



# **openPMD-api Documentation**

*Release 0.6.2-alpha*

**The openPMD Community**

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# INSTALLATION

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This library provides an abstract API for openPMD file handling. It provides both support for writing & reading into various formats and works both serial and parallel (MPI). Implemented backends include HDF5 and ADIOS1.



**DOXYGEN**

The latest Doxygen docs for the C++ API are published at:

<http://www.openpmd.org/openPMD-api>





## SUPPORTED OPENPMD STANDARD VERSIONS

openPMD-api is a library using [semantic versioning](#), starting with version 1.0.0.

The supported version of the [openPMD standard](#) are reflected as follows: `standardMAJOR.apiMAJOR.apiMINOR`.

openPMD-api version	supported openPMD standard versions
0.1.0-0.6.2 (alpha)	1.0.0-1.1.0
1.0.0+	1.0.1-1.1.0 (not released yet)
2.0.0+	2.0.0+ (not released yet)

## 2.1 Installation

### 2.1.1 Installation

Choose *one* of the install methods below to get started:

#### Using the Spack Package

A package for openPMD-api is available on the Spack package manager.

```
# optional: +python ^python@3:
spack install openpmd-api
spack load -r openpmd-api
```

#### Using the conda Package

A package for serial openPMD-api is available on the Conda package manager.

```
conda install -c conda-forge openpmd-api
```

#### From Source with CMake

You can also install `openPMD-api` from source with CMake. This requires that you have all [dependencies](#) installed on your system. The developer section on [build options](#) provides further details on variants of the build.

## Linux & OSX

```
git clone https://github.com/openPMD/openPMD-api.git

mkdir -p openPMD-api-build
cd openPMD-api-build

# optional: for full tests
../openPMD-api/.travis/download_samples.sh

# for own install prefix append:
# -DCMAKE_INSTALL_PREFIX=$HOME/somepath
# for options append:
# -DopenPMD_USE_...=...
# e.g. for python support add:
# -DopenPMD_USE_PYTHON=ON -DPYTHON_EXECUTABLE=$(which python)
cmake ../openPMD-api

cmake --build .

# optional
ctest

# sudo might be required required for system paths
cmake --build . --target install
```

## Windows

Replace the last commands with:

```
cmake --build . --config Release

ctest -C Release

cmake --build . --config Release --target install
```

## Post “From Source” Install

If you installed to a non-system path on Linux or OSX, you need to express where your newly installed library can be found.

Adjust the lines below accordingly, e.g. replace `$HOME/somepath` with your install location prefix in `-DCMAKE_INSTALL_PREFIX=...` CMake will summarize the install paths for you before the build step.

```
# install prefix          |-----|
export CMAKE_PREFIX_PATH=$HOME/somepath:$CMAKE_PREFIX_PATH
export LD_LIBRARY_PATH=$HOME/somepath/lib:$LD_LIBRARY_PATH

#                          change path to your python MAJOR.MINOR version
export PYTHONPATH=$HOME/somepath/lib/python3.5/site-packages:$PYTHONPATH
```

Adding those lines to your `$HOME/.bashrc` and re-opening your terminal will set them permanently.

Set hints on Windows with the CMake printed paths accordingly, e.g.:

```
set CMAKE_PREFIX_PATH=C:\\Program Files\\openPMD;%CMAKE_PREFIX_PATH%
set PATH=C:\\Program Files\\openPMD\\Lib;%PATH%
set PYTHONPATH=C:\\Program Files\\openPMD\\Lib\\site-packages;%PYTHONPATH%
```

## 2.1.2 Changelog

### 0.6.2-alpha

**Date:** 2018-09-25

Python Stride: Regression

A regression in the last fix for python strides made the relaxation not efficient for 2-D and higher.

### Changes to “0.6.1-alpha”

#### Bug Fixes

- Python: relax strides further

### 0.6.1-alpha

**Date:** 2018-09-24

Relaxed Python Stride Checks

Python stride checks have been relaxed and one-element n-d arrays are allowed for scalars.

### Changes to “0.6.0-alpha”

#### Bug Fixes

- Python:
  - stride check too strict #369
  - allow one-element n-d arrays for scalars in `store`, `make_constant` #314

#### Other

- dependency change: Catch2 2.3.0+
- Python: add extended write example #314

### 0.6.0-alpha

**Date:** 2018-09-20

Particle Patches Improved, Constant Scalars and Python Containers Fixed

Scalar records properly support const-ness. The Particle Patch load interface was changed, loading now all patches at once, and Python bindings are available. Numpy `dtype` is now a first-class citizen for Python `Datatype` control, being accepted and returned instead of enums. Python lifetime in garbage collection for containers such as `meshes`, `particles` and `iterations` is now properly implemented.

## Changes to “0.5.0-alpha”

### Features

- Python:
  - accept & return `numpy.dtype` for `Datatype` #351
  - better check for (unsupported) numpy array strides #353
  - implement `Record_Component.make_constant` #354
  - implement `Particle_Patches` #362
- comply with runtime constraints w.r.t. `written` status #352
- load at once `ParticlePatches.load()` #364

### Bug Fixes

- `dataOrder`: mesh attribute is a string #355
- constant scalar Mesh Records: reading corrected #358
- particle patches: stricter `load( idx )` range check #363, then removed in #364
- Python: lifetime of `Iteration.meshes/particles` and `Series.iterations` members #354

### Other

- test cases for mixed constant/non-constant Records #358
- examples: close handles explicitly #359 #360

## 0.5.0-alpha

**Date:** 2018-09-17

### Refactored Type System

The type system for `Datatype::`s` was refactored. Integer types are now represented by `SHORT`, `INT`, `LONG` and `LONGLONG` as fundamental C/C++ types. Python support enters “alpha” stage with fixed floating point storage and `Attribute` handling.

