ledger state references: to those blocks where the database indicates that the write buffer has been flushed since the previous block.

17.4 Feasibility

A disk backend based on a log structured merge tree (LSM tree) could fairly naturally support multiple writable versions, and at relatively low cost. In an LSM, all "data runs" are in files that are immutable. This makes sharing existing data straightforward, though it somewhat complicates the tracking of which old files are unused and can be safely deleted. To work correctly, the key characteristic needed is that as new files are written for independent writable versions, those file names are distinct. LSMs also use an in-memory write buffer, and this can achieve the required properties by using a traditional persistent data structure.

17.5 A new requirement for a new disk backend

It seems reasonable to conclude that a new custom backend should be required to support multiple writable references to versions of the database. The incremental cost of this feature appears to be low: given that a new custom backend is required anyway. The value it brings is the opportunity for savings in complexity (and thus maintenance) in the existing consensus layer, and for very significant memory savings for a future Ouroboros Leios consensus layer.

18 Recommendations

The current MVP is suitable for deployment as an interim solution. The MVP will not remain suitable indefinitely however as the UTxO scales, and nor will the MVP be able to hit more than the minimum 'threshold' targets for memory use, sync speed and TPS.

The project should continue with the implementation and integration of a new on-disk backend to replace the LMDB backend. The new backend should:

1. be designed to help achieve the higher performance targets;
2. support the new and improved operations required by the ledger to be able to move the stake-related tables to disk; and

3. to be able to be tested in the context of the integrated consensus layer using the I/O fault testing framework.

The functional and performance requirements for the new backend should be specified in terms of the component in isolation, though of course these requirements should be chosen with the consensus interfaces and overall consensus performance in mind.

18.1 Recommended development approach

There would be two main phases to the development of a new on-disk backend. There is also the opportunity for a third phase (or a later project) to fully exploit a new on-disk backend.

1. the development of the on-disk backend as a stand alone component, meeting certain functional and performance requirements;
2. the integration of the new backend with the existing consensus layer of the node; and
3. optionally, a project to further increase the node's synchronisation performance by exploiting I/O parallelism and CPU parallelism.

The first phase could be done as an 'arms length' project, because it could be specified in isolation and could be developed without the need for a great deal of coordination between development teams. The second phase, the integration phase, would need coordination between development teams and so is not an 'arms length' activity. The third phase/project would primarily involve changes to the existing consensus code and so, apart from some design and prototyping work, it would also not be an 'arms length' activity.

From here on we will restrict our attention to the two main phases.

18.2 Recommended functional requirements for a new on-disk backend

The on-disk backend should meet the following functional requirements.

1. It should have an interface that is capable of implementing the existing interface used by the existing consensus layer for its on-disk backends.
2. The basic properties of being a key value store should be demonstrated using an appropriate test or tests.
3. It should have an extended interface that supports key-range lookups, and this should be demonstrated using an appropriate test or tests.
4. It should have an extended interface that supports a 'monoidal update' operation in addition to the normal insert, delete and lookup. The choice of monoid should be per table / mapping (not per operation). The behaviour of this operation should be demonstrated using an appropriate test.
5. It should have an extended interface that exposes the ability to support multiple independently writable references to different versions of the datastore. The behaviour of this functionality should be demonstrated using an appropriate test. For further details see Section 17.
6. It should have an extended interface that supports taking snapshots of tables. This should have $\mathcal{O}(\log n)$ time complexity. The behaviour of this operation should be demonstrated using an appropriate test. For further details see Sections 7.5 and 7.6.
7. It should have an extended interface that supports merging monoidal tables. This should have $\mathcal{O}(\log n)$ time complexity at the point it is used, on the assumption that it is used

at most every n steps. The behaviour of this operation should be demonstrated using an appropriate test. For further details see Section 7.7.

8. It should be able to run within the `io-sim` simulator, and do all disk I/O operations via the `fs-sim` simulation API (which may be extended as needed). It should be able to detect file data corruption upon startup/restoration. Detection of corruption during startup should be reported by an appropriate mechanism. During normal operation any I/O exceptions should be reported by an appropriate mechanism, but it need not detect 'silent' data corruption. The behaviour of this corrupted detection should be demonstrated using an appropriate test. For further details see Section 14.2.

18.3 Recommended performance requirements for a new on-disk backend

The business requirements in Section 6 are for the node as a whole. As mentioned above, to allow for a development of the new on-disk backend as a stand alone component – with the option to do the development as an arms length project – the functional and performance requirements for the new backend must be specified in terms of the component in isolation. This requires a certain amount of educated guesswork, because we sadly lack a formal performance model of the consensus layer[13].

What is clear is that the performance of the consensus layer is limited by the performance of the on-disk backend ('performance impairment' can only be accumulated, never discarded). So the requirements on the performance of insert, delete and lookup operations translate directly from node level requirements to component level requirements.

The more subtle issue to consider is how much CPU resource can be used by the backend to achieve the performance targets for insert, delete and lookup operations. This is because the CPU resource must be shared by both the on-disk backend and the consensus layer and the rest of the node.

The on-disk backend should meet the following requirements, with the given assumptions.

