

WaveSimPP

1.0

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# Chapter 1

## Main Page

### 1.1 COMSW4995 Final Project: WaveSimPP

This is the repository for our final project for the discipline COMSW4995: Design in C++ at Columbia University during the Fall of 2022.

This project aims to implement in modern C++ a wave equation solver for geophysical application.

In addition, a custom implementation of numpy in modern C++ is also included as a header library. That library aims to make c++ more pythonic and easier to use for scientific computing. Instead of numpy n-dimensional arrays the library use `boost::multi_array` and contains many utilities to expand the functionality of the library.

Please check the [Readme file](#) for more information.

#### 1.1.1 Authors

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Yan Cheng - PhD Candidate - Applied Mathematics - Columbia University

#### 1.1.2 License

This project is licensed under the MIT License - see the LICENSE.md file for details





## Chapter 2

# Tutorial

### 2.1 Using the executable

If all you want is to run one simulation with custom parameters, you can use the executable that is generated when you build the project. The executable is located in the build folder.

To build the executable you can use the following commands:

```
mkdir build
cd build
cmake ..
make WaveSimPPExec
```

And then run it with the following command:

```
./WaveSimPPExec
```

The executable will ask you for the parameters of the simulation. A complete description of the parameters can be found in the the help menu of the executable. To see the help menu you can run the executable with the -h flag:

```
./WaveSimPPExec -h
```

### 2.2 Creating a wave simulation and solving it

The source code of this tutorial can be found in [src/examples/wave\\_solver\\_with\\_animation.cpp](#)

The first part of creating the wave simulation is to define the constants for the simulation. These constants are the number of grid points in the x and z directions, the number of time steps, the differentiation values, the domain, the source parameters, and the source location.

It is important to pay attention to the fact that the plane is XZ not XY due to geophysical conventions.

```
// Define the constants for the simulation
// Number of x and z grid points
int nx = 100;
int nz = 100;
// Number of time steps
int nt = 1000;
// Differentiation values
double dx = 0.01;
double dz = 0.01;
double dt = 0.001;
// Define the domain
double xmin = 0.0;
double xmax = nx * dx;
double zmin = 0.0;
double zmax = nz * dz;
double tmin = 0.0;
double tmax = nt * dt;
// Define the source parameters
```

```
double f_M = 10.0;
double amp = 1e0;
double shift = 0.1;
// Source location
int source_is = 50;
int source_js = 50;
```

The next step is to create the source object and the velocity profile

```
// Create the source
boost::multi_array<double, 3> f = waveSimPPore::ricker(source_is, source_js, f_M, amp, shift, tmin, tmax,
    nt, nx, nz);
// Create the velocity profile
double r = 150.0;
boost::multi_array<double, 2> vel = waveSimPPore::get_profile(xmin, xmax, zmin, zmax, nx, nz, r);
```

Then we can proceed to solve the wave equation using the wave solver.

```
// Solve the wave equation
boost::multi_array<double, 3> u = waveSimPPore::wave_solver(vel, dt, dx, dz, nt, nx, nz, f);
```

`u` is the `multi_array` that contains the result of the simulation. It has the shape `(nt, nx, nz)`. That means that the first index is the time step, the second index is the `x` grid point, and the third index is the `z` grid point.

You can access the result of a specific time step by simply using:

```
boost::multi_array<double, 2> u_at_time_20 = u[20];
```

## 2.3 Obtaining the results

To see the results you have two main options:

- Use the `wavePlotter::Plotter` class to plot the results and/or create an animation.
- Export all the frames to a series of csv files for processing in another program.

### 2.3.1 Plotting the results using the `wavePlotter::Plotter` class

You should do some light processing to convert the domain from a `boost::multi_array` to a `matplotlib::vector_2d`. This is done using the `np::convert_to_matplot` function.

After that you can convert the result of each frame to a `matplotlib::vector_2d` and plot it using the `wavePlotter::Plotter` class.

```
// Define the number of different levels for the contour plot
int num_levels = 100;
// Create the levels for the contour plot based on the min and max values of u
double min_u = np::min(u);
double max_u = np::max(u);
std::vector<double> levels = matplotlib::linspace(min_u, max_u, num_levels);
// Create the x and z axis for the contour plot and convert them to matplotlib format
boost::multi_array<double, 1> x = np::linspace(xmin, xmax, nx);
boost::multi_array<double, 1> z = np::linspace(zmin, zmax, nz);
const boost::multi_array<double, 1> axis[2] = {x, z};
std::vector<boost::multi_array<double, 2>> XcZ = np::meshgrid(axis, false, np::xy);
matplotlib::vector_2d Xp = np::convert_to_matplot(XcZ[0]);
matplotlib::vector_2d Zp = np::convert_to_matplot(XcZ[1]);
```

From this point on you can plot it as you wish, for example, if you want a filled contour plot you can do:

```
matplotlib::vector_2d Up = np::convert_to_matplot(this->u[frame_index]);
matplotlib::contourf(this->Xp, this->Zp, Up, this->levels);
matplotlib::show();
```

Another option is to pass the data to the `wavePlotter::Plotter` class and use the `plot` function to render all frames

```
// Create the plotter object and animate the results
wavePlotter::Plotter my_plotter(u, Xp, Zp, num_levels, nt);
// If you want to render a specific frame, use this:
// my_plotter.renderFrame(int frame_index);
// Renders the entire animation from start_frame to end_frame
int start_frame = 20;
int end_frame = nt - 1;
int fps = 30;
my_plotter.animate("example-wave.mp4", start_frame, end_frame, fps);
```

The animation will be saved in `.` and the frames will be saved to `./output`

### 2.3.2 Exporting the results to csv files

You can export the results to a series of individual csv files using the `wavePlotter::Plotter` class.

```
// Create the plotter object and animate the results
wavePlotter::Plotter my_plotter(u, Xp, Zp, num_levels, nt);
// If you want to export a specific frame, use this:
// my_plotter.exportFrame(int frame_index);
// Exports the entire simulation from start_frame to end_frame
int start_frame = 20;
int end_frame = nt - 1;
my_plotter.exportAllFrames(start_frame, end_frame);
```

The frames will be saved to `./output`

Each frame is saved as a csv file with the following format:

```
data at 0_0, data at 0_1, data at 0_2, ..., data at 0_nz
data at 1_0, data at 1_1, data at 1_2, ..., data at 1_nz
data at 2_0, data at 2_1, data at 2_2, ..., data at 2_nz
.
.
.
```

If you want to import the data into a python program you can use the following code:

```
frames = []
for i in range(999):
    filename = "output/frame_" + f'{i:08}' + ".csv"
    frames.append(pd.read_csv(filename))
```

Please refer to `src/examples/PythonLoadingExample.ipynb` for a complete example on how to load the data into a python program and render it using matplotlib (of course you can use any other library to render the data).



## Chapter 3

# README

### 3.1 COMSW4995 Final Project: WaveSimPP

This is the repository for our final project for the discipline COMSW4995: Design in C++ at Columbia University during the Fall of 2022.

This project aims to implement in modern C++ a wave equation solver for geophysical application.

In addition, a custom implementation of numpy in modern C++ is also included as a header library. That library aims to make c++ more pythonic and easier to use for scientific computing. Instead of numpy n-dimensional arrays the library use `boost::multi_array` and contains many utilities to expand the functionality of the library.

[Detailed documentation](#)

#### 3.1.1 Authors

Victor Barros - Undergraduate Student - Mechanical Engineering - Columbia University

Yan Cheng - PhD Candidate - Applied Mathematics - Columbia University

#### 3.1.2 Acknowledgments

We would like to thank Professor Bjarne Stroustrup for his guidance and support during the development of this project.



### 3.2.4 Multi Arrays and how math is done on them

Representing arrays with more than one dimensions is a difficult task in any programming language, specially in a language like C++ that implements strict type checking. To implement that in a flexible and typesafe way, we chose to build our code around the `boost::multi_array`. This library provides a container that can be used to represent arrays with any number of dimensions. The library is very flexible and allows the user to define the type of the array and the number of dimensions at compile time. The library is sadly not very well documented but the documentation can be found here: [https://www.boost.org/doc/libs/1\\_75\\_0/libs/multi\\_array/doc/index.html](https://www.boost.org/doc/libs/1_75_0/libs/multi_array/doc/index.html)

We decided to build the math functions in a pythonic way, so we implemented numpy functions into our C++ library in a way that they would accept n-dimensions through a template parameters and act accordingly while enforcing dimensional consistency at compile time. We also used concepts and other modern C++ concepts to make sure that, for example, a python call such as `np.max(my_n_dimensional_array)` would be translated to `np::max(my_n_dimensional_array)` in C++.

To perform operations on an n-dimensional array we choose to iterate over it and convert the pointers to indexes using a simple arithmetic operation with one division. This is somewhat time consuming since we don't have  $O(1)$  time access to any point in the array, instead having  $O(n)$  where  $n$  is the amount of elements in the multi array. This is the tradeoff necessary to have n-dimensions represented in memory, hopefully in modern cpus this overhead won't be too high. Better solutions could be investigated further.

We also implemented simple arithmetic operators with multi arrays to make them more arithmetic friendly such as they are in python.

Only one small subset of numpy functions were implemented, but the library is easily extensible and more functions can be added in the future.

## 3.3 Building

Please be aware that since this library uses a few C++ 20 features it is only been tested on gcc-11 and above. It is possible that it will work on other compilers but it is not guaranteed.

### 3.3.1 Install the boost library

It is important to install the boost library before building the project. The boost library is used for data structures and algorithms. The boost library can be installed using the following command on ubuntu:

```
sudo apt-get install libboost-all-dev
```

For Mac:

```
brew install boost
```

### 3.3.2 Install Matplotlibplusplus

This is the library used to generate graphics in the project. To be able to compile this project you must have it installed in your system. First install its dependencies:

```
sudo apt-get install gnuplot
```

or in Mac:

```
brew install gnuplot
```

Then install the library itself by cloning from source:

```
cd src/ExternalLibraries
git clone https://github.com/alandefreitas/matplotlibplusplus
cd matplotlibplusplu
mkdir build
cd build
cmake .. -DCMAKE_BUILD_TYPE=Release -DCMAKE_CXX_FLAGS="-O2" -DBUILD_EXAMPLES=OFF -DBUILD_TESTS=OFF
sudo cmake --build . --parallel 2 --config Release
sudo cmake --install .
```

If you are using clang on mac, make sure to force CMAKE to use gcc by adding the following flag to the first cmake command:

```
-DCMAKE_C_COMPILER=/usr/bin/gcc -DCMAKE_CXX_COMPILER=/usr/bin/g++
```

(or equivalent paths depending on where your gcc is installed)

### 3.3.3 Building the project

```
mkdir build
cd build
cmake ..
make all
```

You can also build only the executable by running:

```
make WaveSimPPExec
```

### 3.3.4 Running the executable

```
./WaveSimPPExec
```

Use the help flag -h to see the available runtime options and the full list and description of the parameters.

### 3.3.5 Building the documentation

Docs building script:

```
./compileDocs.sh
```

Manually:

```
doxygen dconfig
cd documentation/latex
pdflatex refman.tex
cp refman.pdf ../WaveSimPP-1.0-doc.pdf
```



## Chapter 4

# Module Index

### 4.1 Modules

Here is a list of all modules:

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Np . . . . .	26
WavePlotter . . . . .	31



## Chapter 5

# Namespace Index

### 5.1 Namespace List

Here is a list of all documented namespaces with brief descriptions:

<a href="#">np</a>	Custom implementation of numpy in C++ . . . . .	35
<a href="#">wavePlotter</a>	Custom plotter class . . . . .	48
<a href="#">waveSimCore</a>	. . . . .	49



## Chapter 6

# Class Index

### 6.1 Class List

Here are the classes, structs, unions and interfaces with brief descriptions:

[wavePlotter::Plotter](#)

This class is used to plot the wave field TODO: make it multithreaded . . . . . [51](#)



## Chapter 7

# File Index

### 7.1 File List

Here is a list of all documented files with brief descriptions:

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src/tests/variadic.cpp	72





## Chapter 8

# Module Documentation

### 8.1 WaveSimCore

#### Namespaces

- namespace [waveSimCore](#)

#### Functions

- `boost::multi_array< double, 2 > waveSimCore::get\_sigma\_1` (`boost::multi_array< double, 1 > x`, `double dx`, `int nx`, `int nz`, `double c_max`, `int n=15`, `double R=1e-3`, `double m=2.0`)
- `boost::multi_array< double, 2 > waveSimCore::get\_sigma\_2` (`boost::multi_array< double, 1 > z`, `double dz`, `int nx`, `int nz`, `double c_max`, `int n=10`, `double R=1e-3`, `double m=2.0`)
- `boost::multi_array< double, 2 > waveSimCore::get\_profile` (`double xmin`, `double xmax`, `double zmin`, `double zmax`, `int nx`, `int nz`, `double r`)  
*Get the velocity profile of the model as a 2D Array.*
- `boost::multi_array< double, 2 > waveSimCore::dfdxdx` (`boost::multi_array< double, 2 > f`, `double dx`)  
*Takes the partial derivative of a 2D matrix f with respect to x.*
- `boost::multi_array< double, 2 > waveSimCore::dfdxdz` (`boost::multi_array< double, 2 > f`, `double dz`)  
*Takes the partial derivative of a 2D matrix f with respect to z.*
- `boost::multi_array< double, 2 > waveSimCore::d2fdx2` (`boost::multi_array< double, 2 > f`, `double dx`)  
*Takes the second partial derivative of a 2D matrix f with respect to x.*
- `boost::multi_array< double, 2 > waveSimCore::d2fdz2` (`boost::multi_array< double, 2 > f`, `double dz`)  
*Takes the second partial derivative of a 2D matrix f with respect to z.*
- `boost::multi_array< double, 2 > waveSimCore::divergence` (`boost::multi_array< double, 2 > f1`, `boost::multi_array< double, 2 > f2`, `double dx`, `double dz`)
- `boost::multi_array< double, 3 > waveSimCore::wave\_solver` (`boost::multi_array< double, 2 > c`, `double dt`, `double dx`, `double dz`, `int nt`, `int nx`, `int nz`, `boost::multi_array< double, 3 > f`)
- `boost::multi_array< double, 3 > waveSimCore::wave\_solver\_complex` (`boost::multi_array< double, 2 > c`, `double dt`, `double dx`, `double dz`, `int nt`, `int nx`, `int nz`, `boost::multi_array< double, 3 > f`, `boost::multi_array< double, 2 > sigma_1`, `boost::multi_array< double, 2 > sigma_2`)
- `boost::multi_array< double, 3 > waveSimCore::ricker` (`int i_s`, `int j_s`, `double f`, `double amp`, `double shift`, `double tmin`, `double tmax`, `int nt`, `int nx`, `int nz`)  
*Get the Ricker wavelet as a 3D Array.*

### 8.1.1 Detailed Description

### 8.1.2 Function Documentation

#### 8.1.2.1 d2fdx2()

```
boost::multi_array< double, 2 > waveSimCore::d2fdx2 (
    boost::multi_array< double, 2 > f,
    double dx )
```

Takes the second partial derivative of a 2D matrix f with respect to x.