## Changes to “0.4.0-alpha”

### Features

- Removed `Datatype::INT32` types with `SHORT`, `INT` equivalents #337
- `Attribute::get<...>()` performs a `static_cast` now #345

## Bug Fixes

- Refactor type system and `Attribute` set/get
  - integers #337
  - support long double reads on MSVC #184
- `setAttribute`: explicit C-string handling #341
- `Dataset`: `setCompression` warning and error logic #326
- avoid impact on unrelated classes in invasive tests #324
- Python
  - single precision support: `numpy.float` is an alias for `builtins.float` #318 #320
  - `Dataset` method namings to underscores #319
  - container namespace ambiguity #343
  - `set_attribute`: broken numpy, list and string support #330

## Other

- CMake: invasive tests not enabled by default #323
- `store_chunk`: more detailed type mismatch error #322
- `no_such_file_error` & `no_such_attribute_error`: remove c-string constructor #325 #327
- add virtual destructor to `Attributable` #332
- Python: Numpy 1.15+ required #330

## 0.4.0-alpha

**Date:** 2018-08-27

Improved output handling

Refactored and hardened for `fileBased` output. Records are not flushed before the ambiguity between scalar and vector records are resolved. Trying to write globally zero-extent records will throw gracefully instead of leading to undefined behavior in backends.

## Changes to “0.3.1-alpha”

### Features

- do not assume record structure prematurely #297
- throw in (global) zero-extent dataset creation and write #309

## Bug Fixes

- ADIOS1 fileBased IO #297
- ADIOS2 stub header #302
- name sanitization in ADIOS1 and HDF5 backends #310

## Other

- CI updates: #291
  - measure C++ unit test coverage with coveralls
  - clang-format support
  - clang-tidy support
  - include-what-you-use support #291 export headers #300
  - OSX High Sierra support #301
  - individual cache per build # 303
  - readable build names #308
- remove superfluous whitespaces #292
- readme: openPMD is for scientific data #294
- override implies virtual #293
- spack load: -r #298
- default constructors and destructors #304
- string pass-by-value #305
- test cases with 0-sized reads & writes #135

## 0.3.1-alpha

**Date:** 2018-07-07

Refined fileBased Series & Python Data Load

A specification for iteration padding in filenames for fileBased series is introduced. Padding present in read iterations is detected and conserved in processing. Python builds have been simplified and python data loads now work for both meshes and particles.

## Changes to “0.3.0-alpha”

### Features

- CMake:
  - add openPMD : : openPMD alias for full-source inclusion #277
  - include internally shipped pybind11 v2.2.3 #281
  - ADIOS1: enable serial API usage even if MPI is present #252 #254
- introduce detection and specification %0\ d+T of iteration padding #270
- Python:
  - add unit tests #249

- expose record components for particles #284

## Bug Fixes

- improved handling of `fileBased Series` and `READ_WRITE` access
- expose `Container` constructor as `protected` rather than `public` #282
- Python:
  - return actual data in `load_chunk` #286

## Other

- docs:
  - improve “Install from source” section #274 #285
  - Spack python 3 install command #278

## 0.3.0-alpha

**Date:** 2018-06-18

Python Attributes, Better FS Handling and Runtime Checks

This release exposes openPMD attributes to Python. A new independent mechanism for verifying internal conditions is now in place. Filesystem support is now more robust on varying directory separators.

## Changes to “0.2.0-alpha”

### Features

- CMake: add new `openPMD_USE_VERIFY` option #229
- introduce `VERIFY` macro for pre-/post-conditions that replaces `ASSERT` #229 #260
- serial Singularity container #236
- Python:
  - expose attributes #256 #266
  - use lists for offsets & extents #266
- C++:
  - `setAttribute` signature changed to `const ref` #268

### Bug Fixes

- handle directory separators platform-dependent #229
- recursive directory creation with existing base #261
- `FindADIOS.cmake`: reset on multiple calls #263
- `SerialIOTest`: remove variable shadowing #262
- ADIOS1: memory violation in string attribute writes #269

## Other

- enforce platform-specific directory separators on user input #229
- docs:
  - link updates to https #259
  - minimum MPI version #251
  - title updated #235
- remove MPI from serial ADIOS interface #258
- better name for scalar record in examples #257
- check validity of internally used pointers #247
- various CI updates #246 #250 #261

## 0.2.0-alpha

**Date:** 2018-06-11

Initial Numpy Bindings

Adds first bindings for record component reading and writing. Fixes some minor CMake issues.

## Changes to “0.1.1-alpha”

### Features

- Python: first NumPy bindings for record component chunk store/load #219
- CMake: add new `BUILD_EXAMPLES` option #238
- CMake: build directories controllable #241

### Bug Fixes

- forgot to bump `version.hpp/__version__` in last release
- CMake: Overwritable Install Paths #237

## 0.1.1-alpha

**Date:** 2018-06-07

ADIOS1 Build Fixes & Less Flushes

We fixed build issues with the ADIOS1 backend. The number of performed flushes in backends was generally minimized.