1. Assume that the SSD hardware meets the minimum requirement for 4k reads of 10k IOPS at QD1 and 100k IOPS at QD32 – as measured by the '`fio`' tool on the benchmark target system.
2. The performance should be evaluated by use of a benchmark with the following characteristics. The performance targets are specified in terms of this benchmark. The benchmark is intended to reasonably accurately reflect the UTxO workload, which is believed to be the most demanding individual workload within the overall design.
   (a) The benchmark should use the external interface of the disk backend, and no internal interfaces.
   (b) The benchmark should use a workload ratio of 1 insert, to 1 delete, to 1 lookup. This is the workload ratio for the UTxO. Thus the performance is to be evaluated on the combination of the operations, not on operations individually.
   (c) The benchmark should use 34 byte keys, and 60 byte values. This corresponds roughly to the UTxO.
   (d) The benchmark should use keys that are evenly spread through the key space, such as cryptographic hashes.

[13] Such a performance model would give us strong evidence that the consensus layer can meet its own performance targets if the on-disk backend can achieve certain performance targets. This kind of compositionality is the promise of $\Delta\mathbf{Q}$ techniques.

(e) The benchmark should start with a table of 100 million entries. This corresponds to the stretch target for the UTxO size. This table may be pre-generated. The time to construct the table should not be included in the benchmark time.

(f) The benchmark workload should ensure that all inserts are for 'fresh' keys, and that all lookups and deletes are for keys that are present. This is the typical workload for the UTxO.

(g) It is acceptable to pre-generate the sequence of operations for the benchmark, or to take any other measure to exclude the cost of generating or reading the sequence of operations.

(h) The benchmark should use the external interface of the disk backend to present batches of operations: a first batch consisting of 256 lookups, followed by a second batch consisting of 256 inserts plus 256 deletes. This corresponds to the UTxO workload using 64kb blocks, with 512 byte txs with 2 inputs and 2 outputs.

(i) The benchmark should be able to run in two modes, using the external interface of the disk backend in two ways: serially (in batches), or fully pipelined (in batches).

3. The *threshold* target for performance in this benchmark should be to achieve 5k lookups, inserts and deletes per second, when using the benchmark in serial mode, while using 100% of one CPU core.
4. The *middle* target for performance in this benchmark should be to achieve 50k lookups, inserts and deletes per second, when using the benchmark in parallel mode, while using the equivalent of 100% of a CPU core.
5. The *stretch* target for performance in this benchmark should be to achieve 100k lookups, inserts and deletes per second – when using an SSD that can achieve 200k IOPS at QD32 – using the benchmark in parallel mode, while using the equivalent of 200% of a CPU core. This target would demonstrate that the design can scale to higher throughput with more or faster hardware.
6. A benchmark should demonstrate that the performance characteristics of the monoidal update operation should be similar to that of the insert or delete operations, and substantially better than the combination of a lookup followed by an insert.
7. A benchmark should demonstrate that the memory use of a table with 10M entries is within 100Mb, and a 100M entry table is within 1Gb. This should be for key value sizes as in the primary benchmark (34 + 60 bytes).

18.4 The integration of the new backend

The new backend should be integrated with the existing consensus layer, making only the necessary changes to the consensus layer to make the new backend work, and to expose the new operations required by the ledger. See Sections 15.1 and 15.2 for details.

It is not required to make the changes required in future by Ouroboros Leios, such as exposing the support for multiple writable references. This functional requirement should be demonstrated on the component in isolation and not via changes to the existing consensus layer.

Fully exploiting the new backend should be planned as a follow-up project, and should not be considered part of integration.

References

Manos Athanassoulis, Michael Kester, Lukas Maas, Radu Stoica, Stratos Idreos, Anastasia Ailamaki, and Mark Callaghan. Designing access methods: The RUM conjecture. In *Proceedings of the 19th International Conference on Extending Database Technology*, EDBT 2016, 2016. doi: 10.5441/002/edbt.2016.42. URL `https://openproceedings.org/2016/conf/edbt/paper-12.pdf`.

Duncan Coutts and Douglas Wilson. Storing the cardano ledger state on disk: API design concepts, November 2021. Version 0.5.

Duncan Coutts, Giorgos Panagiotakos, and Matthias Fitzi. Ouroboros leios: design goals and concepts, November 2022. Version 1.0.

Niv Dayan, Manos Athanassoulis, and Stratos Idreos. Monkey: Optimal navigable key-value store. In *Proceedings of the 2017 ACM International Conference on Management of Data*, SIGMOD '17, 2017. doi: 10.1145/3035918.3064054. URL `https://doi.org/10.1145/3035918.3064054`.

Sanket Kanjalkar, Joseph Kuo, Yunqi Li, and Andrew Miller. *Short Paper: I Can't Believe It's Not Stake! Resource Exhaustion Attacks on PoS*, pages 62–69. 09 2019. ISBN 978-3-030-32100-0. doi: 10.1007/978-3-030-32101-7_4.

Douglas Wilson and Duncan Coutts. Storing the cardano ledger state on disk: analysis and design options, April 2021. Version 1.0.