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CARMA is a header only library providing conversions between Numpy arrays and Armadillo matrices.
CARMA provides fast bidirectional conversions between Numpy arrays and Armadillo matrices, vectors and cubes, much like RcppArmadillo does for R and Armadillo.

The library extends the impressive Pybind11 library with support for Armadillo. For details on Pybind11 and Armadillo refer to their respective documentation [1], [2].

1.1 Installation

CARMA is a header only library that relies on two other header only libraries, Armadillo and Pybind11.

CARMA can be installed using:

```
mkdir build
cd build
# optionally with -DCMAKE_INSTALL_PREFIX:PATH=
cmake -DCARMA_INSTALL_LIB=ON ..
cmake --build . --config Release --target install
```

You can then include it in a project using:

```
FIND_PACKAGE(carma CONFIG REQUIRED)
TARGET_LINK_LIBRARIES(<your_target> PRIVATE carma::carma)
```

The REQUIRED state is propagated to the dependencies of CARMA.

CARMA and Armadillo can then be included using:

```
#include <carma>
#include <armadillo>
```

CARMA can also be used without installation see Build Configuration. CARMA provides a number of configurations that can be set in the carma_config.cmake file at the root of the directory or passed to CMake, see Configuration for details.
1.2 Requirements

CARMA >= v0.5 requires a compiler with support for C++14 and supports:

- Python 3.6 – 3.9
- Numpy >= 1.14
- Pybind11 >= v2.6.0
- Armadillo >= 10.5.2

CARMA makes use of Armadillo’s ARMA_ALIEN_MEM_ALLOC and ARMA_ALIEN_MEM_FREE functionality introduced in version 10.5.2 to use Numpy’s (de)allocator.

1.3 OLS example

A brief example on how conversion can be achieved. We convert the Numpy arrays X and y in using automatic casting (type-caster) and using manual conversion on the way out.

```cpp
#include <carma>
#include <armadillo>
#include <pybind11/pybind11.h>
#include <pybind11/numpy.h>
#include <pybind11/pytypes.h>

py::tuple ols(arma::mat& X, arma::colvec& y) {
    // We borrow the data underlying the numpy arrays
    int n = X.n_rows, k = X.n_cols;
    arma::colvec coeffs = arma::solve(X, y);
    arma::colvec resid = y - X * coeffs;
    double sig2 = arma::as_scalar(arma::trans(resid) * resid / (n-k));
    arma::colvec std_errs = arma::sqrt(sig2 * arma::diagvec(arma::inv(arma::trans(X)*X)));
    // We take ownership of the memory from the armadillo objects and
    // return to python as a tuple containing two Numpy arrays.
    return py::make_tuple(
        carma::col_to_arr(coeffs),
        carma::col_to_arr(std_errs)
    );
}
```

1.4 Considerations

In order to achieve fast conversions the default behaviour is avoid copying both from and to Numpy whenever possible and reasonable. This allows very low overhead conversions but it impacts memory safety and requires user vigilance.

If you intend to return the memory of the input array back as another array, you must make sure to either copy or steal the memory on the conversion in or copy the memory out. If you don’t the memory will be aliased by the two Numpy arrays and bad things will happen.
A second consideration is memory layout. Armadillo is optimised for column-major (Fortran order) memory whereas Numpy defaults to row-major (C order). The default behaviour is to automatically convert, read copy, C-order arrays to F-order arrays upon conversion to Armadillo. Users should note that the library will not convert back to C-order when returning.

For details see the *Memory Management* section.
CHAPTER 2

About

This project was created by Ralph Urlus. Significant improvements to the project have been contributed by Pascal H.

2.1 License

carma is provided under a Apache 2.0 license that can be found in the LICENSE file. By using, distributing, or contributing to this project, you agree to the terms and conditions of this license.
CARMA relies on Pybind11 for the generation of the bindings and casting of the arguments from Python to C++. Make sure you are familiar with Pybind11 before continuing on.

You can embed CARMA in a Pybind11 project using the CMake commands:

```cmake
ADD_SUBDIRECTORY(extern/carma)
TARGET_LINK_LIBRARIES(<your_target> PRIVATE carma)
```

It is advised to use `ADD_SUBDIRECTORY` to incorporate CARMA as this provides an interface target, `carma`, that can be linked to your target. Using this target prevents an include order dependency, see CARMA target for details.

**Warning:** if you are not using CARMA’s cmake target you have to ensure that you include CARMA before Armadillo. Not doing so results in a compile error.

CARMA can provide Armadillo and or Pybind11 at compile time if desired, see Armadillo and Pybind11 details. See Pybind11’s CMake build system documentation or CARMA’s examples for a start.

### 3.1 Build examples

The tests and examples can be compiled using CMake. CMake can be installed with `pip install cmake`, your package manager or directly from `cmake`.

```bash
mkdir build
cd build
cmake -DCMAKE_BUILD_TYPE=Release -DCMAKE_INSTALL_PREFIX=. -DCARMA_BUILD_EXAMPLES=true
-DCARMA_BUILD_TESTS=true .. && make install
```

To run the tests you need to install `pytest`:
pip install pytest

and run:

ctest

To install carma, you have to define

-DMAKE_INSTALL_PREFIX=/installation/path/directory

(default value is /usr/local)

The installation directory contains

| include | # carma headers |
| tests   | # carma tests with python module (if enabled using -DBUILD_TESTS=on) |
| examples| # carma python examples with python module (if enabled using -DBUILD_EXAMPLES=on) |

See section Examples for an overview of the conversion approaches.
CHAPTER 4

Design Patterns

CARMA was designed with three patterns in mind: borrow, transfer ownership and view.