## Changes to “0.1.0-alpha”

### Bug Fixes

- SerialIOTest: loadChunk template missing for ADIOS1 #227
- prepare running serial applications linked against parallel ADIOS1 library #228

### Other

- minimize number of flushes in backend #212

## 0.1.0-alpha

**Date:** 2018-06-06

This is the first developer release of openPMD-api.

Both HDF5 and ADIOS1 are implemented as backends with serial and parallel I/O support. The C++11 API is considered alpha state with few changes expected to come. We also ship an unstable preview of the Python3 API.

## 2.2 Usage

### 2.2.1 First Steps

For brevity, all following examples assume the following includes/imports:

#### C++11

```
#include <openPMD/openPMD.hpp>

using namespace openPMD;
```

#### Python

```
import openPMD
```

### 2.2.2 Serial API

The serial API provides sequential, one-process read and write access. Most users will use this for exploration and processing of their data.

## Reading

### C++

```
#include <openPMD/openPMD.hpp>

#include <iostream>
#include <memory>
#include <cstdint>

using std::cout;
using namespace openPMD;

int main()
{
    Series series = Series(
        "../samples/git-sample/data%T.h5",
        AccessType::READ_ONLY
    );
    cout << "Read a Series with openPMD standard version "
         << series.openPMD() << '\n';

    cout << "The Series contains " << series.iterations.size() << " iterations:";
    for( auto const& i : series.iterations )
        cout << "\n\t" << i.first;
    cout << '\n';

    Iteration i = series.iterations[100];
    cout << "Iteration 100 contains " << i.meshes.size() << " meshes:";
    for( auto const& m : i.meshes )
        cout << "\n\t" << m.first;
    cout << '\n';
    cout << "Iteration 100 contains " << i.particles.size() << " particle species:"
    ↪;
    for( auto const& ps : i.particles )
        cout << "\n\t" << ps.first;
    cout << '\n';

    MeshRecordComponent E_x = i.meshes["E"]["x"];
    Extent extent = E_x.getExtent();
    cout << "Field E/x has shape (";
    for( auto const& dim : extent )
        cout << dim << ',';
    cout << ") and has datatype " << E_x.getDataType() << '\n';

    Offset chunk_offset = {1, 1, 1};
    Extent chunk_extent = {2, 2, 1};
    auto chunk_data = E_x.loadChunk<double>(chunk_offset, chunk_extent);
    cout << "Queued the loading of a single chunk from disk, "
         << "ready to execute\n";
    series.flush();
    cout << "Chunk has been read from disk\n"
         << "Read chunk contains:\n";
    for( size_t row = 0; row < chunk_extent[0]; ++row )
    {
        for( size_t col = 0; col < chunk_extent[1]; ++col )
            cout << "\t"
                 << '(' << row + chunk_offset[0] << '|' << col + chunk_offset[1] <
    ↪ << '|' << 1 << ") \t"
                 << chunk_data.get()[row*chunk_extent[1]+col];
    }
}
```

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```

        cout << '\n';
    }

    /* The files in 'series' are still open until the object is destroyed, on
     * which it cleanly flushes and closes all open file handles.
     * When running out of scope on return, the 'Series' destructor is called.
     */
    return 0;
}

```

An extended example can be found in `examples/6_dump_filebased_series.cpp`.

## Python

```

import openPMD

if __name__ == "__main__":
    series = openPMD.Series("../samples/git-sample/data%T.h5",
                           openPMD.Access_Type.read_only)
    print("Read a Series with openPMD standard version %s" %
          series.openPMD)

    print("The Series contains {0} iterations:".format(len(series.iterations)))
    for i in series.iterations:
        print("\t {0}".format(i))
    print("")

    i = series.iterations[100]
    print("Iteration 100 contains {0} meshes:".format(len(i.meshes)))
    for m in i.meshes:
        print("\t {0}".format(m))
    print("")
    print("Iteration 100 contains {0} particle species:".format(
        len(i.particles)))
    for ps in i.particles:
        print("\t {0}".format(ps))
    print("")

    E_x = i.meshes["E"]["x"]
    shape = E_x.shape

    print("Field E.x has shape {0} and datatype {1}".format(
        shape, E_x.dtype))

    offset = [1, 1, 1]
    extent = [2, 2, 1]
    # TODO buffer protocol / numpy bindings
    # chunk_data = E_x[1:3, 1:3, 1:2]
    chunk_data = E_x.load_chunk(offset, extent)
    # print("Queued the loading of a single chunk from disk, "
    #       "ready to execute")
    series.flush()
    print("Chunk has been read from disk\n"
          "Read chunk contains:")
    print(chunk_data)
    # for row in range(2):
    #     for col in range(2):
    #         print("\t({0}|{1}|{2})\t{3}".format(

```

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```

#           row + 1, col + 1, 1, chunk_data[row*chunk_extent[1]+col])
#       )
#       print("")

# The files in 'series' are still open until the object is destroyed, on
# which it cleanly flushes and closes all open file handles.
# One can delete the object explicitly (or let it run out of scope) to
# trigger this.
del series

