

Libraries

Parallel Storage Systems

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Libraries

Review

Introduction

Example: SIONlib

Example: NetCDF

Example: HDF

Example: ADIOS

Performance Assessment

Summary

- What happens if a file opened with `MPI_MODE_SEQUENTIAL` is accessed non-sequentially?
 1. MPI will fall back to regular access without optimization
 2. MPI will print a warning
 3. Undefined behavior

- What is the point of collective I/O operations?
 1. Synchronize all processes in a communicator
 2. Provide additional information for optimizations
 3. Order operations by rank

- Which benefits do non-contiguous I/O operations have?
 1. Many small operations are faster to execute
 2. Multiple operations can always be merged into a contiguous one
 3. Fewer operations cause less overhead

- Which guarantees does MPI-IO's semantics provide?
 1. Operations can be overlapping and concurrent
 2. Operations can be non-overlapping but concurrent
 3. Operations can be overlapping but non-concurrent
 4. Operations have to be non-overlapping and non-concurrent

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Performance Assessment

Summary

- POSIX and MPI-IO can both be used for parallel I/O
 - Both interfaces are not very comfortable to use
- Low-level interfaces are problematic for scientific applications
 - Exchangeability of data is important
 - POSIX and MPI-IO only offer limited portability
 - Implementing parallel I/O is complicated
 - Byte- or element-based access is cumbersome
 - Achieving high performance is difficult
 - In-depth knowledge about storage system is necessary

- I/O libraries provide additional functionality
 - Self-describing data allows exchanging data more easily
 - Data can be read and interpreted without prior knowledge
 - Internal structuring increases flexibility
 - Such data formats allow storing multiple variables
 - Abstract I/O definitions make it easier for developers
 - I/O calls do not have to be added to the code manually
- Performance problems can be avoided using optimized libraries
 - Strict semantics and missing optimizations can degrade performance

- Benefits
 - Data is more portable
 - Usability is increased
 - Development is made easier
- Drawbacks
 - Introduces additional software layers
 - Interaction between layers becomes more complex

- Some libraries are focused on improving performance
 - SIONlib
- There are multiple self-describing data formats
 - NetCDF (Network Common Data Form)
 - HDF (Hierarchical Data Format)
- Abstract I/O definitions are rather special
 - ADIOS (Adaptable IO System)

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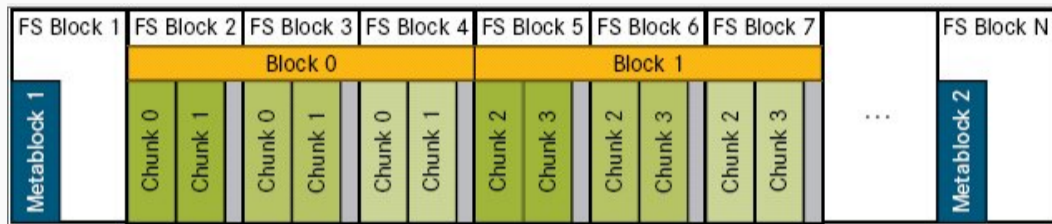
Example: ADIOS

Performance Assessment

Summary

- SIONlib offers efficient access to process-local files
- Accesses are mapped to one or a few physical files
 - Number of files depends on what promises better performance
 - Files are aligned to file system's blocks/stripes
- Access should be as backwards compatible as possible
 - Wrappers for `fread` and `fwrite`
 - Opening and closing files requires special functions

- What is the goal of aligning accesses to file system stripes?
 1. Bypassing read-modify-write overhead
 2. Reducing or eliminating locking overhead
 3. Better support for collective I/O operations



[SIONlib, 2021]

- Data of a process is kept within a file system block
 - File system blocks are separated into chunks
 - Multiple file system blocks are grouped into a block
- Metablock 1: Static metadata (written on open)
- Metablock 2: Dynamic metadata (written on close)