4.1 Borrow

You can borrow the underlying memory of a Numpy array using the `arr_to_*(py::array_t<T>, copy=false)`. The Armadillo object should not be returned without a copy out. Use this when you want to modify the memory in-place. If the array is not well behaved, see Well behaved, the data is copied to well-behaved memory and swapped in place of the input array. If `copy=true` this is equivalent to the copy approach below.

**Note:** the size of the Armadillo object is not allowed change when you borrow, i.e. `strict=true`.

4.2 Transfer ownership

You can transfer ownership to Armadillo using steal or copy. After transferring ownership of the memory, Armadillo behaves as if it has allocated the memory itself, hence it will also free the memory upon destruction using Numpy’s deallocator.

4.2.1 Steal

If you want to take ownership of the underlying memory but don’t want to copy the data you can steal the array. The Armadillo object can be safely returned out without a copy. There are multiple compile time definitions on how the memory is stolen, see Configuration for details. If the memory of the array is not well-behaved a copy of the memory is stolen.

**Note:** the size of the Armadillo object is allowed change after stealing, `strict=false`.
4.2.2 Copy

If you want to give Armadillo full control of underlying memory but also want to keep Numpy as owner you should copy. The Armadillo object can be safely returned out without a copy. If the memory of the array is not well-behaved a copy of the memory is used instead.

Note: the size of the Armadillo object is allowed change after copying, strict=false.

4.3 View

If you want to have a read-only view on the underlying memory you can use arr_to_*_view. If the underlying memory is not well-behaved, excluding writeable, it will be copied.
On a high level CARMA provides two ways to work with Numpy arrays and Armadillo, see the Function specifications section for details about the available functions and the examples directory for runnable examples.

5.1 Manual conversion

The easiest way to use CARMA is manual conversion, it gives you the most control over when to copy or not. You pass a Numpy array as an input and/or as the return type and call the respective conversion function.

**Warning:** Carma will avoid copying by default so make sure not to return the memory of the input array without copying. If you don’t copy out, the memory is aliased by both the input and output arrays which will cause a segfault.

5.1.1 Borrow

```cpp
#include <carma>
#include <armadillo>
#include <pybind11/pybind11.h>
#include <pybind11/numpy.h>

py::array_t<double> manual_example(py::array_t<double> & arr) {
  // convert to Armadillo matrix without copying.
  // Note the size of the matrix cannot be changed when borrowing
  arma::Mat<double> mat = carma::arr_to_mat<double>(arr);

  // normally you do something useful here ...
  arma::Mat<double> result = arma::Mat<double>(arr.shape(0), arr.shape(1),
                 arma::fill::randu);
```

(continues on next page)
// convert to Numpy array and copy out
return carma::mat_to_arr(result, true);
}

5.1.2 Transfer ownership

If you want to transfer ownership to the C++ side you can use:

```cpp
#include <carma>
#include <armadillo>
#include <pybind11/pybind11.h>
#include <pybind11/numpy.h>

py::array_t<double> steal_array(py::array_t<double> & arr) {
    // convert to armadillo matrix
    arma::Mat<double> mat = carma::arr_to_mat<double>(std::move(arr));
    // armadillo now owns and manages the lifetime of the memory
    // if you want to return you don't need to copy out
    return mat_to_arr(mat);
}

py::array_t<double> copy_array(py::array_t<double> & arr) {
    // convert to armadillo matrix
    arma::Mat<double> mat = carma::arr_to_mat<double>(arr, true);
    // armadillo now owns and manages the lifetime of the memory
    // if you want to return you don't need to copy out
    return mat_to_arr(mat);
}

py::array_t<double> copy_const_array(const py::array_t<double> & arr) {
    // convert to armadillo matrix
    arma::Mat<double> mat = carma::arr_to_mat<double>(arr);
    // armadillo now owns and manages the lifetime of the memory
    // if you want to return you don't need to copy out
    return mat_to_arr(mat);
}

5.2 Automatic conversion

For automatic conversion you specify the desired Armadillo type for either or both the return type and the function parameter. When calling the function from Python, Pybind11 will call CARMA's type caster when a Numpy array is passed or returned, see Return policies for details.

**Warning:** Make sure to include carma in every compilation unit that makes use of the type caster, not including it results in undefined behaviour.