Definition at line 32 of file [helper\\_func.hpp](#).

```
00033     {
00034         boost::multi_array<double, 2> df = dfdx(f, dx);
00035         boost::multi_array<double, 2> df2 = dfdx(df, dx);
00036         return df2;
00037     }
```

#### 8.1.2.2 d2fdz2()

```
boost::multi_array< double, 2 > waveSimCore::d2fdz2 (
    boost::multi_array< double, 2 > f,
    double dz )
```

Takes the second partial derivative of a 2D matrix f with respect to z.

Definition at line 40 of file [helper\\_func.hpp](#).

```
00041     {
00042         boost::multi_array<double, 2> df = dfdz(f, dz);
00043         boost::multi_array<double, 2> df2 = dfdz(df, dz);
00044         return df2;
00045     }
```

#### 8.1.2.3 dfdx()

```
boost::multi_array< double, 2 > waveSimCore::dfdx (
    boost::multi_array< double, 2 > f,
    double dx )
```

Takes the partial derivative of a 2D matrix f with respect to x.

Definition at line 18 of file [helper\\_func.hpp](#).

```
00019     {
00020         std::vector<boost::multi_array<double, 2> grad_f = np::gradient(f, {dx, dx});
00021         return grad_f[0];
00022     }
```

### 8.1.2.4 dfdz()

```
boost::multi_array< double, 2 > waveSimCore::dfdz (
    boost::multi_array< double, 2 > f,
    double dz )
```

Takes the partial derivative of a 2D matrix f with respect to z.

Definition at line 25 of file [helper\\_func.hpp](#).

```
00026     {
00027         std::vector<boost::multi_array<double, 2> grad_f = np::gradient(f, {dz, dz});
00028         return grad_f[1];
00029     }
```

### 8.1.2.5 divergence()

```
boost::multi_array< double, 2 > waveSimCore::divergence (
    boost::multi_array< double, 2 > f1,
    boost::multi_array< double, 2 > f2,
    double dx,
    double dz )
```

Takes the divergence of a 2D matrices fx,fz with respect to x and z  
Returns  $dfx/dx + dfz/dz$

Definition at line 49 of file [helper\\_func.hpp](#).

```
00051     {
00052         boost::multi_array<double, 2> f_x = dfdx(f1, dx);
00053         boost::multi_array<double, 2> f_z = dfdz(f2, dz);
00054         boost::multi_array<double, 2> div = f_x + f_z;
00055         return div;
00056     }
```

### 8.1.2.6 get\_profile()

```
boost::multi_array< double, 2 > waveSimCore::get_profile (
    double xmin,
    double xmax,
    double zmin,
    double zmax,
    int nx,
    int nz,
    double r )
```

Get the velocity profile of the model as a 2D Array.

Definition at line 16 of file [computational.hpp](#).

```
00017     {
00018         boost::multi_array<double, 2> c(boost::extents[nx][nz]);
00019
00020         boost::multi_array<double, 1> x = np::linspace(xmin, xmax, nx);
00021         boost::multi_array<double, 1> z = np::linspace(zmin, zmax, nz);
00022
00023         const boost::multi_array<double, 1> axis[2] = {x, z};
00024         std::vector<boost::multi_array<double, 2> XZ = np::meshgrid(axis, false, np::ij);
00025
00026         double x_0 = xmax / 2.0;
00027         double z_0 = zmax / 2.0;
```

```

00028
00029     for (int i = 0; i < nx; i++)
00030     {
00031         for (int j = 0; j < nz; j++)
00032         {
00033             if (np::pow(XZ[0][i][j] - x_0, 2.0) + np::pow(XZ[1][i][j] - z_0, 2.0) <= np::pow(r,
2.0))
00034                 c[i][j] = 3.0;
00035             else
00036                 c[i][j] = 3.0;
00037         }
00038     }
00039     return c;
00040 }
00041

```

### 8.1.2.7 get\_sigma\_1()

```

boost::multi_array< double, 2 > waveSimCore::get_sigma_1 (
    boost::multi_array< double, 1 > x,
    double dx,
    int nx,
    int nz,
    double c_max,
    int n = 15,
    double R = 1e-3,
    double m = 2.0 )

```

Returns the sigma 1 coefficient for the PML boundary conditions

sigma\_1 and sigma\_2 are the coefficients for the x and z directions respectively

Check Johnson, Steven G. (2021).

Definition at line 21 of file [coeff.hpp](#).

```

00023 {
00024     boost::multi_array<double, 2> sigma_1(boost::extents[nx][nz]);
00025     const double PML_width = n * dx;
00026
00027     const double sigma_max = -c_max * log(R) * (m + 1.0) / np::pow(PML_width, m + 1.0);
00028
00029     const double x_0 = np::max(x) - PML_width;
00030
00031     boost::multi_array<double, 1> polynomial(boost::extents[nx]);
00032
00033     for (int i = 0; i < nx; i++)
00034     {
00035         if (x[i] > x_0)
00036         {
00037             polynomial[i] = sigma_max * np::pow(np::abs(x[i] - x_0), m);
00038             polynomial[nx - 1 - i] = polynomial[i];
00039         }
00040         else
00041         {
00042             polynomial[i] = 0;
00043         }
00044     }
00045
00046     for (int i = 0; i < nx; i++)
00047         for (int j = 0; j < nz; j++)
00048             sigma_1[i][j] = polynomial[i];
00049
00050     return sigma_1;
00051 }

```

### 8.1.2.8 get\_sigma\_2()

```
boost::multi_array< double, 2 > waveSimCore::get_sigma_2 (
    boost::multi_array< double, 1 > z,
    double dz,
    int nx,
    int nz,
    double c_max,
    int n = 10,
    double R = 1e-3,
    double m = 2.0 )
```

Returns the sigma 2 coefficient for the PML boundary conditions

sigma\_1 and sigma\_2 are the coefficients for the x and z directions respectively

Check Johnson, Steven G. (2021).

Definition at line 56 of file [coeff.hpp](#).

```
00058     {
00059         boost::multi_array<double, 2> sigma_2(boost::extents[nx][nz]);
00060         const double PML_width = n * dz;
00061         const double sigma_max = -c_max * log(R) * (m + 1.0) / np::pow(PML_width, m + 1.0);
00062
00063         const double z_0 = np::max(z) - PML_width;
00064
00065         boost::multi_array<double, 1> polynomial(boost::extents[nz]);
00066         for (int j = 0; j < nz; j++)
00067         {
00068             if (z[j] > z_0)
00069             {
00070                 polynomial[j] = sigma_max * np::pow(np::abs(z[j] - z_0), m);
00071                 polynomial[nz - 1 - j] = polynomial[j];
00072             }
00073             else
00074             {
00075                 polynomial[j] = 0;
00076             }
00077         }
00078
00079         for (int i = 0; i < nx; i++)
00080             for (int j = 0; j < nz; j++)
00081                 sigma_2[i][j] = polynomial[j];
00082
00083         return sigma_2;
00084     }
```

### 8.1.2.9 ricker()

```
boost::multi_array< double, 3 > waveSimCore::ricker (
    int i_s,
    int j_s,
    double f,
    double amp,
    double shift,
    double tmin,
    double tmax,
    int nt,
    int nx,
    int nz )
```

Get the Ricker wavelet as a 3D Array.

Definition at line 14 of file [source.hpp](#).

```
00016     {
00017         const double pi = 3.141592654;
```

```

00018
00019     boost::multi_array<double, 1> t = np::linspace(tmin, tmax, nt);
00020     boost::multi_array<double, 1> pft2 = np::pow(pi * f * (t - shift), 2.0);
00021     boost::multi_array<double, 1> r = amp * (1.0 - 2.0 * pft2) * np::exp(-1.0 * pft2);
00022
00023     int dimensions_x[] = {nx};
00024     boost::multi_array<double, 1> x = np::zeros<double>(dimensions_x);
00025
00026     int dimensions_z[] = {nz};
00027     boost::multi_array<double, 1> z = np::zeros<double>(dimensions_z);
00028
00029     x[i_s] = 1.0;
00030     z[j_s] = 1.0;
00031
00032     const boost::multi_array<double, 1> axis[3] = {r, x, z};
00033     std::vector<boost::multi_array<double, 3> RXZ = np::meshgrid(axis, false, np::ij);
00034     boost::multi_array<double, 3> source = RXZ[0] * RXZ[1] * RXZ[2];
00035
00036     return source;
00037 }

```

### 8.1.2.10 wave\_solver()

```

boost::multi_array< double, 3 > waveSimCore::wave_solver (
    boost::multi_array< double, 2 > c,
    double dt,
    double dx,
    double dz,
    int nt,
    int nx,
    int nz,
    boost::multi_array< double, 3 > f )

```

This function solves the wave equation using the methods explained in the readme  
The boundary conditions are so that waves bounce at the boundary

Definition at line 27 of file [solver.hpp](#).

```

00030     {
00031
00032         const boost::multi_array<double, 2> CX = np::pow(c * dt / dx, 2.0);
00033         const boost::multi_array<double, 2> CZ = np::pow(c * dt / dz, 2.0);
00034         const double Cf = np::pow(dt, 2.0);
00035
00036         int dimensions_1[] = {nt, nx, nz};
00037         boost::multi_array<double, 3> u = np::zeros<double>(dimensions_1);
00038         int dimensions_4[] = {nx, nz};
00039         boost::multi_array<double, 2> u_xx = np::zeros<double>(dimensions_4);
00040         int dimensions_5[] = {nx, nz};
00041         boost::multi_array<double, 2> u_zz = np::zeros<double>(dimensions_5);
00042
00043         for (int n = 1; n < nt - 1; n++)
00044         {
00045             for (int i = 1; i < nx - 1; i++)
00046             {
00047                 for (int j = 1; j < nz - 1; j++)
00048                 {
00049                     u_xx[i][j] = u[n][i + 1][j] + u[n][i - 1][j] - 2.0 * u[n][i][j];
00050                     u_zz[i][j] = u[n][i][j + 1] + u[n][i][j - 1] - 2.0 * u[n][i][j];
00051                 }
00052             }
00053
00054             // ! Update u
00055             for (int i = 0; i < nx; i++)
00056             {
00057                 for (int j = 0; j < nz; j++)
00058                 {
00059                     u[n + 1][i][j] = 2.0 * u[n][i][j] + CX[i][j] * u_xx[i][j] + CZ[i][j] * u_zz[i][j]
+ Cf * f[n][i][j] - u[n - 1][i][j];
00060                 }
00061             }
00062
00063             // Dirichlet boundary condition
00064             for (int i = 0; i < nx; i++)

```

```

00065         {
00066             u[n + 1][i][0] = 0.0;
00067             u[n + 1][i][nz - 1] = 0.0;
00068         }
00069         for (int j = 0; j < nz; j++)
00070         {
00071             u[n + 1][0][j] = 0.0;
00072             u[n + 1][nx - 1][j] = 0.0;
00073         }
00074     }
00075     return u;
00076 }

```

### 8.1.2.11 wave\_solver\_complex()

```

boost::multi_array< double, 3 > waveSimCore::wave_solver_complex (
    boost::multi_array< double, 2 > c,
    double dt,
    double dx,
    double dz,
    int nt,
    int nx,
    int nz,
    boost::multi_array< double, 3 > f,
    boost::multi_array< double, 2 > sigma_1,
    boost::multi_array< double, 2 > sigma_2 )

```

Solves the wave equation using a more complex solver compared to `wave_solver`  
 Also has different boundary conditions. In this one the boundary extends to infinity

Definition at line 22 of file [solver\\_complex.hpp](#).

```

00026     {
00027
00028         const boost::multi_array<double, 2> C1 = 1.0 + (dt * (sigma_1 + sigma_2) * 0.5);
00029         const boost::multi_array<double, 2> C2 = (sigma_1 * sigma_2 * np::pow(dt, 2.0)) - 2.0;
00030         const boost::multi_array<double, 2> C3 = 1.0 - (dt * (sigma_1 + sigma_2) * 0.5);
00031         const boost::multi_array<double, 2> C4 = np::pow(dt * c, 2.0);
00032         const boost::multi_array<double, 2> C5 = 1.0 + (dt * sigma_1 * 0.5);
00033         const boost::multi_array<double, 2> C6 = 1.0 + (dt * sigma_2 * 0.5);
00034         const boost::multi_array<double, 2> C7 = 1.0 - (dt * sigma_1 * 0.5);
00035         const boost::multi_array<double, 2> C8 = 1.0 - (dt * sigma_2 * 0.5);
00036
00037         int dimensions_1[] = {nt, nx, nz};
00038         boost::multi_array<double, 3> u = np::zeros<double>(dimensions_1);
00039
00040         int dimensions_2[] = {nx, nz};
00041         boost::multi_array<double, 2> q_1 = np::zeros<double>(dimensions_2);
00042         int dimensions_3[] = {nx, nz};
00043         boost::multi_array<double, 2> q_2 = np::zeros<double>(dimensions_3);
00044
00045         int dimensions_4[] = {nx, nz};
00046         boost::multi_array<double, 2> u_xx = np::zeros<double>(dimensions_4);
00047         int dimensions_5[] = {nx, nz};
00048         boost::multi_array<double, 2> u_zz = np::zeros<double>(dimensions_5);
00049
00050         boost::multi_array<double, 2> f_n(boost::extents[nx][nz]);
00051         boost::multi_array<double, 2> u_n(boost::extents[nx][nz]);
00052         boost::multi_array<double, 2> u_n_1(boost::extents[nx][nz]);
00053
00054         for (int n = 1; n < nt - 1; n++)
00055         {
00056
00057             for (int i = 0; i < nx; i++)
00058             {
00059                 for (int j = 0; j < nz; j++)
00060                 {
00061                     f_n[i][j] = f[n][i][j];
00062                     u_n[i][j] = u[n][i][j];
00063                     u_n_1[i][j] = u[n - 1][i][j];
00064                 }
00065             }
00066

```

```

00067         boost::multi_array<double, 2> div = divergence(q_1 * sigma_1, q_2 * sigma_2, dx, dz);
00068         boost::multi_array<double, 2> dq_1dx = dfdx(q_1, dx);
00069         boost::multi_array<double, 2> dq_2dz = dfdz(q_2, dz);
00070         u_xx = d2fdx2(u_n, dx); // (nx, nz)
00071         u_zz = d2fdz2(u_n, dz); // (nx, nz)
00072         boost::multi_array<double, 2> dudx = dfdx(u_n, dx);
00073         boost::multi_array<double, 2> dudz = dfdz(u_n, dz);
00074
00075         //         for (int i = 1; i < nx-1; i++)
00076         //         {
00077         //             for (int j = 1; j < nz-1; j++)
00078         //             {
00079         //                 u_xx[i][j] = u_n[i+1][j] + u_n[i-1][j] - 2.0 * u_n[i][j];
00080         //                 u_zz[i][j] = u_n[i][j+1] + u_n[i][j-1] - 2.0 * u_n[i][j];
00081         //             }
00082         //         }
00083
00084         // ! Update u
00085         for (int i = 0; i < nx; i++)
00086         {
00087             for (int j = 0; j < nz; j++)
00088             {
00089                 u[n + 1][i][j] = (C4[i][j] * ((u_xx[i][j] / np::pow(dx, 2.0)) + (u_zz[i][j] /
np::pow(dz, 2.0)) - div[i][j] + sigma_2[i][j] * dq_1dx[i][j] + sigma_1[i][j] * dq_2dz[i][j] +
f_n[i][j]) - (C2[i][j] * u_n[i][j]) - (C3[i][j] * u_n_1[i][j])) / C1[i][j];
00090             }
00091         }
00092
00093         // ! Update q_1, q_2
00094         for (int i = 0; i < nx; i++)
00095         {
00096             for (int j = 0; j < nz; j++)
00097             {
00098                 q_1[i][j] = (dt * dudx[i][j] + C7[i][j] * q_1[i][j]) / C5[i][j];
00099                 q_2[i][j] = (dt * dudz[i][j] + C8[i][j] * q_2[i][j]) / C6[i][j];
00100             }
00101         }
00102         //
00103         // Dirichlet boundary condition
00104         for (int i = 0; i < nx; i++)
00105         {
00106             u[n + 1][i][0] = 0.0;
00107             u[n + 1][i][nz - 1] = 0.0;
00108         }
00109         for (int j = 0; j < nz; j++)
00110         {
00111             u[n + 1][0][j] = 0.0;
00112             u[n + 1][nx - 1][j] = 0.0;
00113         }
00114     }
00115     return u;
00116 }