- numfiles: Number of physical files (-1 for automatic detection)
- chunksize: Maximum size of a write
- fsblocksize: Size of a file system block (-1 for automatic detection)

```
1  int fd;
2  FILE* fp;
3
4  fd = sion_paropen_mpi(..., &numfiles,
5                        ..., &chunksize,
6                        &fsblocksize,
7                        ..., &fp, ...);
8
9  for (...) {
10     fwrite(..., fp);
11 }
12
13 sion_parclose_mpi(fd);
```


- SIONlib offers multiple access modes
 - Collective open using `sion_paropen_mpi`
 - Works similar to `MPI_File_open`
 - Individual open using `sion_open_rank`
 - Allows accessing the chunks of a specific process
 - Serial access using `sion_open` and `sion_close`
- Mapping and alignment are handled intelligently
 - Exclusive use of individual file system blocks by processes
 - Performance is improved at the cost of potentially unused space due to padding
 - Mapping to internal file layout is handled transparently
 - Application developers can focus on their problem at hand

- SIONlib is focused on performance and works around deficiencies in file systems
- Too many files can have negative impacts on performance
 - Creating and opening many files requires significant metadata performance
 - File systems are typically not designed for large file and directory counts
- Too few files can also degrade performance due to locking
 - Necessary to minimize locking using appropriate file layouts and access patterns

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Performance Assessment

Summary

- Developed by the Unidata Program Center
 - University Corporation for Atmospheric Research
- Project started in 1989
 - Based on NASA's Common Data Format
- Mainly used in scientific applications
 - Most commonly used in climate science, meteorology and oceanography
- Consists of libraries and data formats

- There are four data formats
 1. Classical format (CDF-1)
 2. Classical format with 64 bit offsets (CDF-2)
 3. Classical format with full 64 bit support (CDF-5)
 4. NetCDF-4 format
- NetCDF's data formats are open standards
 - CDF-1 and CDF-2 are international standards of the Open Geospatial Consortium
- CDF-1, CDF-2 and CDF-5 are independent formats
 - NetCDF-4 uses the underlying HDF5 format

- Initially no support for parallel I/O when using CDF-1 and CDF-2
 - Lead to the development of Parallel-NetCDF with an incompatible interface
- Since NetCDF-4 there is support for parallel I/O via HDF5
 - Parallel I/O was limited to the NetCDF-4 format
- Recent versions support parallel I/O for all formats
 - NetCDF-4 is supported via HDF5
 - CDF-1, CDF-2 and CDF-5 are supported via Parallel-NetCDF

- NetCDF has bindings for a wide range of programming languages
 - C, Fortran, C++, Java, R, Perl, Python, Ruby etc.
- Data formats are independent of the used architecture
 - Automatic conversion according to endianness etc.
- NetCDF supports groups and variables
 - Groups contain variables, variables contain data
 - Flat hierarchy since groups cannot contain groups
- Additional attributes can be attached to variables

- NetCDF supports multi-dimensional arrays
 - char, byte, short, int, float and double
 - Since CDF-5: ubyte, ushort, uint, int64 and uint64
 - NetCDF-4: ubyte, ushort, uint, int64, uint64 and string
- Dimensions can be arbitrarily large
 - Only one unlimited dimension in CDF-1, CDF-2 and CDF-5
 - Example: Matrix can only grow in the time dimension
 - Multiple unlimited dimensions in NetCDF-4
 - Requires a more complex data formats (provided by HDF5)


```
1 netcdf ... {
2 dimensions:
3     time = UNLIMITED ; // (8760 currently)
4 variables:
5     double time(time) ;
6         string time:units = "days" ;
7         string time:long_name = "Julian_date" ;
8
9 // global attributes:
10     string :Conventions = "None" ;
11     string :creation_date = "Wed Jul 16 12:52:44 CEST 2014" ;
12 }
```

