ZIL Performance: How I Doubled Sync Write Speed

Agenda

1. What is the ZIL?
2. How is it used? How does it work?
3. The problem to be fixed; the solution.
4. Details on the changes I made.
5. Performance testing and results.

*Press "p" for notes, and "c" for split view.

1 – What is the ZIL?

What is the ZIL?

- ZIL: Acronym for (Z)FS (I)ntent (L)og
    - Logs synchronous operations to disk, before `spa_sync()`
    - What constitutes a "synchronous operation"?
        - most *modifying* ZPL operations:
            - e.g. `zfs_create`, `zfs_unlink`, `zfs_write` (some), etc.
        - doesn't include non-modifying ZPL operations:
            - e.g. `zfs_read`, `zfs_seek`, etc.

When is the ZIL used?

- Always*
  - ZPL operations (`itx`'s) logged via in-memory lists
  - lists of in-memory `itx`'s written to disk via `zil_commit()`
  - `zil_commit()` called for:
    - *any* sync write
    - other sync operations (e.g. create, unlink), **and** `sync=always`
    - *some* reads (`sync=always` or `FRSYNC` set)

*Except when dataset configured with: `sync=disabled`

What is the SLOG?

- SLOG: Acronym for (S)eperate (LOG) Device
    - An SLOG is not necessary
    - An SLOG can be used to improve latency of ZIL writes
- Conceptually, SLOG is different than the ZIL
- ZIL is used, even if no SLOG attached

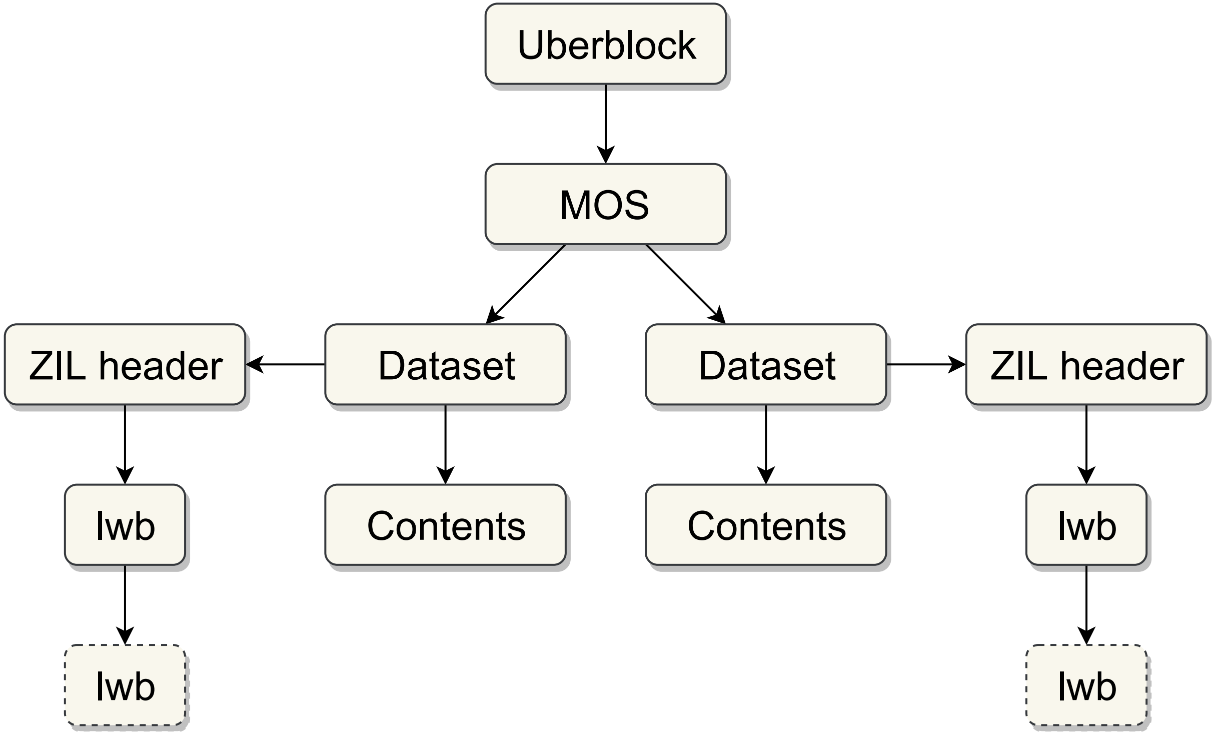
Why does the ZIL exist?

- Writes in ZFS are "write-back"
- Without the ZIL, sync operations inherit latency of `spa_sync()`[*]
  - `spa_sync()` can take tens of seconds (or more) to complete
- Further, with the ZIL, write amplification can be mitigated
- ZIL is essentially a performance optimization

[*] All operations inherit this latency, but only sync operations wait for completion

ZIL On-Disk Format

- Each dataset has it's own unique ZIL on-disk
- ZIL stored on-disk as a singly linked list of ZIL blocks (`lwb`'s)



2 – How is the ZIL used?

How is the ZIL used?

- ZPL will generally interact with the ZIL in two phases:

    1. Log the operation(s) — `zil_itx_assign`
    2. Commit the operation(s) — `zil_commit`

Example: zfs_write

- zfs_write → zfs_log_write
- zfs_log_write

  → zil_itx_create

  → zil_itx_assign
- zfs_write → zil_commit
- Most ZPL operations have a corresponding zfs_log_* function
  - zfs_log_create
  - zfs_log_remove
  - zfs_log_link
  - zfs_log_symlink
  - zfs_log_truncate
  - zfs_log_setattr
  - ...

Example: `zfs_fsync`

- `zfs_fsync` → `zil_commit`
  - no *new* operations to log… no `zfs_log_fysnc` function

Contract between ZIL and ZPL.

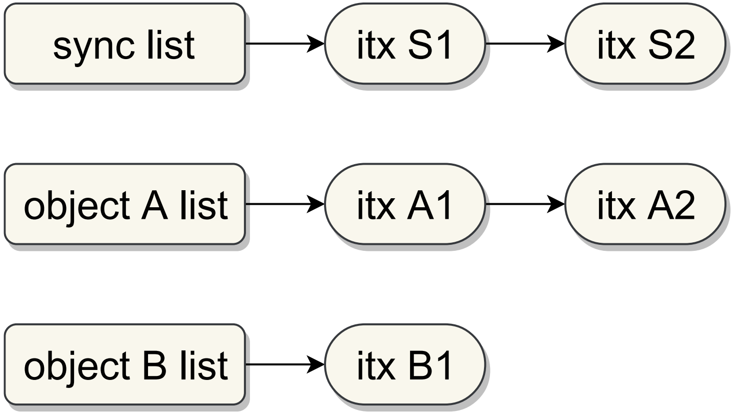
- Parameters to `zil_commit`: ZIL pointer, object number
  - These uniquely identify an object whose data is to be committed
- When `zil_commit` returns:
  - Operations *relevant* to the object specified, will be *persistent* on disk
  - relevant – all operations that would modify that object
  - persistent – Log block(s) written (completed) → disk flushed
- Interface of `zil_commit` doesn't specify *which* operation(s) to commit

2 – How does the ZIL work?

How does the ZIL work?

- In memory ZIL contains per-txg `itxg_t` structures
- Each `itxg_t` contains:
  - A single list of sync operations (for all objects)
  - Object specific lists of async operations

Example: itx lists



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- `zil_commit` handles the process of writing `itx_t`'s to disk:

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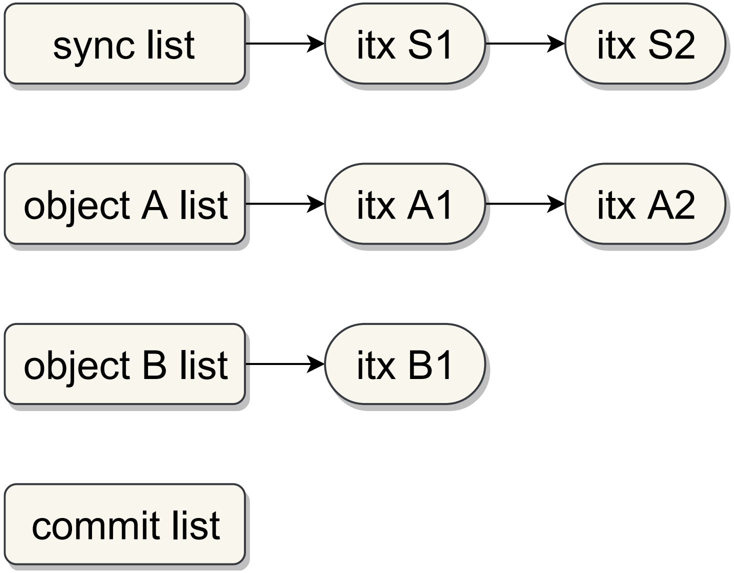
- `zil_commit` handles the process of writing `itx_t`'s to disk:

    1. find all relavant `itx`'s, move them to the "commit list"

Example: `zil_commit` Object B



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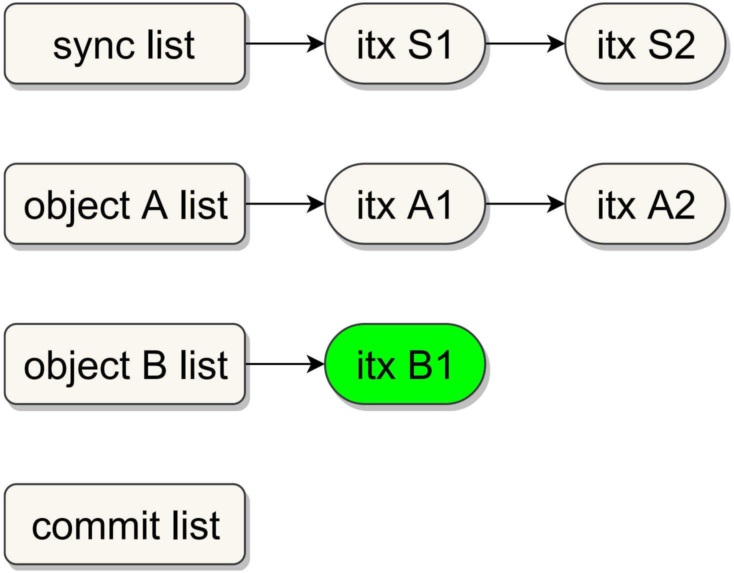

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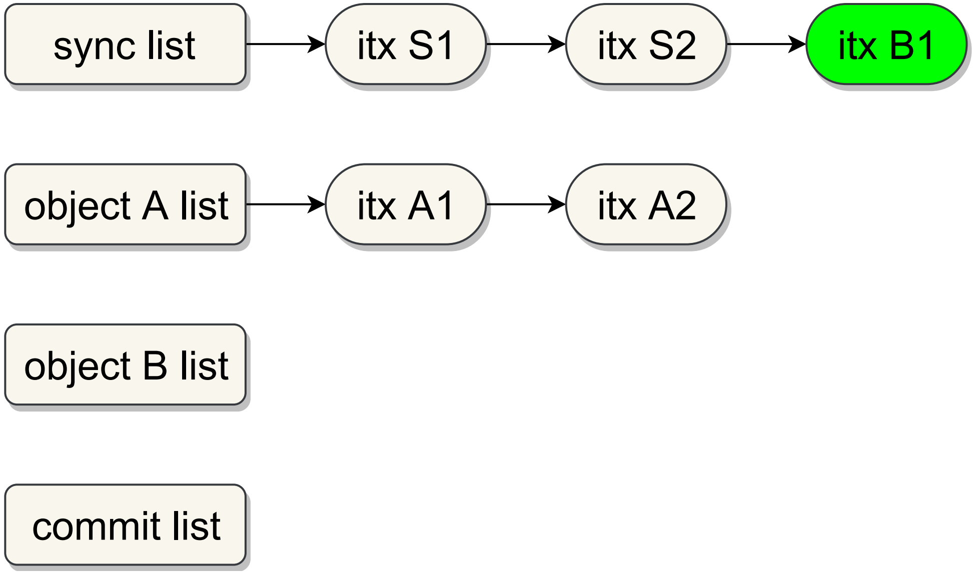

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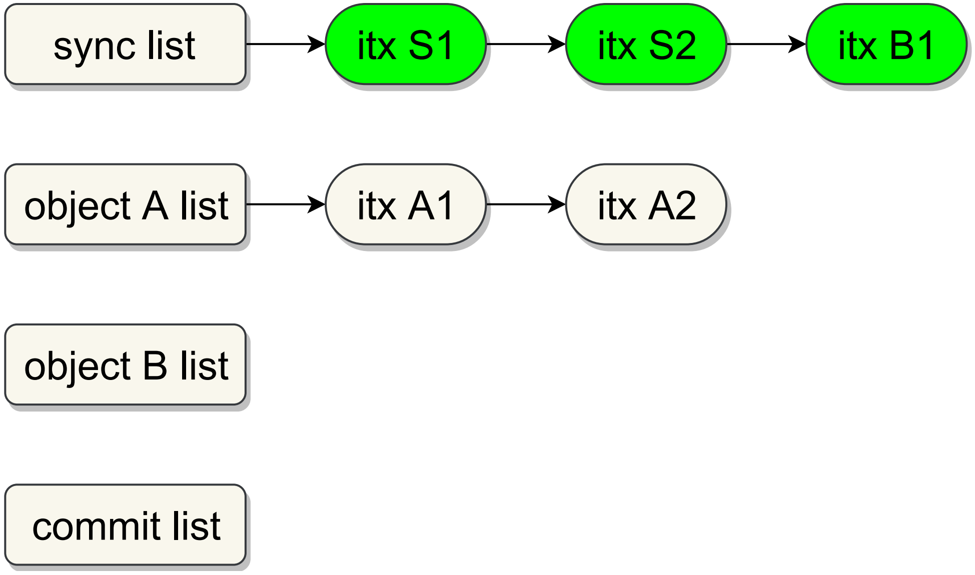

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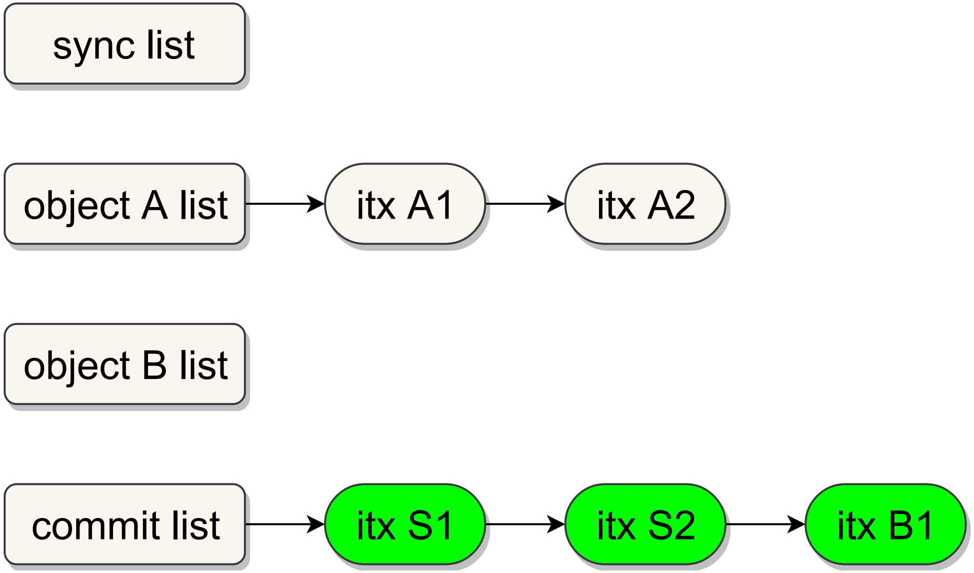

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- `zil_commit` handles the process of writing `itx_t`'s to disk:

    1. Move async itx's for object being commited, to the sync list

    2. Write all commit list `itx`'s to disk

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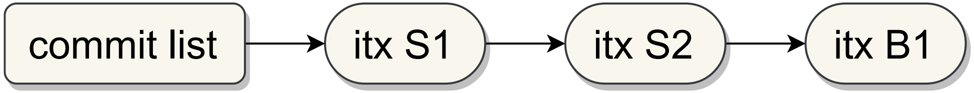

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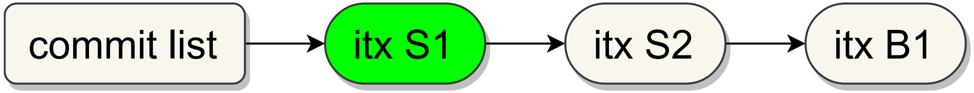

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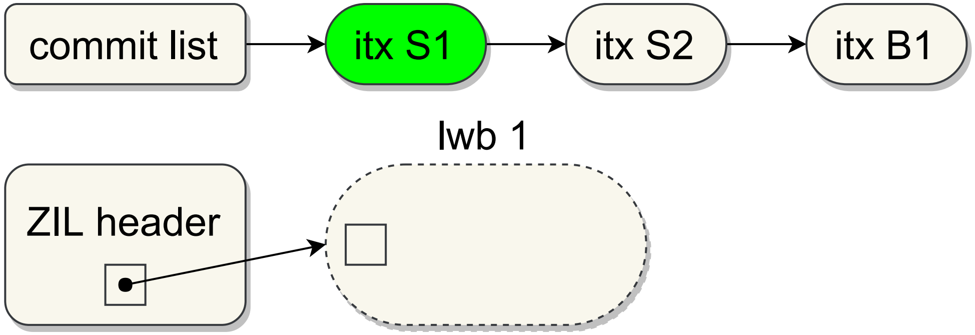