```

## 8.2 Np

### Namespaces

- namespace `np`  
*Custom implementation of numpy in C++.*

### Functions

- `template<class T, long unsigned int ND>`  
`boost::multi_array< T, ND > operator* (boost::multi_array< T, ND > const &lhs, boost::multi_array< T, ND > const &rhs)`  
*Multiplication operator between two multi arrays, element-wise.*
- `template<class T, long unsigned int ND>`  
`boost::multi_array< T, ND > operator* (T const &lhs, boost::multi_array< T, ND > const &rhs)`  
*Multiplication operator between a multi array and a scalar.*
- `template<class T, long unsigned int ND>`  
`boost::multi_array< T, ND > operator* (boost::multi_array< T, ND > const &lhs, T const &rhs)`



*Multiplication operator between a multi array and a scalar.*

- `template<class T, long unsigned int ND>`  
`boost::multi_array< T, ND > operator+ (boost::multi_array< T, ND > const &lhs, boost::multi_array< T, ND > const &rhs)`

*Addition operator between two multi arrays, element wise.*

- `template<class T, long unsigned int ND>`  
`boost::multi_array< T, ND > operator+ (T const &lhs, boost::multi_array< T, ND > const &rhs)`

*Addition operator between a multi array and a scalar.*

- `template<class T, long unsigned int ND>`  
`boost::multi_array< T, ND > operator+ (boost::multi_array< T, ND > const &lhs, T const &rhs)`

*Addition operator between a scalar and a multi array.*

- `template<class T, long unsigned int ND>`  
`boost::multi_array< T, ND > operator- (boost::multi_array< T, ND > const &lhs, boost::multi_array< T, ND > const &rhs)`

*Minus operator between two multi arrays, element-wise.*

- `template<class T, long unsigned int ND>`  
`boost::multi_array< T, ND > operator- (T const &lhs, boost::multi_array< T, ND > const &rhs)`

*Minus operator between a scalar and a multi array, element-wise.*

- `template<class T, long unsigned int ND>`  
`boost::multi_array< T, ND > operator- (boost::multi_array< T, ND > const &lhs, T const &rhs)`

*Minus operator between a multi array and a scalar, element-wise.*

- `template<class T, long unsigned int ND>`  
`boost::multi_array< T, ND > operator/ (boost::multi_array< T, ND > const &lhs, boost::multi_array< T, ND > const &rhs)`

*Division between two multi arrays, element wise.*

- `template<class T, long unsigned int ND>`  
`boost::multi_array< T, ND > operator/ (T const &lhs, boost::multi_array< T, ND > const &rhs)`

*Division between a scalar and a multi array, element wise.*

- `template<class T, long unsigned int ND>`  
`boost::multi_array< T, ND > operator/ (boost::multi_array< T, ND > const &lhs, T const &rhs)`

*Division between a multi array and a scalar, element wise.*

- `matplotlib::vector_2d np::convert_to_matplot (const boost::multi_array< double, 2 > &arr)`

*Convert a 2D boost::multi\_array to a matplotlib::vector\_2d.*

## 8.2.1 Detailed Description

## 8.2.2 Function Documentation

### 8.2.2.1 convert\_to\_matplot()

```
matplotlib::vector_2d np::convert_to_matplot (
    const boost::multi_array< double, 2 > & arr ) [inline]
```

Convert a 2D boost::multi\_array to a matplotlib::vector\_2d.

Definition at line 16 of file `np_to_matplot.hpp`.

```
00017 {
00018     std::vector<double> x = matplotlib::linspace(0, 0, arr.shape()[0]);
00019     std::vector<double> y = matplotlib::linspace(0, 0, arr.shape()[1]);
00020     matplotlib::vector_2d result = std::get<0>(matplotlib::meshgrid(x, y));
```

```

00021         // std::cout << "arr.shape()[0] = " << arr.shape()[0] << " arr.shape()[1] = " << arr.shape()[1] <<
std::endl;
00022         for (size_t i = 0; i < arr.shape()[0]; i++)
00023         {
00024             for (size_t j = 0; j < arr.shape()[1]; j++)
00025             {
00026                 result[i][j] = arr[i][j];
00027             }
00028         }
00029         return result;
00030     }

```

### 8.2.2.2 operator\*() [1/3]

```

template<class T , long unsigned int ND>
boost::multi_array< T, ND > operator* (
    boost::multi_array< T, ND > const & lhs,
    boost::multi_array< T, ND > const & rhs ) [inline]

```

Multiplication operator between two multi arrays, element-wise.

Definition at line 504 of file [np.hpp](#).

```

00505 {
00506     std::function<T(T, T)> func = std::multiplies<T>();
00507     return np::element_wise_duo_apply(lhs, rhs, func);
00508 }

```

### 8.2.2.3 operator\*() [2/3]

```

template<class T , long unsigned int ND>
boost::multi_array< T, ND > operator* (
    boost::multi_array< T, ND > const & lhs,
    T const & rhs ) [inline]

```

Multiplication operator between a multi array and a scalar.

Definition at line 520 of file [np.hpp](#).

```

00521 {
00522     return rhs * lhs;
00523 }

```

### 8.2.2.4 operator\*() [3/3]

```

template<class T , long unsigned int ND>
boost::multi_array< T, ND > operator* (
    T const & lhs,
    boost::multi_array< T, ND > const & rhs ) [inline]

```

Multiplication operator between a multi array and a scalar.

Definition at line 512 of file [np.hpp](#).

```

00513 {
00514     std::function<T(T)> func = [lhs](T item)
00515     { return lhs * item; };
00516     return np::element_wise_apply(rhs, func);
00517 }

```

**8.2.2.5 operator+() [1/3]**

```
template<class T , long unsigned int ND>
boost::multi_array< T, ND > operator+ (
    boost::multi_array< T, ND > const & lhs,
    boost::multi_array< T, ND > const & rhs )
```

Addition operator between two multi arrays, element wise.

Definition at line 528 of file [np.hpp](#).

```
00529 {
00530     std::function<T(T, T)> func = std::plus<T>();
00531     return np::element_wise_duo_apply(lhs, rhs, func);
00532 }
```

**8.2.2.6 operator+() [2/3]**

```
template<class T , long unsigned int ND>
boost::multi_array< T, ND > operator+ (
    boost::multi_array< T, ND > const & lhs,
    T const & rhs ) [inline]
```

Addition operator between a scalar and a multi array.

Definition at line 545 of file [np.hpp](#).

```
00546 {
00547     return rhs + lhs;
00548 }
```

**8.2.2.7 operator+() [3/3]**

```
template<class T , long unsigned int ND>
boost::multi_array< T, ND > operator+ (
    T const & lhs,
    boost::multi_array< T, ND > const & rhs ) [inline]
```

Addition operator between a multi array and a scalar.

Definition at line 536 of file [np.hpp](#).

```
00537 {
00538     std::function<T(T)> func = [lhs](T item)
00539     { return lhs + item; };
00540     return np::element_wise_apply(rhs, func);
00541 }
```

**8.2.2.8 operator-() [1/3]**

```
template<class T , long unsigned int ND>
boost::multi_array< T, ND > operator- (
    boost::multi_array< T, ND > const & lhs,
    boost::multi_array< T, ND > const & rhs )
```

Minus operator between two multi arrays, element-wise.

Definition at line 553 of file [np.hpp](#).

```
00554 {
00555     std::function<T(T, T)> func = std::minus<T>();
00556     return np::element_wise_duo_apply(lhs, rhs, func);
00557 }
```

**8.2.2.9 operator-() [2/3]**

```
template<class T , long unsigned int ND>
boost::multi_array< T, ND > operator- (
    boost::multi_array< T, ND > const & lhs,
    T const & rhs ) [inline]
```

Minus operator between a multi array and a scalar, element-wise.

Definition at line 570 of file [np.hpp](#).

```
00571 {
00572     return rhs - lhs;
00573 }
```

**8.2.2.10 operator-() [3/3]**

```
template<class T , long unsigned int ND>
boost::multi_array< T, ND > operator- (
    T const & lhs,
    boost::multi_array< T, ND > const & rhs ) [inline]
```

Minus operator between a scalar and a multi array, element-wise.

Definition at line 561 of file [np.hpp](#).

```
00562 {
00563     std::function<T(T)> func = [lhs](T item)
00564     { return lhs - item; };
00565     return np::element_wise_apply(rhs, func);
00566 }
```

**8.2.2.11 operator/()** [1/3]

```
template<class T , long unsigned int ND>
boost::multi_array< T, ND > operator/ (
    boost::multi_array< T, ND > const & lhs,
    boost::multi_array< T, ND > const & rhs )
```

Division between two multi arrays, element wise.

Definition at line 578 of file [np.hpp](#).

```
00579 {
00580     std::function<T(T, T)> func = std::divides<T>();
00581     return np::element_wise_duo_apply(lhs, rhs, func);
00582 }
```

**8.2.2.12 operator/()** [2/3]

```
template<class T , long unsigned int ND>
boost::multi_array< T, ND > operator/ (
    boost::multi_array< T, ND > const & lhs,
    T const & rhs ) [inline]
```

Division between a multi array and a scalar, element wise.

Definition at line 595 of file [np.hpp](#).

```
00596 {
00597     std::function<T(T)> func = [rhs](T item)
00598     { return item / rhs; };
00599     return np::element_wise_apply(lhs, func);
00600 }
```

**8.2.2.13 operator/()** [3/3]

```
template<class T , long unsigned int ND>
boost::multi_array< T, ND > operator/ (
    T const & lhs,
    boost::multi_array< T, ND > const & rhs ) [inline]
```

Division between a scalar and a multi array, element wise.

Definition at line 586 of file [np.hpp](#).

```
00587 {
00588     std::function<T(T)> func = [lhs](T item)
00589     { return lhs / item; };
00590     return np::element_wise_apply(rhs, func);
00591 }
```

**8.3 WavePlotter****Namespaces**

- namespace [wavePlotter](#)  
*Custom plotter class.*

## Classes

- class [wavePlotter::Plotter](#)

*This class is used to plot the wave field TODO: make it multithreaded.*

## Functions

- [wavePlotter::Plotter::Plotter](#) (const boost::multi\_array< double, 3 > &u, const matplotlib::vector\_2d &Xp, const matplotlib::vector\_2d &Zp, int num\_levels, int nt)  
*Constructor.*
- void [wavePlotter::Plotter::renderFrame](#) (int index)  
*Renders a frame of the wave field to a image on disk.*
- void [wavePlotter::Plotter::renderAllFrames](#) (int begin\_frame\_index, int end\_frame\_index)  
*Renders all frames of the wave field to form an animation to be saved on disk.*
- void [wavePlotter::Plotter::animate](#) (std::string output\_file\_name, int begin\_frame\_index, int end\_frame\_index, int frame\_rate)  
*Renders a complete video animation of the wave field.*
- void [wavePlotter::Plotter::exportFrame](#) (int index)  
*Export a frame of the wave field to a .csv format for external use.*
- void [wavePlotter::Plotter::exportAllFrames](#) (int begin\_frame\_index, int end\_frame\_index)  
*Export all frames of the wave field to a .csv format for external use.*
- void [wavePlotter::Plotter::setSaveDirectory](#) (std::string save\_directory)  
*Set the save directory for the rendered frames.*

### 8.3.1 Detailed Description

### 8.3.2 Function Documentation

#### 8.3.2.1 animate()

```
void wavePlotter::Plotter::animate (
    std::string output_file_name,
    int begin_frame_index,
    int end_frame_index,
    int frame_rate ) [inline]
```

Renders a complete video animation of the wave field.

Definition at line 56 of file [wavePlotter.hpp](#).

```
00057     {
00058         renderAllFrames(begin_frame_index, end_frame_index);
00059         std::string ffmpeg_render_command = "ffmpeg -framerate " + std::to_string(frame_rate) + "
-pattern_type glob -i '" + save_directory + "/*.png' -c:v libx264 -pix_fmt yuv420p " +
output_file_name;
00060         std::system(ffmpeg_render_command.c_str());
00061     }
```

### 8.3.2.2 exportAllFrames()

```
void wavePlotter::Plotter::exportAllFrames (
    int begin_frame_index,
    int end_frame_index ) [inline]
```

Export all frames of the wave field to a .csv format for external use.

Definition at line 82 of file [wavePlotter.hpp](#).

```
00083     {
00084         for (int i = begin_frame_index; i < end_frame_index; i++)
00085         {
00086             exportFrame(i);
00087         }
00088     }
```

### 8.3.2.3 exportFrame()

```
void wavePlotter::Plotter::exportFrame (
    int index ) [inline]
```

Export a frame of the wave field to a .csv format for external use.

Definition at line 63 of file [wavePlotter.hpp](#).

```
00064     {
00065         matplotlib::vector_2d Up = np::convert_to_matplot(this->u[index]);
00066         std::ofstream outfile;
00067         outfile.open(save_directory + "/frame_" + format_num(index) + ".csv");
00068         for (std::size_t i = 0; i < Up.size(); i++)
00069         {
00070             for (std::size_t j = 0; j < Up[i].size(); j++)
00071             {
00072                 outfile << Up[i][j];
00073                 if (j != Up[i].size() - 1)
00074                     outfile << ",";
00075             }
00076             outfile << "\n";
00077         }
00078         outfile.close();
00079     }
```

### 8.3.2.4 Plotter()

```
wavePlotter::Plotter::Plotter (
    const boost::multi_array< double, 3 > & u,
    const matplotlib::vector_2d & Xp,
    const matplotlib::vector_2d & Zp,
    int num_levels,
    int nt ) [inline]
```

Constructor.

Definition at line 25 of file [wavePlotter.hpp](#).

```
00026     {
00027         this->u.resize(boost::extents[u.shape()[0]][u.shape()[1]][u.shape()[2]]);
00028         this->u = u;
00029         this->Xp = Xp;
00030         this->Zp = Zp;
00031         this->num_levels = num_levels;
00032         this->nt = nt;
00033         double min_u = np::min(u);
00034         double max_u = np::max(u);
00035         std::cout << "min_u = " << min_u << " max_u = " << max_u << "\n";
00036         this->levels = matplotlib::linspace(min_u, max_u, num_levels);
00037     }
```

### 8.3.2.5 renderAllFrames()

```
void wavePlotter::Plotter::renderAllFrames (
    int begin_frame_index,
    int end_frame_index ) [inline]
```

Renders all frames of the wave field to form an animation to be saved on disk.