- ncdump can be used to inspect the data

- There are two major cases when reading data
 1. File structure is unknown (different application etc.)
 - Available groups and variables have to be determined
 2. File structure is known (same application, documentation)
 - Groups and variables can be accessed directly using their names
- 1. File is opened using `nc_open`
 - Parallel access with `nc_open_par`
- 2. Group IDs can be queried via `nc_inq_ncid`
- 3. Variable IDs can be queried using `nc_inq_varid`
- 4. Variables are read with `nc_get_var`
- 5. File is closed via `nc_close`

- Self-describing nature of NetCDF requires two modes
 - Define mode: Automatically active after creating a file
 - Data mode: Active after opening an existing file
- Define mode allows changing the file's structure
 - For example, adding dimensions, attributes and variables
 - Some settings can only be changed directly after definition
 - Including compression, endianness, error correction and fill values
- Data mode allows storing data
- NetCDF-4 changes the mode automatically and on demand
 - Can be done manually via `nc_redef` and `nc_enddef`

- Parallel-NetCDF is an alternative implementation for parallel I/O
 - Supports CDF-1, CDF-2 and CDF-5
- Developed by Northwestern University and Argonne National Laboratory
 - Developer overlap with MPI-IO and OrangeFS
- Interface itself is not compatible with NetCDF
 - NetCDF-4 can make use of Parallel-NetCDF

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- HDF consists of data formats and libraries
 - Allows managing self-describing data, similar to NetCDF
- Current version is HDF5
 - HDF4 is still actively supported
- Earlier versions had problems with their interface
 - Application programming interface was complicated to use
 - Limitations like 32 bit offsets etc.

- HDF supports groups and data sets
 - Data sets store data as multi-dimensional arrays
 - Groups can be used to structure the namespace
 - Groups and data sets are similar to directories and files
- Groups can contain both data sets and further groups
 - Leads to a hierarchical namespace, similar to POSIX
- Attributes can be attached to data sets and groups
 - For instance: Physical units, minimum, maximum etc.

- Objects can be accessed using POSIX-like paths
 - Example: /path/to/dataset
 - Path can be used to describe data
- HDF files are self-describing
 - Can be opened without a-priori knowledge about the structure and content
 - Attributes allow interpreting the actual data

- Data sets are multi-dimensional arrays of base data types
 - Integer, float, character, bit field, opaque, enumeration, reference, array, variable-length and compound
- Data sets have certain properties
 - Size, precision, endianness etc.
- Arrays can have multiple unlimited dimensions

```
1 HDF5 "... " {
2   GROUP "/" {
3     ATTRIBUTE "creation_date" {
4       DATATYPE H5T_STRING {
5         STRSIZE H5T_VARIABLE;
6         STRPAD H5T_STR_NULLTERM;
7         CSET H5T_CSET_ASCII;
8         CTYPE H5T_C_S1;
9       }
10    DATASPACE SIMPLE { ( 1 ) / ( 1 ) }
11  }
12 }
13 }
```

- h5dump can be used to inspect the data (like ncdump)

- HDF stores data differently depending on the used programming language
 - Data is stored row-major (according to the C conventions)
 - Fortran data (column-major) is converted automatically

1	2	3
4	5	6
7	8	9

3×3 array

1	2	3	4	5	6	7	8	9
---	---	---	---	---	---	---	---	---

Row-major storage (C)

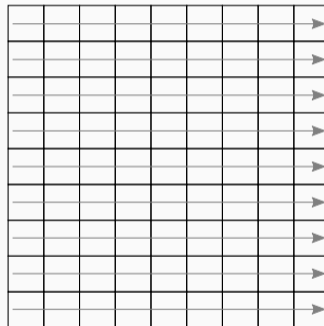
1	4	7	2	5	8	3	6	9
---	---	---	---	---	---	---	---	---

Column-major storage (Fortran)