```

## Writing

### C++

```

#include <openPMD/openPMD.hpp>

#include <iostream>
#include <memory>
#include <numeric>
#include <cstdlib>

using std::cout;
using namespace openPMD;

int main(int argc, char *argv[])
{
    // user input: size of matrix to write, default 3x3
    size_t size = (argc == 2 ? atoi(argv[1]) : 3);

    // matrix dataset to write with values 0...size*size-1
    std::vector<double> global_data(size*size);
    std::iota(global_data.begin(), global_data.end(), 0.);

    cout << "Set up a 2D square array (" << size << "x" << size
          << ") that will be written\n";

    // open file for writing
    Series series = Series(
        "../samples/3_write_serial.h5",
        AccessType::CREATE
    );
    cout << "Created an empty " << series.iterationEncoding() << " Series\n";

    MeshRecordComponent rho =
        series
            .iterations[1]
            .meshes["rho"][MeshRecordComponent::SCALAR];
    cout << "Created a scalar mesh Record with all required openPMD attributes\n";

    Datatype datatype = determineDatatype(shareRaw(global_data));
    Extent extent = {size, size};
    Dataset dataset = Dataset(datatype, extent);
    cout << "Created a Dataset of size " << dataset.extent[0] << "x" << dataset.
    ↪extent[1]
        << " and Datatype " << dataset.dtype << "\n";

    rho.resetDataset(dataset);
    cout << "Set the dataset properties for the scalar field rho in iteration 1\n";
}

```

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```

series.flush();
cout << "File structure and required attributes have been written\n";

Offset offset = {0, 0};
rho.storeChunk(offset, extent, shareRaw(global_data));
cout << "Stored the whole Dataset contents as a single chunk, "
      "ready to write content\n";

series.flush();
cout << "Dataset content has been fully written\n";

/* The files in 'series' are still open until the object is destroyed, on
 * which it cleanly flushes and closes all open file handles.
 * When running out of scope on return, the 'Series' destructor is called.
 */
return 0;
}

```

An extended example can be found in `examples/7_extended_write_serial.cpp`.

## Python

```

import openPMD
import numpy as np

if __name__ == "__main__":
    # user input: size of matrix to write, default 3x3
    size = 3

    # matrix dataset to write with values 0...size*size-1
    global_data = np.arange(size*size, dtype=np.double)

    print("Set up a 2D square array ({0}x{1}) that will be written".format(
        size, size))

    # open file for writing
    series = openPMD.Series(
        "../samples/3_write_serial_py.h5",
        openPMD.Access_Type.create
    )

    print("Created an empty {0} Series".format(series.iteration_encoding))

    print(len(series.iterations))
    rho = series.iterations[1]. \
        meshes["rho"][openPMD.Mesh_Record_Component.SCALAR]

    datatype = openPMD.Datatype.DOUBLE
    # datatype = openPMD.determineDatatype(global_data)
    extent = [size, size]
    dataset = openPMD.Dataset(datatype, extent)

    print("Created a Dataset of size {0}x{1} and Datatype {2}".format(
        dataset.extent[0], dataset.extent[1], dataset.dtype))

    rho.reset_dataset(dataset)
    print("Set the dataset properties for the scalar field rho in iteration 1")

```

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```

# writing fails on already open file error
series.flush()
print("File structure has been written")

offset = [0, 0]
# TODO implement slicing protocol
# E[offset[0]:extent[0], offset[1]:extent[1]] = global_data
rho.store_chunk(offset, extent, global_data)
print("Stored the whole Dataset contents as a single chunk, " +
      "ready to write content")

series.flush()
print("Dataset content has been fully written")

# The files in 'series' are still open until the object is destroyed, on
# which it cleanly flushes and closes all open file handles.
# One can delete the object explicitly (or let it run out of scope) to
# trigger this.
del series

```

## 2.2.3 Parallel API

The following examples show parallel reading and writing of domain-decomposed data with MPI.

### Reading

```

#include <openPMD/openPMD.hpp>

#include <mpi.h>

#include <iostream>
#include <memory>
#include <cstdint>

using std::cout;
using namespace openPMD;

int main(int argc, char *argv[])
{
    MPI_Init(&argc, &argv);

    int mpi_size;
    int mpi_rank;

    MPI_Comm_size(MPI_COMM_WORLD, &mpi_size);
    MPI_Comm_rank(MPI_COMM_WORLD, &mpi_rank);

    /* note: this scope is intentional to destruct the openPMD::Series object
     *      prior to MPI_Finalize();
     */
    {
        Series series = Series(
            "../samples/git-sample/data%T.h5",
            AccessType::READ_ONLY,
            MPI_COMM_WORLD

```

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```

    );
    if( 0 == mpi_rank )
        cout << "Read a series in parallel with " << mpi_size << " MPI ranks\n";

    MeshRecordComponent E_x = series.iterations[100].meshes["E"]["x"];

    Offset chunk_offset = {
        static_cast< long unsigned int >(mpi_rank) + 1,
        1,
        1
    };
    Extent chunk_extent = {2, 2, 1};

    auto chunk_data = E_x.loadChunk<double>(chunk_offset, chunk_extent);

    if( 0 == mpi_rank )
        cout << "Queued the loading of a single chunk per MPI rank from disk, "
              << "ready to execute\n";
    series.flush();

    if( 0 == mpi_rank )
        cout << "Chunks have been read from disk\n";

    for( int i = 0; i < mpi_size; ++i )
    {
        if( i == mpi_rank )
        {
            cout << "Rank " << mpi_rank << " - Read chunk contains:\n";
            for( size_t row = 0; row < chunk_extent[0]; ++row )
            {
                for( size_t col = 0; col < chunk_extent[1]; ++col )
                {
                    cout << "\t"
                        << '(' << row + chunk_offset[0] << '|' << col + chunk_
<offset[1] << '|' << 1 << ") \t"
                        << chunk_data.get() [row*chunk_extent[1]+col];
                    cout << std::endl;
                }
            }