```cpp
#include <carma>
#include <armadillo>
#include <pybind11/pybind11.h>
#include <pybind11/numpy.h>
```
arma::Mat<
    double>
  automatic_example(arma::Mat<
    double>
    & mat) {
    arma::Mat<
        double>
    rand = arma::Mat<
        double>
        (mat.n_rows, mat.n_cols,
         arma::fill::randu);
    arma::Mat<
        double>
    result = mat + rand;
    return result;
  }

**Warning:** The automatic conversion will not copy the Numpy array’s memory when converting to Armadillo objects. When converting back to Numpy arrays the memory will not be copied out by default. You should specify return_value_policy::copy if you want to return the input array.

### 5.3 ArrayStore

There are use-cases where you would want to keep the data in C++ and only return when requested. For example, you write an Ordinary Least Squares (OLS) class and you want to store the residuals, covariance matrix, … in C++ for when additional tests need to be run on the values without converting back and forth.

ArrayStore is a convenience class that provides conversion methods back and forth. It is intended to be used as an attribute as below:

**Warning:** The ArrayStore owns the data, the returned numpy arrays are views that are tied to the lifetime of ArrayStore.

```cpp
#include <armadillo>
#include <carma>
#include <pybind11/pybind11.h>
#include <pybind11/numpy.h>

class ExampleClass {
  private:
    carma::ArrayStore<arma::Mat<double>> _x;
    carma::ArrayStore<arma::Mat<double>> _y;
  
  public:
    ExampleClass(py::array_t<double> & x, py::array_t<double> & y) :
      // copy the array and store it as an Armadillo matrix
      _x{carma::ArrayStore<arma::Mat<double>>(x, true)},
      // steal the array and store it as an Armadillo matrix
      _y{carma::ArrayStore<arma::Mat<double>>(y, false)},
    
    py::array_t<double> member_func() {
      // normally you would something useful here
      _x.mat += _y.mat;
      // return mutable view off arma matrix
      return _x.get_view(true);
    }
}
```

(continues on next page)
void bind_exampleclass(py::module &m) {
    py::class_<ExampleClass>(m, "ExampleClass")
        .def(py::init<py::array_t<double> &, py::array_t<double> &>(), R"pbdoc(Initialise ExampleClass.
Parameters
-----------
arr1: np.ndarray
    array to be stored in armadillo matrix
arr2: np.ndarray
    array to be stored in armadillo matrix)
)pbdoc")
        .def("member_func", &ExampleClass::member_func, R"pbdoc(Compute ....)
)pbdoc");
}

5.4 Ordinary Least Squares

Combining the above approaches to compute the Ordinary Least Squares:

```cpp
#include <carma>
#include <armadillo>
#include <pybind11/pybind11.h>
#include <pybind11/numpy.h>
#include <pybind11/pytypes.h>

py::tuple ols(arma::mat& X, arma::colvec& y) {
    // We borrow the data underlying the numpy arrays
    int n = X.n_rows, k = X.n_cols;
    arma::colvec coefs = arma::solve(X, y);
    arma::colvec resid = y - X * coefs;
    double sig2 = arma::as_scalar(arma::trans(resid) * resid / (n-k));
    arma::colvec std_errs = arma::sqrt(sig2 * arma::diagvec(arma::inv(arma::trans(X)*X)));

    // We take ownership of the memory from the armadillo objects and
    // return to python as a tuple containing two Numpy arrays.
    return py::make_tuple(
        carma::col_to_arr(coefs),
        carma::col_to_arr(std_errs)
    );
}
```

Which can be called using:

```python
y = np.linspace(1, 100, num=100) + np.random.normal(0, 0.5, 100)
X = np.hstack((np.ones(100)[:, None], np.arange(1, 101)[:, None]))
```
coeff, std_err = carma.ols(X, y)

The repository contains tests, examples and CMake build instructions that can be used as a reference.
A significant difference between Numpy arrays and Armadillo matrices is the memory order. Armadillo is optimised for column-major (Fortran order) memory whereas Numpy defaults to row-major (C order).

The default behaviour is to automatically convert matrices and cubes, read copy, C-order arrays to F-order arrays upon conversion to Armadillo. This behaviour can be disabled at compile time, see \textit{Configuration}.

This conversion can be avoided by ensuring all data generated by Numpy is done with \texttt{order='F'} or converted using:

\[ \texttt{np.asarray(cdata, type=np.float64, order='F')} \]

\textbf{Note:} Carma will not convert F-order memory back to C-order when returning, this has consequences for matrices and cubes.
Armadillo will not always hold the same memory for the entirety of a object’s lifetime, e.g. you add columns to a matrix. To be able to transfer ownership we have to be sure that the memory will be deallocated by the function matching the allocator. In the case of CARMA this means Armadillo must use the Numpy allocator (PyDataMem_NEW) and deallocator (PyDataMem_FREE). Numpy’s allocator is compatible with Armadillo as both call/wrap malloc/calloc.
In order to provide fast conversions the default behaviour of CARMA is to avoid copying where possible. However, this requires users to be vigilant to avoid aliasing of memory. This section describes when copies are made by default.

Note when borrowing the memory of an array the Armadillo object cannot be changed in size, this will trigger an exception. If the Armadillo object will change in size you should use a copy or steal.

**Warning:** Armadillo objects are **not** copied out by default. You should not return an object without copying when the Armadillo object points to borrowed memory as this will cause double frees and segfaults.
Armadillo expects the memory to be aligned and Fortran order (column contiguous). To ensure this we check if the array is **well-behaved** which is not true when one of the following is true:

1. memory is not aligned
2. memory is not writable
3. array does not own the memory (OWNDATA=false)
4. array has \( ndim \geq 2 \) and memory is not F-contiguous

**Note:** Conditions 3 and 4 can be disabled, independently, with compile time definitions, see the section *Configuration*.

Based on the type of conversion, steal, borrow or view, the effect on the input array differs.

### 9.1 Borrow

The memory of the array is copied to well-behaved memory and swapped in the place of the original memory. This is done to ensure the design that pattern that borrowed arrays don’t require a return to reflect the changes.

### 9.2 Stealing

If an array will be stolen but it’s not well-behaved the memory is copied to well-behaved memory and ownership of the new memory is transferred to Armadillo. Note this steals a reference to the input array, which will be destructed by Numpy/Python.
9.3 Copy

If an array will be copied it is automatically copied to well-behaved memory and ownership of the new memory is transferred to Armadillo. This has no effect on the input array.

9.4 View

For view’s the definition of well-behaved ignores the writeable flag as the Armadillo object will be read-only.
CARMA offers a number of compile-time settings that determine when the input array’s memory is not considered well-behaved and how to handle stealing the memory of an incoming array.

You can find the configuration file, `carma_config.cmake`, in the root of the repository where you can enable or disable the various settings.

### 10.1 Array conditions

As detailed in the section *Well behaved* input arrays are copied when they don’t meet the criteria. Two of these criteria can be turned off.