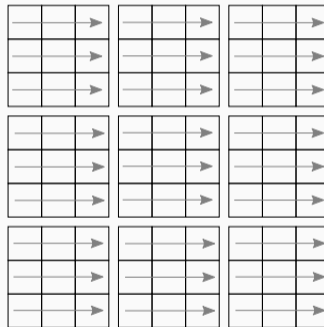
- How would you read Fortran data into a C application?
 1. Use non-contiguous data types
 2. Read sequentially and transpose in memory
 3. Read individual elements in row-major order

- Chunking splits up data sets into smaller portions
 - Required for features such as compression and other filters
- Chunking allows extending data in all dimensions
 - Not easily possible when using contiguous storage
- Enables optimizations not possible when stored contiguously
 - Data can be aligned to stripes or allow efficient column-major access
- Chunking also causes some overhead
 - Chunk index has to be managed efficiently
 - Often results in lower performance than contiguous storage

- Data sets are stored contiguously
 - Simple layout with little overhead
- Data set can be extended in one direction
 - Other directions can be mapped to a static size



- Data sets are split up into chunks
 - Can be extended in multiple directions
 - More complex management
- Chunks are read or written completely
 - HDF5 uses a chunk cache internally



- Which chunk size would you choose when compressing data?
 1. 64 KiB
 2. 1 MiB
 3. 64 MiB
 4. 1 GiB

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Summary

- ADIOS provides an abstract I/O interface
 - No byte- oder element-based access to data
 - ADIOS directly supports application data structures
- ADIOS has been designed for high performance
 - It is used in a wide range of scientific applications
 - Performance is increased using caching, merging of operations etc.

- ADIOS1 allows specifying an I/O configuration via an XML file
 - XML contains a description of relevant data structures
 - Code is automatically generated from this abstract description
- Allows developers to work on a high level of abstraction
 - No need for dealing with the middleware or the file system
 - Some changes to the I/O configuration do not require a recompilation

```
1 <adios-config host-language="C">
2   <adios-group name="checkpoint">
3     <var name="rows" type="integer"/>
4     <var name="columns" type="integer"/>
5     <var name="matrix" type="double" dimensions="rows,columns"/>
6   </adios-group>
7   <method group="checkpoint" method="MPI"/>
8   <buffer size-MB="100" allocate-time="now"/>
9 </adios-config>
```

- Variables are combined into groups
 - Each group can have a separate I/O method
- Allows optionally setting buffer sizes etc.

```
1 adios_open(&adios_fd, "checkpoint", "checkpoint.bp", "w", MPI_COMM_WORLD);  
2 #include "gwrite_checkpoint.ch"  
3 adios_close(adios_fd);
```

- Code is generated by the gpp.py script
 - gread_checkpoint.ch and gwrite_checkpoint.ch
- Developers have to include the appropriate header
 - Variable names etc. have to match ADIOS's generated code

```
1 adios_groupsize = 4 \  
2                 + 4 \  
3                 + 8 * (rows) * (columns);  
4 adios_group_size (adios_handle, adios_groupsize, &adios_totalsize);  
5 adios_write (adios_handle, "rows", &rows);  
6 adios_write (adios_handle, "columns", &columns);  
7 adios_write (adios_handle, "matrix", matrix);
```

- Group size determined automatically
- adios_write calls write the actual data
 - Write operations are cached as much as possible

```
1 s = adios_selection_writeblock (rank);  
2 adios_schedule_read (fp, s, "matrix", 1, 1, matrix);  
3 adios_perform_reads (fp, 1);  
4 adios_selection_delete (s);
```

- Reading is more complex than writing
 - Offers additional functionality
- Parts of the data can be selected for reading
 - ADIOS then determines the best reading strategy
- Multiple read operations can be scheduled
 - Scheduled operations are only queued and later executed in a batch

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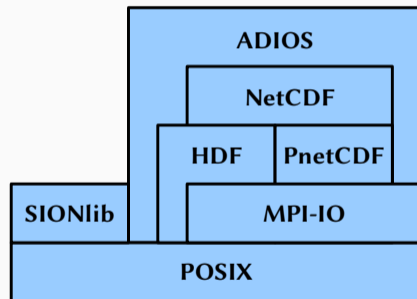
Example: HDF