            // this barrier is not necessary but structures the example output
            MPI_Barrier(MPI_COMM_WORLD);
        }
    }

    // openPMD::Series MUST be destructed at this point
    MPI_Finalize();

    return 0;
}

```

## Writing

```

#include <openPMD/openPMD.hpp>

#include <mpi.h>

#include <iostream>
#include <memory>

using std::cout;
using namespace openPMD;

int main(int argc, char *argv[])
{
    MPI_Init(&argc, &argv);

    int mpi_size;
    int mpi_rank;

    MPI_Comm_size(MPI_COMM_WORLD, &mpi_size);
    MPI_Comm_rank(MPI_COMM_WORLD, &mpi_rank);

    /* note: this scope is intentional to destruct the openPMD::Series object
     *      prior to MPI_Finalize();
     */
    {
        // allocate a data set to write
        std::shared_ptr< double > global_data(new double[mpi_size], [](double *p)
→{ delete[] p; });
        for( int i = 0; i < mpi_size; ++i )
            global_data.get()[i] = i;
        if( 0 == mpi_rank )
            cout << "Set up a 1D array with one element per MPI rank (" << mpi_size
                << ") that will be written to disk\n";

        std::shared_ptr< double > local_data(new double);
        *local_data = global_data.get()[mpi_rank];
        if( 0 == mpi_rank )
            cout << "Set up a 1D array with one element, representing the view of_
→the MPI rank\n";

        // open file for writing
        Series series = Series(
            "../samples/5_parallel_write.h5",
            AccessType::CREATE,
            MPI_COMM_WORLD
        );
        if( 0 == mpi_rank )
            cout << "Created an empty series in parallel with "
                << mpi_size << " MPI ranks\n";

        MeshRecordComponent id =
            series
                .iterations[1]
                .meshes["id"][MeshRecordComponent::SCALAR];

        Datatype datatype = determineDatatype(local_data);
        Extent dataset_extent = {static_cast< long unsigned int >(mpi_size)};
        Dataset dataset = Dataset(datatype, dataset_extent);

        if( 0 == mpi_rank )

```

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```

        cout << "Created a Dataset of size " << dataset.extent[0]
              << " and Datatype " << dataset.dtype << '\n';

        id.resetDataset(dataset);
        if( 0 == mpi_rank )
            cout << "Set the global on-disk Dataset properties for the scalar_
↪field id in iteration 1\n";

        series.flush();
        if( 0 == mpi_rank )
            cout << "File structure has been written to disk\n";

        Offset chunk_offset = {static_cast< long unsigned int >(mpi_rank)};
        Extent chunk_extent = {1};
        id.storeChunk(chunk_offset, chunk_extent, local_data);
        if( 0 == mpi_rank )
            cout << "Stored a single chunk per MPI rank containing its_
↪contribution, "
                  "ready to write content to disk\n";

        series.flush();
        if( 0 == mpi_rank )
            cout << "Dataset content has been fully written to disk\n";
    }

    // openPMD::Series MUST be destructed at this point
    MPI_Finalize();

    return 0;
}

```

## 2.3 Development

### 2.3.1 Contribution Guide

#### GitHub

The best starting point is the [GitHub issue tracker](#).

For existing tasks, the labels [good first issue](#) and [help wanted](#) are great for contributions. In case you want to start working on one of those, just *comment* in it first so no work is duplicated.

New contributions in form of [pull requests](#) always need to go in the dev (development) branch. The master branch contains the last stable release and receives updates only when a new version is drafted.

Maintainers organize priorities and progress in the [projects tab](#).

## Style Guide

For coding style, please try to follow the guides in [ComputationalRadiationPhysics/contributing](#) for new code.

## 2.3.2 Repository Structure

### Branches

- `master`: the latest stable release, always tagged with a version
- `dev`: the development branch where all features start from and are merged to
- `release-X.Y.Z`: release candidate for version `X.Y.Z` with an upcoming release, receives updates for bug fixes and documentation such as change logs but usually no new features

### Directory Structure

- `include/`
  - C++ header files
  - `set -I` here
  - prefixed with project name
- `src/`
  - C++ source files
- `lib/`
  - `python/`
    - \* modules, e.g. additional python interfaces and helpers
    - \* set `PYTHONPATH` here
- `examples/`
  - read and write examples
- `samples/`
  - example files; need to be added manually with: `.travis/download_samples.sh`
- `share/openPMD/`
  - `cmake/`
    - \* `cmake` scripts
  - `thirdParty/`
    - \* included third party software
- `test/`
  - unit tests which are run with `ctest` (`make test`)
- `.travis/`
  - setup scripts for our continuous integration systems
- `docs/`
  - documentation files

### 2.3.3 How to Write a Backend

Adding support for additional types of file storage or data transportation is possible by creating a backend. Backend design has been kept independent of the openPMD-specific logic that maintains all constraints within a file. This should allow easy introduction of new file formats with only little knowledge about the rest of the system.

