
HDF5 Single-writer/Multiple-reader User's Guide

This document describes the HDF5 Library's single-writer/multiple-reader feature and describes how to use the feature. The feature allows concurrent access of HDF5 files by writer and reader processes.



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1. Introduction

Versions of the HDF5 Library prior to the 1.10.0 release do not support a concurrent read from an HDF5 file while it is being written to without explicit coordination between the processes. This limitation makes inspecting data while it is being collected impossible at the file level.

The primary reason for this lack of concurrent read/write access is the complexity of the HDF5 file format combined with the presence of a caching layer in the library. The internal structure of an HDF5 file includes internal file addresses. It is possible that a file metadata object can be flushed to the disk before other objects it references are flushed. This would create a transiently invalid file. A reader that opens this partially written file could attempt to resolve the invalid file address and read garbage instead of the expected file object. Other considerations, such as free space recycling in the file, are also problematic under concurrent access.

In order to address this issue, HDF5 developers have implemented a mechanism to allow for concurrent access by a single writer process with any number of reader processes. This data access pattern is known as single-writer/multiple-reader or SWMR for short.

Some of the HDF5 Library's internal structures were enhanced to be SWMR-safe, and tests were added to validate the SWMR functionality.

While the general SWMR feature is far from completion, the HDF5 SWMR implementation described in this document supports a particular SWMR access pattern that might be of interest to many application developers: a writer process can append data to the datasets in an HDF5 file while several reader processes can concurrently read the new data from the file. No communications between the processes and no file locking are required. The processes can run on the same or on different platforms.

This document was written for application developers who might be interested in working with SWMR and providing feedback to the HDF5 development team.

1.1. POSIX-compliant Requirement

The HDF5 file that is accessed by SWMR HDF5 applications must be located on a file system that complies with the POSIX write() semantics, and the writer and reader processes must follow the SWMR programming model to assure correct results.

2. The SWMR Design

To solve the difficulties involved with allowing concurrent access to write and read processes, HDF5 developers used an approach that is lock-free and that does not require any communication between processes.

This approach is based on the assumption that the HDF5 file resides on a file system compliant with POSIX write semantics. The ordering feature of the POSIX write semantics is critical for the implementation: POSIX I/O writes must be performed in a sequentially consistent manner.

These semantics apply to any processes that access the file from any location.

The HDF5 SWMR feature was tested on Linux clusters with GPFS and Lustre, Linux systems with ext3/4, FreeBSD with UFS2, OS X with HFS+, and Windows with NTFS and GPFS. The SWMR feature does not work on network file systems (NFS, SMB/Windows file shares, and so on) since write ordering may not be preserved on those systems.

The HDF5 1.10.0 release includes simple SWMR test programs that attempt to expose deficiencies in a file system that prevents proper SWMR operation. Those tests are described in the “Testing SWMR” section.

For more information on SWMR-safe design, see the [“HDF5 SWMR Feature Design and Semantics”](#) document. [1]

Word of Caution: Please note that HDF5 files created with SWMR access cannot not be read by the tools based on the HDF5 1.8 libraries due to the file format changes in the HDF5 1.10 version of the library. In particular, the library uses new chunk indexing schemas when creating chunked datasets. New schemas use a checksum on metadata information allowing the library to verify the validity of a metadata item such as a B-tree node. This is critical for the SWMR implementation to assure that a SWMR reader application will always see consistent metadata created by the SWMR writer.

One can use the [h5repack](#) or [h5format_convert](#) tools to convert an HDF5 file created by the HDF5 Library version 1.10.0 to be accessible by the HDF5 Library version 1.8. The `h5repack` tool rewrites the whole file; `h5format_convert` modifies the file “in place” by rewriting only metadata information according to the 1.8 format while leaving raw data intact. [2]

An application built with the HDF5 Library 1.10.0 can always read and modify files created by all previous versions of HDF5.

3. SWMR Scope and Limitations

The current SWMR implementation scope is as follows:

1. The writer process is only allowed to modify raw data of **existing** datasets by:
 - a. Appending data along any unlimited dimension.
 - b. Modifying existing data.

The following operations are **not** allowed:

2. The writer is not allowed to add any new objects to the file such as groups, datasets, links, committed datatypes, and attributes.
3. The writer is not allowed to delete HDF5 objects such as groups, datasets, links, committed datatypes, and attributes.
4. The writer is not allowed to modify or append to any data items containing variable-size datatypes (including string and region references datatypes).
5. File space recycling is not allowed. As a result, the sizes of a file modified by a SWMR writer may be larger than if a non-SWMR writer modified it.

