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LAD 2021: Lustre Single Stream Performance

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Note on Benchmarks

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- Benchmarks from several sources, primary system:
  DDN AI 400
  1 x Client(1 x XeonGold 6338, 512GB DDR4 3200MHz, 1 x IB-HDR200, , CentOS8.3, MOFED-5.2)
- Best case numbers: IOR with 256 MB I/O size, 4M stripe size

Single Stream Performance: Definitions

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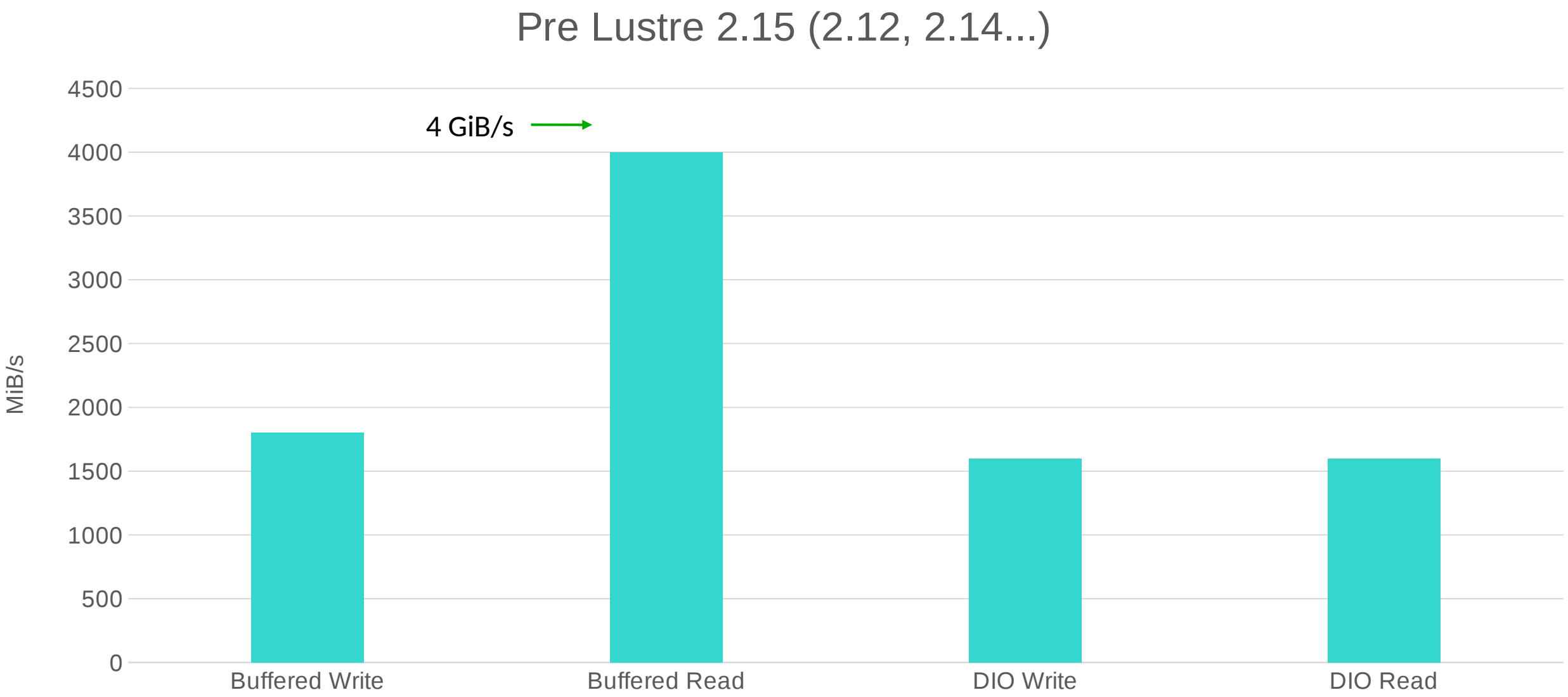
- "single stream": The I/O output of a single userspace process using standard POSIX interfaces
- "How fast can dd go?"