```
OPTION(ENABLE_CARMA_DONT_REQUIRE_OWNDATA "Enable CARMA_DONT_REQUIRE_OWNDATA" ON)
```

**Warning:** When using this option you have make sure that the memory of the input array can be safely freed using Numpy’s deallocator (PyDataMem_FREE) as this is used to manage the memory after transferring ownership to Armadillo.

Do **not** copy arrays if the data is not owned by Numpy, default behaviour is to copy when OWNDATA is False. Note this will lead to segfaults when the array’s data is stolen or otherwise aliased by Armadillo. Is useful when you want to pass back and forth arrays previously converted by CARMA.

```
OPTION(ENABLE_CARMA_DONT_REQUIRE_F_CONTIGUOUS "Enable CARMA_DONT_REQUIRE_F_CONTIGUOUS" ON)
```

Do **not** copy C-contiguous arrays, default behaviour is to copy C-contiguous arrays to Fortran order as this is what Armadillo is optimised for. Note that on the conversion back, it is assumed that the memory of the Armadillo object has Fortran order layout.
10.2 Stealing

The default behaviour is to only set OWNDATA=false when stealing the data of an array. This is fast and leaves the array usable. However, two additional options exists that make it clearer when an array has been stolen.

```bash
OPTION(ENABLE_CARMA_SOFT_STEAL "Enable CARMA_SOFT_STEAL" ON)
```

When stealing the data of an array replace it with an array containing a single NaN. This is a safer but slower option compared to HARD_STEAL but easier to notice than the default.

```bash
OPTION(ENABLE_CARMA_HARD_STEAL "Enable CARMA_HARD_STEAL" ON)
```

When stealing the data of an array CARMA sets a `nullptr` in place of the pointer to the memory. Note this will cause a `segfault` when accessing the original array’s data. However, this ensures stolen arrays are not accidentally used later on.

10.3 Debugging

```bash
OPTION(ENABLE_CARMA_EXTRA_DEBUG "Enable CARMA_EXTRA_DEBUG" ON)
OPTION(ENABLE_ARMA_EXTRA_DEBUG "Enable ARMA_EXTRA_DEBUG" ON)
```

Turn this setting on if you want to debug conversions. Debug prints are generated that specify when arrays are not well-behaved, stolen or swapped in place. Note that the additional debugging information from Armadillo can be enabled using the second setting.

10.4 Release

```bash
OPTION(ENABLE_ARMA_NO_DEBUG "Enable ENABLE_ARMA_NO_DEBUG" OFF)
```

This option sets ARMA_NO_DEBUG as part of the release flags.

“Disable all run-time checks, such as bounds checking. This will result in faster code, but you first need to make sure that your code runs correctly! We strongly recommend to have the run-time checks enabled during development, as this greatly aids in finding mistakes in your code, and hence speeds up development. We recommend that run-time checks be disabled only for the shipped version of your program (i.e. final release build).” – Armadillo documentation

10.5 Developer settings

Two settings exists to facilitate development of CARMA:

