File Aggregation for Asynchronous Multi-Level Checkpointing

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MOTIVATION

» **Checkpointing serves** numerous **defensive, administrative, and productive** tasks making it a **fundamental I/O pattern** of HPC applications
» Checkpointing involves **large quantities of data being written to stable storage** such as a parallel file system (PFS) ***concurrently***
» Historically, checkpointing is performed **synchronously** – e.g. blocking the application from progress until the checkpoint is persisted to the PFS
  ✓ Eliminates competition for finite resources (CPUs, network bandwidth, memory)
  × Suffers from increasing synchronization overhead at large scale
» **Asynchronous checkpointing** is becoming the default method for checkpointing – e.g. use multi-level storage tiers to capture checkpoints locally (DRAM, NVMe, etc.), then persist them (PFS) in the background concurrently with the application
  ✓ Reduces time the application is ***directly*** blocked
  × Introduces competition for finite resources which may ***indirectly*** block the application

VELOC

» **VELOC** [1] is a state-of-the-art **asynchronous multi-level checkpointing library**
» Natively adopts one of the following flushing strategies:
  » **N-to-N (file-per-process):**
    ✓ Low complexity
    × Oversubscribes I/O resources (metadata servers, storage devices) as N grows
    × Difficult for users to manage
  » **N-to-1 :**
    ✓ Easier for users to manage
    × Contention for storage devices as N grows
    × Data layout is vital

COMPARISON OF FLUSHING STRATEGIES

» **N-to-M chooses a subset of processes (M) as *I/O leaders*** to interact with I/O infrastructure on behalf of all processes
  ✓ Reduces contention for storage devices
  ✓ Reduces metadata concurrency
  × May require communication and/or synchronization
» **N-to-M alleviates serialization bottlenecks of N-to-1** and **over-utilization of resources characteristic of N-to-N**

Strategy	No I/O Locks?	No Communication? (Synchronization)	Scalable?	User Manageability
N-to-N	✓	✓	x	x
N-to-1	x	✓	x	✓
N-to-M	✓	✓	✓	✓

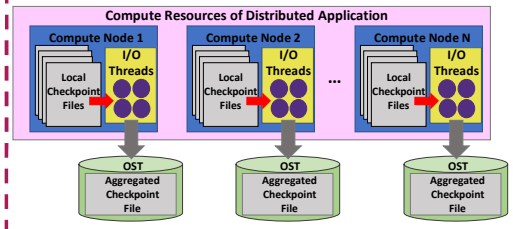
✓ = good, ✓ = depends on implementation, x = bad

CHALLENGES

» Current **aggregation libraries (MPI-IO) are not designed for asynchronous workflows** [5]:
  × High, frequent synchronization costs for collective operations
  × Unbounded resource competition (CPU cores, network bandwidth, memory) with the application
» Multi-threaded implementations are needed to overcome serialization but require synchronization
» How to:
  1. **Avoid I/O locks and contention for storage targets?**
  2. **Reduce synchronization overhead between threads?**
  3. **Minimize impact on concurrently running workloads?**
  4. **Maximize the I/O throughput of the checkpoint flush?**

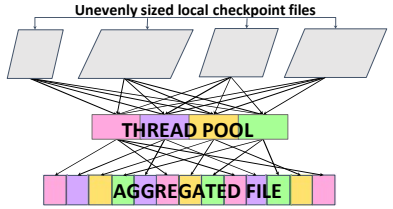
CONTRIBUTIONS

» **Prototype an optimized, tunable flushing aggregation implementation** within VELOC
  » Selects M compute nodes (tunable by user) as I/O leaders
  » Leaders flush checkpoints to the PFS in fine-grained chunks avoiding over-utilization of resources
» Remove communication overhead between compute nodes by letting **M = # compute nodes** and combine local checkpoints of co-located processes on the same compute node into 1 file
» Analyze performance of our aggregation strategy compared to expected peak performance
» Compare our aggregation to state-of-the-art aggregation libraries ADIOS2 [3] and an optimized implementation of MPI-IO (GenericIO [2])



FLUSH STRATEGY

Spawn a number of I/O threads equal to the number of local files which process each file sequentially in small chunks (64 MB) until all local data has been transferred



✓ Eliminates busy-waiting or idleness on fast threads
✓ Low memory footprint avoids interference with concurrent workloads
× Incurs OS-level and thread-level synchronization costs
× Contention for OSTs (mitigated if stripe size = chunk size)

TESTING METHODOLOGY

» To compare our aggregation strategy to other aggregation libraries/strategies we **develop a checkpointing microbenchmark** using 64 processes across 8 nodes (8 processes per node); each process checkpoints 1 GB (+/- 20%)
» **Find expected maximum aggregated throughput when aggregating eight 1 GB files of data** (= local data per compute node in our microbenchmark) to 1 file with 8 threads via:
  » Linux system utility call `dd` (a wrapper for sys. call `write`)
  » OpenMP microbenchmark [4]
» We calculate the maximum aggregate throughput via:

$$\frac{\text{total checkpoint size } [GB]}{\text{slowest thread } [s]}$$

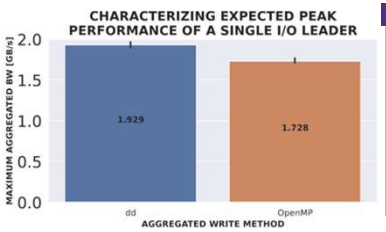
» Run each experiment 3 times and average
» We configure ADIOS2 to flush files under the same constraints as our aggregation strategy (e.g. 8 I/O threads and 64 MB buffers)