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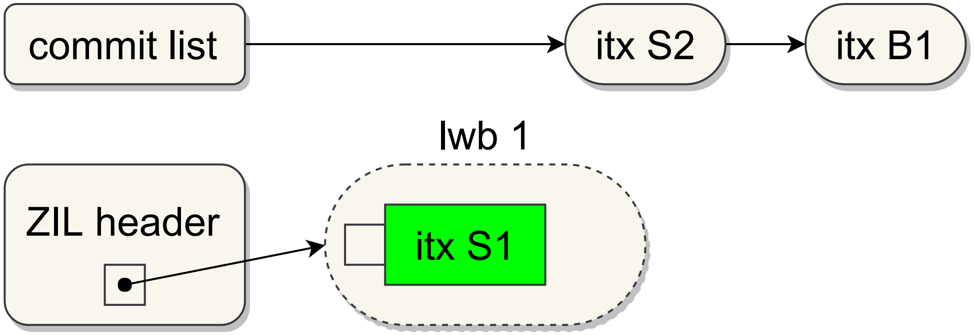

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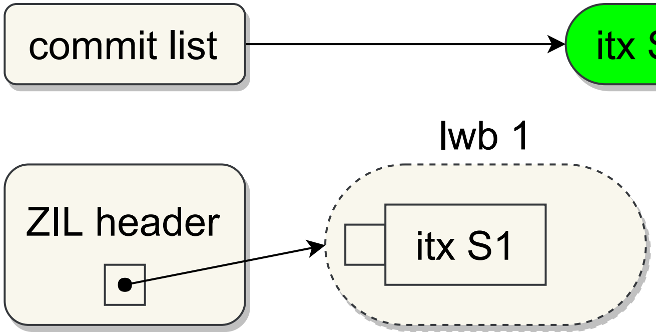

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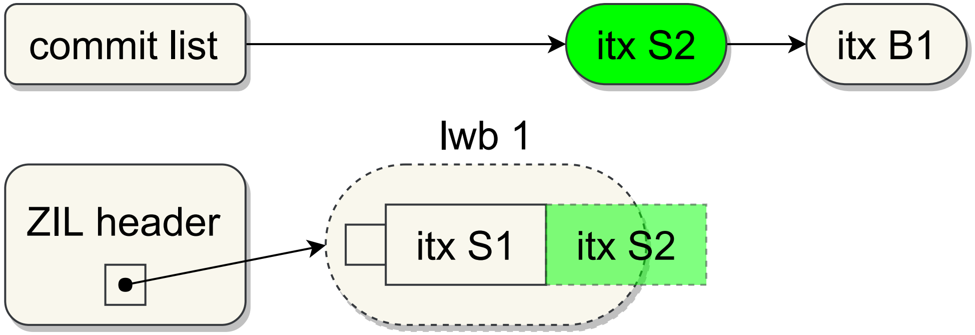

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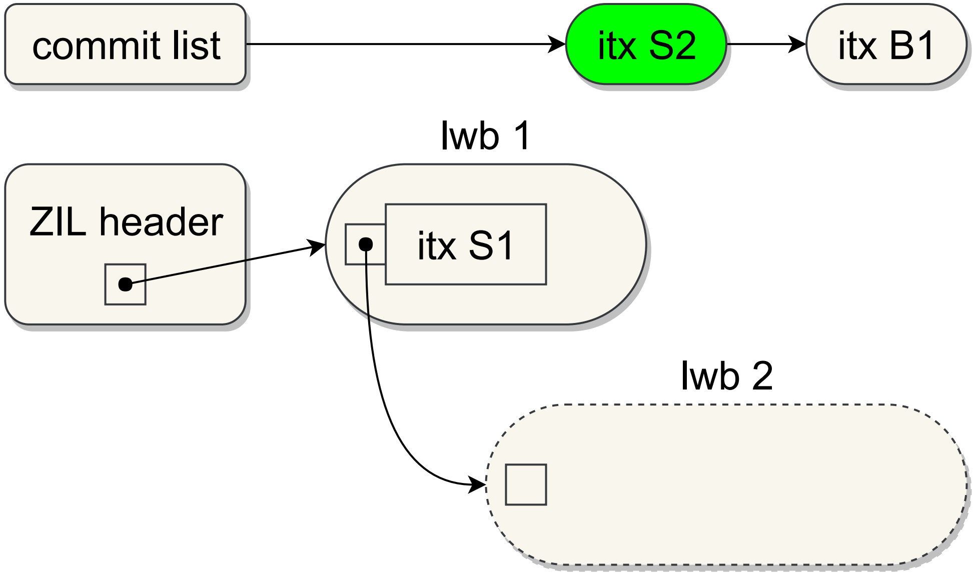

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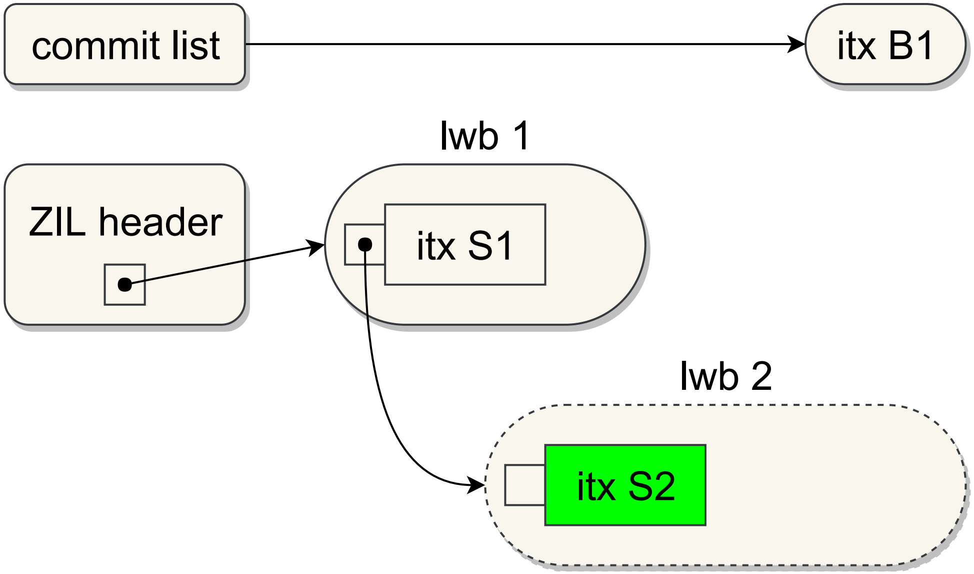

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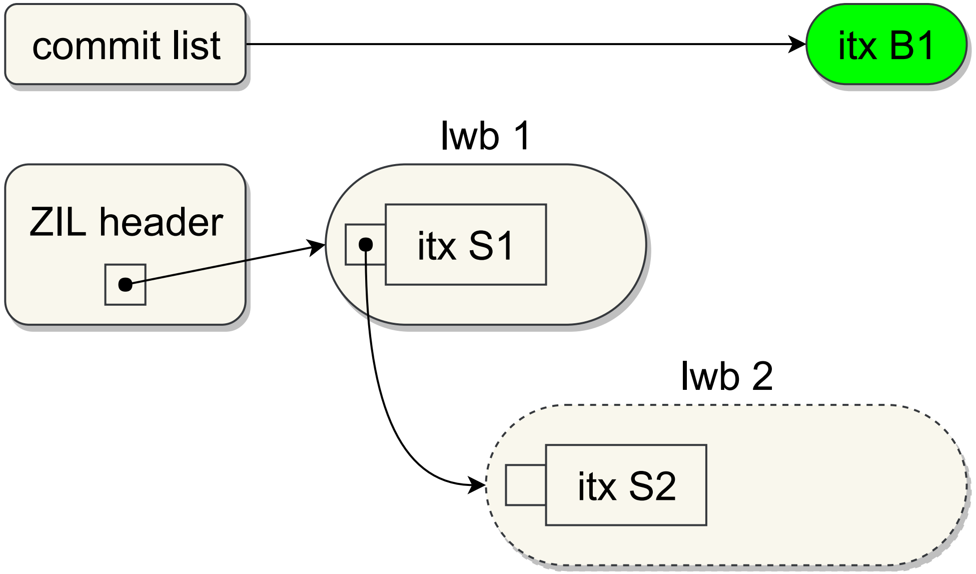

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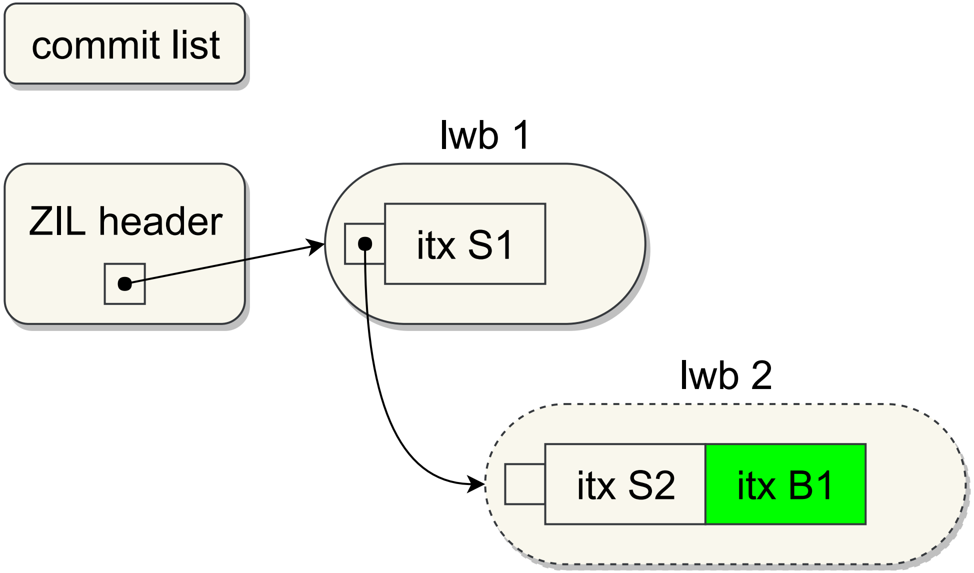

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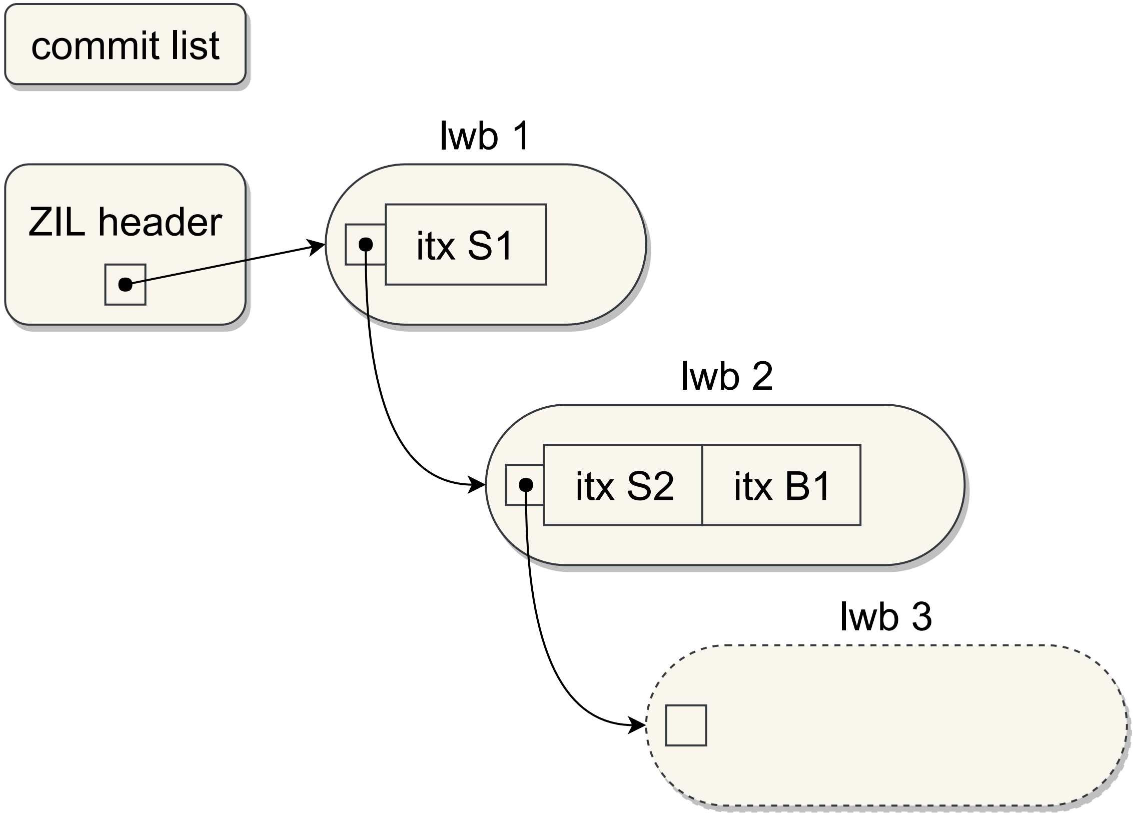

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- `zil_commit` handles the process of writing `itx_t`'s to disk:

    1. Move async itx's for object being commited, to the sync list

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    3. Wait for all ZIL block writes to complete

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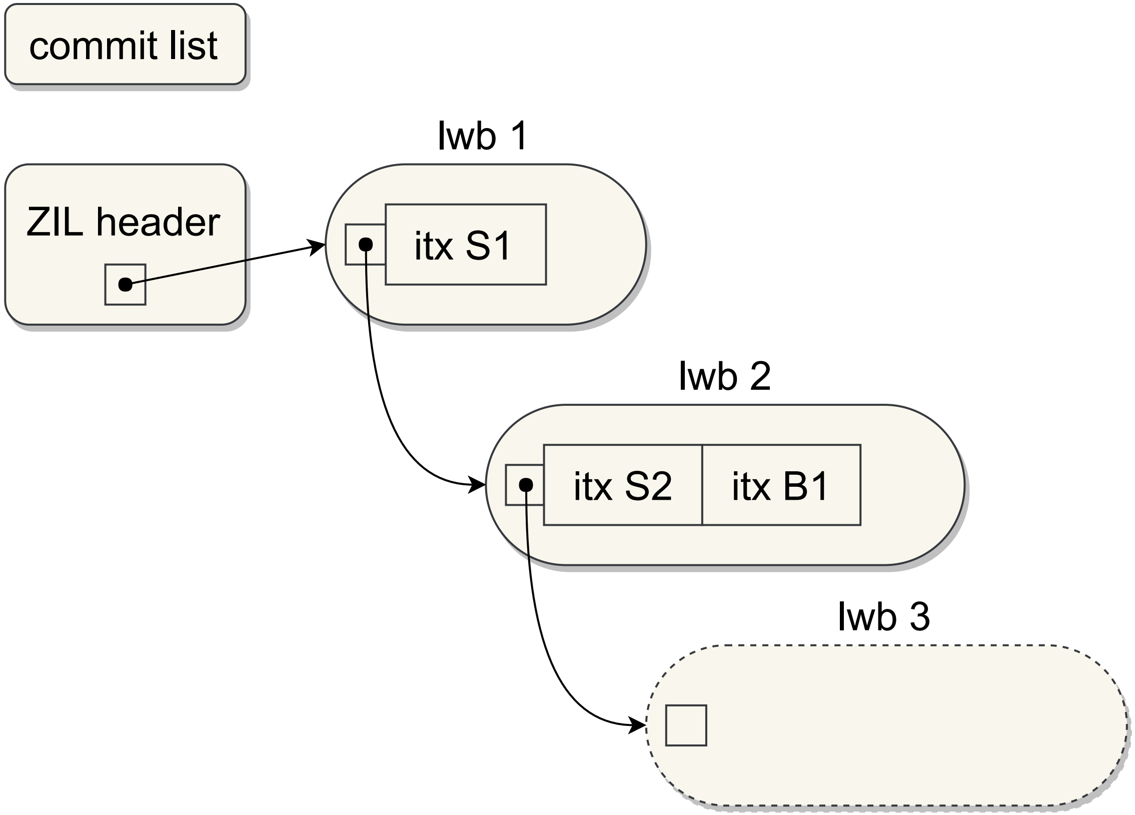