```bash
-DCARMA_DEV_MODE=ON
```

This enables:

- CARMA_BUILD_TESTS=ON
- CARMA_DEV_TARGET=ON
- CMAKE_EXPORT_COMPILE_COMMANDS=1
- CMAKE_INSTALL_PREFIX ${PROJECT_SOURCE_DIR}/build)
-DCARMA_DEV_DEBUG_MODE=ON

Turns on CARMA_DEV_MODE and ENABLE_CARMA_EXTRA_DEBUG.
CARMA v0.5 requires a compiler with support for C++14 and supports:

- Python 3.6 – 3.9
- Numpy >= 1.14
- Pybind11 >= v2.6.0
- Armadillo >= 10.5.2

## 11.1 CMake build

CARMA provides a CMake configuration that can be used to integrate into existing builds. You can either use it directly or install it first. To edit the configuration please see

It is advised to use the `carma::carma` interface target that can be linked to your target. This target pre-compiles the `cnalloc.h` header containing wrappers around Numpy’s (de)allocator that are then picked up by Armadillo. By pre-compiling the header we can ensure that the `ARMA_ALIEN_MEM_ALLOC` and `ARMA_ALIEN_MEM_FREE` definitions exist when including Armadillo regardless of the include order.

**Warning:** if you are not using CARMA’s cmake target you have to ensure that you include CARMA before Armadillo. Not doing so results in a compile error.

### 11.1.1 Installation

Make sure to change the configuration if desired before installing CARMA.

CARMA can be installed using:
mkdir build
cd build
# optionally with -DCMAKE_INSTALL_PREFIX:PATH=
cmake -DCARMA_INSTALL_LIB=ON ..
cmake --build . --config Release --target install

You can than include it in a project using:

```
FIND_PACKAGE(carma CONFIG REQUIRED)
TARGET_LINK_LIBRARIES(<your_target> PRIVATE carma::carma)
```

The REQUIRED state is propagated to the dependencies of CARMA.

**Variables**

The FIND_PACKAGE call sets the following variables

- `carma_FOUND` – true if CARMA was found
- `carma_INCLUDE_DIR` – the path to CARMA’s include directory
- `carma_INCLUDE_DIRS` – the paths to CARMA’s include directory and the paths to the include directories of the dependencies.

**Components**

When including carma using FIND_PACKAGE two targets are created:

- `carma::carma`

  carma::carma has been linked with Python, Numpy, Pybind11 and Armadillo and pre-compiles the `cnalloc.h` header which means that there is no required order to includes or carma and armadillo. If you only want this component you can use `FIND_PACKAGE(carma CONFIG REQUIRED COMPONENTS carma)`

- `carma::headers`

  If you want to have a header-only target that is not linked with the dependencies and does not pre-compile `cnalloc.h`. You must than make sure to link it to it’s dependencies and make sure to always include carma before armadillo. If you only want this component you can use `FIND_PACKAGE(carma CONFIG REQUIRED COMPONENTS headers)`

**11.1.2 Subdirectory**

Alternatively, you can use CARMA without installing it by using:

```
ADD_SUBDIRECTORY(extern/carma)
TARGET_LINK_LIBRARIES(<your_target> PRIVATE carma::carma)
```

The same targets and conditions as for the installation hold, however, this build will obtain Armadillo and Pybind11 if they have not been provided.
11.2 Armadillo

Users can provide a specific Armadillo version by making sure the target `armadillo` is set before including CARMA or by setting:

```
-DARMADILLO_ROOT_DIR=/path/to/armadillo/root/directory
```

When using the subdirectory build, if neither is set, CARMA will provide the `armadillo` target at build time and store a clone of armadillo in `carma/extern/armadillo-code`. The Armadillo version, by default 10.5.2, can be set using:

```
-DUSE_ARMA_VERSION=10.5.x
```

11.3 Pybind11

Users can provide a specific Pybind11 version by making sure the target `pybind11` is set before including CARMA or by setting:

```
-DPYBIND11_ROOT_DIR=/path/to/pybind11/root/directory
```

When using the subdirectory build, if neither is set, CARMA will provide the `pybind11` target at build time and store a clone in `carma/extern/pybind11`. The Pybind11 version, by default v2.6.2, can be set using:

```
-DUSE_PYBIND11_VERSION=v2.6.2
```

11.4 Python

CARMA needs to link against Python’s and Numpy’s headers and uses CMake’s `FIND_PYTHON` to locate them. `FIND_PYTHON` doesn’t always find the right Python, e.g. when using `pyenv`. When this happens you can set `Python3_EXECUTABLE`, which is then also passed on to Pybind11 to ensure the same Python versions are found.