Example: ADIOS

Performance Assessment

Summary

- Libraries use underlying interfaces
 - Interfaces can be provided by other I/O libraries
 - Sometimes depend on multiple interfaces
- Debugging might require knowledge of dependencies and their optimizations
 - Unclear which dependency causes problems



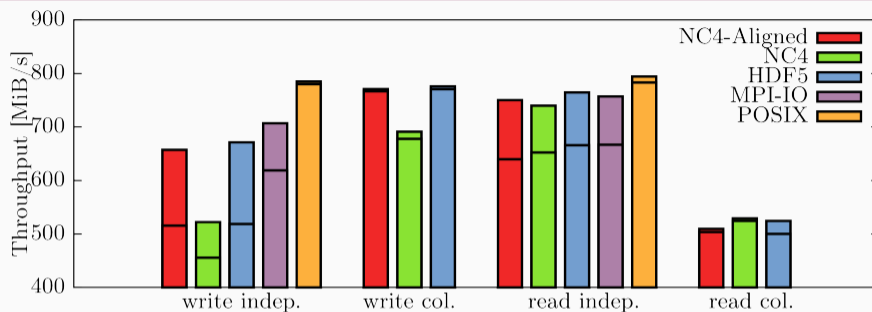


Fig. 5. Disjoint Pattern

- Clients are responsible for contiguous blocks of data
 - Regions are disjoint to avoid conflicts and locking
- Each client potentially communicates with all servers

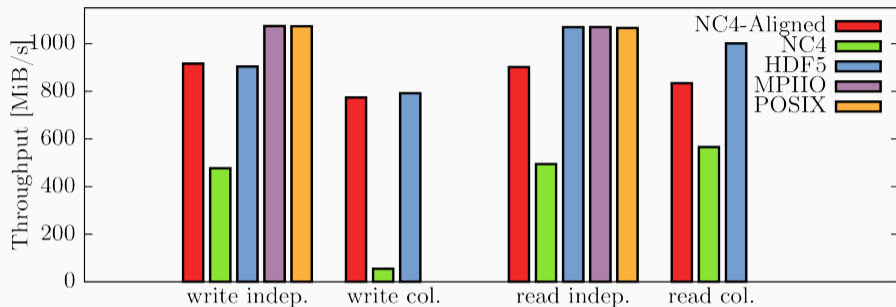


Fig. 6. 1-OST Pattern

- Each client communicates with exactly one server
 - Lower communication overhead and fewer potential conflicts

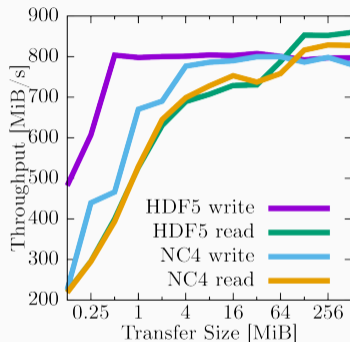


Fig. 7. Varying Transfer Size

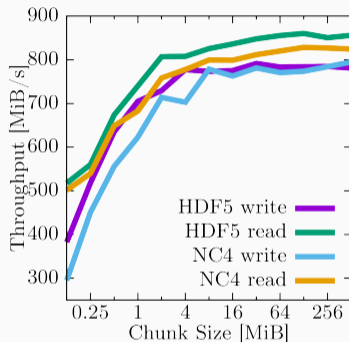


Fig. 8. Chunked Layout

- Performance heavily depends on access and chunk sizes

- Interaction between I/O libraries is complex
 - Achievable performance cannot be predicted easily
 - Potential performance problems and optimizations on all layers
 - Analysis is complicated by having to capture all layers
- Optimizations are necessary for almost all storage systems
 - HDF5 and SIONlib allow adapting to the file system boundaries
 - NetCDF only has limited support for alignment