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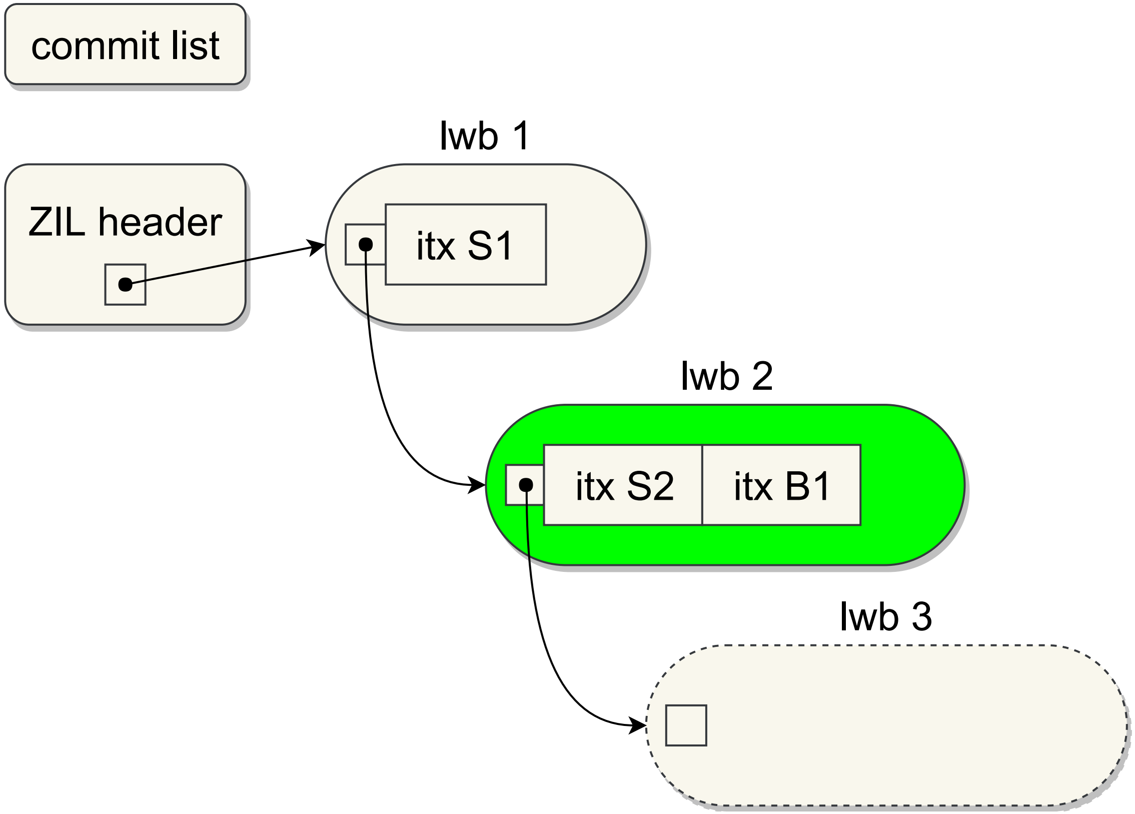

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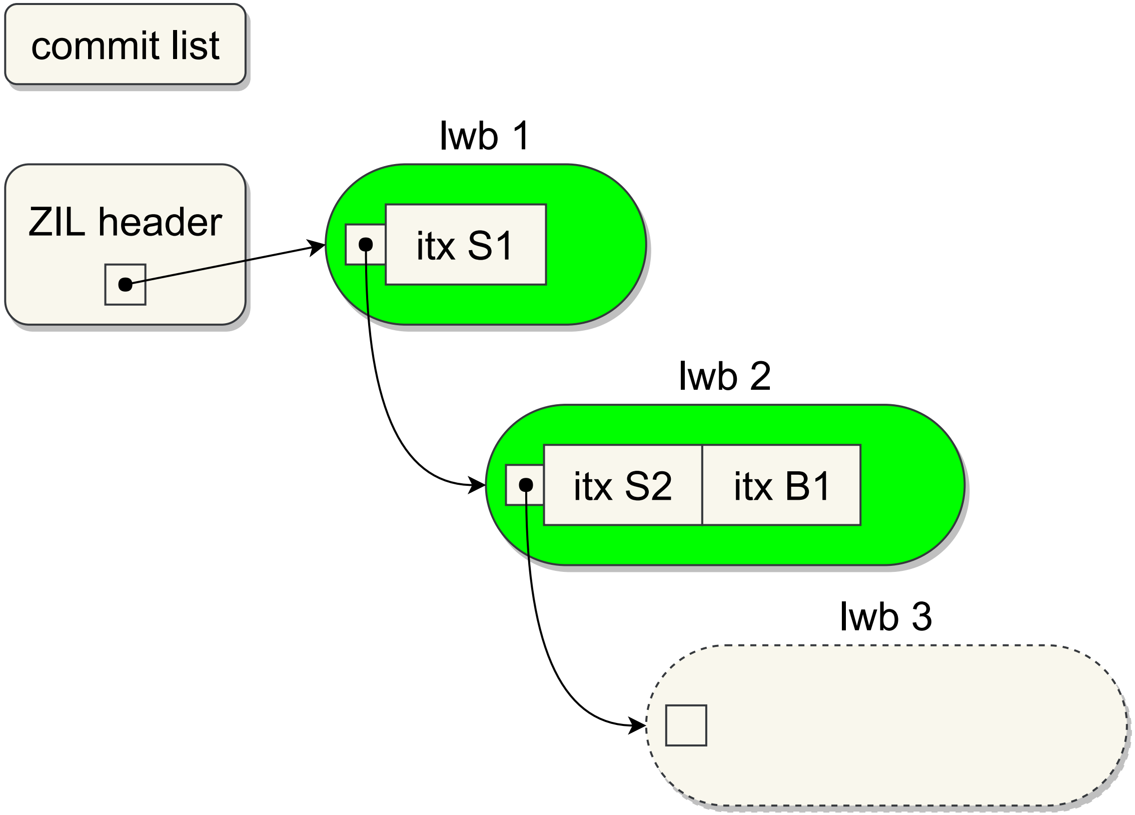

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- `zil_commit` handles the process of writing `itx_t`'s to disk:
    1. Move async itx's for object being commited, to the sync list
    2. Write all commit list `itx`'s to disk
    3. Wait for all ZIL block writes to complete
    4. Flush VDEVs and notify waiting threads

2 – ZIL Block Sizing + Performance

ZIL Block Sizing + Performance

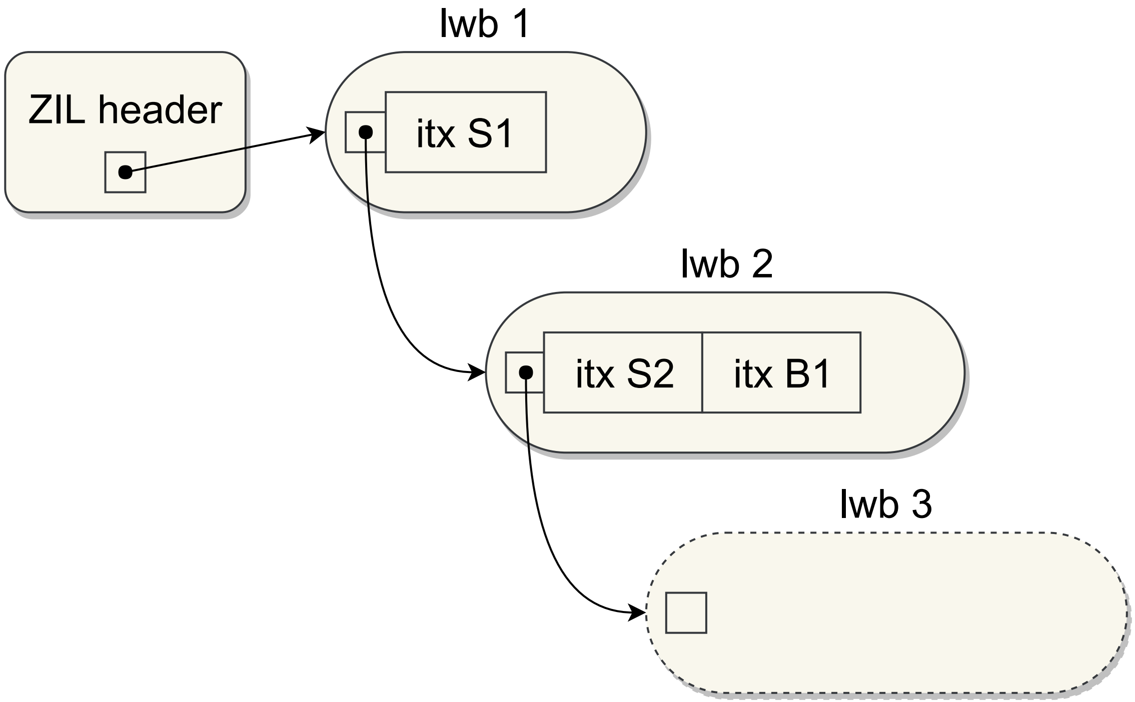
- ZIL blocks must be "pre-allocated", due to on-disk format
    - Block size chosen at time of allocation
- Allocated block size can dramatically impact performance:
    - "too big" – wasted space
    - "too small" – too many (small) IOPs issued to disk
    - "just right" – large IOPs filled with `itx`'s

3 – Problem

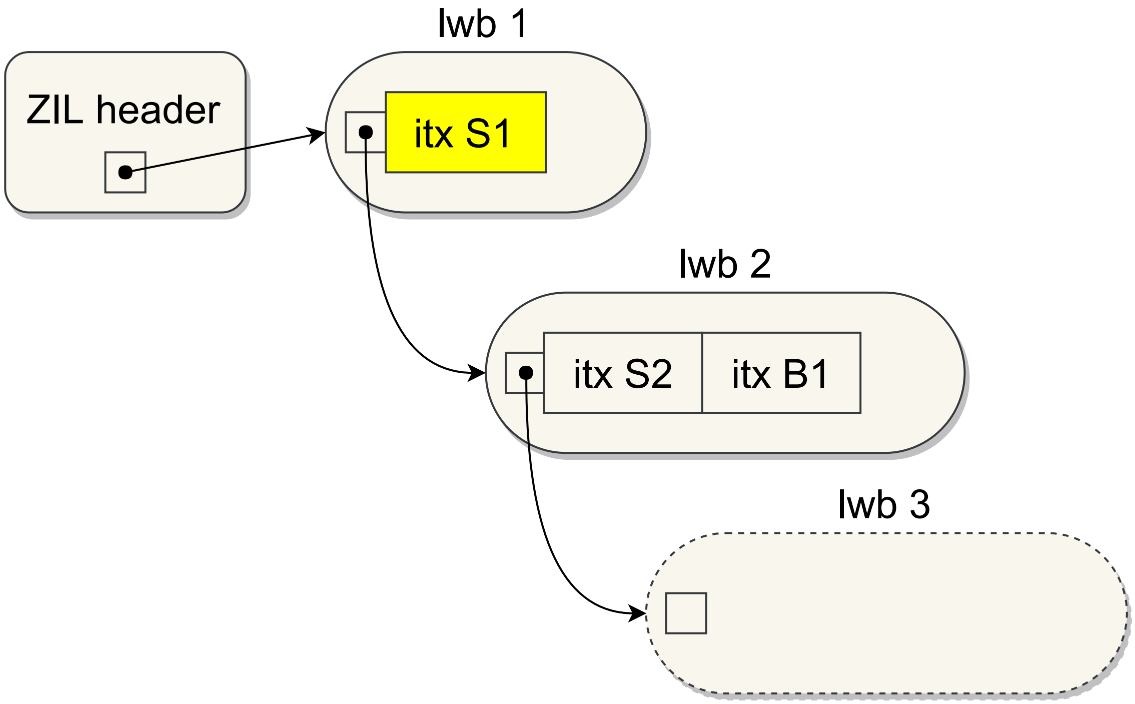
Problem

1. `itx`'s grouped and written in "batches"
    - The commit list constitutes a batch
    - Batch size proportional to sync workload on system
2. Waiting threads only notified when *all* ZIL blocks in batch complete
3. Only a single batch processed at a time

Example Batch



Example "itx S1"



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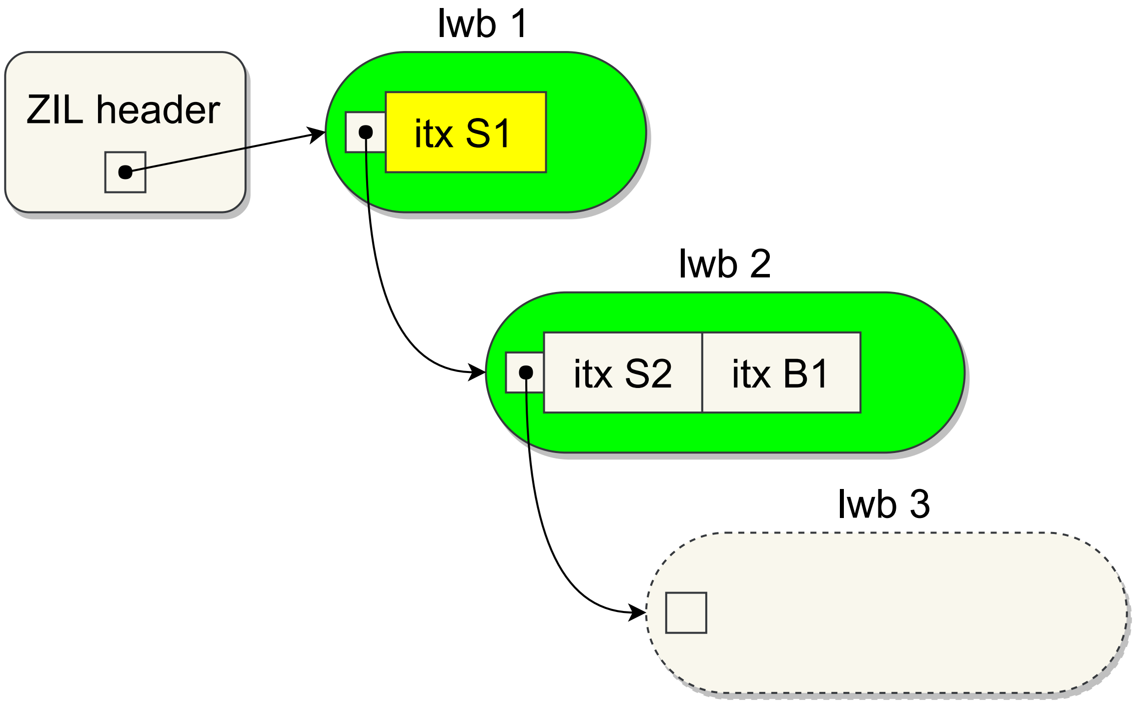


Implications

1. `zil_commit` latency proportional to system workload, *not* disk latency
2. Disk "anomalies" → larger batches → increased `zil_commit` latency
3. New calls to `zil_commit` wait for "current" batch, *and* "next" batch

3 – Solution

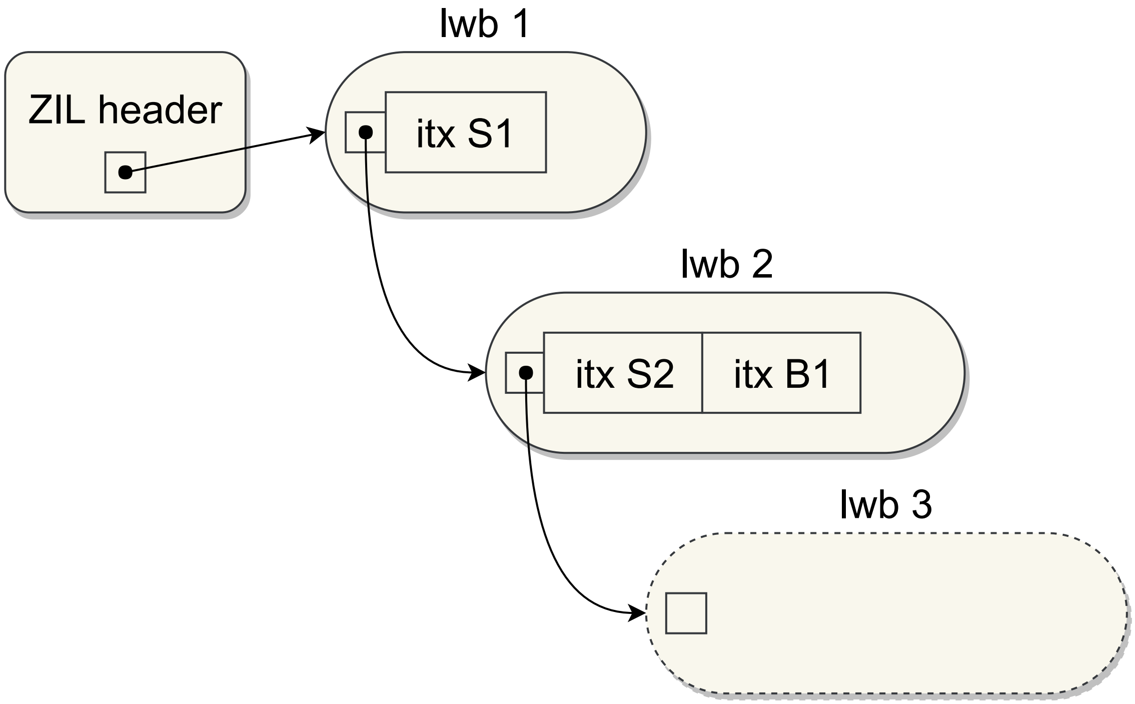
Solution

- Remove concept of "batches":

  1. Allow `zil_commit` to issue new ZIL block writes immediately

  2. Notify threads immediately when *dependent* `itx`'s on disk

Example "Batch"