```
-DPython3_EXECUTABLE=$(which python3)
# or
-DPython3_EXECUTABLE=$(python3 -c 'import sys; print(sys.executable)')
```
CARMA provides a set of functions for manual conversion of Numpy arrays and Armadillo matrices. Manual conversion should be used when fine grained control of memory is required.

## 12.1 Numpy to Armadillo

Functions to convert Numpy arrays to Armadillo matrices, vectors or cubes

### 12.1.1 Matrix

**arma::Mat<T> arr_to_mat(py::array<T>& arr, bool copy=false)**

Convert Numpy array to Armadillo matrix. When borrowing the the array, copy=false, if it is not well-behaved we perform a in-place swap to a well behaved array

If the array is 1D we create a column oriented matrix (N, 1)

**Parameters**

- **arr** – numpy array to be converted
- **copy** – copy the memory of the array, default is false

**Raises**

- **runtime_error** – if n_dims > 2 or memory is not initialised (nullptr)
- **runtime_error** – if copy is false and the array is not well-behaved and not writable as this prevents an inplace-swap.

**arma::Mat<T> arr_to_mat(const py::array<T>& arr)**

Copy the memory of the Numpy array in the conversion to Armadillo matrix.

If the array is 1D we create a column oriented matrix (N, 1)

**Parameters** **arr** – numpy array to be converted
Renames runtime_error – if n_dims > 2 or memory is not initialised (nullptr)

arma::Mat<T> arr_to_mat(py::array<T>&& arr)
Steal the memory of the Numpy array in the conversion to Armadillo matrix. If the memory is not well-behaved we steal a copy of the array
If the array is 1D we create a column oriented matrix (N, 1)

Parameters arr – numpy array to be converted

Raises runtime_error – if n_dims > 2 or memory is not initialised (nullptr)

const arma::Mat<T> arr_to_mat_view(const py::array<T>& arr)
Copy the memory of the Numpy array in the conversion to Armadillo matrix if not well behaved otherwise borrow.
If the array is 1D we create a column oriented matrix (N, 1)

Parameters arr – numpy array to be converted

Raises runtime_error – if n_dims > 2 or memory is not initialised (nullptr)

12.1.2 Vector

arma::Col<T> arr_to_col(py::array<T>& arr, bool copy=false)
Convert Numpy array to Armadillo column. When borrowing the array, copy=false, if it is not well-behaved we perform an in-place swap to a well-behaved array

Parameters

• arr – numpy array to be converted
• copy – copy the memory of the array, default is false

Raises

• runtime_error – if n_cols > 1 or memory is not initialised (nullptr)
• runtime_error – if copy is false and the array is not well-behaved and not writable as this prevents an inplace-swap.

arma::Col<T> arr_to_col(const py::array<T>& arr)
Copy the memory of the Numpy array in the conversion to Armadillo column.

Parameters arr – numpy array to be converted

Raises runtime_error – if n_cols > 1 or memory is not initialised (nullptr)

arma::Col<T> arr_to_col(py::array<T>&& arr)
Steal the memory of the Numpy array in the conversion to Armadillo column. If the memory is not well-behaved we steal a copy of the array

Parameters arr – numpy array to be converted

Raises runtime_error – if n_cols > 1 or memory is not initialised (nullptr)

const arma::Col<T> arr_to_col_view(const py::array<T>& arr)
Create a read-only view on the array as a Armadillo Col. Copy the memory of the Numpy array in the conversion to Armadillo column if not well_behaved otherwise borrow the array.

Parameters arr – numpy array to be converted

Raises runtime_error – if n_cols > 1 or memory is not initialised (nullptr)
arma::Row<T> arr_to_row(py::array<T>& arr, bool copy=false)
Convert Numpy array to Armadillo row. When borrowing the array, copy=false, if it is not well-behaved we perform a in-place swap to a well behaved array.

Parameters
- arr – numpy array to be converted
- copy – copy the memory of the array, default is false

Raises
- runtime_error – if n_rows > 1 or memory is not initialised (nullptr)
- runtime_error – if copy is false and the array is not well-behaved and not writable as this prevents an inplace-swap.

arma::Row<T> arr_to_col(const py::array<T>& arr)
Copy the memory of the Numpy array in the conversion to Armadillo row.

Parameters
arr – numpy array to be converted

Raises runtime_error – if n_rows > 1 or memory is not initialised (nullptr)

arma::Row<T> arr_to_col(py::array<T>&& arr)
Steal the memory of the Numpy array in the conversion to Armadillo row. If the memory is not well-behaved we steal a copy of the array.

Parameters
arr – numpy array to be converted

Raises runtime_error – if n_cols > 1 or memory is not initialised (nullptr)

cst arma::Row<T> arr_to_col_view(const py::array<T>& arr)
Create a read-only view on the array as a Armadillo Col. Copy the memory of the Numpy array if not well_behaved otherwise borrow the array.

Parameters
arr – numpy array to be converted

Raises runtime_error – if n_rows > 1 or memory is not initialised (nullptr)

12.1.3 Cube

arma::Cube<T> arr_to_cube(py::array<T>& arr, bool copy=false)
Convert Numpy array to Armadillo Cube. When borrowing the array, copy=false, if it is not well-behaved we perform a in-place swap to a well behaved array.

Parameters
- arr – numpy array to be converted
- copy – copy the memory of the array, default is false

Raises
- runtime_error – if n_dims < 3 or memory is not initialised (nullptr)
- runtime_error – if copy is false and the array is not well-behaved and not writable as this prevents an inplace-swap.

arma::Cube<T> arr_to_cube(const py::array<T>& arr)
Copy the memory of the Numpy array in the conversion to Armadillo Cube.

Parameters
arr – numpy array to be converted

Raises runtime_error – if n_dims < 3 or memory is not initialised (nullptr)
arma::Cube<T> arr_to_cube(py::array<T>&& arr)

Steal the memory of the Numpy array in the conversion to Armadillo Cube. If the memory is not well-behaved we steal a copy of the array

Parameters arr – numpy array to be converted

Raises runtime_error – if n_dims < 3 or memory is not initialised (nullptr)

const arma::Cube<T> arr_to_cube_view(const py::array<T>& arr)

Create a read-only view on the array as a Armadillo Cube. Copy the memory of the Numpy array if not well_behaved otherwise borrow the array.

Parameters arr – numpy array to be converted

Raises runtime_error – if n_dims < 3 or memory is not initialised (nullptr)

12.1.4 to_arma

to_arma is a convenience wrapper around the arr_to_* functions and has the same behaviour and rules. For example,

arma::Mat<double> mat = to_arma::from<arma::Mat<double>>(arr, copy=false);

template <typename armaT> armaT to_arma::from(const py::array_t<eT>& arr)
template <typename armaT> armaT to_arma::from(py::array_t<eT>& arr, bool copy)
template <typename armaT> armaT to_arma::from( py::array_t<eT>&& arr)

12.2 Armadillo to Numpy

This section documents the functions to convert Armadillo matrices, vectors or cubes to Numpy arrays.

12.2.1 Matrix

py::array_t<T> mat_to_arr(arma::Mat<T>& src, bool copy=false)

Convert Armadillo matrix to Numpy array, note the returned array will have column contiguous memory (F-order)

Note the returned array will have F order memory.

Parameters

• src – armadillo object to be converted.
• copy – copy the memory of the array, default is false which steals the memory

py::array_t<T> mat_to_arr(const arma::Mat<T>& src)

Copy the memory of the Armadillo matrix in the conversion to Numpy array.

Note the returned array will have F order memory.

Parameters src – armadillo object to be converted.

py::array_t<T> mat_to_arr(arma::Mat<T>&& src)

Steal the memory of the Armadillo matrix in the conversion to Numpy array.

Note the returned array will have F order memory.
Parameters `src` – armadillo object to be converted.