It is the user's responsibility to follow the SWMR scope since the HDF5 Library does not enforce the scope.

4. The SWMR-enabled HDF5 Library

The purpose of this chapter is to describe what must be installed and configured so that the SWMR feature can be used.

4.1. Getting the Source

The SWMR feature is available in HDF5 version 1.10.0 and later.

4.2. Building the Library

No special configuration options are required to build the HDF5 library with the SWMR functionality. The usual `configure`, `make`, `make check`, and `make install` process should be followed for building the library. Please see the `release_docs/INSTALL` file in the source distribution for more information about building and installing the HDF5 Library.

The HDF5 SWMR implementation is currently only supported on Unix-like systems. The implementation is not being tested on Windows systems at this time.

4.3. Testing SWMR

SWMR functionality is tested as a part of the `make check` build step as described below:

- POSIX atomicity tests `test/atomic_writer.c` and `test/atomic_reader.c` check to confirm if a file system supports POSIX atomicity. Information on how to run the POSIX tests can be found in the `test/AtomicWriterReader.txt` file.
- The metadata cache test exercises the flush ordering functionality required for SWMR. See the `test/swmr*.c` files.
- Basic SWMR operation between processes is tested via a shell script named `testswmr.sh`. This script invokes a writer and some readers which then operate on a central file using the SWMR access pattern.
- The programs `test/use_append_chunk` and `test/use_append_mchunk` append data to datasets with unlimited dimensions and exercise the main functionality of the current SWMR implementation. The programs would be useful to anyone who would like to start using the SWMR feature in their HDF5 applications and who needs to know how to create writer and reader applications. The programs are described in detail in the “SWMR Examples” chapter beginning on page 12.

- A test script `test_usecases.sh` is installed in the same directory as the programs and is used to run the programs during `make check`.

Output from the tests is displayed on `stdout` and `stderr` like all other HDF5 test results. No special log files are created.

5. The Programming Model

Our main consideration in this stage of the implementation is appending data to chunked datasets with unlimited dimensions. We anticipate this to be the most common scenario where SWMR semantics are needed. Any number of dimensions (up to the limit of the library) is supported, and any of those dimensions can be unlimited in size. No new file objects can be created under SWMR operation. Variable-length and reference datatypes are not supported.

The current SWMR implementation does not support data updates of the fixed-size chunked datasets due to a chunk indexing method that has not been fully converted and tested with SWMR-safe semantics. The work-around is to declare one dimension to be unlimited using `H5S_UNLIMITED`.

Note that applications that want to take advantage of the SWMR feature must follow the SWMR programming model to assure correct results. The model is described below.

5.1. Setting up SWMR Access to an HDF5 File

Go through the sequence of steps below to use the SWMR data access pattern:

1. Set up the file

- a. Create the HDF5 file using either one of the following ways:

- i. Create the file with the latest file format:

```
H5P_set_libver_bounds(fapl, H5F_LIBVER_LATEST, H5F_LIBVER_LATEST);  
fid = H5Fcreate(FILE, H5F_ACC_TRUNC, fcp1, fapl);
```

- ii. Create the file specifying SWMR access:

```
fid = H5Fcreate(FILE, H5F_ACC_TRUNC|H5F_ACC_SWMR_WRITE, fcp1, H5P_DEFAULT);
```

- b. Create any file objects such as datasets and groups that are required for data storage.

- c. Close the file.

2. Start a writer process

- a. Open the file by calling `H5Fopen` using the `H5F_ACC_SWMR_WRITE` flag and begin writing to the dataset. Here is a sample:

```
fid = H5Fopen(FILE, H5F_ACC_RDWR | H5F_ACC_SWMR_WRITE, H5P_DEFAULT);
```

- b. Use `H5Dflush` periodically to flush the data for a particular dataset to the file. New data will appear as file objects are evicted/flushed from the cache (see page 10).

3. Start at least one reader process

- a. Open the file by calling `H5Fopen` using the `H5F_ACC_SWMR_READ` flag and begin reading data from the dataset. Here is a sample:

```
fid = H5Fopen(FILE, H5F_ACC_RDONLY | H5F_ACC_SWMR_READ, H5P_DEFAULT);
```

b. Poll the dataset. SWMR presumes no communication between processes. Newly appended data is checked for via polling the dataset. Polling is done by calling `H5Drefresh` on the dataset, checking the number of stored elements in each dimension of interest (via `H5S*extent` calls), and comparing this with the previous number of elements (see page 11). When the size has been seen to change, the new data is read from the file using the usual `H5Dread` calls.