Definition at line 47 of file [wavePlotter.hpp](#).

```
00048     {
00049         for (int i = begin_frame_index; i < end_frame_index; i++)
00050         {
00051             renderFrame(i);
00052         }
00053     }
```

### 8.3.2.6 renderFrame()

```
void wavePlotter::Plotter::renderFrame (
    int index ) [inline]
```

Renders a frame of the wave field to a image on disk.

Definition at line 39 of file [wavePlotter.hpp](#).

```
00040     {
00041         matplotlib::vector_2d Up = np::convert_to_matplotlib(this->u[index]);
00042         matplotlib::contourf(this->Xp, this->Zp, Up, this->levels);
00043         matplotlib::save(save_directory + "/contourf_" + format_num(index) + ".png");
00044     }
```

### 8.3.2.7 setSaveDirectory()

```
void wavePlotter::Plotter::setSaveDirectory (
    std::string save_directory ) [inline]
```

Set the save directory for the rendered frames.

Definition at line 91 of file [wavePlotter.hpp](#).

```
00092     {
00093         this->save_directory = save_directory;
00094     }
```



## Chapter 9

# Namespace Documentation

### 9.1 np Namespace Reference

Custom implementation of numpy in C++.

#### Typedefs

- typedef double [ndArrayValue](#)

#### Enumerations

- enum **indexing** { **xy** , **ij** }

#### Functions

- template<std::size\_t ND>  
boost::multi\_array< ndArrayValue, ND >::index [getIndex](#) (const boost::multi\_array< ndArrayValue, ND > &m, const ndArrayValue \*requestedElement, const unsigned short int direction)  
*Gets the index of one element in a multi\_array in one axis.*
- template<std::size\_t ND>  
boost::array< typename boost::multi\_array< ndArrayValue, ND >::index, ND > [getIndexArray](#) (const boost::multi\_array< ndArrayValue, ND > &m, const ndArrayValue \*requestedElement)  
*Gets the index of one element in a multi\_array.*
- template<typename Array , typename Element , typename Functor >  
void [for\\_each](#) (const boost::type< Element > &type\_dispatch, Array A, Functor &xform)
- template<typename Element , typename Functor >  
void [for\\_each](#) (const boost::type< Element > &, Element &Val, Functor &xform)  
*Function to apply a function to all elements of a multi\_array.*
- template<typename Element , typename Iterator , typename Functor >  
void [for\\_each](#) (const boost::type< Element > &type\_dispatch, Iterator begin, Iterator end, Functor &xform)  
*Function to apply a function to all elements of a multi\_array.*
- template<typename Array , typename Functor >  
void [for\\_each](#) (Array &A, Functor xform)

- `template<typename T, long unsigned int ND>`  
requires `std::is_floating_point<T>`  
`::value constexpr std::vector< boost::multi_array< T, ND > > gradient (boost::multi_array< T, ND > inArray, std::initializer_list< T > args)`
- `boost::multi_array< double, 1 > linspace (double start, double stop, long unsigned int num)`  
*Implements the numpy linspace function.*
- `template<typename T, long unsigned int ND>`  
requires `std::is_arithmetic<T>`  
`::value constexpr std::vector< boost::multi_array< T, ND > > meshgrid (const boost::multi_array< T, 1 > (&input)[ND], bool sparsing=false, indexing indexing_type=xy)`
- `template<class T, long unsigned int ND>`  
requires `std::is_arithmetic<T>`  
`::value constexpr boost::multi_array< T, ND > element\_wise\_apply (const boost::multi_array< T, ND > &input_array, std::function< T(T)> func)`  
*Creates a new array and fills it with the values of the result of the function called on the input array element-wise.*
- `template<class T, long unsigned int ND>`  
requires `std::is_arithmetic<T>`  
`::value constexpr boost::multi_array< T, ND > sqrt (const boost::multi_array< T, ND > &input_array)`  
*Implements the numpy sqrt function on multi arrays.*
- `template<class T >`  
requires `std::is_arithmetic<T>`  
`::value constexpr T sqrt (const T input)`  
*Implements the numpy sqrt function on scalars.*
- `template<class T, long unsigned int ND>`  
requires `std::is_arithmetic<T>`  
`::value constexpr boost::multi_array< T, ND > exp (const boost::multi_array< T, ND > &input_array)`  
*Implements the numpy exp function on multi arrays.*
- `template<class T >`  
requires `std::is_arithmetic<T>`  
`::value constexpr T exp (const T input)`  
*Implements the numpy exp function on scalars.*
- `template<class T, long unsigned int ND>`  
requires `std::is_arithmetic<T>`  
`::value constexpr boost::multi_array< T, ND > log (const boost::multi_array< T, ND > &input_array)`  
*Implements the numpy log function on multi arrays.*
- `template<class T >`  
requires `std::is_arithmetic<T>`  
`::value constexpr T log (const T input)`  
*Implements the numpy log function on scalars.*
- `template<class T, long unsigned int ND>`  
requires `std::is_arithmetic<T>`  
`::value constexpr boost::multi_array< T, ND > pow (const boost::multi_array< T, ND > &input_array, const T exponent)`  
*Implements the numpy pow function on multi arrays.*
- `template<class T >`  
requires `std::is_arithmetic<T>`  
`::value constexpr T pow (const T input, const T exponent)`  
*Implements the numpy pow function on scalars.*
- `template<class T, long unsigned int ND>`  
`constexpr boost::multi_array< T, ND > element\_wise\_duo\_apply (boost::multi_array< T, ND > const &lhs, boost::multi_array< T, ND > const &rhs, std::function< T(T, T)> func)`
- `template<typename T, typename inT, long unsigned int ND>`  
requires `std::is_integral<inT>`  
`::value &&std::is_arithmetic< T >::value constexpr boost::multi_array< T, ND > zeros (inT(&dimensions_... input)[ND])`

*Implements the numpy zeros function for an n-dimensional multi array.*

- `template<typename T , long unsigned int ND>`  
`requires std::is_arithmetic<T>`  
`::value constexpr T max (boost::multi_array< T, ND > const &input_array)`

*Implements the numpy max function for an n-dimensional multi array.*

- `template<class T , class... Ts, class = std::enable_if_t<(std::is_same_v<T, Ts> && ...)>>`  
`requires std::is_arithmetic<T>`  
`::value constexpr T max (T input1, Ts... inputs)`

*Implements the numpy max function for an variadic number of arguments.*

- `template<typename T , long unsigned int ND>`  
`requires std::is_arithmetic<T>`  
`::value constexpr T min (boost::multi_array< T, ND > const &input_array)`

*Implements the numpy min function for an n-dimensional multi array.*

- `template<class T , class... Ts, class = std::enable_if_t<(std::is_same_v<T, Ts> && ...)>>`  
`requires std::is_arithmetic<T>`  
`constexpr T min (T input1, Ts... inputs)`

*Implements the numpy min function for an variadic number of arguments.*

- `template<typename T >`  
`requires std::is_arithmetic<T>`  
`::value constexpr T abs (T input)`

*Implements the numpy abs function for a scalar.*

- `template<typename T , long unsigned int ND>`  
`requires std::is_arithmetic<T>`  
`::value constexpr boost::multi_array< T, ND - 1 > slice (boost::multi_array< T, ND > const &input_array, std::size_t slice_index)`

*Slices the array through one dimension and returns a ND - 1 dimensional array.*

- `matplotlib::vector_2d convert\_to\_matplotlib (const boost::multi_array< double, 2 > &arr)`  
*Convert a 2D boost::multi\_array to a matplotlib::vector\_2d.*

### 9.1.1 Detailed Description

Custom implementation of numpy in C++.

### 9.1.2 Typedef Documentation

#### 9.1.2.1 ndarrayValue

```
typedef double np::ndArrayValue
```

Definition at line 22 of file [np.hpp](#).

### 9.1.3 Enumeration Type Documentation

### 9.1.3.1 indexing

enum np::indexing

Definition at line 172 of file [np.hpp](#).

```
00173     {
00174         xy,
00175         ij
00176     };
```

## 9.1.4 Function Documentation

### 9.1.4.1 abs()

```
template<typename T >
requires std::is_arithmetic<T>
::value constexpr T np::abs (
    T input ) [inline], [constexpr]
```

Implements the numpy abs function for a scalar.

Definition at line 463 of file [np.hpp](#).

```
00464     {
00465         return std::abs(input);
00466     }
```

### 9.1.4.2 element\_wise\_apply()

```
template<class T , long unsigned int ND>
requires std::is_arithmetic<T>
::value constexpr boost::multi_array< T, ND > np::element_wise_apply (
    const boost::multi_array< T, ND > & input_array,
    std::function< T(T)> func ) [inline], [constexpr]
```

Creates a new array and fills it with the values of the result of the function called on the input array element-wise.

Definition at line 243 of file [np.hpp](#).

```
00244     {
00245         // Create output array copying extents
00246         using arrayIndex = boost::multi_array<double, ND>::index;
00247         using ndIndexArray = boost::array<arrayIndex, ND>;
00248         boost::detail::multi_array::extent_gen<ND> output_extents;
00249         std::vector<size_t> shape_list;
00250         for (std::size_t i = 0; i < ND; i++)
00251         {
00252             shape_list.push_back(input_array.shape()[i]);
00253         }
00254         std::copy(shape_list.begin(), shape_list.end(), output_extents.ranges_.begin());
00255         boost::multi_array<T, ND> output_array(output_extents);
00256         // Looping through the elements of the output array
00257         const T *p = input_array.data();
00258         ndIndexArray index;
00259         for (std::size_t i = 0; i < input_array.num_elements(); i++)
00260         {
00261             index = getIndexArray(input_array, p);
00262             output_array(index) = func(input_array(index));
00263             ++p;
00264         }
00265         return output_array;
00266     }
```

### 9.1.4.3 element\_wise\_duo\_apply()

```
template<class T , long unsigned int ND>
constexpr boost::multi_array< T, ND > np::element_wise_duo_apply (
    boost::multi_array< T, ND > const & lhs,
    boost::multi_array< T, ND > const & rhs,
    std::function< T(T, T)> func ) [inline], [constexpr]
```

Creates a new array in which the value at each index is the the result of the input function applied to an element of the left hand side array and one on the right hand side array in the same index Outputs a copy of the result

Definition at line 337 of file [np.hpp](#).

```
00338     {
00339         // Create output array copying extents
00340         using arrayIndex = boost::multi_array<double, ND>::index;
00341         using ndIndexArray = boost::array<arrayIndex, ND>;
00342         boost::detail::multi_array::extent_gen<ND> output_extents;
00343         std::vector<size_t> shape_list;
00344         for (std::size_t i = 0; i < ND; i++)
00345         {
00346             shape_list.push_back(lhs.shape()[i]);
00347         }
00348         std::copy(shape_list.begin(), shape_list.end(), output_extents.ranges_.begin());
00349         boost::multi_array<T, ND> output_array(output_extents);
00350
00351         // Looping through the elements of the output array
00352         const T *p = lhs.data();
00353         ndIndexArray index;
00354         for (std::size_t i = 0; i < lhs.num_elements(); i++)
00355         {
00356             index = getIndexArray(lhs, p);
00357             output_array(index) = func(lhs(index), rhs(index));
00358             ++p;
00359         }
00360         return output_array;
00361     }
```

### 9.1.4.4 exp() [1/2]

```
template<class T , long unsigned int ND>
requires std::is_arithmetic<T>
::value constexpr boost::multi_array< T, ND > np::exp (
    const boost::multi_array< T, ND > & input_array ) [inline], [constexpr]
```

Implements the numpy exp function on multi arrays.

Definition at line 289 of file [np.hpp](#).

```
00290     {
00291         std::function<T(T)> func = (T(*) (T))std::exp;
00292         return element_wise_apply(input_array, func);
00293     }
```

### 9.1.4.5 exp() [2/2]

```
template<class T >
requires std::is_arithmetic<T>
::value constexpr T np::exp (
    const T input ) [inline], [constexpr]
```

Implements the numpy exp function on scalars.

Definition at line 297 of file [np.hpp](#).

```
00298     {
00299         return std::exp(input);
00300     }
```

**9.1.4.6 for\_each() [1/4]**

```
template<typename Array , typename Functor >
void np::for_each (
    Array & A,
    Functor xform ) [inline]
```

Function to apply a function to all elements of a multi\_array Simple overload

Definition at line 80 of file [np.hpp](#).

```
00081     {
00082         // Dispatch to the proper function
00083         for_each(boost::type<typename Array::element>(), A.begin(), A.end(), xform);
00084     }
```

**9.1.4.7 for\_each() [2/4]**

```
template<typename Element , typename Functor >
void np::for_each (
    const boost::type< Element > & ,
    Element & Val,
    Functor & xform ) [inline]
```

Function to apply a function to all elements of a multi\_array.

Definition at line 59 of file [np.hpp](#).

```
00060     {
00061         Val = xform(Val);
00062     }
```

**9.1.4.8 for\_each() [3/4]**

```
template<typename Array , typename Element , typename Functor >
void np::for_each (
    const boost::type< Element > & type_dispatch,
    Array A,
    Functor & xform ) [inline]
```

Function to apply a function to all elements of a multi\_array Simple overload

Definition at line 51 of file [np.hpp](#).

```
00053     {
00054         for_each(type_dispatch, A.begin(), A.end(), xform);
00055     }
```

#### 9.1.4.9 for\_each() [4/4]

```
template<typename Element , typename Iterator , typename Functor >
void np::for_each (
    const boost::type< Element > & type_dispatch,
    Iterator begin,
    Iterator end,
    Functor & xform ) [inline]
```

Function to apply a function to all elements of a multi\_array.

Definition at line 66 of file [np.hpp](#).

```
00069     {
00070         while (begin != end)
00071         {
00072             for_each(type_dispatch, *begin, xform);
00073             ++begin;
00074         }
00075     }
```

#### 9.1.4.10 getIndex()

```
template<std::size_t ND>
boost::multi_array< ndArrayValue, ND >::index np::getIndex (
    const boost::multi_array< ndArrayValue, ND > & m,
    const ndArrayValue * requestedElement,
    const unsigned short int direction ) [inline]
```

Gets the index of one element in a multi\_array in one axis.

Definition at line 27 of file [np.hpp](#).

```
00028     {
00029         int offset = requestedElement - m.origin();
00030         return (offset / m.strides()[direction] % m.shape()[direction] + m.index_bases()[direction]);
00031     }
```

#### 9.1.4.11 getIndexArray()

```
template<std::size_t ND>
boost::array< typename boost::multi_array< ndArrayValue, ND >::index, ND > np::getIndexArray
(
    const boost::multi_array< ndArrayValue, ND > & m,
    const ndArrayValue * requestedElement ) [inline]
```

Gets the index of one element in a multi\_array.