```cpp
py::array_t<T> mat_to_arr(arma::Mat<T>* src, bool copy=false)
```

Convert Armadillo matrix to Numpy array.

Note the returned array will have F order memory.

Parameters

- `src` – armadillo object to be converted.
- `copy` – copy the memory of the array, default is false

### 12.2.2 Vector

```cpp
py::array_t<T> col_to_arr(arma::Col<T>& src, bool copy=false)
```

Convert Armadillo col to Numpy array, note the returned array will have column contiguous memory (F-order)

Note the returned array will have F order memory.

Parameters

- `src` – armadillo object to be converted.
- `copy` – copy the memory of the array, default is false which steals the memory

```cpp
py::array_t<T> col_to_arr(const arma::Col<T>& src)
```

Copy the memory of the Armadillo Col in the conversion to Numpy array.

Note the returned array will have F order memory.

Parameters `src` – armadillo object to be converted.

```cpp
py::array_t<T> col_to_arr(arma::Col<T>&& src)
```

Steal the memory of the Armadillo Col in the conversion to Numpy array.

Note the returned array will have F order memory.

Parameters `src` – armadillo object to be converted.

```cpp
py::array_t<T> row_to_arr(arma::Row<T>& src, bool copy=false)
```

Convert Armadillo Row to Numpy array.

Note the returned array will have F order memory.

Parameters

- `src` – armadillo object to be converted.
- `copy` – copy the memory of the array, default is false

```cpp
py::array_t<T> row_to_arr(const arma::Row<T>& src)
```

Copy the memory of the Armadillo Row in the conversion to Numpy array.

Note the returned array will have F order memory.
Parameters `src` – armadillo object to be converted.

```cpp
py::array_t<T> row_to_arr(arma::Row<T>&& src)
```
Steal the memory of the Armadillo Row in the conversion to Numpy array.

**Note** the returned array will have F order memory.

Parameters `src` – armadillo object to be converted.

```cpp
py::array_t<T> row_to_arr(arma::Row<T>* src, bool copy=false)
```
Convert Armadillo Row to Numpy array.

**Note** the returned array will have F order memory.

Parameters

- `src` – armadillo object to be converted.
- `copy` – copy the memory of the array, default is false

### 12.2.3 Cube

```cpp
py::array_t<T> cube_to_arr(arma::Cube<T>& src, bool copy=false)
```
Convert Armadillo Cube to Numpy array, note the returned array will have column contiguous memory (F-order)

**Note** the returned array will have F order memory.

Parameters

- `src` – armadillo object to be converted.
- `copy` – copy the memory of the array, default is false which steals the memory

```cpp
py::array_t<T> Cube_to_arr(const arma::Cube<T>& src)
```
Copy the memory of the Armadillo Cube in the conversion to Numpy array.

**Note** the returned array will have F order memory.

Parameters `src` – armadillo object to be converted.

```cpp
py::array_t<T> cube_to_arr(arma::Cube<T>&& src)
```
Steal the memory of the Armadillo cube in the conversion to Numpy array.

**Note** the returned array will have F order memory.

Parameters `src` – armadillo object to be converted.

```cpp
py::array_t<T> cube_to_arr(arma::Cube<T>* src, bool copy=false)
```
Convert Armadillo matrix to Numpy array.

**Note** the returned array will have F order memory.

Parameters

- `src` – armadillo object to be converted.
- `copy` – copy the memory of the array, default is false

### 12.2.4 to_numpy

to_numpy has overloads for `Mat<T>`, `Row<T>`, `Col<T>` and `Cube<T>`. It should be called with e.g.