#### File Formats

To get started, you should create a new file format in `include/openPMD/IO/Format.hpp` representing the new backend. Note that this enumeration value will never be seen by users of openPMD-api, but should be kept short and concise to improve readability.

```
enum class Format
{
    JSON
};
```

In order to use the file format through the API, you need to provide unique and characteristic filename extensions that are associated with it. This happens in `src/Series.cpp`:

```
Format
determineFormat(std::string const& filename)
{
    if( auxiliary::ends_with(filename, ".json") )
        return Format::JSON;
}
```

```
std::string
cleanFilename(std::string const& filename, Format f)
{
    switch( f )
    {
        case Format::JSON:
            return auxiliary::replace_last(filename, ".json", "");
    }
}
```

```
std::function< bool(std::string const&) >
matcher(std::string const& name, Format f)
{
    switch( f )
    {
        case Format::JSON:
        {
            std::regex pattern(auxiliary::replace_last(name + ".json$", "%T",
↪ "[[:digit:]]+"));
            return [pattern](std::string const& filename) -> bool { return_
↪ std::regex_search(filename, pattern); };
        }
    }
}
```

Unless your file format imposes additional restrictions to the openPMD constraints, this is all you have to do in the frontend section of the API.

## IO Handler

Now that the user can specify that the new backend is to be used, a concrete mechanism for handling IO interactions is required. We call this an `IOHandler`. It is not concerned with any logic or constraints enforced by openPMD, but merely offers a small set of elementary IO operations.

On the very basic level, you will need to derive a class from `AbstractIOHandler`:

```
/* file: include/openPMD/IO/JSON/JSONIOHandler.hpp */
#include "openPMD/IO/AbstractIOHandler.hpp"

namespace openPMD
{
class JSONIOHandler : public AbstractIOHandler
{
public:
    JSONIOHandler(std::string const& path, AccessType);
    virtual ~JSONIOHandler();

    std::future< void > flush() override;
}
} // openPMD
```

```
/* file: src/IO/JSON/JSONIOHandler.cpp */
#include "openPMD/IO/JSON/JSONIOHandler.hpp"

namespace openPMD
{
JSONIOHandler::JSONIOHandler(std::string const& path, AccessType at)
    : AbstractIOHandler(path, at)
{ }

JSONIOHandler::~~JSONIOHandler()
{ }

std::future< void >
JSONIOHandler::flush()
{ return std::future< void >(); }
} // openPMD
```

Familiarizing your backend with the rest of the API happens in just one place in `src/IO/AbstractIOHandlerHelper.cpp`:

```
#if openPMD_HAVE_MPI
std::shared_ptr< AbstractIOHandler >
createIOHandler(
    std::string const& path,
    AccessType at,
    Format f,
    MPI_Comm comm
)
{
    switch( f )
    {
        case Format::JSON:
            std::cerr << "No MPI-aware JSON backend available. "
                        "Falling back to the serial backend! "
                        "Possible failure and degraded performance!" << std::endl;
            return std::make_shared< JSONIOHandler >(path, at);
    }
}
#endif
```

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```

std::shared_ptr< AbstractIOHandler >
createIOHandler(
    std::string const& path,
    AccessType at,
    Format f
)
{
    switch( f )
    {
        case Format::JSON:
            return std::make_shared< JSONIOHandler >(path, at);
    }
}

```

In this state, the backend will do no IO operations and just act as a dummy that ignores all queries.

## IO Task Queue

Operations between the logical representation in this API and physical storage are funneled through a queue `m_work` that is contained in the newly created `IOHandler`. Contained in this queue are `IOTask` s that have to be processed in FIFO order (unless you can prove sequential execution guarantees for out-of-order execution) when `AbstractIOHandler::flush()` is called. A **recommended** skeleton is provided in `AbstractIOHandlerImpl`. Note that emptying the queue this way is not required and might not fit your IO scheme.

Using the provided skeleton involves

- deriving an `IOHandlerImpl` for your `IOHandler` and
- delegating all flush calls to the `IOHandlerImpl`:

```

/* file: include/openPMD/IO/JSON/JSONIOHandlerImpl.hpp */
#include "openPMD/IO/AbstractIOHandlerImpl.hpp"

namespace openPMD
{
class JSONIOHandlerImpl : public AbstractIOHandlerImpl
{
public:
    JSONIOHandlerImpl(AbstractIOHandler*);
    virtual ~JSONIOHandlerImpl();

    void createFile(Writable*, Parameter< Operation::CREATE_FILE > const&) ↪override;
    void createPath(Writable*, Parameter< Operation::CREATE_PATH > const&) ↪override;
    void createDataset(Writable*, Parameter< Operation::CREATE_DATASET > const&) ↪override;
    void extendDataset(Writable*, Parameter< Operation::EXTEND_DATASET > const&) ↪override;
    void openFile(Writable*, Parameter< Operation::OPEN_FILE > const&) ↪override;
    void openPath(Writable*, Parameter< Operation::OPEN_PATH > const&) ↪override;
    void openDataset(Writable*, Parameter< Operation::OPEN_DATASET > &) ↪override;
    void deleteFile(Writable*, Parameter< Operation::DELETE_FILE > const&) ↪override;
    void deletePath(Writable*, Parameter< Operation::DELETE_PATH > const&) ↪override;
    void deleteDataset(Writable*, Parameter< Operation::DELETE_DATASET > const&) ↪override;
    void deleteAttribute(Writable*, Parameter< Operation::DELETE_ATT > const&) ↪override;

```

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```

    void writeDataset(Writable*, Parameter< Operation::WRITE_DATASET > const&) override;
    void writeAttribute(Writable*, Parameter< Operation::WRITE_ATT > const&) override;
    void readDataset(Writable*, Parameter< Operation::READ_DATASET > &) override;
    void readAttribute(Writable*, Parameter< Operation::READ_ATT > &) override;
    void listPaths(Writable*, Parameter< Operation::LIST_PATHS > &) override;
    void listDatasets(Writable*, Parameter< Operation::LIST_DATASETS > &) override;
    void listAttributes(Writable*, Parameter< Operation::LIST_ATT > &) override;
}
// openPMD