4. Stop the writer process
 - a. The writer process closes the file.
5. Stop Reader(s)
 - a. Each reader process closes the file.

It is the user's responsibility to assure that the writer process started before any reader comes in.

If a reader process opens a file before a writer process, the writer will not be able to modify the file due to the lock the reader puts on the file. The lock can be shared with any other reader thus allowing multiple readers. It is the user's responsibility to start the writer and readers in the correct order.

If a writer opens the file first, it locks the file and modifies the file's superblock to indicate that the file is open for SWMR write access. After the superblock is flushed to the disk, the writer releases the lock, and any reader can open the file. Any other writer will fail to open the file due to the SWMR write access flag in the file superblock. For more information, see "File Locking in HDF5 1.10". [5]

Please remember that file locking is not used for coordinating SWMR writer and readers. It is used only to protect an HD5 file from accidental access by another application that may corrupt the data.

5.2. H5Dflush and H5Drefresh

Two new APIs were introduced in HDF5 1.10.0 to allow applications to flush and refresh cached metadata in order for readers to see new data in the file. This section provides a short description of each function.

5.2.1. H5Dflush

Signature: `herr_t H5Dflush(hid_t dset_id)`

Purpose: Flushes all data and metadata associated with a dataset.

Description: The function flushes the specified dataset's metadata from the metadata cache to the file and all raw data buffers associated with the dataset to the file. If the dataset is chunked, raw data chunks are written to the file when this call is issued.

Parameters:

`hid_t dset_id` IN: Dataset identifier

Returns: Non-negative on success; negative on failure.

5.2.2. H5Drefresh

Signature: `herr_t H5Drefresh(hid_t dset_id)`

Purpose: Refreshes metadata items associated with a dataset in a metadata cache.

Description: The function refreshes all metadata items associated with the dataset in the metadata cache.

Parameters:

`hid_t dset_id` IN: Dataset identifier

Returns: Non-negative on success; negative on failure.

6. SWMR Examples

The HDF5 1.10 source distribution contains two example programs for the SWMR access feature: `test/use_append_chunk` and `test/use_append_mchunk`. Each example consists of a writer and a reader(s) that use the SWMR programming model. The writer adds data along an unlimited dimension, and the reader(s) reads newly appended data. These programs are described below.

HDF5 version 1.10.0 and later also has a new tool called `h5watch` which is located in the `h1/tools/h5watch` directory. The tool is an example of a polling application and is described in “The `h5watch` Tool” section on page 17.

6.1. Appending a Single Chunk to a Dataset

6.1.1. Description of `use_append_chunk`

The program `use_append_chunk` appends a single chunk of raw data to a dataset along an unlimited dimension within a pre-created file and reads the new data back.

The program first creates one 3-dimensional dataset using chunked storage. Each chunk is a `(1, chunksize, chunksize)` square. The dataset dimensions are `(unlimited, chunksize, chunksize)`. The datatype is a 2 byte integer. No data is written to a dataset; in other words, the size of the first current dimension is 0.

The writer first appends planes, each of `(1, chunksize, chunksize)`, to the dataset. Next, it fills each plane with a plane number `n`, and then it writes new plane at the `nth` plane. The writer increases the plane number and repeats until the first dimension becomes `chunksize` long. The end dataset is a `chunksize3` cube as shown in the figure below.

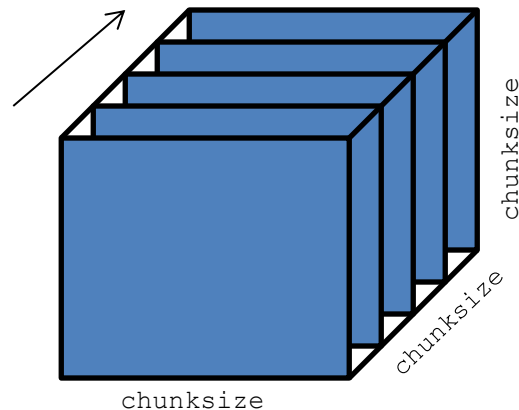


Figure 1. Writer fills cube with planes along the slowest changing dimension

The reader is a separate process running concurrently with the writer. It reads planes from the dataset as the dataset is growing. When it detects that the size of the unlimited dimension increases, the reader will read in the new planes, one by one, and verify the correctness of the data. The n^{th} plane should contain all "n" (all values = n). When the unlimited dimension grows to the `chunksize`, which is the expected end of data, the reader exits.

6.1.2. Running `use_append_chunk`

The simplest way to run the program is without specifying any arguments:

```
$ use_append_chunk
```

The program first creates a skeleton dataset (0,256,256) of 2 byte integers. Next, it forks off a process, which becomes the reader process to read planes from the dataset, while the original process continues as the writer process to append planes onto the dataset.