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Summary

- Low-level I/O interfaces are often not convenient to use
 - I/O libraries provide high-level interfaces for structured access
 - Annotations and metadata enable exchanging of data
- Zoo of libraries available for different use cases
 - Analysis of errors and performance problems is complicated
 - SIONlib works around performance problems of current file systems
 - NetCDF and HDF provide similar functionality for self-describing data

References

[Bartz et al., 2015] Bartz, C., Chasapis, K., Kuhn, M., Nerge, P., and Ludwig, T. (2015). **A Best Practice Analysis of HDF5 and NetCDF-4 Using Lustre.** In Kunkel, J. M. and Ludwig, T., editors, *High Performance Computing - 30th International Conference, ISC High Performance 2015, Frankfurt, Germany, July 12-16, 2015, Proceedings*, volume 9137 of *Lecture Notes in Computer Science*, pages 274–281. Springer.

[SIONlib, 2021] SIONlib (2021). **File Format.**

https://apps.fz-juelich.de/jsc/sionlib/docu/fileformat_page.html.

- NetCDF comes with additional features
 - Data can be compressed transparently
- Tools expand the usability of NetCDF further
 - ncdump comes with NetCDF and allows printing file contents
 - NetCDF Operators (NCO) can perform a variety of operations on data
- NetCDF is used as the foundation of further standards
 - The Climate Data Interface supports NetCDF and other formats

1. Create file with `nc_create("file.nc", . . . , &ncid)`
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 - Backend can be selected with `NC_MPIIO` or `NC_NETCDF4`

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7. Write variable with `nc_put_var_*(grp_id, varid, . . .)`
8. Close file with `nc_close(ncid)`

- HDF supports multiple backends (Virtual File Layer)
 - Used to realize access using POSIX and MPI-IO (and more)
 - MPI-IO allows efficient parallel access to shared HDF files
- HDF contains several tools to work with data
 - h5dump can be used to print data
- Additional functionality similar to NetCDF
 - Transparent compression and user-defined filters
- HDF is under active development
 - Virtual Object Layer (VOL) allows alternative storage approaches
 - Higher level of abstraction in comparison to the VFL
 - Additional features for exascale and cloud

- ADIOS uses its own file format (Binary Packed)
 - BP can be converted to HDF5, NetCDF and ASCII
- ADIOS supports data transformations
 - Compression is a common data transformation
- Read operations are scheduled for efficient execution
 - Can be used to stage data to different tiers
- Annotations can be used to improve performance further
 - `adios_{start,stop}_calculation`: Marks the calculation phases to allow performing I/O in parallel to computation
 - `adios_end_iteration`: Provides timing information for flushing data

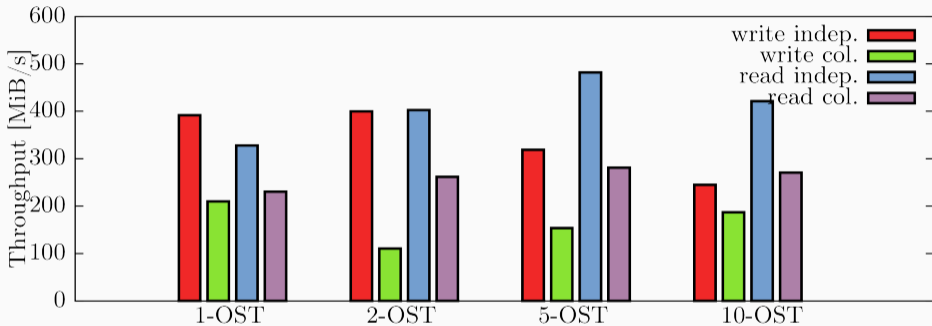


Fig. 9. 1- to 10-OST Pattern, HDF5 with Chunked I/O

- Performance varies depending on the number of servers to contact