```

```

/* file: include/openPMD/IO/JSON/JSONIOHandler.hpp */
#include "openPMD/IO/AbstractIOHandler.hpp"
#include "openPMD/IO/JSON/JSONIOHandlerImpl.hpp"

namespace openPMD
{
class JSONIOHandler : public AbstractIOHandler
{
public:
    /* ... */
private:
    JSONIOHandlerImpl m_impl;
}
// openPMD

```

```

/* file: src/IO/JSON/JSONIOHandler.cpp */
#include "openPMD/IO/JSON/JSONIOHandler.hpp"

namespace openPMD
{
    /*...*/
    std::future< void >
    JSONIOHandler::flush()
    {
        return m_impl->flush();
    }
}
// openPMD

```

Each IOTask contains a pointer to a Writable that corresponds to one object in the openPMD hierarchy. This object may be a group or a dataset. When processing certain types of IOTasks in the queue, you will have to assign unique FilePositions to these objects to identify the logical object in your physical storage. For this, you need to derive a concrete FilePosition for your backend from AbstractFilePosition. There is no requirement on how to identify your objects, but ids from your IO library and positional strings are good candidates.

```

/* file: include/openPMD/IO/JSON/JSONFilePosition.hpp */
#include "openPMD/IO/AbstractFilePosition.hpp"

namespace openPMD
{
struct JSONFilePosition : public AbstractFilePosition
{
    JSONFilePosition(uint64_t id)
        : id{id}
    { }

    uint64_t id;
};
// openPMD

```

From this point, all that is left to do is implement the elementary IO operations provided in the `IOHandlerImpl`. The `Parameter` structs contain both input parameters (from storage to API) and output parameters (from API to storage). The easy way to distinguish between the two parameter sets is their C++ type: Input parameters are `std::shared_ptr`s that allow you to pass the requested data to their destination. Output parameters are all objects that are *not* `std::shared_ptr`s. The contract of each function call is outlined in `include/openPMD/IO/AbstractIOHandlerImpl`.

```
/* file: src/IO/JSON/JSONIOHandlerImpl.cpp */
#include "openPMD/IO/JSONIOHandlerImpl.hpp"

namespace openPMD
{
void
JSONIOHandlerImpl::createFile(Writable* writable,
                             Parameter< Operation::CREATE_FILE > const&
                             parameters)
{
    if( !writable->written )
    {
        path dir(m_handler->directory);
        if( !exists(dir) )
            create_directories(dir);

        std::string name = m_handler->directory + parameters.name;
        if( !auxiliary::ends_with(name, ".json") )
            name += ".json";

        uint64_t id = /*...*/
        VERIFY(id >= 0, "Internal error: Failed to create JSON file");

        writable->written = true;
        writable->abstractFilePosition = std::make_shared< JSONFilePosition >(id);
    }
}
/*...*/
} // openPMD
```

Note that you might have to keep track of open file handles if they have to be closed explicitly during destruction of the `IOHandlerImpl` (prominent in C-style frameworks).

## 2.3.4 Build Dependencies

*Section author: Axel Huebl*

`openPMD-api` depends on a series of third-party projects. These are currently:

## Required

- CMake 3.10.0+
- C++11 capable compiler, e.g. g++ 4.8+, clang 3.9+, VS 2015+

## Shipped internally

The following libraries are shipped internally in `share/openPMD/thirdParty/` for convenience:

- `MPark.Variant` 1.3.0+ (BSL-1.0)
- `Catch2` 2.3.0+ (BSL-1.0)
- `pybind11` 2.2.3+ (new BSD)

## Optional: I/O backends

- `HDF5` 1.8.13+
- `ADIOS1` 1.13.1+
- `ADIOS2` 2.1+ (*not yet implemented*)

while those can be build either with or without:

- MPI 2.1+, e.g. OpenMPI 1.6.5+ or MPICH2

## Optional: language bindings

- Python:
  - Python 3.X+
  - `pybind11` 2.2.3+
  - `numpy` 1.15+

## 2.3.5 Build Options

*Section author: Axel Huebl*

### Variants

The following options can be added to the `cmake` call to control features. CMake controls options with prefixed `-D`, e.g. `-DopenPMD_USE_MPI=OFF`:

CMake Option	Values	Description
<code>openPMD_USE_MPI</code>	<b>AUTO</b> /ON/OFF	Enable MPI support
<code>openPMD_USE_HDF5</code>	<b>AUTO</b> /ON/OFF	Enable support for HDF5
<code>openPMD_USE_ADIOS1</code>	<b>AUTO</b> /ON/OFF	Enable support for ADIOS1
<code>openPMD_USE_ADIOS2</code>	<b>AUTO</b> /ON/OFF	Enable support for ADIOS2 <sup>1</sup>
<code>openPMD_USE_PYTHON</code>	<b>AUTO</b> /ON/OFF	Enable Python bindings
<code>openPMD_USE_INVASIVE_TESTING</code>	<b>AUTO</b> /ON/OFF	Enable unit tests that modify source code <sup>2</sup>
<code>openPMD_USE_VERIFY</code>	<b>ON</b> /OFF	Enable internal <code>VERIFY</code> (assert) macro independent of build type <sup>3</sup>
<code>PYTHON_EXECUTABLE</code>	(first found)	Path to Python executable