Definition at line 36 of file [np.hpp](#).

```
00037     {
00038         using indexType = boost::multi_array<ndArrayValue, ND>::index;
00039         boost::array<indexType, ND> _index;
00040         for (unsigned int dir = 0; dir < ND; dir++)
00041         {
00042             _index[dir] = getIndex(m, requestedElement, dir);
00043         }
00044         return _index;
00045     }
```

### 9.1.4.12 gradient()

```
template<typename T , long unsigned int ND>
requires std::is_floating_point<T>
::value constexpr std::vector< boost::multi_array< T, ND > > np::gradient (
    boost::multi_array< T, ND > inArray,
    std::initializer_list< T > args ) [inline], [constexpr]
```

Takes the gradient of a n-dimensional multi\_array Uses ij indexing Todo: Implement xy indexing

Definition at line 90 of file [np.hpp](#).

```
00091 {
00092     // static_assert(args.size() == ND, "Number of arguments must match the number of dimensions
of the array");
00093     using arrayIndex = boost::multi_array<T, ND>::index;
00094
00095     using ndIndexArray = boost::array<arrayIndex, ND>;
00096
00097     // constexpr std::size_t n = sizeof...(Args);
00098     std::size_t n = args.size();
00099     // std::tuple<Args...> store(args...);
00100     std::vector<T> arg_vector = args;
00101     boost::multi_array<T, ND> my_array;
00102     std::vector<boost::multi_array<T, ND> output_arrays;
00103     for (std::size_t i = 0; i < n; i++)
00104     {
00105         boost::multi_array<T, ND> dfdh = inArray;
00106         output_arrays.push_back(dfdh);
00107     }
00108
00109     ndArrayValue *p = inArray.data();
00110     ndIndexArray index;
00111     for (std::size_t i = 0; i < inArray.num_elements(); i++)
00112     {
00113         index = getIndexArray(inArray, p);
00114         /*
00115         std::cout << "Index: ";
00116         for (std::size_t j = 0; j < n; j++)
00117         {
00118             std::cout << index[j] << " ";
00119         }
00120         std::cout << "\n";
00121         */
00122         // Calculating the gradient now
00123         // j is the axis/dimension
00124         for (std::size_t j = 0; j < n; j++)
00125         {
00126             ndIndexArray index_high = index;
00127             T dh_high;
00128             if ((long unsigned int)index_high[j] < inArray.shape()[j] - 1)
00129             {
00130                 index_high[j] += 1;
00131                 dh_high = arg_vector[j];
00132             }
00133             else
00134             {
00135                 dh_high = 0;
00136             }
00137             ndIndexArray index_low = index;
00138             T dh_low;
00139             if (index_low[j] > 0)
00140             {
00141                 index_low[j] -= 1;
00142                 dh_low = arg_vector[j];
00143             }
00144             else
00145             {
00146                 dh_low = 0;
00147             }
00148             T dh = dh_high + dh_low;
00149             T gradient = (inArray(index_high) - inArray(index_low)) / dh;
00150             // std::cout << gradient << "\n";
00151             output_arrays[j](index) = gradient;
00152         }
00153         // std::cout << " value = " << inArray(index) << " check = " << *p << std::endl;
00154         ++p;
00155     }
00156     return output_arrays;
00157 }
00158 }
```



#### 9.1.4.13 linspace()

```
boost::multi_array< double, 1 > np::linspace (
    double start,
    double stop,
    long unsigned int num ) [inline]
```

Implements the numpy linspace function.

Definition at line 161 of file [np.hpp](#).

```
00162     {
00163         double step = (stop - start) / (num - 1);
00164         boost::multi_array<double, 1> output(boost::extents[num]);
00165         for (std::size_t i = 0; i < num; i++)
00166         {
00167             output[i] = start + i * step;
00168         }
00169         return output;
00170     }
```

#### 9.1.4.14 log() [1/2]

```
template<class T , long unsigned int ND>
requires std::is_arithmetic<T>
::value constexpr boost::multi_array< T, ND > np::log (
    const boost::multi_array< T, ND > & input_array ) [inline], [constexpr]
```

Implements the numpy log function on multi arrays.

Definition at line 304 of file [np.hpp](#).

```
00305     {
00306         std::function<T(T)> func = std::log<T>();
00307         return element_wise_apply(input_array, func);
00308     }
```

#### 9.1.4.15 log() [2/2]

```
template<class T >
requires std::is_arithmetic<T>
::value constexpr T np::log (
    const T input ) [inline], [constexpr]
```

Implements the numpy log function on scalars.

Definition at line 312 of file [np.hpp](#).

```
00313     {
00314         return std::log(input);
00315     }
```

#### 9.1.4.16 max() [1/2]

```
template<typename T , long unsigned int ND>
requires std::is_arithmetic<T>
::value constexpr T np::max (
    boost::multi_array< T, ND > const & input_array ) [inline], [constexpr]
```

Implements the numpy max function for an n-dimensional multi array.

Definition at line 384 of file [np.hpp](#).

```
00385     {
00386         T max = 0;
00387         bool max_not_set = true;
00388         const T *data_pointer = input_array.data();
00389         for (std::size_t i = 0; i < input_array.num_elements(); i++)
00390         {
00391             T element = *data_pointer;
00392             if (max_not_set || element > max)
00393             {
00394                 max = element;
00395                 max_not_set = false;
00396             }
00397             ++data_pointer;
00398         }
00399         return max;
00400     }
```

#### 9.1.4.17 max() [2/2]

```
template<class T , class... Ts, class = std::enable_if_t<(std::is_same_v<T, Ts> && ...) >>
requires std::is_arithmetic<T>
::value constexpr T np::max (
    T input1,
    Ts... inputs ) [inline], [constexpr]
```

Implements the numpy max function for an variadic number of arguments.

Definition at line 404 of file [np.hpp](#).

```
00405     {
00406         T max = input1;
00407         for (T input : {inputs...})
00408         {
00409             if (input > max)
00410             {
00411                 max = input;
00412             }
00413         }
00414         return max;
00415     }
```

#### 9.1.4.18 meshgrid()

```
template<typename T , long unsigned int ND>
requires std::is_arithmetic<T>
::value constexpr std::vector< boost::multi_array< T, ND > > np::meshgrid (
    const boost::multi_array< T, 1 >(&) cinput[ND],
    bool sparsing = false,
    indexing indexing_type = xy ) [inline], [constexpr]
```

Implementation of meshgrid TODO: Implement sparsing=true If the indexing type is xx, then reverse the order of the first two elements of ci if the number of dimensions is 2 or 3 In accordance with the numpy implementation

Definition at line 184 of file [np.hpp](#).

```

00185     {
00186         using arrayIndex = boost::multi_array<T, ND>::index;
00187         using oneDArrayIndex = boost::multi_array<T, 1>::index;
00188         using ndIndexArray = boost::array<arrayIndex, ND>;
00189         std::vector<boost::multi_array<T, ND>> output_arrays;
00190         boost::multi_array<T, 1> ci[ND];
00191         // Copy elements of cinput to ci, do the proper inversions
00192         for (std::size_t i = 0; i < ND; i++)
00193         {
00194             std::size_t source = i;
00195             if (indexing_type == xy && (ND == 3 || ND == 2))
00196             {
00197                 if (i == 0)
00198                     source = 1;
00199                 else if (i == 1)
00200                     source = 0;
00201                 else
00202                     source = i;
00203             }
00204             ci[i] = boost::multi_array<T, 1>();
00205             ci[i].resize(boost::extents[cinput[source].num_elements()]);
00206             ci[i] = cinput[source];
00207         }
00208         // Deducing the extents of the N-Dimensional output
00209         boost::detail::multi_array::extent_gen<ND> output_extents;
00210         std::vector<size_t> shape_list;
00211         for (std::size_t i = 0; i < ND; i++)
00212         {
00213             shape_list.push_back(ci[i].shape()[0]);
00214         }
00215         std::copy(shape_list.begin(), shape_list.end(), output_extents.ranges_.begin());
00216
00217         // Creating the output arrays
00218         for (std::size_t i = 0; i < ND; i++)
00219         {
00220             boost::multi_array<T, ND> output_array(output_extents);
00221             ndArrayValue *p = output_array.data();
00222             ndIndexArray index;
00223             // Looping through the elements of the output array
00224             for (std::size_t j = 0; j < output_array.num_elements(); j++)
00225             {
00226                 index = getIndexArray(output_array, p);
00227                 oneDArrayIndex index_1d;
00228                 index_1d = index[i];
00229                 output_array(index) = ci[i][index_1d];
00230                 ++p;
00231             }
00232             output_arrays.push_back(output_array);
00233         }
00234         if (indexing_type == xy && (ND == 3 || ND == 2))
00235         {
00236             std::swap(output_arrays[0], output_arrays[1]);
00237         }
00238         return output_arrays;
00239     }

```

#### 9.1.4.19 min() [1/2]

```

template<typename T, long unsigned int ND>
requires std::is_arithmetic<T>
::value constexpr T np::min (
    boost::multi_array< T, ND > const & input_array ) [inline], [constexpr]

```

Implements the numpy min function for an n-dimensionl multi array.

Definition at line 419 of file [np.hpp](#).

```

00420     {
00421         T min = 0;
00422         bool min_not_set = true;
00423         const T *data_pointer = input_array.data();
00424         for (std::size_t i = 0; i < input_array.num_elements(); i++)

```

```

00425     {
00426         T element = *data_pointer;
00427         if (min_not_set || element < min)
00428         {
00429             min = element;
00430             min_not_set = false;
00431         }
00432         ++data_pointer;
00433     }
00434     return min;
00435 }

```

#### 9.1.4.20 min() [2/2]

```

template<class T , class... Ts, class = std::enable_if_t<(std::is_same_v<T, Ts> && ...) >>
requires std::is_arithmetic<T>
constexpr T np::min (
    T input1,
    Ts... inputs ) [inline], [constexpr]

```

Implements the numpy min function for an variadic number of arguments.

Definition at line 439 of file [np.hpp](#).

```

00440     {
00441         T min = input1;
00442         for (T input : {inputs...})
00443         {
00444             if (input < min)
00445             {
00446                 min = input;
00447             }
00448         }
00449         return min;
00450     }
00451
00452     template <typename T, long unsigned int ND>
00453     requires std::is_arithmetic<T>::value inline constexpr boost::multi_array<T, ND>
00454     abs(boost::multi_array<T, ND> const &input_array)
00455     {
00456         std::function<T(T)> abs_func = [](T input)
00457         { return std::abs(input); };
00458         return element_wise_apply(input_array, abs_func);
00459     }

```

#### 9.1.4.21 pow() [1/2]

```

template<class T , long unsigned int ND>
requires std::is_arithmetic<T>
::value constexpr boost::multi_array< T, ND > np::pow (
    const boost::multi_array< T, ND > & input_array,
    const T exponent ) [inline], [constexpr]

```

Implements the numpy pow function on multi arrays.

Definition at line 319 of file [np.hpp](#).

```

00320     {
00321         std::function<T(T)> pow_func = [exponent](T input)
00322         { return std::pow(input, exponent); };
00323         return element_wise_apply(input_array, pow_func);
00324     }

```

#### 9.1.4.22 pow() [2/2]

```
template<class T >
requires std::is_arithmetic<T>
::value constexpr T np::pow (
    const T input,
    const T exponent ) [inline], [constexpr]
```

Implements the numpy pow function on scalars.

Definition at line 328 of file [np.hpp](#).

```
00329     {
00330         return std::pow(input, exponent);
00331     }
```

#### 9.1.4.23 slice()

```
template<typename T , long unsigned int ND>
requires std::is_arithmetic<T>
::value constexpr boost::multi_array< T, ND - 1 > np::slice (
    boost::multi_array< T, ND > const & input_array,
    std::size_t slice_index ) [inline], [constexpr]
```

Slices the array through one dimension and returns a ND - 1 dimensional array.

Definition at line 470 of file [np.hpp](#).

```
00471     {
00472
00473         // Deducing the extents of the N-Dimensional output
00474         boost::detail::multi_array::extent_gen<ND - 1> output_extents;
00475         std::vector<size_t> shape_list;
00476         for (std::size_t i = 1; i < ND; i++)
00477         {
00478             shape_list.push_back(input_array.shape()[i]);
00479         }
00480         std::copy(shape_list.begin(), shape_list.end(), output_extents.ranges_.begin());
00481
00482         boost::multi_array<T, ND - 1> output_array(output_extents);
00483
00484         const T *p = input_array.data();
00485         boost::array<std::size_t, ND> index;
00486         for (std::size_t i = 0; i < input_array.num_elements(); i++)
00487         {
00488             index = getIndexArray(input_array, p);
00489             output_array(index) = input_array[slice_index](index);
00490             p++;
00491         }
00492         return output_array;
00493     }
```

#### 9.1.4.24 sqrt() [1/2]

```
template<class T , long unsigned int ND>
requires std::is_arithmetic<T>
::value constexpr boost::multi_array< T, ND > np::sqrt (
    const boost::multi_array< T, ND > & input_array ) [inline], [constexpr]
```

Implements the numpy sqrt function on multi arrays.

Definition at line 274 of file [np.hpp](#).

```
00275     {
00276         std::function<T(T)> func = (T(*) (T))std::sqrt;
00277         return element_wise_apply(input_array, func);
00278     }
```

#### 9.1.4.25 sqrt() [2/2]

```
template<class T >
requires std::is_arithmetic<T>
::value constexpr T np::sqrt (
    const T input ) [inline], [constexpr]
```

Implements the numpy sqrt function on scalars.

Definition at line 282 of file [np.hpp](#).

```
00283     {
00284         return std::sqrt(input);
00285     }
```

#### 9.1.4.26 zeros()

```
template<typename T , typename inT , long unsigned int ND>
requires std::is_integral<inT>
::value &&std::is_arithmetic< T >::value constexpr boost::multi_array< T, ND > np::zeros (
    inT(&) dimensions_input[ND] ) [inline], [constexpr]
```

Implements the numpy zeros function for an n-dimensional multi array.

Definition at line 365 of file [np.hpp](#).

```
00366     {
00367         // Deducing the extents of the N-Dimensional output
00368         boost::detail::multi_array::extent_gen<ND> output_extents;
00369         std::vector<size_t> shape_list;
00370         for (std::size_t i = 0; i < ND; i++)
00371         {
00372             shape_list.push_back(dimensions_input[i]);
00373         }
00374         std::copy(shape_list.begin(), shape_list.end(), output_extents.ranges_.begin());
00375         // Applying a function to return zero always to all of its elements
00376         boost::multi_array<T, ND> output_array(output_extents);
00377         std::function<T(T)> zero_func = [](T input)
00378         { return 0; };
00379         return element_wise_apply(output_array, zero_func);
00380     }
```

## 9.2 wavePlotter Namespace Reference

Custom plotter class.

### Classes

- class [Plotter](#)

*This class is used to plot the wave field TODO: make it multithreaded.*

### 9.2.1 Detailed Description

Custom plotter class.