- Interesting because:
  - Foundation of other performance behavior
  - Behavior of one stream creates (or prevents) scalability across many streams
  - Many activities have single stream portions

Single Stream Performance: Where We Started



Single Stream: Current Performance

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- This is **best case**, any I/O size, any stripe/RPC size, etc.
- Limited to ~1.5-2.0 GiB/s for buffered or direct I/O (except for buffered reads)
- Has only increased with CPU speed since ~2012
- NB: Buffered reads 3.5-4.0 GiB/s with parallel readahead

- Not that fast – GPFS is faster, and some object stores much faster
- Why don't we do better? Buffered I/O is hard, but what about direct I/O…?

Direct I/O: Simple

- User provides aligned memory
- No need for memcopy() or allocation of pages in the kernel
- No page cache – don’t have to insert and manage pages
- Much simpler than buffered I/O, much more scalable w/multiple processes
- Expected to be synced to disk after write call completes sync is costly, but makes for simple I/O lifecycle

Direct I/O: Simple, not fast(?)

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- Small direct I/O performs badly
  - cost of sync() is painful for writes
  - no readahead possible for reads (because no cache)
- But … what about large Direct I/O?
- If a user provides (or asks for) a large amount of data, why can't we write or read that data quickly?
- There's no cache to fill, so we should be able to process more rapidly than for buffered I/O
- But Lustre direct I/O doesn't scale with size.

Direct I/O is Serial(!)

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- It turns out Direct I/O RPC issuance is serialized with each RPC sync()'ed before sending others(!)
- Example: User does 16 MiB I/O, Lustre using 4 MiB RPCs:
  Prepare 4 MiB RPC wait for sync() prepare 4 MiB RPC wait for sync() … etc. (Read is similar)
- Time to write (or read) data:
  Prep RPC + sync + prep RPC + sync … = n*(prep RPC + sync), where n is # of RPCs
- Zero parallelism(!)

Parallel Direct I/O

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- Prepare RPC send Prepare RPC send … sync() after all data is sent.
- Send all RPCs and *then* wait. For the 16 MiB I/O and 4 MiB RPCs, we send 4 RPCs.
- Time is:

  rpc … rpc … rpc … rpc
  sync ……..
  sync ……..
  sync ……..
  sync ……..
- Time = n*(create RPC) + sync*1 (all sync()s are in parallel)

Performance with Parallel DIO

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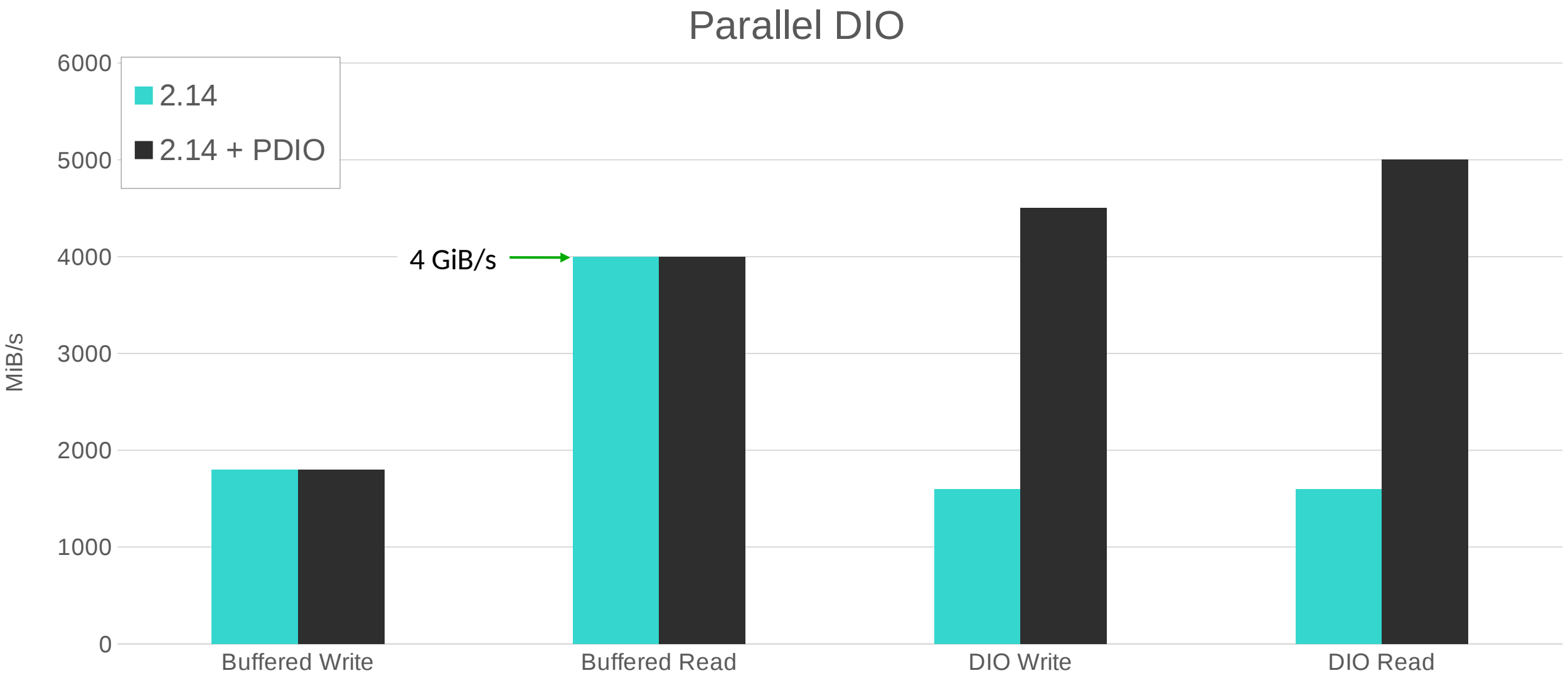