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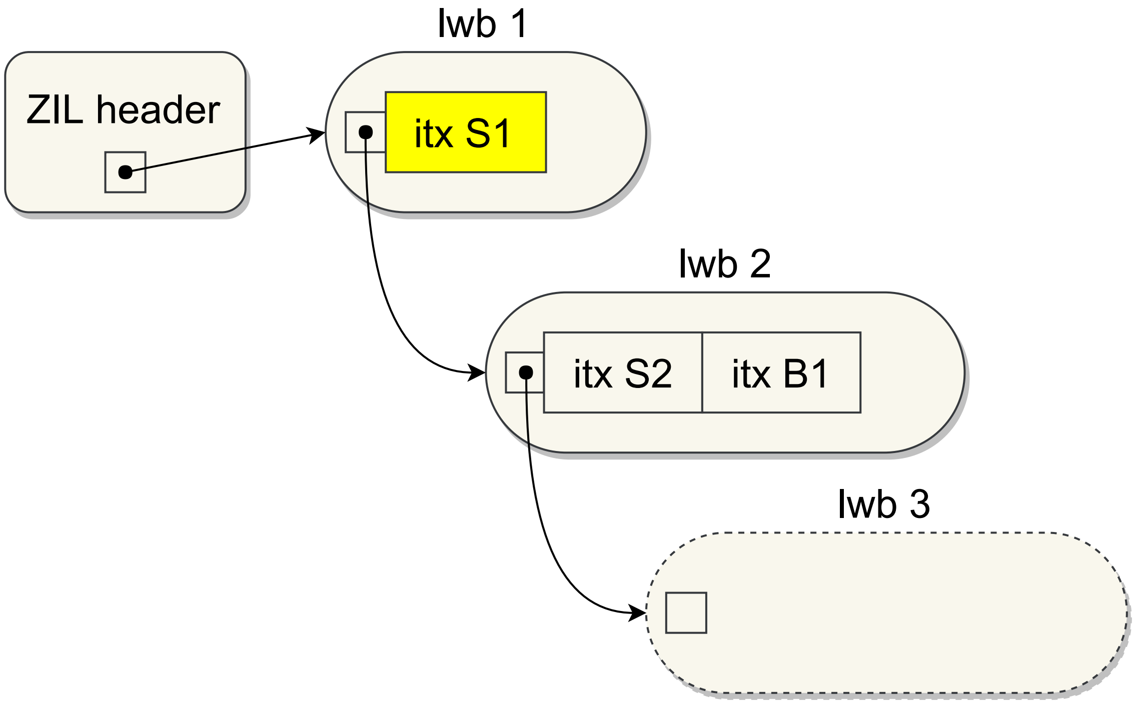

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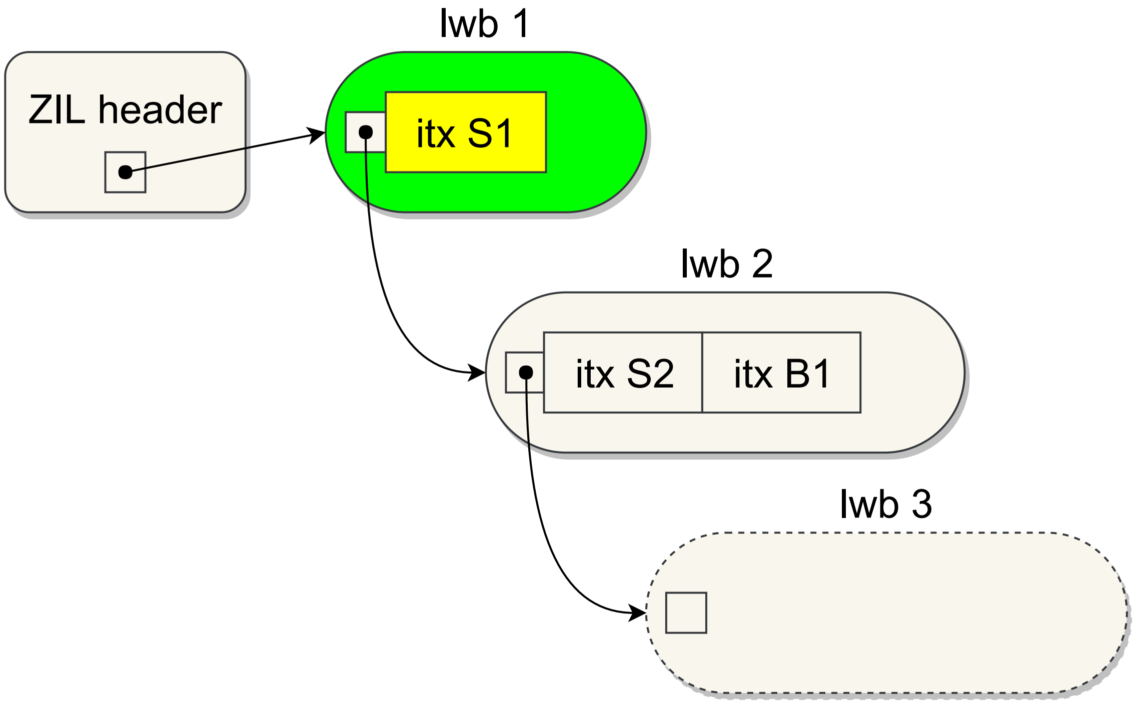
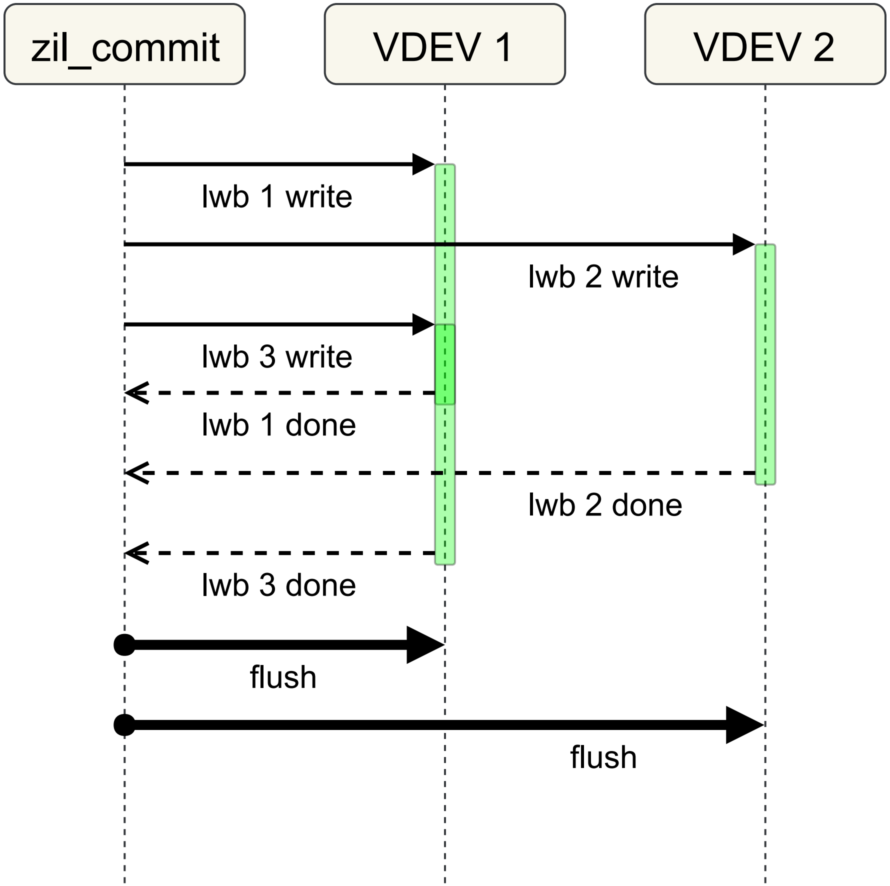


4 – Changes to VDEV Flush

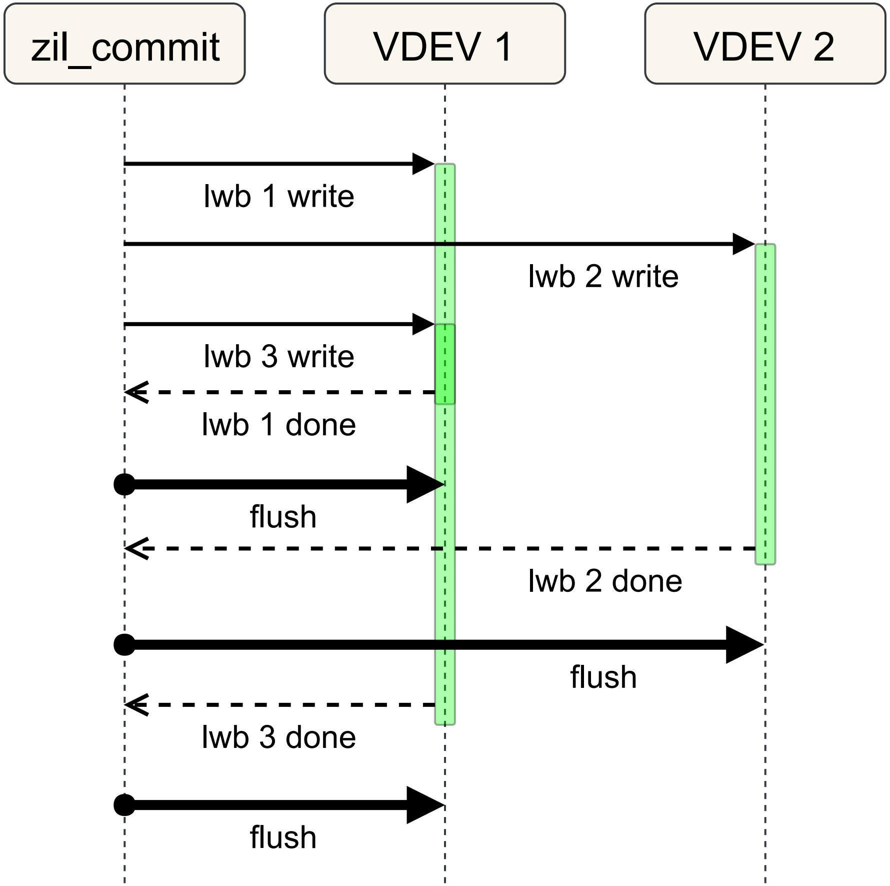
Details

- A ZIL block is not "persistent" until the VDEV is flushed
- Prior mechanics:
    - Single VDEV flush for each VDEV, after batch completes
    - 1 flush per many lwb's
- New mechanics:
    - VDEV flush issued after each ZIL block written
    - 1 flush per 1 lwb

Example: Before



Example: After



4 – Changes to ZIL Block ZIO Tree

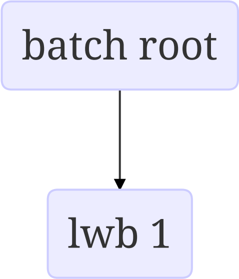
Details

- ZIL blocks issued to disk using ZIOs
- Prior mechanics:
    - "root" ZIO created for each batch
        - "write" ZIOs, for all `lwb`'s in batch, are children of root ZIO
    - "flush" ZIOs issued separately after root ZIO completes
- New mechanics:
    - "root" ZIO created for each lwb
        - "write" and "flush" ZIOs are child of root ZIO
    - "next" lwb root ZIO become parent of "current" lwb root ZIO

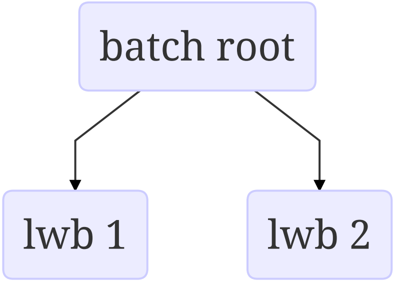
Example: Before

batch root

Example: Before



Example: Before



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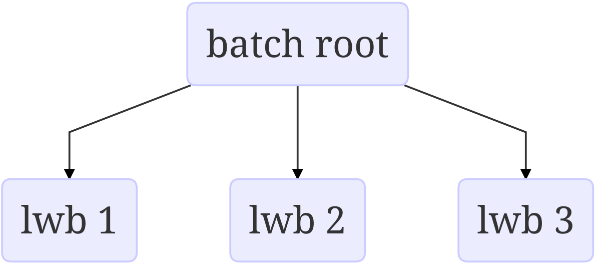

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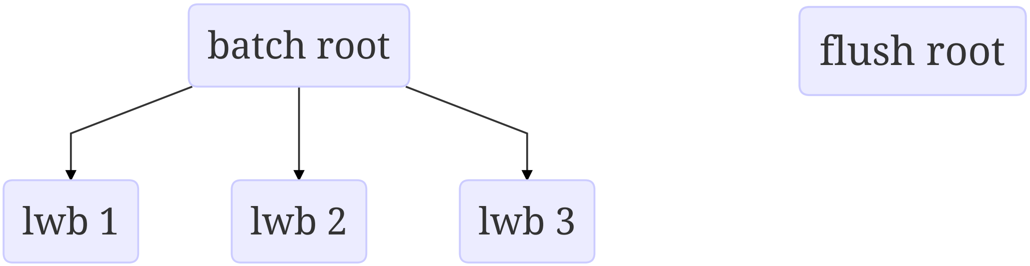


batch root

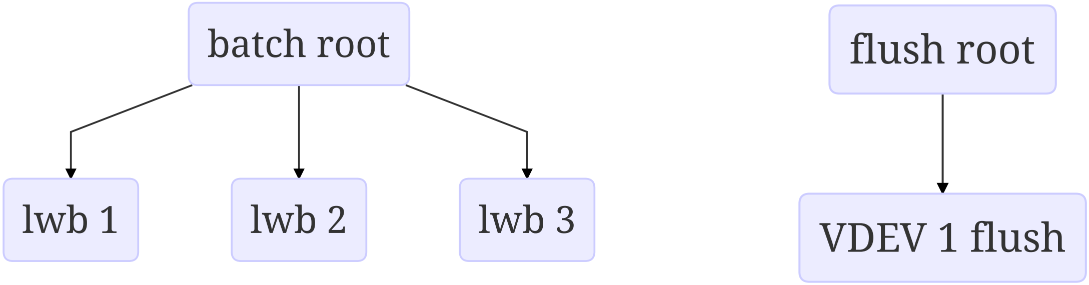
lwb 1

lwb 2

lwb 3

flush root

Example: Before



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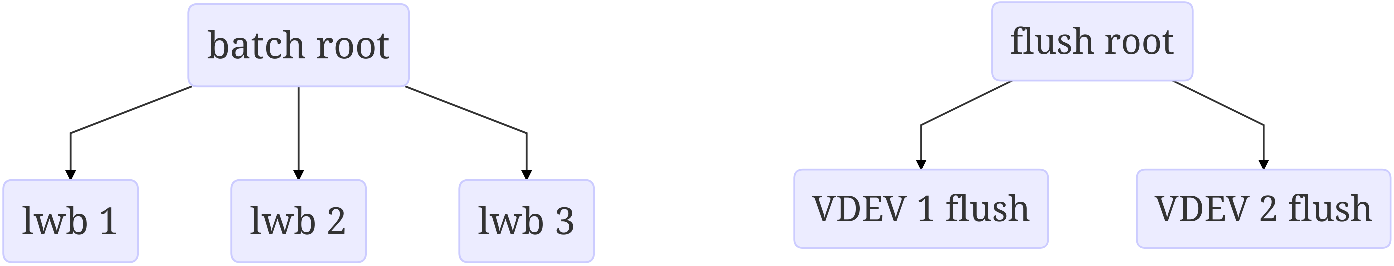


batch root

lwb 1

lwb 2

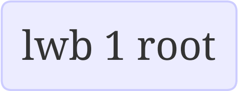
lwb 3

flush root

VDEV 1 flush

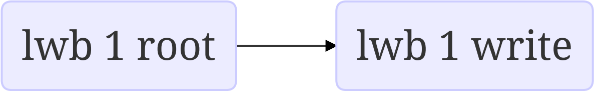
VDEV 2 flush

Example: After



lwb 1 root

Example: After



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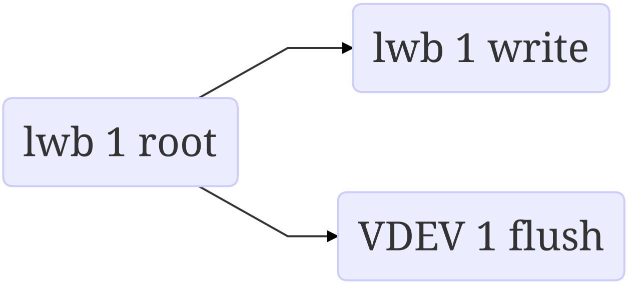

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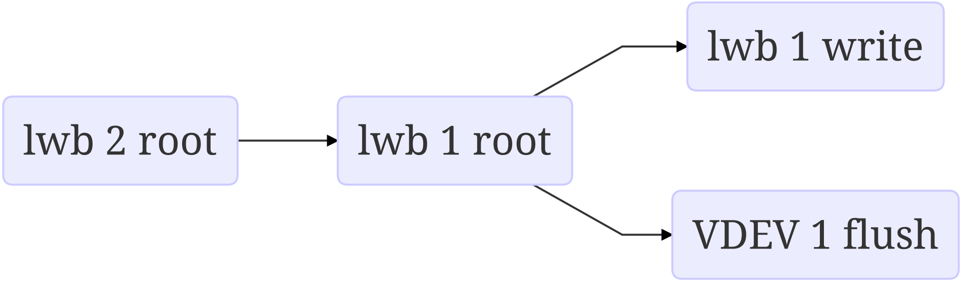