## 9.3 waveSimCore Namespace Reference

### Functions

- `boost::multi_array< double, 2 > get_sigma_1` (`boost::multi_array< double, 1 > x`, `double dx`, `int nx`, `int nz`, `double c_max`, `int n=15`, `double R=1e-3`, `double m=2.0`)
- `boost::multi_array< double, 2 > get_sigma_2` (`boost::multi_array< double, 1 > z`, `double dz`, `int nx`, `int nz`, `double c_max`, `int n=10`, `double R=1e-3`, `double m=2.0`)
- `boost::multi_array< double, 2 > get_profile` (`double xmin`, `double xmax`, `double zmin`, `double zmax`, `int nx`, `int nz`, `double r`)  
*Get the velocity profile of the model as a 2D Array.*
- `boost::multi_array< double, 2 > dfdx` (`boost::multi_array< double, 2 > f`, `double dx`)  
*Takes the partial derivative of a 2D matrix f with respect to x.*
- `boost::multi_array< double, 2 > dfdz` (`boost::multi_array< double, 2 > f`, `double dz`)  
*Takes the partial derivative of a 2D matrix f with respect to z.*
- `boost::multi_array< double, 2 > d2fdx2` (`boost::multi_array< double, 2 > f`, `double dx`)  
*Takes the second partial derivative of a 2D matrix f with respect to x.*
- `boost::multi_array< double, 2 > d2fdz2` (`boost::multi_array< double, 2 > f`, `double dz`)  
*Takes the second partial derivative of a 2D matrix f with respect to z.*
- `boost::multi_array< double, 2 > divergence` (`boost::multi_array< double, 2 > f1`, `boost::multi_array< double, 2 > f2`, `double dx`, `double dz`)
- `boost::multi_array< double, 3 > wave_solver` (`boost::multi_array< double, 2 > c`, `double dt`, `double dx`, `double dz`, `int nt`, `int nx`, `int nz`, `boost::multi_array< double, 3 > f`)
- `boost::multi_array< double, 3 > wave_solver_complex` (`boost::multi_array< double, 2 > c`, `double dt`, `double dx`, `double dz`, `int nt`, `int nx`, `int nz`, `boost::multi_array< double, 3 > f`, `boost::multi_array< double, 2 > sigma_1`, `boost::multi_array< double, 2 > sigma_2`)
- `boost::multi_array< double, 3 > ricker` (`int i_s`, `int j_s`, `double f`, `double amp`, `double shift`, `double tmin`, `double tmax`, `int nt`, `int nx`, `int nz`)  
*Get the Ricker wavelet as a 3D Array.*

### 9.3.1 Detailed Description

This namespace contains all the core algorithm for solving wave equation

For the core algorithm, we need six functionalities:

- 1) create the computational domain,
- 2) create a velocity profile (1 & 2 can be put together)
- 3) create attenuation coefficients,
- 4) create source functions,
- 5) helper functions to compute eg.  $df/dx$
- 6) use all above to create a solver function for wave equation





## Chapter 10

# Class Documentation

### 10.1 wavePlotter::Plotter Class Reference

This class is used to plot the wave field TODO: make it multithreaded.

```
#include <wavePlotter.hpp>
```

#### Public Member Functions

- [Plotter](#) (const boost::multi\_array< double, 3 > &u, const matplot::vector\_2d &Xp, const matplot::vector\_2d &Zp, int num\_levels, int nt)  
*Constructor.*
- void [renderFrame](#) (int index)  
*Renders a frame of the wave field to a image on disk.*
- void [renderAllFrames](#) (int begin\_frame\_index, int end\_frame\_index)  
*Renders all frames of the wave field to form an animation to be saved on disk.*
- void [animate](#) (std::string output\_file\_name, int begin\_frame\_index, int end\_frame\_index, int frame\_rate)  
*Renders a complete video animation of the wave field.*
- void [exportFrame](#) (int index)  
*Export a frame of the wave field to a .csv format for external use.*
- void [exportAllFrames](#) (int begin\_frame\_index, int end\_frame\_index)  
*Export all frames of the wave field to a .csv format for external use.*
- void [setSaveDirectory](#) (std::string save\_directory)  
*Set the save directory for the rendered frames.*

#### 10.1.1 Detailed Description

This class is used to plot the wave field TODO: make it multithreaded.

[Plotter](#) class

Definition at line 21 of file [wavePlotter.hpp](#).

The documentation for this class was generated from the following file:

- src/CustomLibraries/wavePlotter.hpp



# Chapter 11

## File Documentation

### 11.1 coeff.hpp

```
00001 //
00002 // Created by Yan Cheng on 11/28/22.
00003 //
00004
00005 #ifndef WAVESIMC_COEFF_HPP
00006 #define WAVESIMC_COEFF_HPP
00007
00008 #include "CustomLibraries/np.hpp"
00009 #include <math.h>
00010
00016 namespace waveSimCore
00017 {
00021     boost::multi_array<double, 2> get_sigma_1(boost::multi_array<double, 1> x, double dx, int nx, int
nz,
00022                                             double c_max, int n = 15, double R = 1e-3, double m =
2.0)
00023     {
00024         boost::multi_array<double, 2> sigma_1(boost::extents[nx][nz]);
00025         const double PML_width = n * dx;
00026
00027         const double sigma_max = -c_max * log(R) * (m + 1.0) / np::pow(PML_width, m + 1.0);
00028
00029         const double x_0 = np::max(x) - PML_width;
00030
00031         boost::multi_array<double, 1> polynomial(boost::extents[nx]);
00032
00033         for (int i = 0; i < nx; i++)
00034         {
00035             if (x[i] > x_0)
00036             {
00037                 polynomial[i] = sigma_max * np::pow(np::abs(x[i] - x_0), m);
00038                 polynomial[nx - 1 - i] = polynomial[i];
00039             }
00040             else
00041             {
00042                 polynomial[i] = 0;
00043             }
00044         }
00045
00046         for (int i = 0; i < nx; i++)
00047             for (int j = 0; j < nz; j++)
00048                 sigma_1[i][j] = polynomial[i];
00049
00050         return sigma_1;
00051     }
00052
00056     boost::multi_array<double, 2> get_sigma_2(boost::multi_array<double, 1> z, double dz, int nx, int
nz,
00057                                             double c_max, int n = 10, double R = 1e-3, double m =
2.0)
00058     {
00059         boost::multi_array<double, 2> sigma_2(boost::extents[nx][nz]);
00060         const double PML_width = n * dz;
00061         const double sigma_max = -c_max * log(R) * (m + 1.0) / np::pow(PML_width, m + 1.0);
00062
00063         const double z_0 = np::max(z) - PML_width;
00064
00065         boost::multi_array<double, 1> polynomial(boost::extents[nz]);
```

```

00066         for (int j = 0; j < nz; j++)
00067         {
00068             if (z[j] > z_0)
00069             {
00070                 polynomial[j] = sigma_max * np::pow(np::abs(z[j] - z_0), m);
00071                 polynomial[nz - 1 - j] = polynomial[j];
00072             }
00073             else
00074             {
00075                 polynomial[j] = 0;
00076             }
00077         }
00078
00079         for (int i = 0; i < nx; i++)
00080             for (int j = 0; j < nz; j++)
00081                 sigma_2[i][j] = polynomial[j];
00082
00083         return sigma_2;
00084     }
00085 }
00086 #endif // WAVESIMC_COEFF_HPP

```

## 11.2 computational.hpp

```

00001 //
00002 // Created by Yan Cheng on 11/28/22.
00003 //
00004
00005 #ifndef WAVESIMC_COMPUTATIONAL_HPP
00006 #define WAVESIMC_COMPUTATIONAL_HPP
00007
00013 namespace waveSimCore
00014 {
00016     boost::multi_array<double, 2> get_profile(double xmin, double xmax, double zmin, double zmax, int
00017         nx, int nz, double r)
00018     {
00019         boost::multi_array<double, 2> c(boost::extents[nx][nz]);
00020
00021         boost::multi_array<double, 1> x = np::linspace(xmin, xmax, nx);
00022         boost::multi_array<double, 1> z = np::linspace(zmin, zmax, nz);
00023
00024         const boost::multi_array<double, 1> axis[2] = {x, z};
00025         std::vector<boost::multi_array<double, 2>> XZ = np::meshgrid(axis, false, np::ij);
00026
00027         double x_0 = xmax / 2.0;
00028         double z_0 = zmax / 2.0;
00029
00030         for (int i = 0; i < nx; i++)
00031         {
00032             for (int j = 0; j < nz; j++)
00033             {
00034                 if (np::pow(XZ[0][i][j] - x_0, 2.0) + np::pow(XZ[1][i][j] - z_0, 2.0) <= np::pow(r,
00035                     2.0))
00036                     c[i][j] = 3.0;
00037                 else
00038                     c[i][j] = 0.0;
00039             }
00040         }
00041         return c;
00042     }
00043 #endif // WAVESIMC_COMPUTATIONAL_HPP

```

## 11.3 helper\_func.hpp

```

00001 //
00002 // Created by Yan Cheng on 11/28/22.
00003 //
00004
00005 #ifndef WAVESIMC_HELPER_FUNC_HPP
00006 #define WAVESIMC_HELPER_FUNC_HPP
00007
00008 #include "CustomLibraries/np.hpp"
00009
00015 namespace waveSimCore
00016 {
00018     boost::multi_array<double, 2> dfdx(boost::multi_array<double, 2> f, double dx)
00019     {

```

```

00020         std::vector<boost::multi_array<double, 2> grad_f = np::gradient(f, {dx, dx});
00021         return grad_f[0];
00022     }
00023
00025     boost::multi_array<double, 2> dfdz(boost::multi_array<double, 2> f, double dz)
00026     {
00027         std::vector<boost::multi_array<double, 2> grad_f = np::gradient(f, {dz, dz});
00028         return grad_f[1];
00029     }
00030
00032     boost::multi_array<double, 2> d2fdx2(boost::multi_array<double, 2> f, double dx)
00033     {
00034         boost::multi_array<double, 2> df = dfdx(f, dx);
00035         boost::multi_array<double, 2> df2 = dfdx(df, dx);
00036         return df2;
00037     }
00038
00040     boost::multi_array<double, 2> d2fdz2(boost::multi_array<double, 2> f, double dz)
00041     {
00042         boost::multi_array<double, 2> df = dfdz(f, dz);
00043         boost::multi_array<double, 2> df2 = dfdz(df, dz);
00044         return df2;
00045     }
00046
00049     boost::multi_array<double, 2> divergence(boost::multi_array<double, 2> f1,
boost::multi_array<double, 2> f2,
00050                                             double dx, double dz)
00051     {
00052         boost::multi_array<double, 2> f_x = dfdx(f1, dx);
00053         boost::multi_array<double, 2> f_z = dfdz(f2, dz);
00054         boost::multi_array<double, 2> div = f_x + f_z;
00055         return div;
00056     }
00057
00058 }
00059 #endif // WAVESIMC_HELPER_FUNC_HPP

```

## 11.4 solver.hpp

```

00001 //
00002 // Created by Yan Cheng on 12/6/22.
00003 //
00004
00005 #ifndef CORETESTS_CPP_SOLVER2_HPP
00006 #define CORETESTS_CPP_SOLVER2_HPP
00007
00008 #include "CustomLibraries/np.hpp"
00009
00023 namespace waveSimCore
00024 {
00027     boost::multi_array<double, 3> wave_solver(boost::multi_array<double, 2> c,
double dt, double dx, double dz, int nt, int nx, int nz,
00028                                             boost::multi_array<double, 3> f)
00029     {
00030
00031
00032         const boost::multi_array<double, 2> CX = np::pow(c * dt / dx, 2.0);
00033         const boost::multi_array<double, 2> CZ = np::pow(c * dt / dz, 2.0);
00034         const double Cf = np::pow(dt, 2.0);
00035
00036         int dimensions_1[] = {nt, nx, nz};
00037         boost::multi_array<double, 3> u = np::zeros<double>(dimensions_1);
00038         int dimensions_4[] = {nx, nz};
00039         boost::multi_array<double, 2> u_xx = np::zeros<double>(dimensions_4);
00040         int dimensions_5[] = {nx, nz};
00041         boost::multi_array<double, 2> u_zz = np::zeros<double>(dimensions_5);
00042
00043         for (int n = 1; n < nt - 1; n++)
00044         {
00045             for (int i = 1; i < nx - 1; i++)
00046             {
00047                 for (int j = 1; j < nz - 1; j++)
00048                 {
00049                     u_xx[i][j] = u[n][i + 1][j] + u[n][i - 1][j] - 2.0 * u[n][i][j];
00050                     u_zz[i][j] = u[n][i][j + 1] + u[n][i][j - 1] - 2.0 * u[n][i][j];
00051                 }
00052             }
00053
00054             // ! Update u
00055             for (int i = 0; i < nx; i++)
00056             {
00057                 for (int j = 0; j < nz; j++)
00058                 {
00059                     u[n + 1][i][j] = 2.0 * u[n][i][j] + CX[i][j] * u_xx[i][j] + CZ[i][j] * u_zz[i][j]
+ Cf * f[n][i][j] - u[n - 1][i][j];

```

```

00060         }
00061     }
00062
00063     // Dirichlet boundary condition
00064     for (int i = 0; i < nx; i++)
00065     {
00066         u[n + 1][i][0] = 0.0;
00067         u[n + 1][i][nz - 1] = 0.0;
00068     }
00069     for (int j = 0; j < nz; j++)
00070     {
00071         u[n + 1][0][j] = 0.0;
00072         u[n + 1][nx - 1][j] = 0.0;
00073     }
00074 }
00075 return u;
00076 }
00077 }
00078 #endif // CORETESTS_CPP_SOLVER2_HPP

```

## 11.5 solver\_complex.hpp

```

00001 //
00002 // Created by Yan Cheng on 11/28/22.
00003 //
00004
00005 #ifndef WAVESIMC_SOLVER_COMPLEX_HPP
00006 #define WAVESIMC_SOLVER_COMPLEX_HPP
00007
00008 #include "CustomLibraries/np.hpp"
00009 #include "helper_func.hpp"
00010
00011 #include <cmath>
00012
00013 namespace waveSimCore
00014 {
00015     boost::multi_array<double, 3> wave_solver_complex(boost::multi_array<double, 2> c,
00016                                                         double dt, double dx, double dz, int nt, int nx,
00017                                                         int nz,
00018                                                         boost::multi_array<double, 3> f,
00019                                                         boost::multi_array<double, 2> sigma_1,
00020                                                         boost::multi_array<double, 2> sigma_2)
00021     {
00022
00023         const boost::multi_array<double, 2> C1 = 1.0 + (dt * (sigma_1 + sigma_2) * 0.5);
00024         const boost::multi_array<double, 2> C2 = (sigma_1 * sigma_2 * np::pow(dt, 2.0)) - 2.0;
00025         const boost::multi_array<double, 2> C3 = 1.0 - (dt * (sigma_1 + sigma_2) * 0.5);
00026         const boost::multi_array<double, 2> C4 = np::pow(dt * c, 2.0);
00027         const boost::multi_array<double, 2> C5 = 1.0 + (dt * sigma_1 * 0.5);
00028         const boost::multi_array<double, 2> C6 = 1.0 + (dt * sigma_2 * 0.5);
00029         const boost::multi_array<double, 2> C7 = 1.0 - (dt * sigma_1 * 0.5);
00030         const boost::multi_array<double, 2> C8 = 1.0 - (dt * sigma_2 * 0.5);
00031
00032         int dimensions_1[] = {nt, nx, nz};
00033         boost::multi_array<double, 3> u = np::zeros<double>(dimensions_1);
00034
00035         int dimensions_2[] = {nx, nz};
00036         boost::multi_array<double, 2> q_1 = np::zeros<double>(dimensions_2);
00037         int dimensions_3[] = {nx, nz};
00038         boost::multi_array<double, 2> q_2 = np::zeros<double>(dimensions_3);
00039
00040         int dimensions_4[] = {nx, nz};
00041         boost::multi_array<double, 2> u_xx = np::zeros<double>(dimensions_4);
00042         int dimensions_5[] = {nx, nz};
00043         boost::multi_array<double, 2> u_zz = np::zeros<double>(dimensions_5);
00044
00045         boost::multi_array<double, 2> f_n(boost::extents[nx][nz]);
00046         boost::multi_array<double, 2> u_n(boost::extents[nx][nz]);
00047         boost::multi_array<double, 2> u_n_1(boost::extents[nx][nz]);
00048
00049         for (int n = 1; n < nt - 1; n++)
00050         {
00051             for (int i = 0; i < nx; i++)
00052             {
00053                 for (int j = 0; j < nz; j++)
00054                 {
00055                     f_n[i][j] = f[n][i][j];
00056                     u_n[i][j] = u[n][i][j];
00057                     u_n_1[i][j] = u[n - 1][i][j];
00058                 }
00059             }
00060         }
00061     }
00062 }