Other possible options:

1. `-z` specifies a different chunk size. The default chunk size value is 256.

```
$ use_append_chunk -z 1024
```

The command above uses (1,1024,1024) chunks to produce a 1024^3 cube, about 2 GB in size.

2. `-f filename` specifies different file name

```
$ use_append_chunk -f /gpfs/tmp/append_data.h5
```

The data file is `/gpfs/tmp/append_data.h5`. This allows two independent processes in separate compute nodes to access the HDF5 file on the shared `/gpfs` file system.

3. *-l option* launches only the reader or writer process.

```
$ use_append_chunk -f /gpfs/tmp/append_data.h5 -l w # in node X
$ use_append_chunk -f /gpfs/tmp/append_data.h5 -l r # in node Y
```

Valid values for *option* are `w` for writer and `r` for reader.

In node X, launch the writer process to create the data file and append to it. In node Y, launch the read process to read the data file. Note that one needs to time the read process to start AFTER the write process has created the skeleton data file. Otherwise, the reader will encounter errors such as data file not found.

4. *-n option* specifies the number of planes to write or read. The default value is the same as the chunk size as specified by option *-z*.

```
$ use_append_chunk -n 1000
```

The command above writes 1000 planes in one HDF5 I/O call.

5. *-s option* enables the SWMR file access mode. The default value is yes.

```
$ use_append_chunk -s 0
```

The command above opens the HDF5 data file without the SWMR access mode (0 means off). This likely will result in error. This option is provided for users to see the effect of the needed SWMR access mode for concurrent access.

6.2. Appending a Hyperslab of Multiple Chunks

6.2.1. Description of `use_append_mchunk`

The program `use_append_mchunk` appends a hyperslab that spans several chunks of a dataset with unlimited dimensions within a pre-created file and reads the new data back.

The program first creates one 3-dimensional dataset using chunked storage. Each chunk is a $(1, \text{chunksize}, \text{chunksize})$ square. The dataset dimensions are $(\text{unlimited}, 2 * \text{chunksize}, 2 * \text{chunksize})$. The datatype is a 2 byte integer. Therefore, each plane consists of 4 chunks. No data is written to a dataset; in other words, the size of the first current dimension is 0.

The writer first appends planes, each of $(1, 2 \times \text{chunksize}, 2 \times \text{chunksize})$ to the dataset. Next, it fills each plane with a plane number n and then writes the new plane at the n^{th} plane. The writer increases the plane number and repeats until the first dimension becomes $2 \times \text{chunksize}$ long. The end dataset is a $(2 \times \text{chunksize})^3$ cube as shown in the figure below.

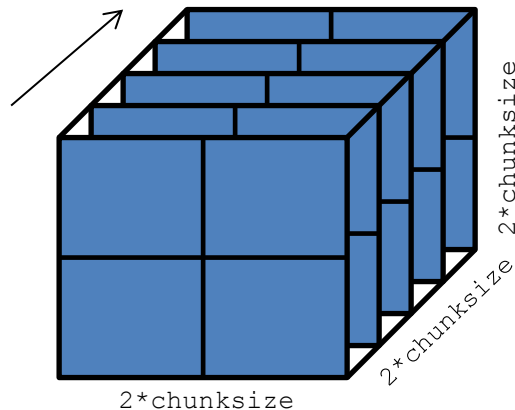


Figure 2. Writer fills cube with planes along the slowest changing dimension
Each plane consists of four chunks.

The reader is a separate process running concurrently with the writer. It reads planes from the dataset as the dataset is growing. When it detects that the size of the unlimited dimension increases, the reader will read in the new planes, one by one, and verify the correctness of the data. The n^{th} plane should contain all “ n ” (all values = n). When the unlimited dimension grows to $2 \times \text{chunksize}$, which is the expected end of data, the reader exits.

6.2.2. Running use_append_mchunk

The simplest way to run the program is without specifying any arguments:

```
$ use_append_mchunk
```

The program creates a skeleton dataset (0,512,512) of 2 byte integers. Next, it forks off a process, which becomes the reader process to read planes from the dataset, while the original process continues as the writer process to append planes onto the dataset.

Other possible options:

1. **-z** specifies different chunk size. The default chunk size value is 256.

```
$ use_append_mchunk -z 512
```

The command above uses (1,512,512) chunks to produce a 1024^3 cube, about 2 GB size.