Parallel Direct I/O: First results

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- Results: 4.5-5.0 GiB/s best case (compare to previous 1.5-2 GiB/s)
- This is great! But … can we do better?
- The answer is yes – very much so.

Direct I/O Code Efficiency

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- Direct I/O code was never made efficient - not visible because all time spent waiting for sync() (so more efficient direct I/O code just spent more time waiting for sync())
- Much code shared with buffered (ie, page cache) path – careful page management for caching/concurrent access
- Every page in the page cache has an independent life – can be accessed, updated, or removed by itself, at any time
- Managing page state is expensive – set up, refcounting, locking…
- None of this is required for direct I/O

Direct I/O Code Efficiency

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- Direct I/O pages are not accessible to other threads – they only exist during the I/O, and are not in cache
- No independent life cycle for each page, so (almost) no per-page:
  Locking
  Refcounting
  State management
- There is not **zero** management required for direct I/O pages – but it's close.
- Many small changes to take advantage of this in 2.15… Cuts per page time by ~70%.

Changes (Examples from LU-13799)

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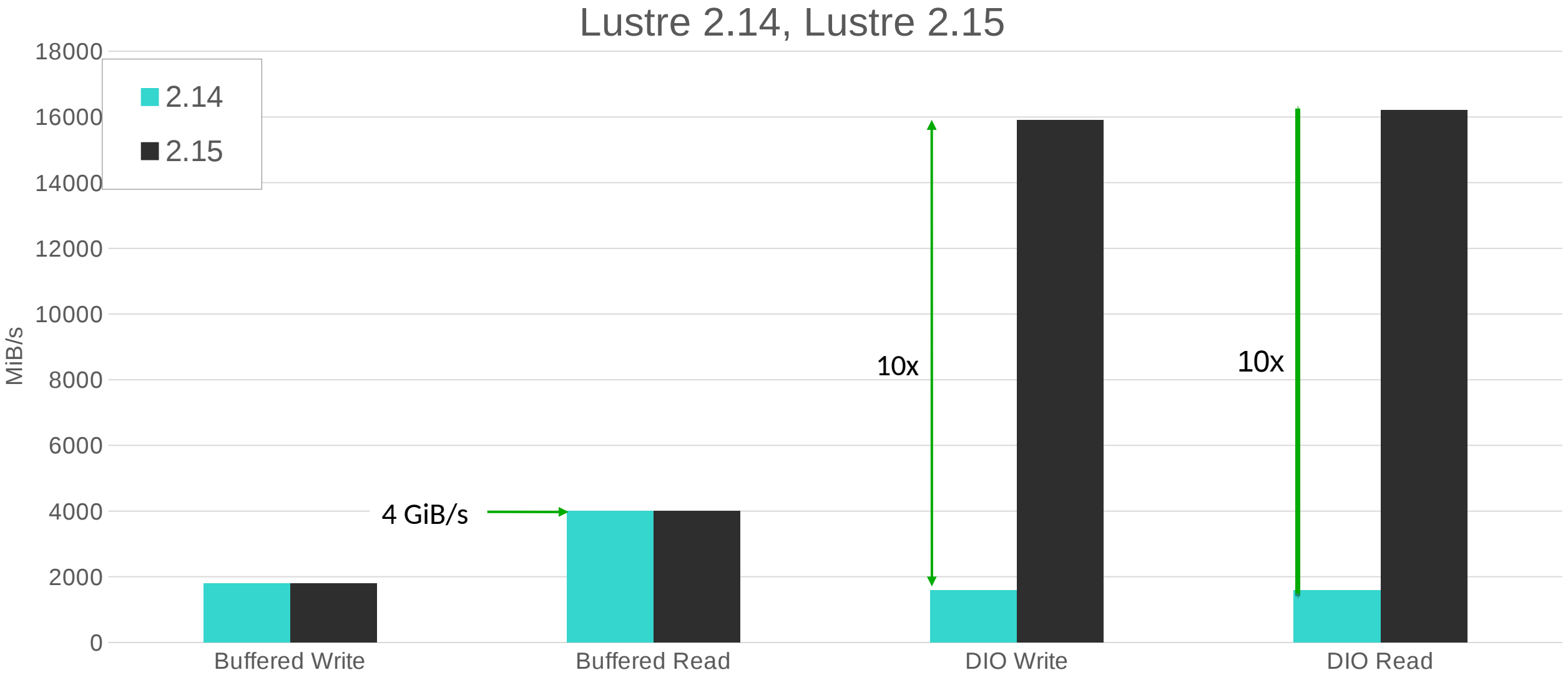
- lov: Cache stripe offset calculation
- llite: Move free user pages
- llite: Implement lower/upper aio
- osc: Always set aio in anchor
- llite: Simplify cda_no_aio_complete use
- osc: Improve osc_queue_sync_pages
- clio: Skip prep for transients
- llite: Adjust dio refcounting
- lov: Improve DIO submit
- llite: Remove transient page counting
- llite: Modify AIO/DIO reference counting
- osc: Simplify clipping for transient pages
- clio: Implement real list splice
- osc: Don't get time for each page

Where We Are


Lustre 2.14, Lustre 2.15
2.14
2.15
MiB/s
18000
16000
14000
12000
10000
8000
6000
4000
2000
0
4 GiB/s
10x
10x
Buffered Write
Buffered Read
DIO Write
DIO Read

What's left?

- Prototype changes to increase batching (many things only need to be done per I/O)
- Changes to remove more page state tracking
- Various small simplifications and code removals
- Some big stuff left, some element of diminishing returns…