```

```

00067         boost::multi_array<double, 2> div = divergence(q_1 * sigma_1, q_2 * sigma_2, dx, dz);
00068         boost::multi_array<double, 2> dq_1dx = dfdx(q_1, dx);
00069         boost::multi_array<double, 2> dq_2dz = dfdz(q_2, dz);
00070         u_xx = d2fdx2(u_n, dx); // (nx, nz)
00071         u_zz = d2fdz2(u_n, dz); // (nx, nz)
00072         boost::multi_array<double, 2> dudx = dfdx(u_n, dx);
00073         boost::multi_array<double, 2> dudz = dfdz(u_n, dz);
00074
00075         //         for (int i = 1; i < nx-1; i++)
00076         //         {
00077         //             for (int j = 1; j < nz-1; j++)
00078         //             {
00079         //                 u_xx[i][j] = u_n[i+1][j] + u_n[i-1][j] - 2.0 * u_n[i][j];
00080         //                 u_zz[i][j] = u_n[i][j+1] + u_n[i][j-1] - 2.0 * u_n[i][j];
00081         //             }
00082         //         }
00083
00084         // ! Update u
00085         for (int i = 0; i < nx; i++)
00086         {
00087             for (int j = 0; j < nz; j++)
00088             {
00089                 u[n + 1][i][j] = (C4[i][j] * ((u_xx[i][j] / np::pow(dx, 2.0)) + (u_zz[i][j] /
np::pow(dz, 2.0)) - div[i][j] + sigma_2[i][j] * dq_1dx[i][j] + sigma_1[i][j] * dq_2dz[i][j] +
f_n[i][j]) - (C2[i][j] * u_n[i][j]) - (C3[i][j] * u_n_1[i][j])) / C1[i][j];
00090             }
00091         }
00092
00093         // ! Update q_1, q_2
00094         for (int i = 0; i < nx; i++)
00095         {
00096             for (int j = 0; j < nz; j++)
00097             {
00098                 q_1[i][j] = (dt * dudx[i][j] + C7[i][j] * q_1[i][j]) / C5[i][j];
00099                 q_2[i][j] = (dt * dudz[i][j] + C8[i][j] * q_2[i][j]) / C6[i][j];
00100             }
00101         }
00102         //
00103         // Dirichlet boundary condition
00104         for (int i = 0; i < nx; i++)
00105         {
00106             u[n + 1][i][0] = 0.0;
00107             u[n + 1][i][nz - 1] = 0.0;
00108         }
00109         for (int j = 0; j < nz; j++)
00110         {
00111             u[n + 1][0][j] = 0.0;
00112             u[n + 1][nx - 1][j] = 0.0;
00113         }
00114     }
00115     return u;
00116 }
00117 }
00118 #endif // WAVESIMC_SOLVER_HPP

```

## 11.6 source.hpp

```

00001 //
00002 // Created by Yan Cheng on 11/28/22.
00003 //
00004
00005 #ifndef WAVESIMC_SOURCE_HPP
00006 #define WAVESIMC_SOURCE_HPP
00011 namespace waveSimCore
00012 {
00014     boost::multi_array<double, 3> ricker(int i_s, int j_s, double f, double amp, double shift,
00015                                         double tmin, double tmax, int nt, int nx, int nz)
00016     {
00017         const double pi = 3.141592654;
00018
00019         boost::multi_array<double, 1> t = np::linspace(tmin, tmax, nt);
00020         boost::multi_array<double, 1> pft2 = np::pow(pi * f * (t - shift), 2.0);
00021         boost::multi_array<double, 1> r = amp * (1.0 - 2.0 * pft2) * np::exp(-1.0 * pft2);
00022
00023         int dimensions_x[] = {nx};
00024         boost::multi_array<double, 1> x = np::zeros<double>(dimensions_x);
00025
00026         int dimensions_z[] = {nz};
00027         boost::multi_array<double, 1> z = np::zeros<double>(dimensions_z);
00028
00029         x[i_s] = 1.0;
00030         z[j_s] = 1.0;
00031     }

```

```

00032         const boost::multi_array<double, 1> axis[3] = {r, x, z};
00033         std::vector<boost::multi_array<double, 3>> RXZ = np::meshgrid(axis, false, np::ij);
00034         boost::multi_array<double, 3> source = RXZ[0] * RXZ[1] * RXZ[2];
00035
00036         return source;
00037     }
00038 }
00039 #endif // WAVESIMC_SOURCE_HPP

```

## 11.7 wave.cpp

```

00001 // Standard IO libraries
00002 #include <iostream>
00003 #include <fstream>
00004
00005 #include "CustomLibraries/np.hpp"
00006
00007 #include <math.h>
00008
00009 #include "solver.hpp"
00010 #include "computational.hpp"
00011 #include "coeff.hpp"
00012 #include "source.hpp"
00013 #include "helper_func.hpp"
00014
00015 int main()
00016 {
00017     double dx, dy, dz, dt;
00018     dx = 1.0;
00019     dy = 1.0;
00020     dz = 1.0;
00021     dt = 1.0;
00022     std::vector<boost::multi_array<double, 4>> my_arrays = np::gradient(A, {dx, dy, dz, dt});
00023     return 0;
00024 }

```

## 11.8 np.hpp

```

00001 #ifndef NP_H_
00002 #define NP_H_
00003
00004 #include "boost/multi_array.hpp"
00005 #include "boost/array.hpp"
00006 #include "boost/cstdlib.hpp"
00007 #include <type_traits>
00008 #include <cassert>
00009 #include <iostream>
00010 #include <functional>
00011 #include <type_traits>
00012
00019 namespace np
00020 {
00021
00022     typedef double ndArrayValue;
00023
00024     template <std::size_t ND>
00025     inline boost::multi_array<ndArrayValue, ND>::index
00026     getIndex(const boost::multi_array<ndArrayValue, ND> &m, const ndArrayValue *requestedElement,
00027             const unsigned short int direction)
00028     {
00029         int offset = requestedElement - m.origin();
00030         return (offset / m.strides()[direction] % m.shape()[direction] + m.index_bases()[direction]);
00031     }
00032
00033     template <std::size_t ND>
00034     inline boost::array<typename boost::multi_array<ndArrayValue, ND>::index, ND>
00035     getIndexArray(const boost::multi_array<ndArrayValue, ND> &m, const ndArrayValue *requestedElement)
00036     {
00037         using indexType = boost::multi_array<ndArrayValue, ND>::index;
00038         boost::array<indexType, ND> _index;
00039         for (unsigned int dir = 0; dir < ND; dir++)
00040         {
00041             _index[dir] = getIndex(m, requestedElement, dir);
00042         }
00043         return _index;
00044     }
00045
00046     template <typename Array, typename Element, typename Functor>
00050

```



```

00051     inline void for_each(const boost::type<Element> &type_dispatch,
00052                          Array A, Functor &xform)
00053     {
00054         for_each(type_dispatch, A.begin(), A.end(), xform);
00055     }
00056
00057     template <typename Element, typename Functor>
00058     inline void for_each(const boost::type<Element> &, Element &Val, Functor &xform)
00059     {
00060         Val = xform(Val);
00061     }
00062
00063     template <typename Element, typename Iterator, typename Functor>
00064     inline void for_each(const boost::type<Element> &type_dispatch,
00065                          Iterator begin, Iterator end,
00066                          Functor &xform)
00067     {
00068         while (begin != end)
00069         {
00070             for_each(type_dispatch, *begin, xform);
00071             ++begin;
00072         }
00073     }
00074
00075     template <typename Array, typename Functor>
00076     inline void for_each(Array &A, Functor xform)
00077     {
00078         // Dispatch to the proper function
00079         for_each(boost::type<typename Array::element>(), A.begin(), A.end(), xform);
00080     }
00081
00082     template <typename T, long unsigned int ND>
00083     requires std::is_floating_point<T>::value inline constexpr std::vector<boost::multi_array<T, ND>
00084     gradient(boost::multi_array<T, ND> inArray, std::initializer_list<T> args)
00085     {
00086         // static_assert(args.size() == ND, "Number of arguments must match the number of dimensions
00087         of the array");
00088         using arrayIndex = boost::multi_array<T, ND>::index;
00089
00090         using ndIndexArray = boost::array<arrayIndex, ND>;
00091
00092         // constexpr std::size_t n = sizeof...(Args);
00093         std::size_t n = args.size();
00094         // std::tuple<Args...> store(args...);
00095         std::vector<T> arg_vector = args;
00096         boost::multi_array<T, ND> my_array;
00097         std::vector<boost::multi_array<T, ND> output_arrays;
00098         for (std::size_t i = 0; i < n; i++)
00099         {
00100             boost::multi_array<T, ND> dfdh = inArray;
00101             output_arrays.push_back(dfdh);
00102         }
00103
00104         ndArrayValue *p = inArray.data();
00105         ndIndexArray index;
00106         for (std::size_t i = 0; i < inArray.num_elements(); i++)
00107         {
00108             index = getIndexArray(inArray, p);
00109             /*
00110             std::cout << "Index: ";
00111             for (std::size_t j = 0; j < n; j++)
00112             {
00113                 std::cout << index[j] << " ";
00114             }
00115             std::cout << "\n";
00116             */
00117             // Calculating the gradient now
00118             // j is the axis/dimension
00119             for (std::size_t j = 0; j < n; j++)
00120             {
00121                 ndIndexArray index_high = index;
00122                 T dh_high;
00123                 if ((long unsigned int)index_high[j] < inArray.shape()[j] - 1)
00124                 {
00125                     index_high[j] += 1;
00126                     dh_high = arg_vector[j];
00127                 }
00128                 else
00129                 {
00130                     dh_high = 0;
00131                 }
00132                 ndIndexArray index_low = index;
00133                 T dh_low;
00134                 if (index_low[j] > 0)
00135                 {
00136                     index_low[j] -= 1;
00137                     dh_low = arg_vector[j];
00138                 }
00139             }
00140         }

```

```

00143         }
00144         else
00145         {
00146             dh_low = 0;
00147         }
00148
00149         T dh = dh_high + dh_low;
00150         T gradient = (inArray(index_high) - inArray(index_low)) / dh;
00151         // std::cout << gradient << "\n";
00152         output_arrays[j](index) = gradient;
00153     }
00154     // std::cout << " value = " << inArray(index) << " check = " << *p << std::endl;
00155     ++p;
00156 }
00157 return output_arrays;
00158 }
00159
00160 inline boost::multi_array<double, 1> linspace(double start, double stop, long unsigned int num)
00161 {
00162     double step = (stop - start) / (num - 1);
00163     boost::multi_array<double, 1> output(boost::extents[num]);
00164     for (std::size_t i = 0; i < num; i++)
00165     {
00166         output[i] = start + i * step;
00167     }
00168     return output;
00169 }
00170
00171 enum indexing
00172 {
00173     xy,
00174     ij
00175 };
00176
00177 template <typename T, long unsigned int ND>
00178 requires std::is_arithmetic<T>::value inline constexpr std::vector<boost::multi_array<T, ND>
00179 meshgrid(const boost::multi_array<T, 1> (&cinput)[ND], bool sparsing = false, indexing indexing_type
00180 = xy)
00181 {
00182     using arrayIndex = boost::multi_array<T, ND>::index;
00183     using oneDArrayIndex = boost::multi_array<T, 1>::index;
00184     using ndIndexArray = boost::array<arrayIndex, ND>;
00185     std::vector<boost::multi_array<T, ND> output_arrays;
00186     boost::multi_array<T, 1> ci[ND];
00187     // Copy elements of cinput to ci, do the proper inversions
00188     for (std::size_t i = 0; i < ND; i++)
00189     {
00190         std::size_t source = i;
00191         if (indexing_type == xy && (ND == 3 || ND == 2))
00192         {
00193             if (i == 0)
00194                 source = 1;
00195             else if (i == 1)
00196                 source = 0;
00197             else
00198                 source = i;
00199         }
00200         ci[i] = boost::multi_array<T, 1>();
00201         ci[i].resize(boost::extents[cinput[source].num_elements()]);
00202         ci[i] = cinput[source];
00203     }
00204     // Deducing the extents of the N-Dimensional output
00205     boost::detail::multi_array::extent_gen<ND> output_extents;
00206     std::vector<size_t> shape_list;
00207     for (std::size_t i = 0; i < ND; i++)
00208     {
00209         shape_list.push_back(ci[i].shape()[0]);
00210     }
00211     std::copy(shape_list.begin(), shape_list.end(), output_extents.ranges_.begin());
00212
00213     // Creating the output arrays
00214     for (std::size_t i = 0; i < ND; i++)
00215     {
00216         boost::multi_array<T, ND> output_array(output_extents);
00217         ndArrayValue *p = output_array.data();
00218         ndIndexArray index;
00219         // Looping through the elements of the output array
00220         for (std::size_t j = 0; j < output_array.num_elements(); j++)
00221         {
00222             index = getIndexArray(output_array, p);
00223             oneDArrayIndex index_1d;
00224             index_1d = index[i];
00225             output_array(index) = ci[i][index_1d];
00226             ++p;
00227         }
00228         output_arrays.push_back(output_array);
00229     }
00230 }