2. **-f filename** specifies different file name

```
$ use_append_mchunk -f /gpfs/tmp/append_data.h5
```

The data file is /gpfs/tmp/append_data.h5. This allows two independent processes in separate compute nodes to access the HDF5 file on the shared /gpfs file system.

3. **-l option** launches only the reader or writer process.

```
$ use_append_mchunk -f /gpfs/tmp/append_data.h5 -l w # in node X
$ use_append_mchunk -f /gpfs/tmp/append_data.h5 -l r # in node Y
```

Valid values for *option* are *w* for writer and *r* for reader.

In node X, launch the writer process to create the data file and append to it. In node Y, launch the read process to read the data file. Note that one needs to time the read process to start AFTER the write process has created the skeleton data file. Otherwise, the reader will encounter errors such as data file not found.

4. **-n option** specifies the number of planes to write or read. The default value is same as the chunk size as specified by option -z.

```
$ use_append_mchunk -n 1000
```

The command above writes 1000 planes in one HDF5 I/O call.

5. **-s option**: use SWMR file access mode or not. The default value is yes.

```
$ use_append_mchunk -s 0
```

The command above opens the HDF5 data file without the SWMR access mode (0 means off). This likely will result in error. This option is provided for users to see the effect of the needed SWMR access mode for concurrent access.

6.3. Appending n-1 Dimensional Planes

Both `use_append_chunk` and `use_append_mchunk` can be used to append n-1 dimensional planes.

6.3.1. Description

The programs `use_append_chunk` and `use_append_mchunk` append $n-1$ dimensional planes or regions to a chunked dataset where the data does not fill the chunk. This means the chunks have multiple planes, and when a plane is written, only part of each chunk is written. This use case is achieved by extending the previous examples by defining the chunks to have the slowest changing dimension size greater than 1. The `-y` option is implemented for both `use_append_chunk` and `use_append_mchunk`.

6.3.2. Running the Program

The simplest way to run the program `use_append_mchunk` is:

```
$ use_append_mchunk -y 5
```

The program creates a skeleton dataset (0,512,512) of 2 byte integers with chunk sizes (5,512,512). Next, it forks off a process, which becomes the reader process to read one plane at a time, while the original process continues as the writer process to append one plane at a time.

Other possible options will work as in the previous examples.

6.4. The h5watch Tool

6.4.1. Description

The `h5watch` tool allows a user to monitor the growth of a dataset written by an HDF5 application. It prints out the new elements whenever the application extends the size and adds data to that dataset.

`h5watch` polls the specified dataset periodically for changes in its dimension sizes. If at least one of the dataset's dimension sizes has increased, `h5watch` prints out the new appended data. For compound datasets, the tool has an option to print new data for the specified fields in the compound datatype. `h5watch` can be used only on chunked datasets with unlimited dimensions. The application that writes the file needs to ensure that changes to the dataset are flushed to the file with `H5Dflush`.

6.4.2. Running h5watch

To run the tool, use the following command:

```
$ h5watch Path_to_dataset
```

`Path_to_dataset` consists of two parts: the path to the HDF5 file and the path to the dataset within the file. For example, to monitor dataset A in the file `/home/user/file.h5`, the argument `path_to_dataset` is `/home/user/file.h5/A`.

The following are other useful options for `h5watch`:

1. `--help` prints help message

```
$ h5watch --help
```

2. `-polling=N` sets the polling interval to N (in seconds) when the dataset will be checked for changes in dimension sizes. The default interval for polling is 1.

```
$ h5watch -polling=5 ./myfile.h5/mygroup/mydataset
```

With the command-line above, the tool will read data every 5 seconds from the dataset `/mygroup/mydataset` in the file `./myfile.h5`.

For more options, check the tool's help message.

7. References

1. "HDF5 Single-writer/Multiple-reader Feature Design and Semantics" at <https://www.hdfgroup.org/HDF5/docNewFeatures/SWMR/Design-HDF5-SWMR-20130629.v5.2.pdf>.
2. More information on the `h5repack` tool can be found on The HDF Group website at <https://www.hdfgroup.org/HDF5/doc/RM/Tools.html#Tools-Repack>.
3. More information on the `h5format_convert` tool can be found on The HDF Group website at https://www.hdfgroup.org/HDF5/docNewFeatures/SWMR/h5format_convert.htm.
4. More information on the `h5watch` tool can be found on The HDF Group website at <https://www.hdfgroup.org/HDF5/docNewFeatures/SWMR/h5watch.htm>.
5. "Design: File Locking under SWMR – Semantics, Programming Model, and Implementation" at <https://www.hdfgroup.org/HDF5/docNewFeatures/SWMR/Design-HDF5-FileLocking.pdf>.