<sup>1</sup> *not yet implemented*



<sup>2</sup> e.g. C++ keywords, currently disabled only for MSVC

<sup>3</sup> this includes most pre-/post-condition checks, disabling without specific cause is highly discouraged

## Shared or Static

By default, we will build as a static library and install also its headers. You can only build a static (`libopenPMD.a` or `openPMD.lib`) or a shared library (`libopenPMD.so` or `openPMD.dll`) at a time.

The following options can be tried to switch between static and shared builds and control if dependencies are linked dynamically or statically:

CMake Option	Values	Description
<code>BUILD_SHARED_LIBS</code>	<b>ON/OFF</b>	Build the C++ API as shared library
<code>HDF5_USE_STATIC_LIBRARIES</code>	<b>ON/OFF</b>	Require static HDF5 library
<code>ADIOS_USE_STATIC_LIBS</code>	<b>ON/OFF</b>	Require static ADIOS1 library

Note that python modules (`openPMD.cpython.[...].so` or `openPMD.pyd`) are always dynamic libraries. Therefore, if you want to build the python module and prefer static dependencies, make sure to provide all of dependencies build with position independent code (`-fPIC`). The same requirement is true if you want to build a *shared* C++ API library with *static* dependencies.

## Debug

By default, the Release version is built. In order to build with debug symbols, pass `-DCMAKE_BUILD_TYPE=Debug` to your `cmake` command.

## Shipped Dependencies

Additionally, the following libraries are shipped internally for convenience. These might get installed in your `CMAKE_INSTALL_PREFIX` if the option is ON.

The following options allow to switch to external installs of dependencies:

CMake Option	Values	Installs	Library	Version
<code>openPMD_USE_INTERNAL_VARIANT</code>	<b>ON/OFF</b>	Yes	MPark.Variant	1.3.0+
<code>openPMD_USE_INTERNAL_CATCH</code>	<b>ON/OFF</b>	No	Catch2	2.3.0+
<code>openPMD_USE_INTERNAL_PYBIND11</code>	<b>ON/OFF</b>	No	pybind11	2.2.3+

## Tests

By default, tests and examples are built. In order to skip building those, pass `-DBUILD_TESTING=OFF` or `-DBUILD_EXAMPLES=OFF` to your `cmake` command.

## 2.3.6 Sphinx

*Section author: Axel Huebl*

In the following section we explain how to contribute to this documentation.

If you are reading the HTML version on <http://openPMD-api.readthedocs.io> and want to improve or correct existing pages, check the “Edit on GitHub” link on the right upper corner of each document.

Alternatively, go to `docs/source` in our source code and follow the directory structure of `reStructuredText` (`.rst`) files there. For intrusive changes, like structural changes to chapters, please open an issue to discuss them beforehand.

## Build Locally

This document is build based on free open-source software, namely [Sphinx](#), [Doxygen](#) (C++ APIs as XML) and [Breathe](#) (to include doxygen XML in Sphinx). A web-version is hosted on [ReadTheDocs](#).

The following requirements need to be installed (once) to build our documentation successfully:

```
cd docs/

# doxygen is not shipped via pip, install it externally,
# from the homepage, your package manager, conda, etc.
# example:
sudo apt-get install doxygen

# python tools & style theme
pip install -r requirements.txt # --user
```

With all documentation-related software successfully installed, just run the following commands to build your docs locally. Please check your documentation build is successful and renders as you expected before opening a pull request!

```
# skip this if you are still in docs/
cd docs/

# parse the C++ API documentation,
#   enjoy the doxygen warnings!
doxygen
# render the `.rst` files and replace their macros within
#   enjoy the breathe errors on things it does not understand from doxygen :)
make html

# open it, e.g. with firefox :)
firefox build/html/index.html

# now again for the pdf :)
make latexpdf

# open it, e.g. with okular
build/latex/openPMD-api.pdf
```

## Useful Links

- [A primer on writing restFUL files for sphinx](#)
- [Why You Shouldn't Use "Markdown" for Documentation](#)
- [Markdown Limitations in Sphinx](#)

## 2.3.7 Doxygen

*Section author: Axel Huebl*

An online version of our Doxygen build can be found at

<http://www.openPMD.org/openPMD-api/>

We regularly update it via

```
git checkout gh-pages

# optional argument: branch or tag name
```

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```
./update.sh  
  
git commit -a  
git push
```

This section explains what is done when this script is run to build it manually.

## Requirements

First, install [Doxygen](#) and its dependencies for graph generation.

```
# install requirements (Debian/Ubuntu)  
sudo apt-get install doxygen graphviz  
  
# enable HTML output in our Doxyfile  
sed -i 's/GENERATE_HTML.*=.*NO/GENERATE_HTML      = YES/' docs/Doxyfile
```

## Build

Now run the following commands to build the Doxygen HTML documentation locally.

```
cd docs/  
  
# build the doxygen HTML documentation  
doxygen  
  
# open the generated HTML pages, e.g. with firefox  
firefox html/index.html
```