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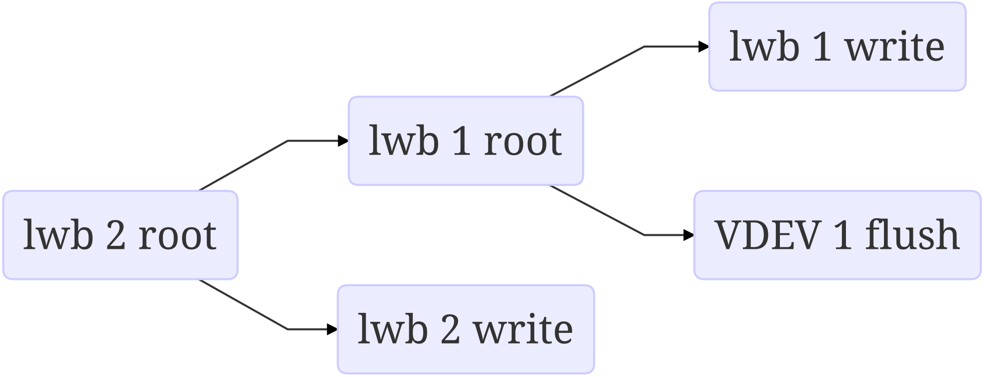

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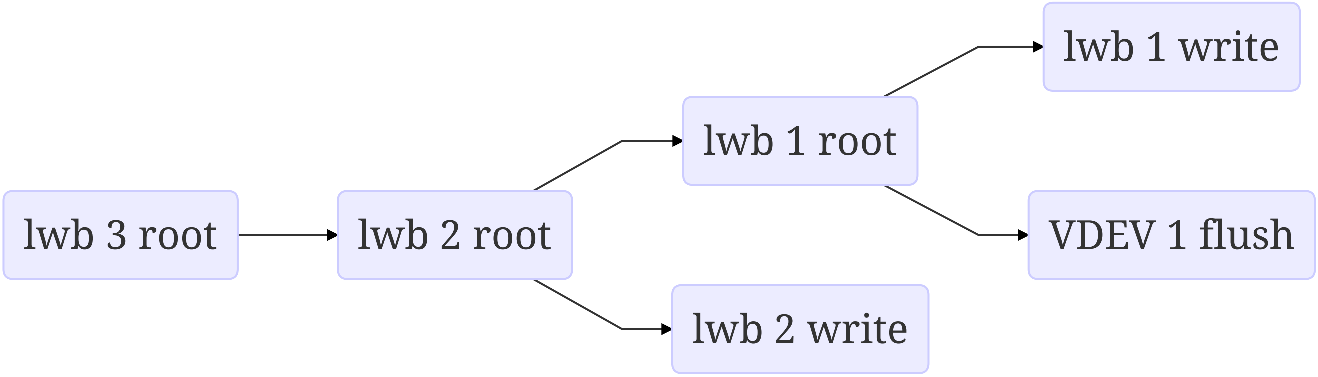

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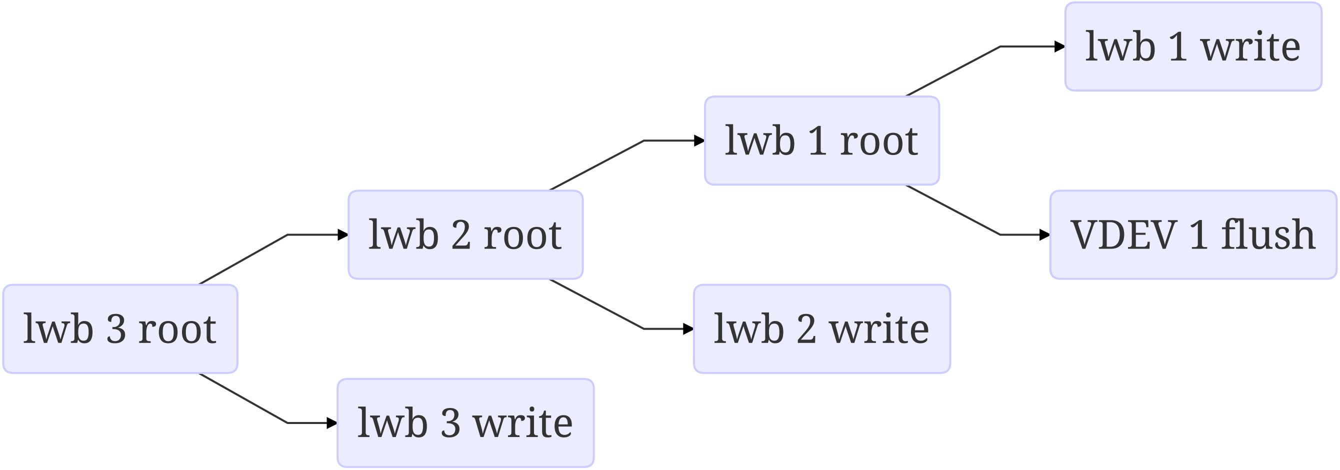

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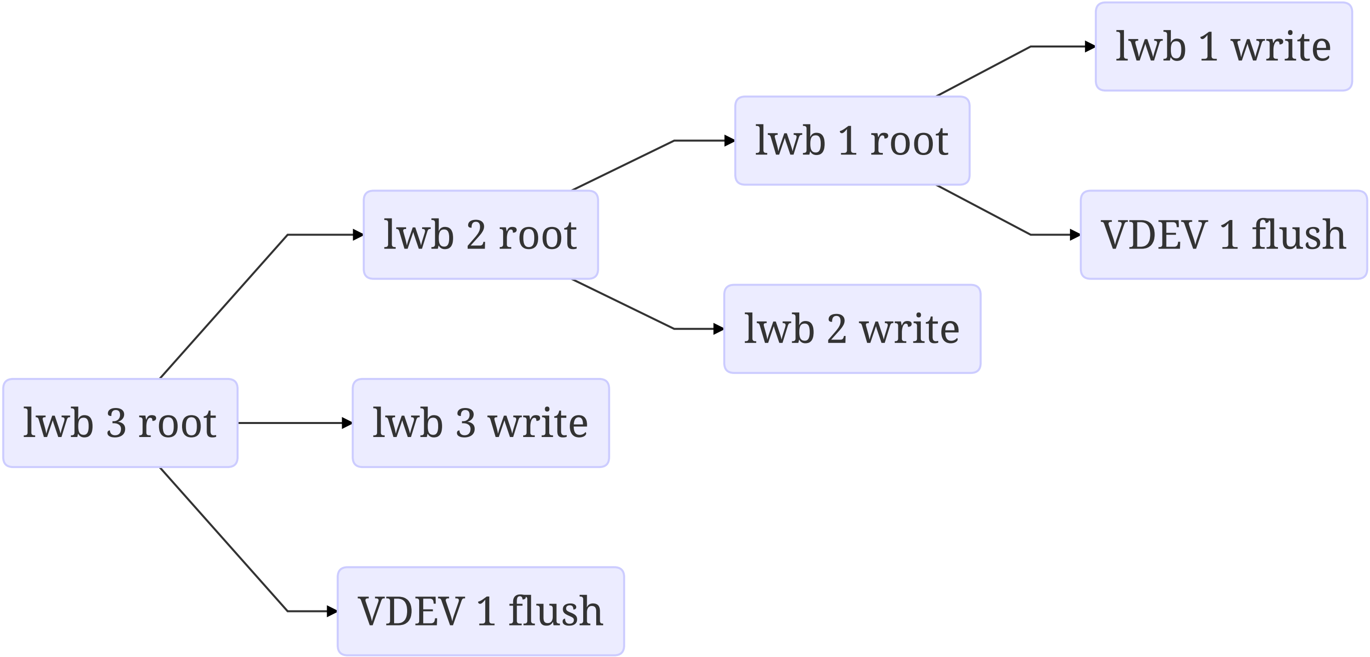

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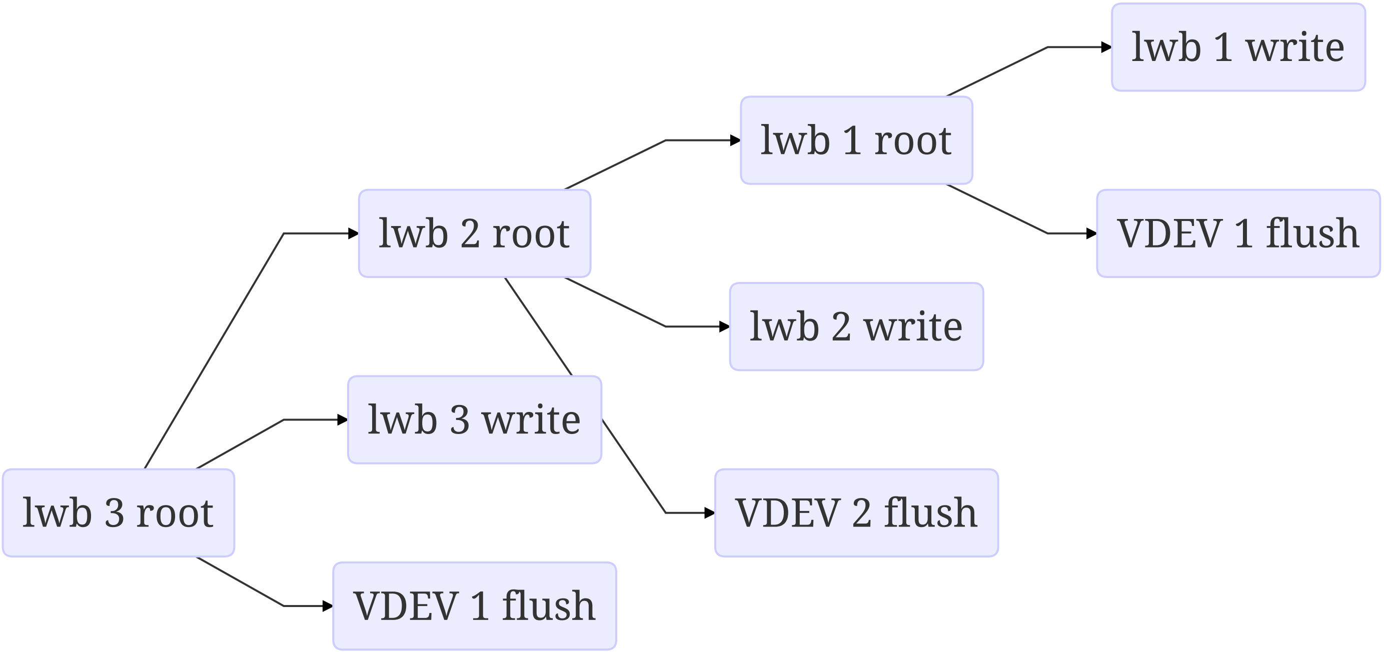

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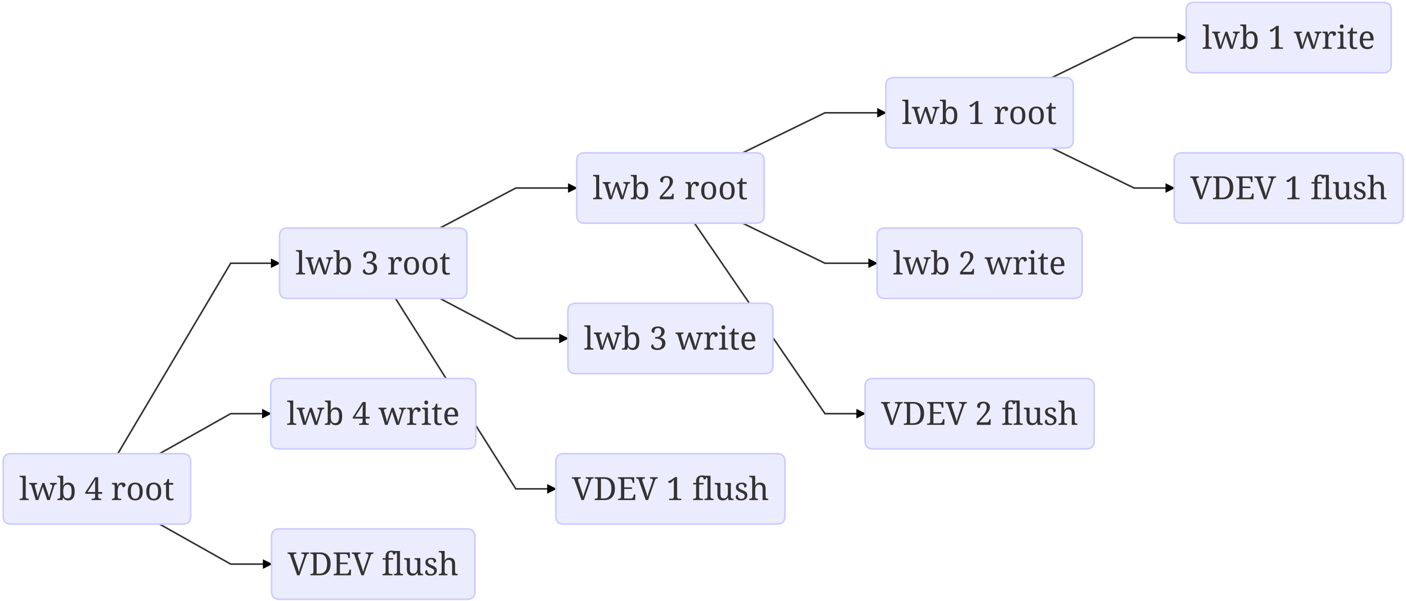

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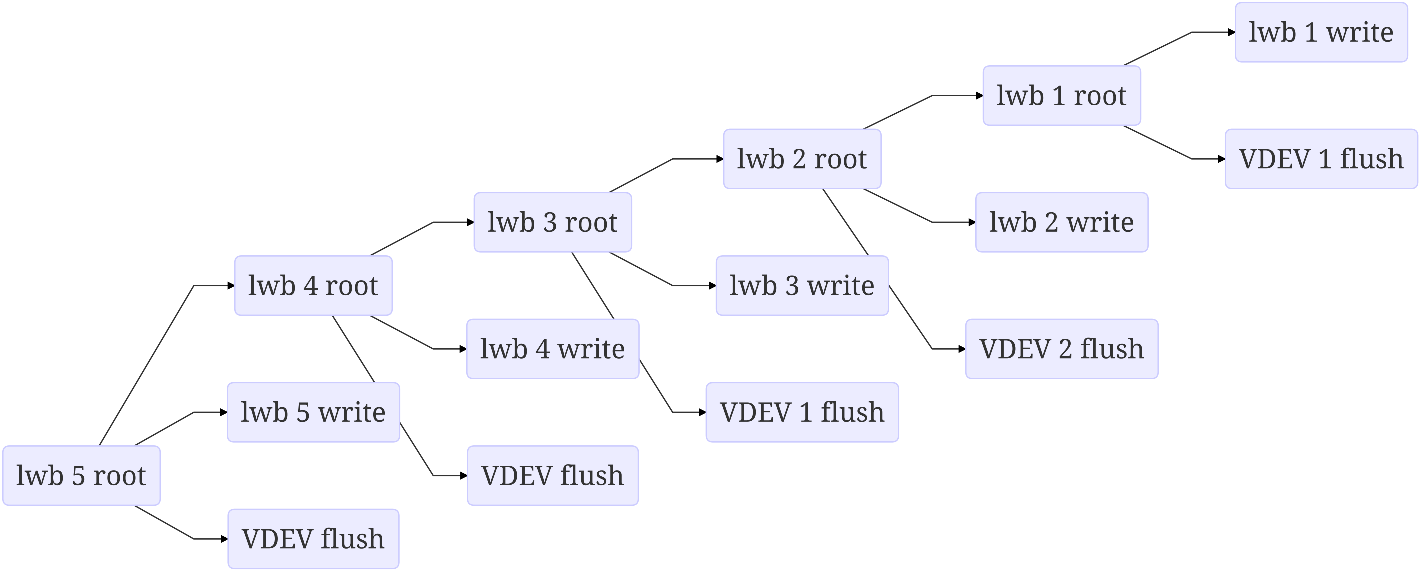