SYSTEM OVERVIEW

» Experiments run on Oak Ridge National Lab's **Frontier**:
  » Lustre parallel file system with maximum aggregated bandwidth of 14 TB/s
  » 1350 OSTs : 450 OSS'
  » 9,408 computes nodes each with a 64-core AMD EPYC CPU and 2 hardware threads per core
» VeloC version 1.7
» GenericIO git tag 20190417
» ADIOS2 version 2.8.3

RESULTS

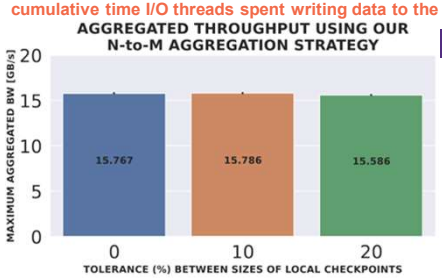
This experiment profiles the expected peak performance of an I/O leader using `dd` and OpenMP



Profiling OSTs with dd and OpenMP

» **dd shows an expected maximum aggregated bandwidth ~2 GB/s** per I/O leader when the block size = 64 MB
» **OpenMP benchmarks show a maximum aggregated BW of ~1.7 GB/s**
» In our 8 node scenario, **we expect that our aggregation should be able to obtain a maximum aggregated BW of ~16 GB/s** (2 GB/s * 8 nodes)

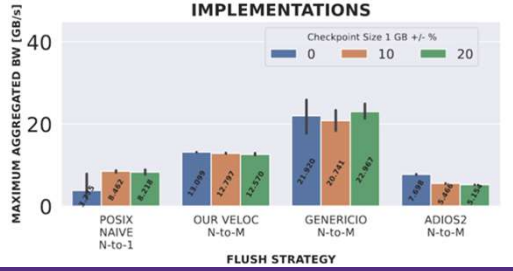
This experiment uses fine-grained timers to calculate cumulative time I/O threads spent writing data to the PFS



N-to-M Fine-Grained Flush Analysis

» **Our aggregation method performs better than expected, obtaining close to 16 GB/s**
» Likely due to the fact **our aggregation strategy is aware of timing imbalance among threads**
» In dd and OpenMP each thread flushes exactly 1 GB of data, however, our strategy allows **faster threads to process more work, ultimately finishing faster**

This test we compare our aggregation strategy against the naive N-to-1 aggregation currently supported by VELOC and two state-of-the-art aggregation libraries, GenericIO and ADIOS2, and calculate throughput via the slowest application process to persist the checkpoint



THROUGHPUT COMPARISON OF AGGREGATION STRATEGIES

» Because the throughput is now measured from the application side, which includes other function calls, we see a small drop in throughput for our aggregation strategy
» **Our aggregation strategy outperforms N-to-1 aggregation by ~1.5x**
» **Because GenericIO is synchronous** (no regard for concurrent workloads), **they get ~2x higher throughput** by mapping the full file into memory and reducing their collective calls, but this is unsuitable for asynchronous workflows like VELOC checkpointing
» **We obtain ~2.5x higher throughput than ADIOS2**

CONCLUSIONS

» **We implement a novel aggregation strategy within VELOC** and profile it's performance on Frontier
» **Our aggregation strategy obtains slightly better throughput than expected**, likely due to our thread management which anticipates timing imbalance among threads
» **GenericIO implements synchronous C/R, blocking the application 30x longer compared to VELOC**, however, because they can fully utilize memory, they achieve 2.5x higher throughput
» **Compared to ADIOS2 we obtain 2.5x greater throughput under the same I/O thread constraints** (8 threads and 64 MB buffers)

FUTURE WORKS

» In modern HPC systems compute nodes outnumber OSTs (on frontier this number is ~7:1), thus, N-to-M is not an ideal aggregation pattern for larger applications
» In the future, we experiment with our aggregation strategy when M << # of compute nodes utilized by application, which will introduce greater synchronization costs and communication overhead
» Evaluate the effects our and other aggregation strategies has on different resource-bound (e.g. memory, compute, or communication) concurrently running workloads

REFERENCES

[1] VELOC – https://veloc.readthedocs.io/en/latest/
[2] GenericIO – https://git.cels.anl.gov/hacc/genericio
[3] ADIOS2 – Adios2.readthedocs.io/
[4] OpenMP Benchmark – https://github.com/FTHPC/HPC_IO_PROFI LING
[5] https://arxiv.org/pdf/2112.02289.pdf

Get in contact:

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