2.15, 2.16+: Direct I/O

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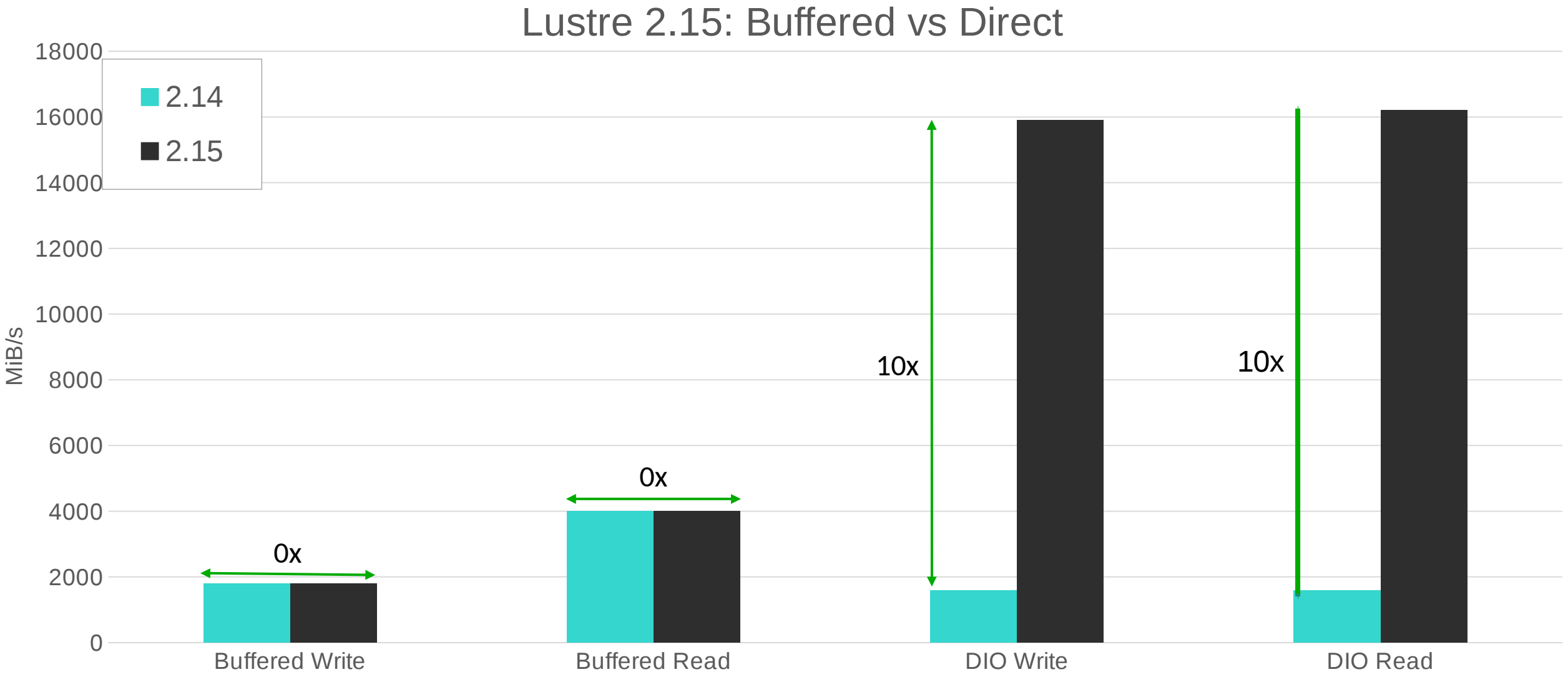
- Currently: ~18 GiB/s (slightly better than graph shows)
- Existing prototype changes to ~25+ GiB/s (2.16?)
- Hard to say final limit. Would prefer not to speculate. Still some headroom.
- Other benefits:
  Direct I/O is lockless(!)
  Improves shared file writes