```cpp
to_numpy(arma::Mat<double>>(m)
```
template <typename armaT> py::array_t<eT> to_numpy_view(const armaT<eT>& src)
Create ‘view’ on Armadillo object as non-writeable Numpy array. :note: the returned array will have F order memory. :param src: armadillo object to be converted.

template <typename armaT> py::array_t<eT> to_numpy(armaT<eT>& src, bool copy=false)
Convert Armadillo object to Numpy array.

Note the returned array will have F order memory.

Parameters

- **src** – armadillo object to be converted.
- **copy** – copy the memory of the array, default is false which steals the memory

template <typename armaT> py::array_t<eT> to_numpy(const armaT<eT>& src)
Copy the memory of the Armadillo object in the conversion to Numpy array.

Note the returned array will have F order memory.

Parameters **src** – armadillo object to be converted.

template <typename armaT> py::array_t<eT> to_numpy(armaT<eT>&& src)
Steal the memory of the Armadillo object in the conversion to Numpy array.

Note the returned array will have F order memory.

Parameters **src** – armadillo object to be converted.

template <typename armaT> py::array_t<eT> to_numpy(armaT<eT>* src)
Convert Armadillo object to Numpy array.

Note the returned array will have F order memory.

Parameters

- **src** – armadillo object to be converted.
- **copy** – copy the memory of the array, default is false
CHAPTER 13

Automatic conversion – Type caster

CARMA provides a type caster which enables automatic conversion using pybind11.

**Warning:** `carma` should included in every compilation unit where automated type casting occurs, otherwise undefined behaviour will occur.

**Note:** The underlying casting function has overloads for `{const lvalue, lvalue, rvalue, pointer}` Armadillo objects of type `{Mat, Col, Row, Cube}`.

### 13.1 Return policies

Pybind11 provides a number of return value policies of which a subset is supported:

To pass the return value policy set it in the binding function:

```
m.def("example_function", &example_function, return_value_policy::copy);
```

- **return_value_policy::move**
  move/steal the memory from the armadillo object
- **return_value_policy::automatic**
  move/steal the memory from the armadillo object
- **return_value_policy::take_ownership**
  move/steal the memory from the armadillo object
- **return_value_policy::copy**
  copy the memory from the armadillo object
ArrayStore is a convenience class for storing the memory in a C++ class.

**Warning:** The ArrayStore owns the data, the returned numpy arrays are views that are tied to the lifetime of ArrayStore.

```cpp
template <typename armaT> ArrayStore

    mat armaT
        Matrix containing the memory of the array.

    ArrayStore (py::array_t<T>& arr, bool copy)
        Class constructor

        Parameters
            • arr – Numpy array to be stored as Armadillo matrix
            • steal – Take ownership of the array if not copy

    template <typename armaT> ArrayStore (const arma & src)
        Class constructor, object is copied

        Parameters src – Armadillo object to be stored

    template <typename armaT> ArrayStore (armaT & src, copy)
        Class constructor, object is copied or moved/stolen

        Parameters src – Armadillo object to be stored

    template <typename armaT> ArrayStore (armaT && src)
        Class constructor, object is moved

        Parameters mat – Armadillo object to be stored

    get_view (bool writeable)
        Obtain a view of the memory as Numpy array.
```
Parameters **writeable** – Mark array as writeable

**set_array** *(py::array_t<T> & arr, bool copy)*
Store new array in the ArrayStore.

Parameters

- **arr** – Numpy array to be stored as Armadillo matrix
- **copy** – Take ownership of the array or copy

**template <typename T> set_data(const armaT& src)**
Store new matrix in the ArrayStore, object is copied.

Parameters **src** – Armadillo object to be stored

**template <typename T> set_data(armaT& src, bool copy)**
Store new object in the ArrayStore, copied or moved.

Parameters **src** – Armadillo object to be stored, matrix is copied

**template <typename T> set_data(arma::Mat<T> && src)**
Store new matrix in the ArrayStore, object is moved.

Parameters **src** – Armadillo matrix to be stored
Utility functions to check flags of numpy arrays.

```cpp
bool is_f_contiguous(const py::array_t<T> & arr)

Check if Numpy array’s memory is Fortran contiguous.

Parameters
arr – numpy array to be checked

bool is_c_contiguous(const py::array_t<T> & arr)

Check if Numpy array’s memory is C contiguous.

Parameters
arr – numpy array to be checked

bool is_writable(const py::array_t<T> & arr)

Check if Numpy array’s memory is mutable.

Parameters
arr – numpy array to be checked

bool is_owndata(const py::array_t<T> & arr)

Check if Numpy array’s memory is owned by numpy.

Parameters
arr – numpy array to be checked

bool is_aligned(const py::array_t<T> & arr)

Check if Numpy array’s memory is aligned.

Parameters
arr – numpy array to be checked

bool requires_copy(const py::array_t<T> & arr)

Check if Numpy array memory needs to be copied out, is true when either not writable, owndata or is not aligned.

Parameters
arr – numpy array to be checked

void set_not_owndata(py::array_t<T> & arr)

Set Numpy array’s flag OWNDATA to false.

Parameters
arr – numpy array to be changed

void set_not_writeable(py::array_t<T> & arr)

Set Numpy array’s flag WRITEABLE to false.
```
Parameters `arr` – numpy array to be changed
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