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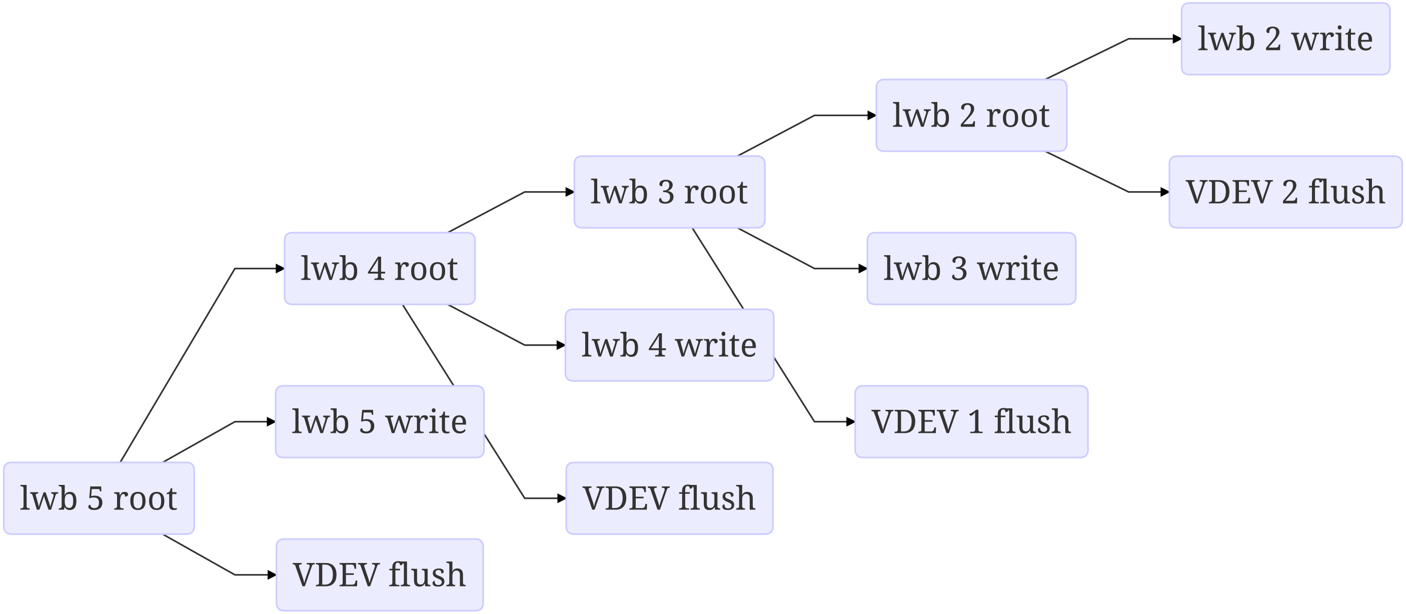

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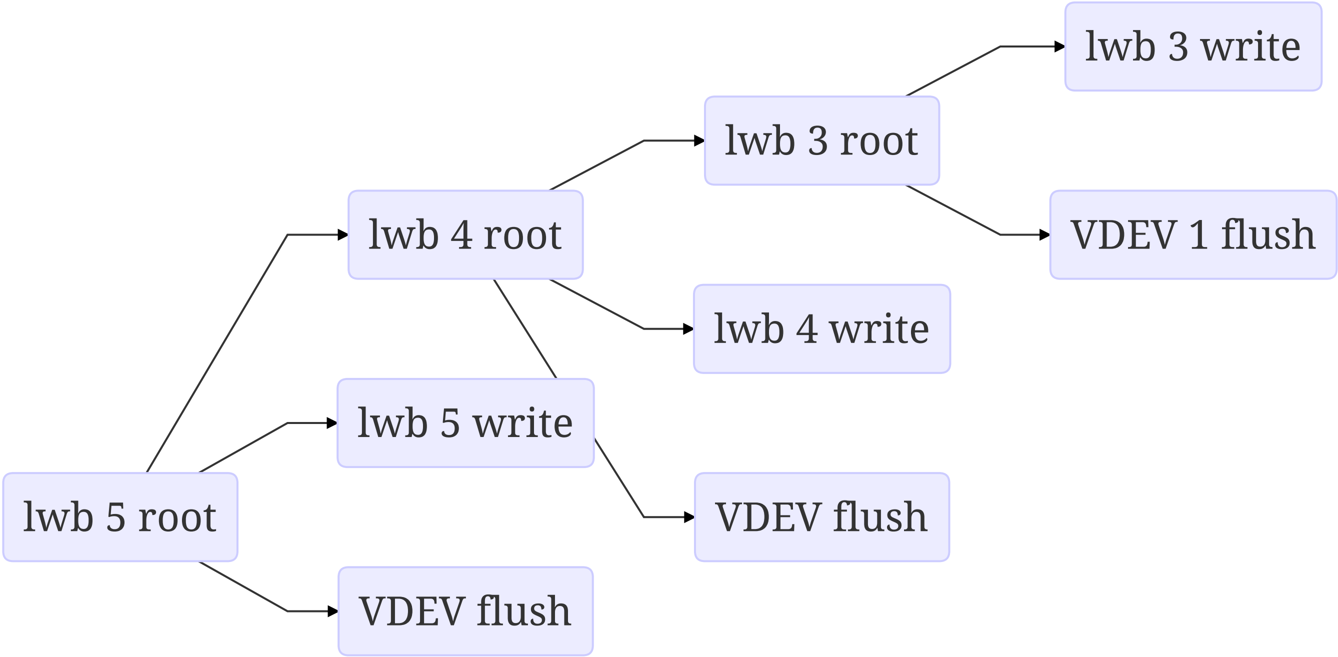
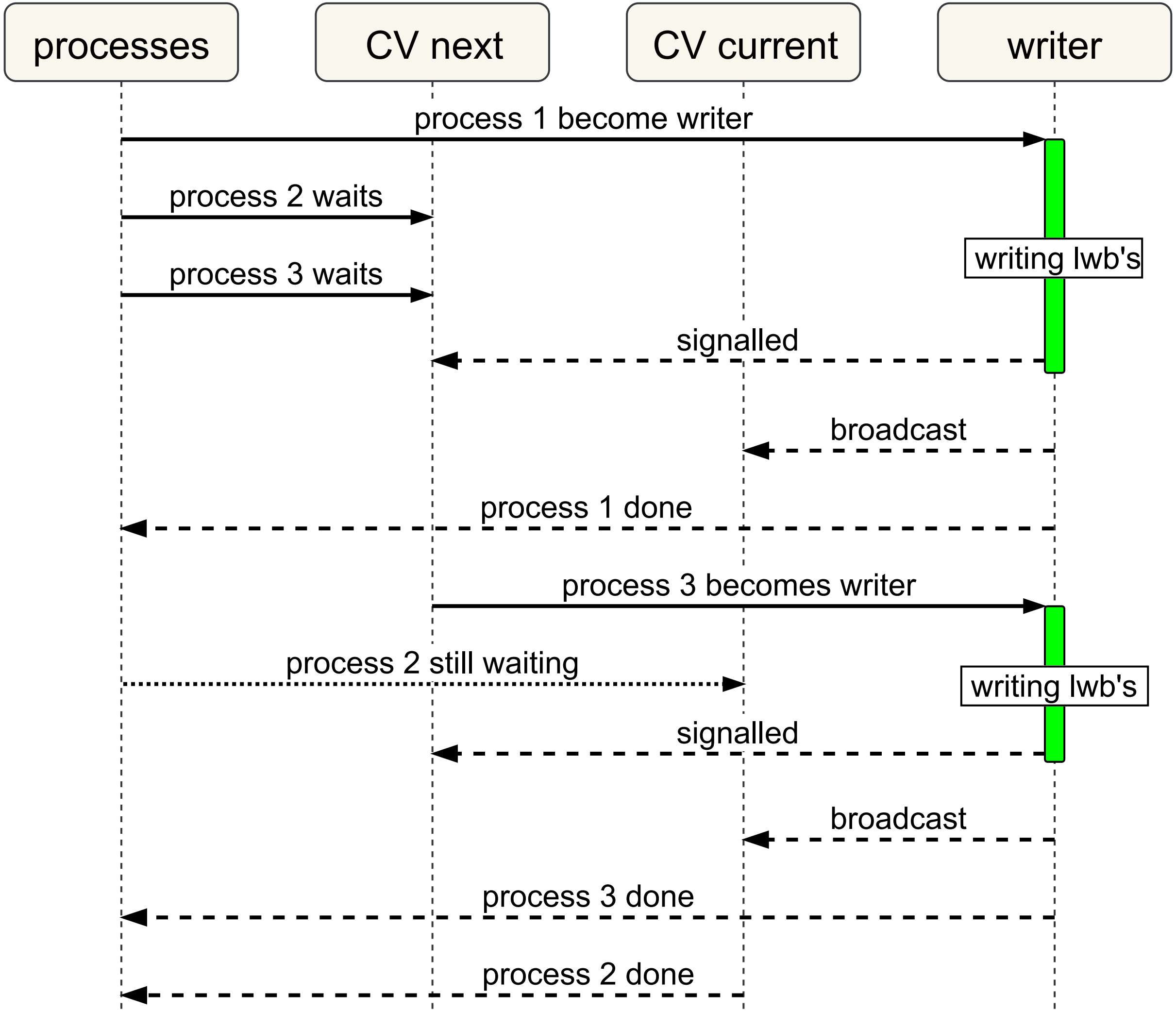


4 – Changes to Waiter Notification

Details: Before

- 2 condition variables (CV), for "current" and "next" batch
- Threads that called `zil_commit`:
    - Assigned to "next batch", wait on next batch's CV
- When "current" batch completes
    1. All threads waiting on "current" signalled, they'd return
    2. One thread waiting on "next" signalled, becomes "writer"
    3. "next" and "current" CV swapped
- Ultimately, these two CVs are the source of original problem

Example: Before



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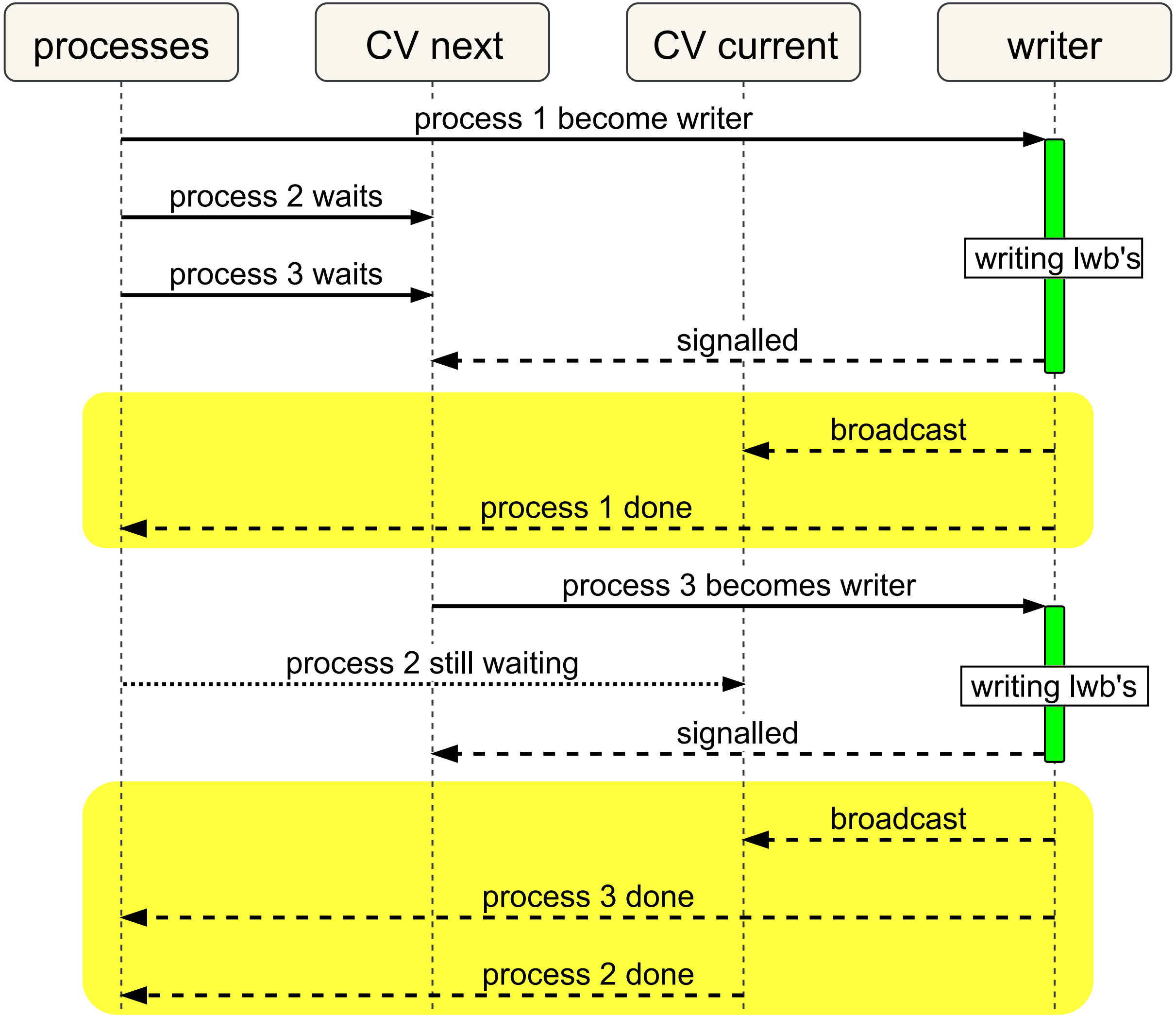
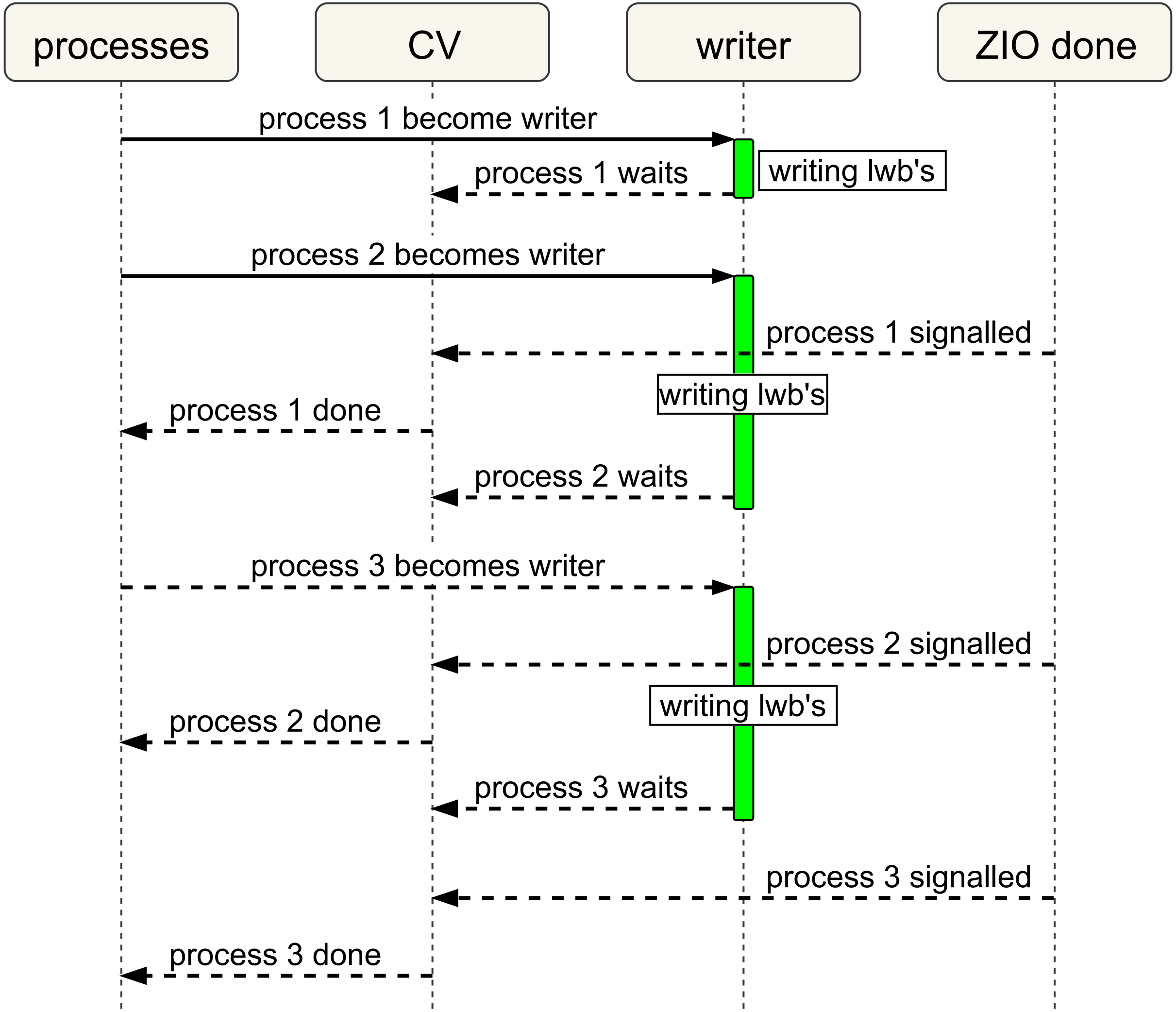