Buffered I/O: Lagging behind



Performance with I/O Size

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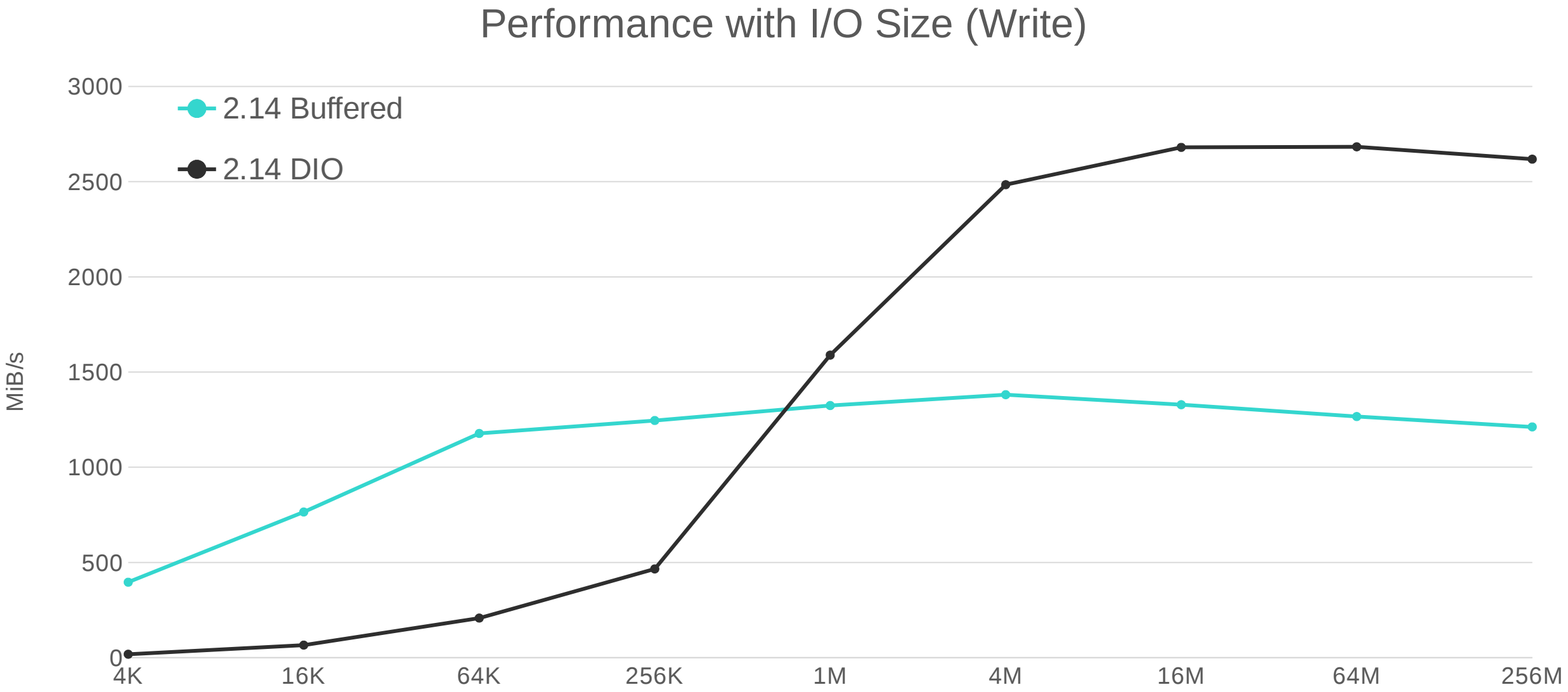

Buffered I/O vs Direct I/O

- Buffered I/O is good at small sizes (aggregation, readahead)
- But doesn’t scale – Direct I/O dominates at larger sizes and in shared files
- Buffered I/O doesn’t scale because of costs of caching (interestingly, **not** memcopy – caching)
- Direct I/O must be aligned – buffered I/O handles alignment inside the kernel (data is still aligned before going on the wire – just done by the kernel)
- But most data is used once: Read once, or written but not read (at least not in the same job)…

Uncached Buffered I/O

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- An ‘uncached’ variant of buffered I/O, where data is copied to a buffer (but not placed in cache), would be **much** faster at larger sizes
- Switch to this **at larger sizes**
- Essentially create a buffer and do direct I/O from that buffer
- Saves expense of placing data in the page cache
- Not as fast as Direct I/O, but much faster than regular buffered I/O (50+% of direct I/O?)
- We can do it – prototyped successfully. (2.16+?)

Wrap Up

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- Direct I/O is serialized at the RPC level, and (it turns out) very inefficient
- 2.15: Direct I/O single stream performance from ~2.0 GiB/s 18 GiB/s
- Future expectations: 20+ Gib/s
- Because Direct I/O is lockless, reduces/removes shared file contention(!)
- Requires using Direct I/O, requiring alignment, has poor performance at smaller sizes

- Future (2.16+):
- Buffered I/O: Cost is mostly in **caching**, not memcopy
- Possible to make a buffered/direct hybrid path: Use buffered at smaller sizes, use new **uncached** buffered I/O at larger sizes
- Much more scalable than existing buffered I/O
- Early prototype

Thank you

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- Thank you for listening.
- See LU-13798, LU-13799 and linked tickets for further details.
- Questions to pfarrell@whamcloud.com

- Quick thanks to Nathan Rutman, Shilong Wang, and Andreas Dilger for assistance and support on this