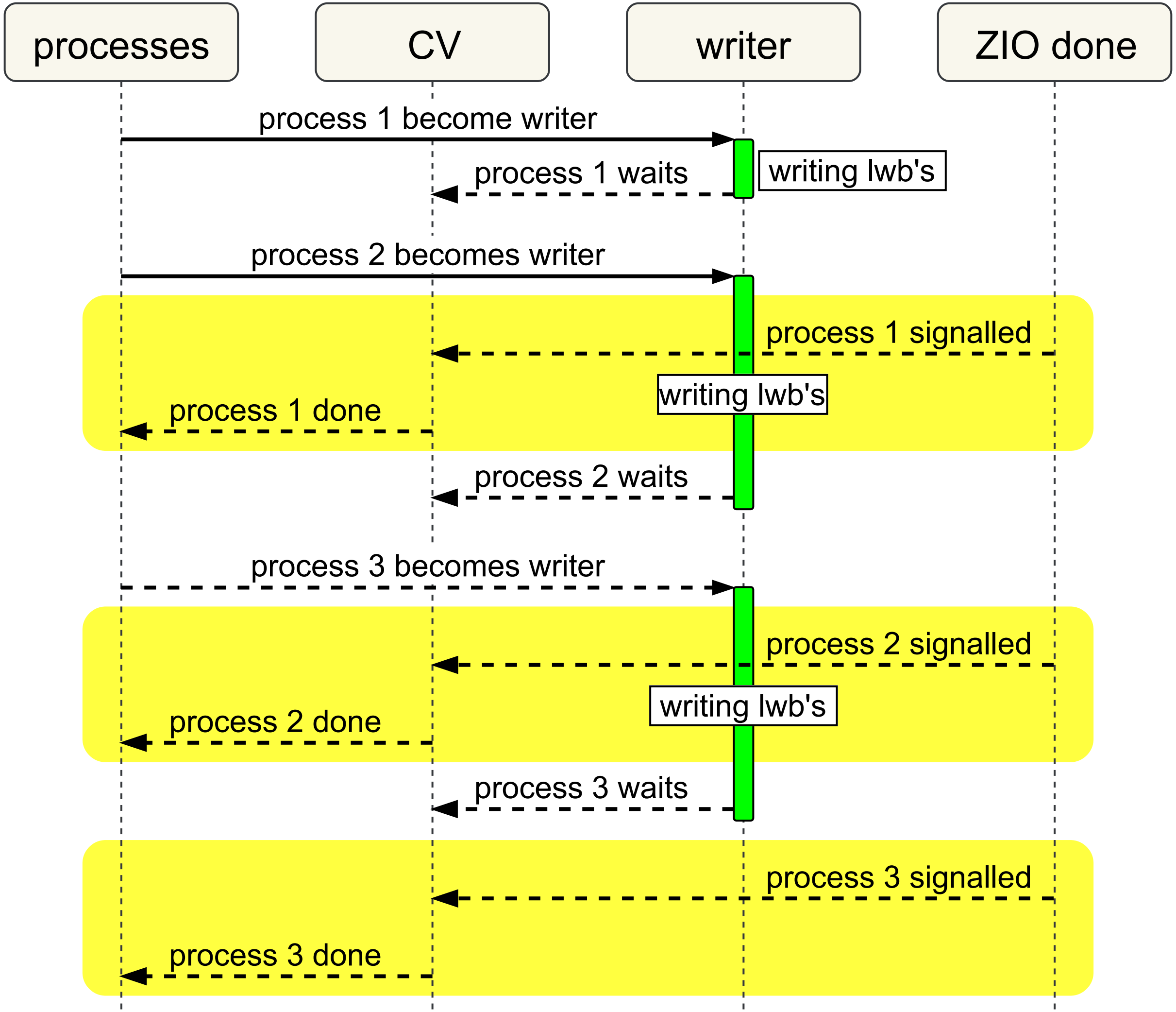
Details: After

- Each time a process calls `zil_commit`:
    - A new CV is allocated for this specific process to wait on
    - A new `TX_COMMIT` itx is inserted into the ZIL itx tree
        - The "commit itx" has a pointer to the process's CV
- When a commit itx is copied to an lwb:
    - No data copied into the lwb's buffer
    - Instead, itx's CV added to lwb's list of CVs
- When lwb's ZIO completes, list of CVs iterated and signalled
    - This is how we map which lwb a process is waiting for

Example: After



Example: After



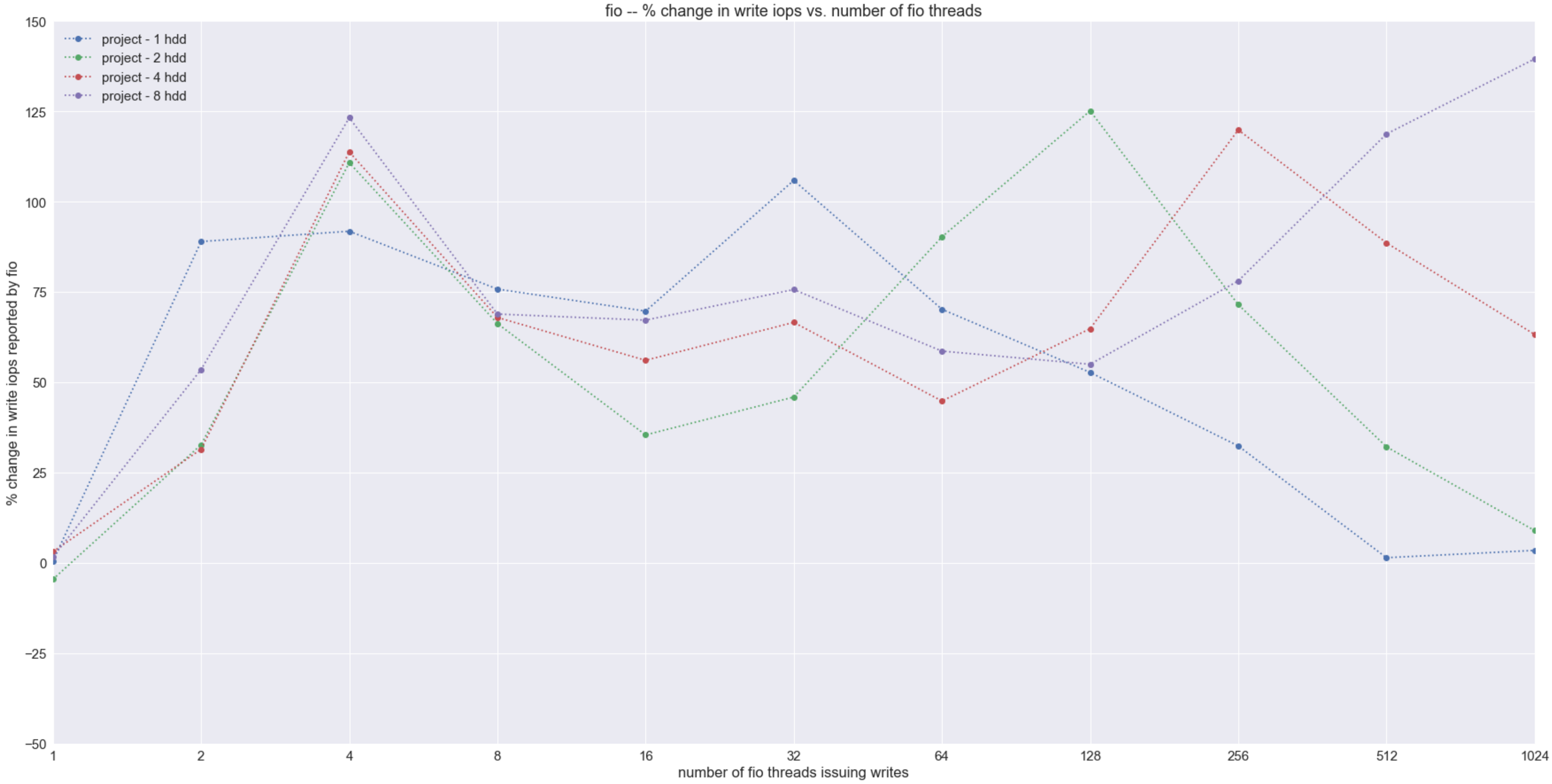
5 – Performance testing and results.

Details

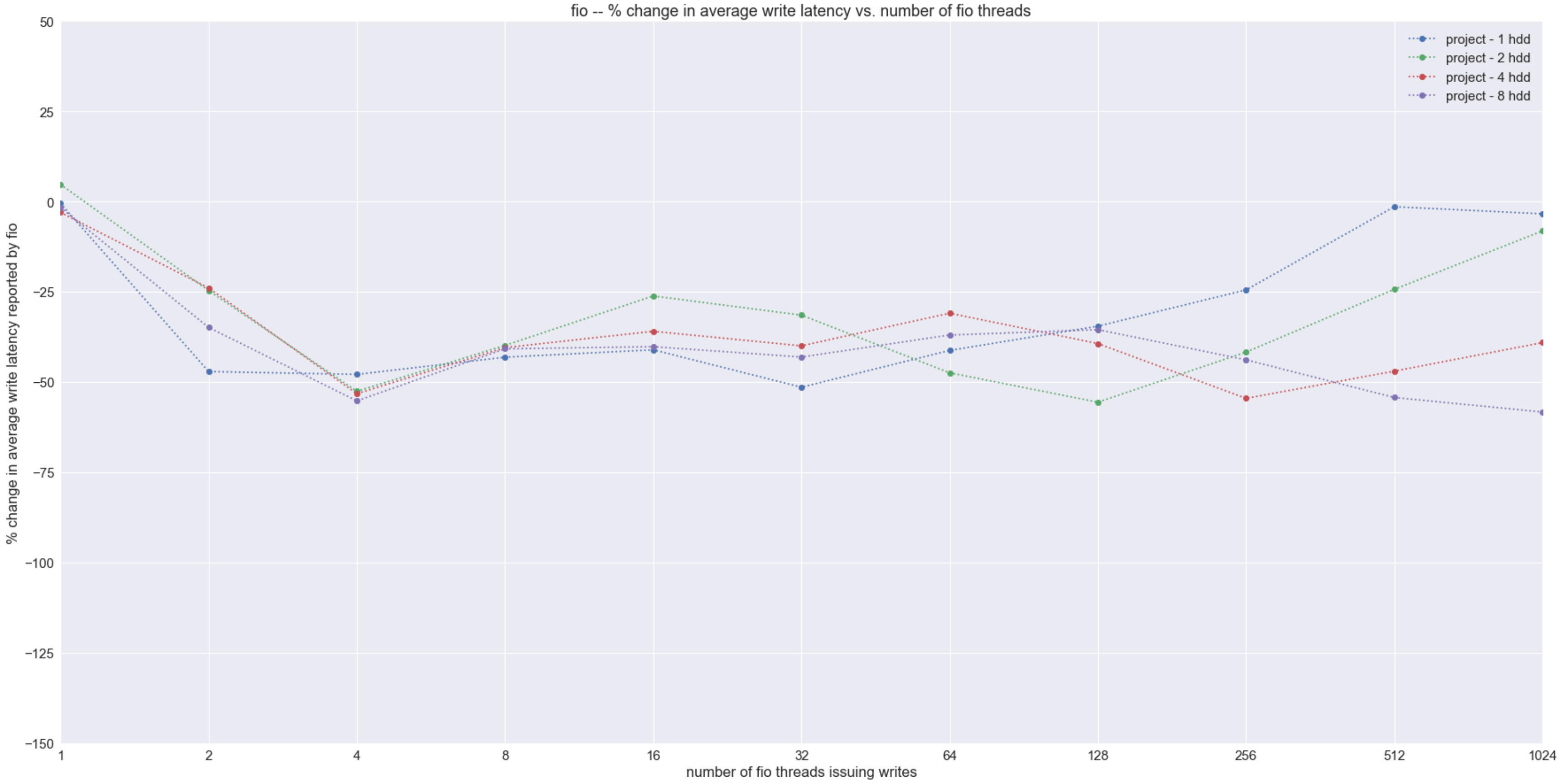
- Two `fio` workloads used to drive a sync write workload
    1. `fio` was trying to perform sync writes as fast as it could
    2. `fio` was trying to perform 64 sync writes per second
- IOPs and latency measured with and without my changes
    - Other metrics also observed (`iostat`, flamegraphs, lwb info, etc.)
- 1, 2, 4, and 8 disk zpools; tested both SSD and HDD
- Full details can be found here

5 – Max Rate Workload – HDDs

% Change IOPs – Max Rate – HDDs

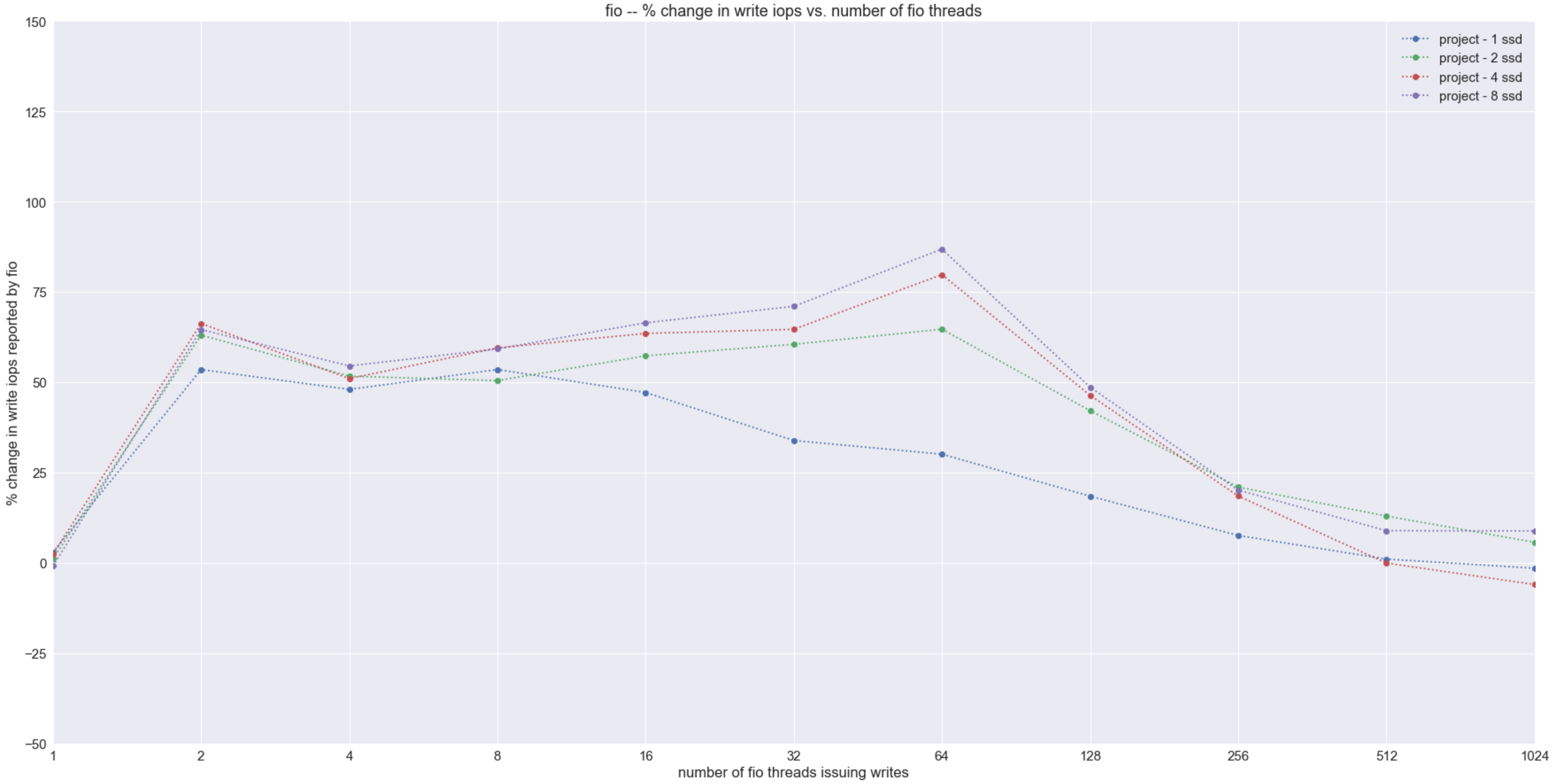


% Change Latency – Max Rate – HDDs

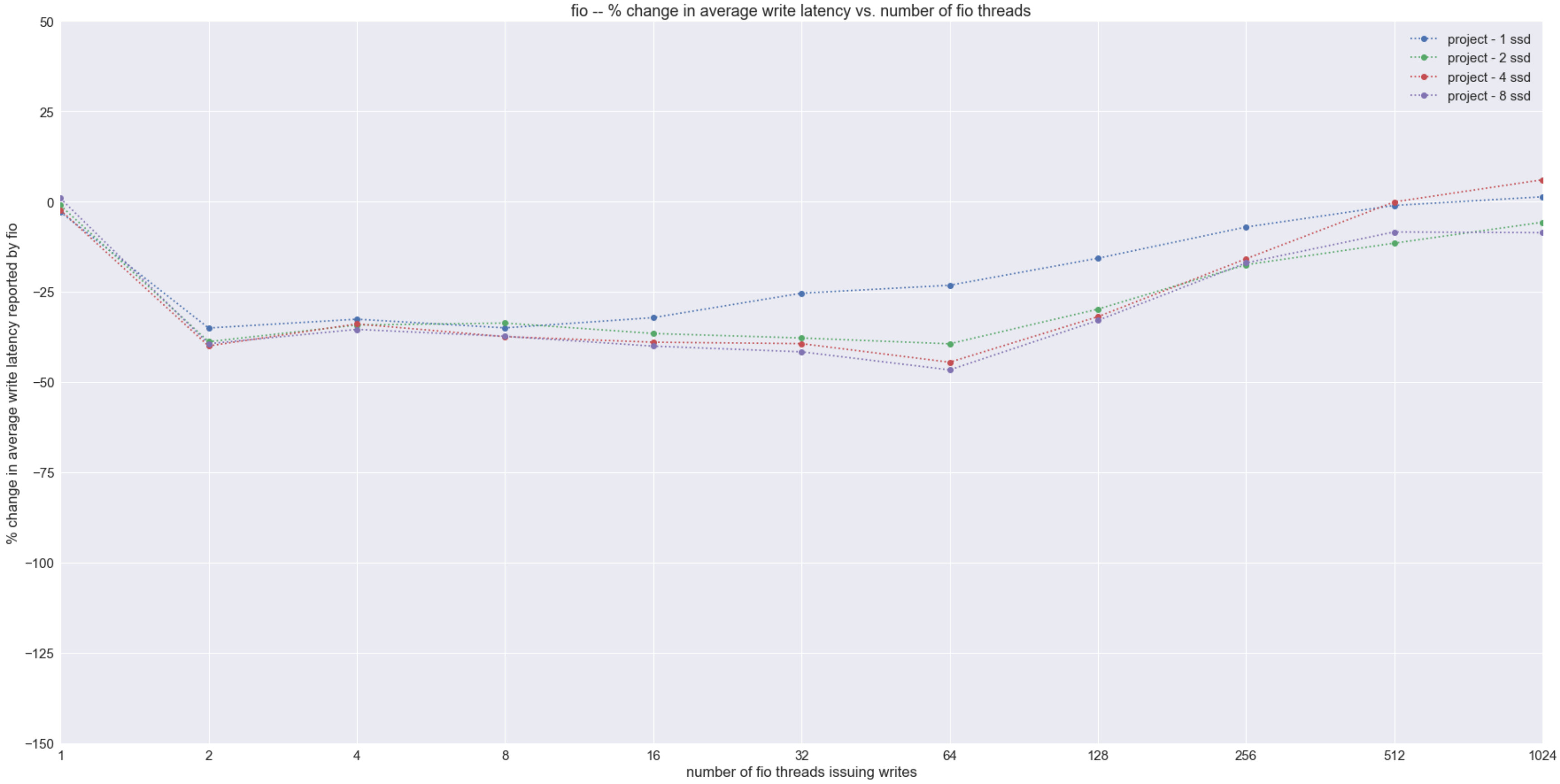


5 – Max Rate Workload – SSDs

% Change IOPs – Max Rate – SSDs

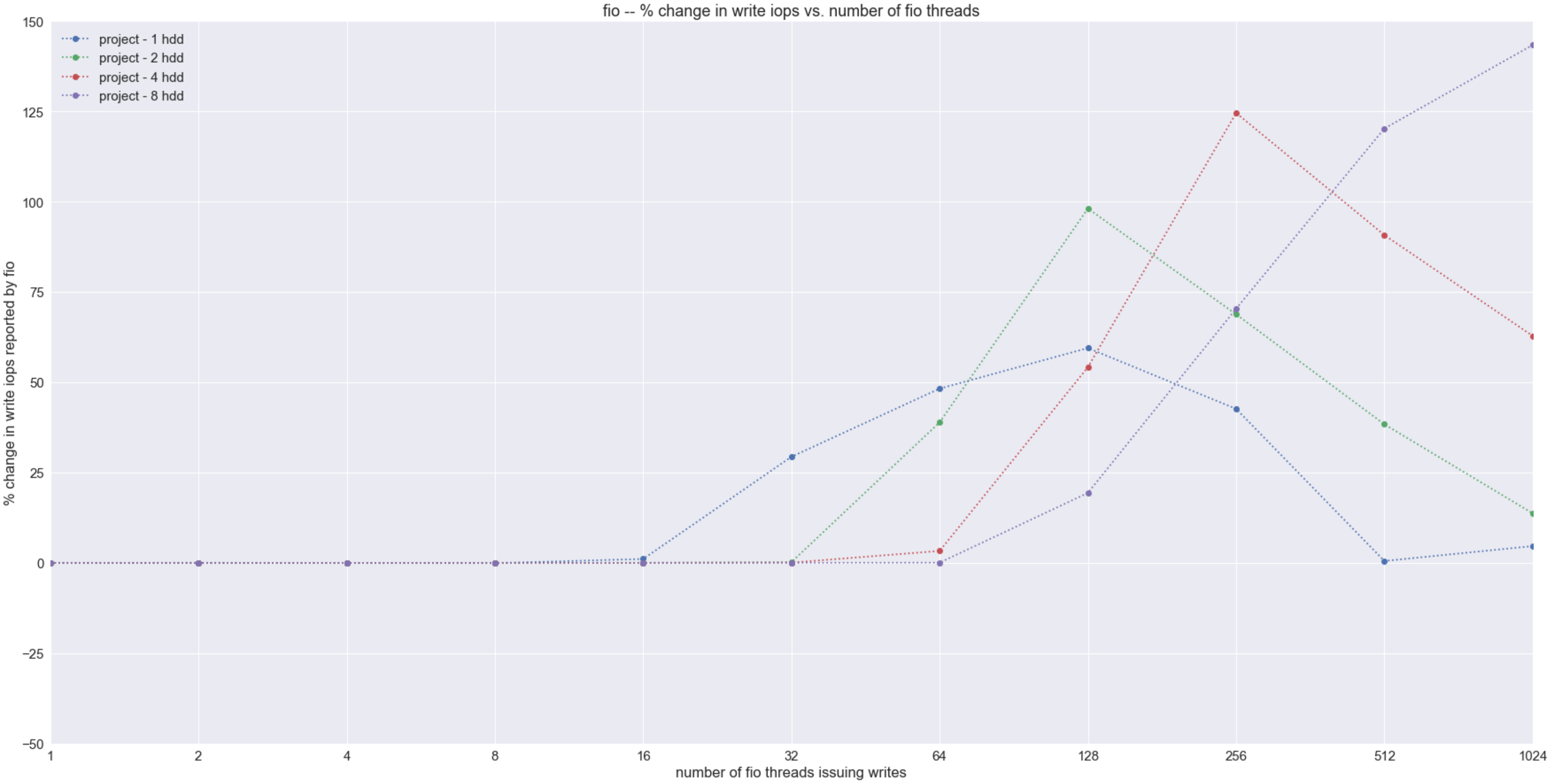


% Change Latency – Max Rate – SSDs

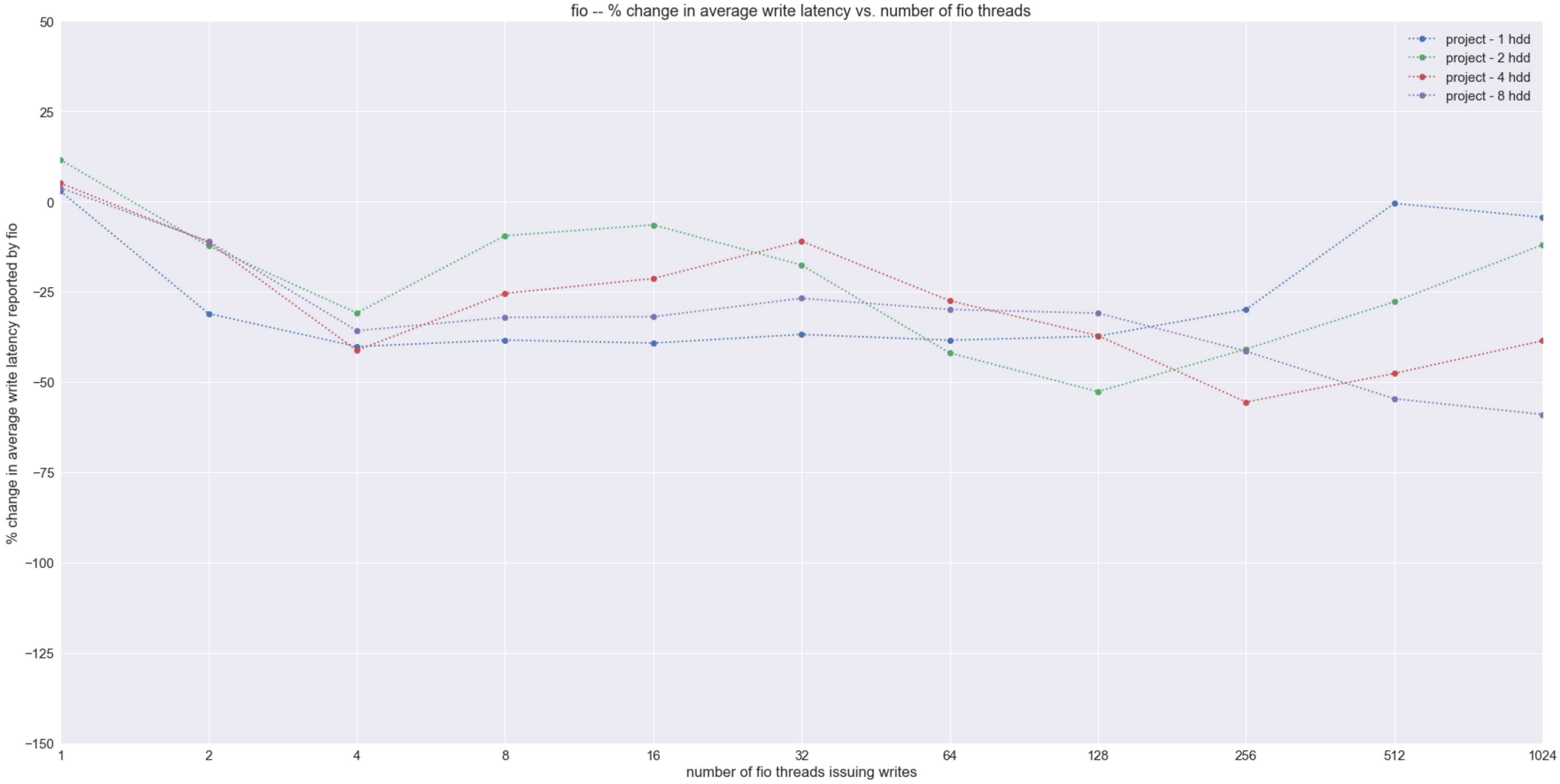


5 – Fixed Rate Workload – HDDs

% Change IOPs – Fixed Rate – HDDs

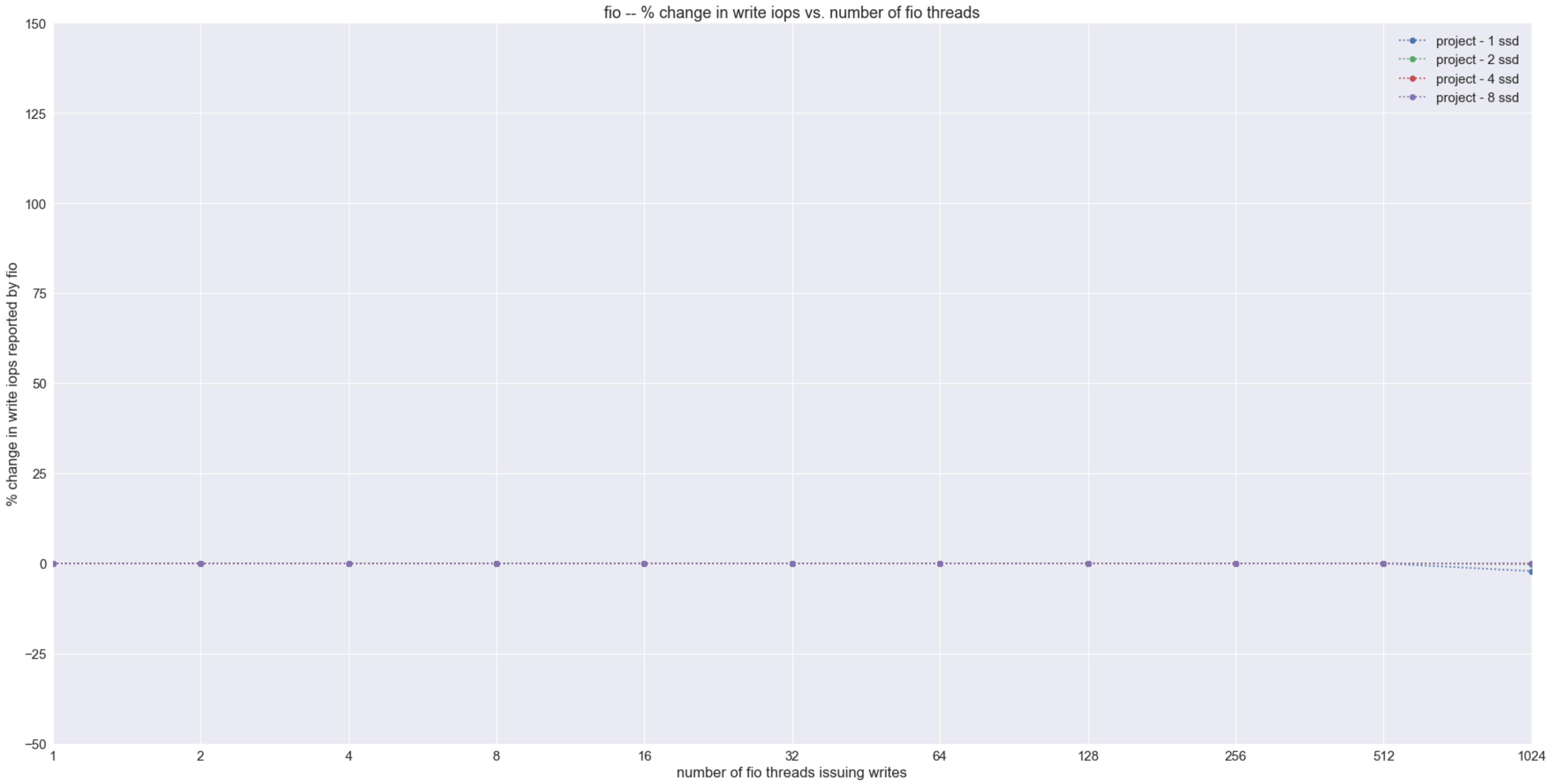


% Change Latency – Fixed Rate – HDDs

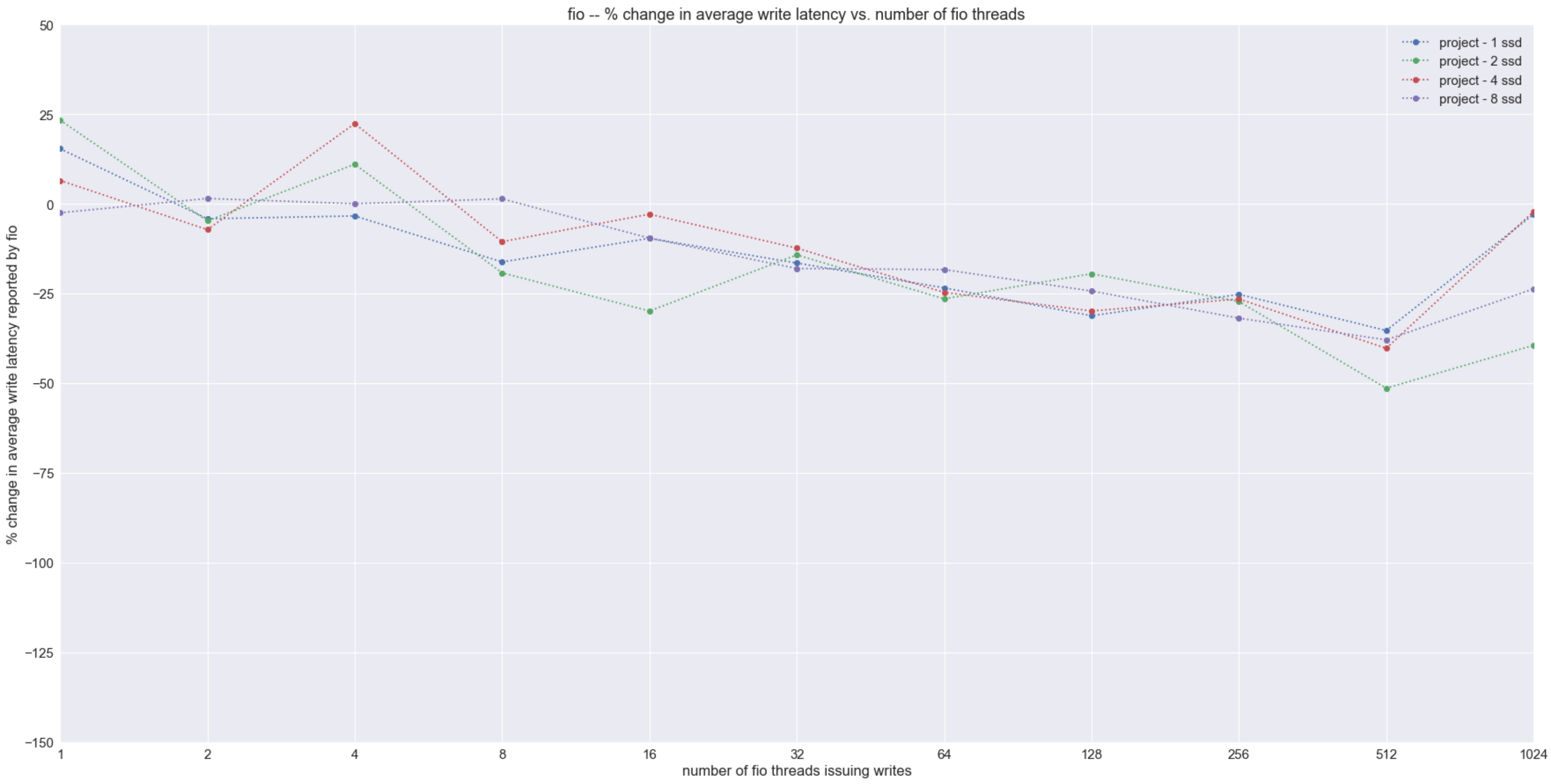


5 – Fixed Rate Workload – SSDs

% Change IOPs – Fixed Rate – SSDs



% Change Latency – Fixed Rate – SSDs



End