```

```

00234         if (indexing_type == xy && (ND == 3 || ND == 2))
00235         {
00236             std::swap(output_arrays[0], output_arrays[1]);
00237         }
00238         return output_arrays;
00239     }
00240
00241     template <class T, long unsigned int ND>
00242     requires std::is_arithmetic<T>::value inline constexpr boost::multi_array<T, ND>
00243     element_wise_apply(const boost::multi_array<T, ND> &input_array, std::function<T(T)> func)
00244     {
00245
00246         // Create output array copying extents
00247         using arrayIndex = boost::multi_array<double, ND>::index;
00248         using ndIndexArray = boost::array<arrayIndex, ND>;
00249         boost::detail::multi_array::extent_gen<ND> output_extents;
00250         std::vector<size_t> shape_list;
00251         for (std::size_t i = 0; i < ND; i++)
00252         {
00253             shape_list.push_back(input_array.shape()[i]);
00254         }
00255         std::copy(shape_list.begin(), shape_list.end(), output_extents.ranges_.begin());
00256         boost::multi_array<T, ND> output_array(output_extents);
00257
00258         // Looping through the elements of the output array
00259         const T *p = input_array.data();
00260         ndIndexArray index;
00261         for (std::size_t i = 0; i < input_array.num_elements(); i++)
00262         {
00263             index = getIndexArray(input_array, p);
00264             output_array(index) = func(input_array(index));
00265             ++p;
00266         }
00267         return output_array;
00268     }
00269
00270     // Complex operations
00271
00272     template <class T, long unsigned int ND>
00273     requires std::is_arithmetic<T>::value inline constexpr boost::multi_array<T, ND> sqrt(const
00274     boost::multi_array<T, ND> &input_array)
00275     {
00276         std::function<T(T)> func = (T(*) (T))std::sqrt;
00277         return element_wise_apply(input_array, func);
00278     }
00279
00280     template <class T>
00281     requires std::is_arithmetic<T>::value inline constexpr T sqrt(const T input)
00282     {
00283         return std::sqrt(input);
00284     }
00285
00286     template <class T, long unsigned int ND>
00287     requires std::is_arithmetic<T>::value inline constexpr boost::multi_array<T, ND> exp(const
00288     boost::multi_array<T, ND> &input_array)
00289     {
00290         std::function<T(T)> func = (T(*) (T))std::exp;
00291         return element_wise_apply(input_array, func);
00292     }
00293
00294     template <class T>
00295     requires std::is_arithmetic<T>::value inline constexpr T exp(const T input)
00296     {
00297         return std::exp(input);
00298     }
00299
00300     template <class T, long unsigned int ND>
00301     requires std::is_arithmetic<T>::value inline constexpr boost::multi_array<T, ND> log(const
00302     boost::multi_array<T, ND> &input_array)
00303     {
00304         std::function<T(T)> func = std::log<T>();
00305         return element_wise_apply(input_array, func);
00306     }
00307
00308     template <class T>
00309     requires std::is_arithmetic<T>::value inline constexpr T log(const T input)
00310     {
00311         return std::log(input);
00312     }
00313
00314     template <class T, long unsigned int ND>
00315     requires std::is_arithmetic<T>::value inline constexpr boost::multi_array<T, ND> pow(const
00316     boost::multi_array<T, ND> &input_array, const T exponent)
00317     {
00318         std::function<T(T)> pow_func = [exponent](T input)
00319         { return std::pow(input, exponent); };
00320         return element_wise_apply(input_array, pow_func);
00321     }
00322
00323

```

```

00324     }
00325
00326     template <class T>
00327     requires std::is_arithmetic<T>::value inline constexpr T pow(const T input, const T exponent)
00328     {
00329         return std::pow(input, exponent);
00330     }
00331
00332     template <class T, long unsigned int ND>
00333     inline constexpr boost::multi_array<T, ND> element_wise_duo_apply(boost::multi_array<T, ND> const
00334     &lhs, boost::multi_array<T, ND> const &rhs, std::function<T(T, T)> func)
00335     {
00336         // Create output array copying extents
00337         using arrayIndex = boost::multi_array<double, ND>::index;
00338         using ndIndexArray = boost::array<arrayIndex, ND>;
00339         boost::detail::multi_array::extent_gen<ND> output_extents;
00340         std::vector<size_t> shape_list;
00341         for (std::size_t i = 0; i < ND; i++)
00342         {
00343             shape_list.push_back(lhs.shape()[i]);
00344         }
00345         std::copy(shape_list.begin(), shape_list.end(), output_extents.ranges_.begin());
00346         boost::multi_array<T, ND> output_array(output_extents);
00347
00348         // Looping through the elements of the output array
00349         const T *p = lhs.data();
00350         ndIndexArray index;
00351         for (std::size_t i = 0; i < lhs.num_elements(); i++)
00352         {
00353             index = getIndexArray(lhs, p);
00354             output_array(index) = func(lhs(index), rhs(index));
00355             ++p;
00356         }
00357         return output_array;
00358     }
00359
00360     template <typename T, typename inT, long unsigned int ND>
00361     requires std::is_integral<inT>::value && std::is_arithmetic<T>::value inline constexpr
00362     boost::multi_array<T, ND> zeros(inT (&dimensions_input)[ND])
00363     {
00364         // Deducing the extents of the N-Dimensional output
00365         boost::detail::multi_array::extent_gen<ND> output_extents;
00366         std::vector<size_t> shape_list;
00367         for (std::size_t i = 0; i < ND; i++)
00368         {
00369             shape_list.push_back(dimensions_input[i]);
00370         }
00371         std::copy(shape_list.begin(), shape_list.end(), output_extents.ranges_.begin());
00372         // Applying a function to return zero always to all of its elements
00373         boost::multi_array<T, ND> output_array(output_extents);
00374         std::function<T(T)> zero_func = [] (T input)
00375         { return 0; };
00376         return element_wise_apply(output_array, zero_func);
00377     }
00378
00379     template <typename T, long unsigned int ND>
00380     requires std::is_arithmetic<T>::value inline constexpr T max(boost::multi_array<T, ND> const
00381     &input_array)
00382     {
00383         T max = 0;
00384         bool max_not_set = true;
00385         const T *data_pointer = input_array.data();
00386         for (std::size_t i = 0; i < input_array.num_elements(); i++)
00387         {
00388             T element = *data_pointer;
00389             if (max_not_set || element > max)
00390             {
00391                 max = element;
00392                 max_not_set = false;
00393             }
00394             ++data_pointer;
00395         }
00396         return max;
00397     }
00398
00399     template <class T, class... Ts, class = std::enable_if_t<(std::is_same_v<T, Ts> && ...) >
00400     requires std::is_arithmetic<T>::value inline constexpr T max(T input1, Ts... inputs)
00401     {
00402         T max = input1;
00403         for (T input : {inputs...})
00404         {
00405             if (input > max)
00406             {
00407                 max = input;
00408             }
00409         }
00410         return max;
00411     }

```

```

00415     }
00416
00417     template <typename T, long unsigned int ND>
00418     requires std::is_arithmetic<T>::value inline constexpr T min(boost::multi_array<T, ND> const
00419     &input_array)
00420     {
00421         T min = 0;
00422         bool min_not_set = true;
00423         const T *data_pointer = input_array.data();
00424         for (std::size_t i = 0; i < input_array.num_elements(); i++)
00425         {
00426             T element = *data_pointer;
00427             if (min_not_set || element < min)
00428             {
00429                 min = element;
00430                 min_not_set = false;
00431             }
00432             ++data_pointer;
00433         }
00434         return min;
00435     }
00436
00437     template <class T, class... Ts, class = std::enable_if_t<(std::is_same_v<T, Ts> && ...)»
00438     inline constexpr T min(T input1, Ts... inputs) requires std::is_arithmetic<T>::value
00439     {
00440         T min = input1;
00441         for (T input : {inputs...})
00442         {
00443             if (input < min)
00444             {
00445                 min = input;
00446             }
00447         }
00448         return min;
00449     }
00450
00451     template <typename T, long unsigned int ND>
00452     requires std::is_arithmetic<T>::value inline constexpr boost::multi_array<T, ND>
00453     abs(boost::multi_array<T, ND> const &input_array)
00454     {
00455         std::function<T(T)> abs_func = [](T input)
00456         { return std::abs(input); };
00457         return element_wise_apply(input_array, abs_func);
00458     }
00459
00460     template <typename T>
00461     requires std::is_arithmetic<T>::value inline constexpr T abs(T input)
00462     {
00463         return std::abs(input);
00464     }
00465
00466     template <typename T, long unsigned int ND>
00467     requires std::is_arithmetic<T>::value inline constexpr boost::multi_array<T, ND - 1>
00468     slice(boost::multi_array<T, ND> const &input_array, std::size_t slice_index)
00469     {
00470         // Deducing the extents of the N-Dimensional output
00471         boost::detail::multi_array::extent_gen<ND - 1> output_extents;
00472         std::vector<size_t> shape_list;
00473         for (std::size_t i = 1; i < ND; i++)
00474         {
00475             shape_list.push_back(input_array.shape()[i]);
00476         }
00477         std::copy(shape_list.begin(), shape_list.end(), output_extents.ranges_.begin());
00478
00479         boost::multi_array<T, ND - 1> output_array(output_extents);
00480
00481         const T *p = input_array.data();
00482         boost::array<std::size_t, ND> index;
00483         for (std::size_t i = 0; i < input_array.num_elements(); i++)
00484         {
00485             index = getIndexArray(input_array, p);
00486             output_array(index) = input_array[slice_index](index);
00487             p++;
00488         }
00489         return output_array;
00490     }
00491
00492 // Override of operators in the boost::multi_array class to make them more np-like
00493 // Basic operators
00494 // All of the are element-wise
00495 // Multiplication operator
00496 template <class T, long unsigned int ND>
00497 inline boost::multi_array<T, ND> operator*(boost::multi_array<T, ND> const &lhs, boost::multi_array<T,

```

```

        ND> const &rhs)
00505 {
00506     std::function<T(T, T)> func = std::multiplies<T>();
00507     return np::element_wise_duo_apply(lhs, rhs, func);
00508 }
00509
00511 template <class T, long unsigned int ND>
00512 inline boost::multi_array<T, ND> operator*(T const &lhs, boost::multi_array<T, ND> const &rhs)
00513 {
00514     std::function<T(T)> func = [lhs](T item)
00515     { return lhs * item; };
00516     return np::element_wise_apply(rhs, func);
00517 }
00519 template <class T, long unsigned int ND>
00520 inline boost::multi_array<T, ND> operator*(boost::multi_array<T, ND> const &lhs, T const &rhs)
00521 {
00522     return rhs * lhs;
00523 }
00524
00525 // Plus operator
00527 template <class T, long unsigned int ND>
00528 boost::multi_array<T, ND> operator+(boost::multi_array<T, ND> const &lhs, boost::multi_array<T, ND>
    const &rhs)
00529 {
00530     std::function<T(T, T)> func = std::plus<T>();
00531     return np::element_wise_duo_apply(lhs, rhs, func);
00532 }
00533
00535 template <class T, long unsigned int ND>
00536 inline boost::multi_array<T, ND> operator+(T const &lhs, boost::multi_array<T, ND> const &rhs)
00537 {
00538     std::function<T(T)> func = [lhs](T item)
00539     { return lhs + item; };
00540     return np::element_wise_apply(rhs, func);
00541 }
00542
00544 template <class T, long unsigned int ND>
00545 inline boost::multi_array<T, ND> operator+(boost::multi_array<T, ND> const &lhs, T const &rhs)
00546 {
00547     return rhs + lhs;
00548 }
00549
00550 // Subtraction operator
00552 template <class T, long unsigned int ND>
00553 boost::multi_array<T, ND> operator-(boost::multi_array<T, ND> const &lhs, boost::multi_array<T, ND>
    const &rhs)
00554 {
00555     std::function<T(T, T)> func = std::minus<T>();
00556     return np::element_wise_duo_apply(lhs, rhs, func);
00557 }
00558
00560 template <class T, long unsigned int ND>
00561 inline boost::multi_array<T, ND> operator-(T const &lhs, boost::multi_array<T, ND> const &rhs)
00562 {
00563     std::function<T(T)> func = [lhs](T item)
00564     { return lhs - item; };
00565     return np::element_wise_apply(rhs, func);
00566 }
00567
00569 template <class T, long unsigned int ND>
00570 inline boost::multi_array<T, ND> operator-(boost::multi_array<T, ND> const &lhs, T const &rhs)
00571 {
00572     return rhs - lhs;
00573 }
00574
00575 // Division operator
00577 template <class T, long unsigned int ND>
00578 boost::multi_array<T, ND> operator/(boost::multi_array<T, ND> const &lhs, boost::multi_array<T, ND>
    const &rhs)
00579 {
00580     std::function<T(T, T)> func = std::divides<T>();
00581     return np::element_wise_duo_apply(lhs, rhs, func);
00582 }
00583
00585 template <class T, long unsigned int ND>
00586 inline boost::multi_array<T, ND> operator/(T const &lhs, boost::multi_array<T, ND> const &rhs)
00587 {
00588     std::function<T(T)> func = [lhs](T item)
00589     { return lhs / item; };
00590     return np::element_wise_apply(rhs, func);
00591 }
00592
00594 template <class T, long unsigned int ND>
00595 inline boost::multi_array<T, ND> operator/(boost::multi_array<T, ND> const &lhs, T const &rhs)
00596 {
00597     std::function<T(T)> func = [rhs](T item)
00598     { return item / rhs; };

```

```

00599     return np::element_wise_apply(lhs, func);
00600 }
00601
00603 #endif

```

## 11.9 np\_to\_matplot.hpp

```

00001 #ifndef NPTOMATPLOT_H_
00002 #define NPTOMATPLOT_H_
00003
00004 #include <matplot/matplot.h>
00005 #include <thread>
00006 #include "boost/multi_array.hpp"
00007 #include "boost/array.hpp"
00013 namespace np
00014 {
00016     inline matplot::vector_2d convert_to_matplot(const boost::multi_array<double, 2> &arr)
00017     {
00018         std::vector<double> x = matplot::linspace(0, 0, arr.shape()[0]);
00019         std::vector<double> y = matplot::linspace(0, 0, arr.shape()[1]);
00020         matplot::vector_2d result = std::get<0>(matplot::meshgrid(x, y));
00021         // std::cout << "arr.shape()[0] = " << arr.shape()[0] << " arr.shape()[1] = " << arr.shape()[1] <<
std::endl;
00022         for (size_t i = 0; i < arr.shape()[0]; i++)
00023         {
00024             for (size_t j = 0; j < arr.shape()[1]; j++)
00025             {
00026                 result[i][j] = arr[i][j];
00027             }
00028         }
00029         return result;
00030     }
00031 }
00032 #endif

```

## 11.10 wavePlotter.hpp

```

00001 #ifndef WAVESOLVER_H_
00002 #define WAVESOLVER_H_
00003 #include <boost/multi_array.hpp>
00004 #include <boost/array.hpp>
00005 #include <fstream>
00006 #include <iostream>
00007 #include "CustomLibraries/np.hpp"
00008 #include "CustomLibraries/np_to_matplot.hpp"
00009
00016 namespace wavePlotter
00017 {
00021     class Plotter
00022     {
00023     public:
00025         Plotter(const boost::multi_array<double, 3> &u, const matplot::vector_2d &Xp, const
matplot::vector_2d &Zp, int num_levels, int nt)
00026         {
00027             this->u.resize(boost::extents[u.shape()[0]][u.shape()[1]][u.shape()[2]]);
00028             this->u = u;
00029             this->Xp = Xp;
00030             this->Zp = Zp;
00031             this->num_levels = num_levels;
00032             this->nt = nt;
00033             double min_u = np::min(u);
00034             double max_u = np::max(u);
00035             std::cout << "min_u = " << min_u << " max_u = " << max_u << "\n";
00036             this->levels = matplot::linspace(min_u, max_u, num_levels);
00037         }
00039         void renderFrame(int index)
00040         {
00041             matplot::vector_2d Up = np::convert_to_matplot(this->u[index]);
00042             matplot::contourf(this->Xp, this->Zp, Up, this->levels);
00043             matplot::save(save_directory + "/contourf_" + format_num(index) + ".png");
00044         }
00045
00047         void renderAllFrames(int begin_frame_index, int end_frame_index)
00048         {
00049             for (int i = begin_frame_index; i < end_frame_index; i++)
00050             {
00051                 renderFrame(i);
00052             }
00053         }

```

```

00054
00056     void animate(std::string output_file_name, int begin_frame_index, int end_frame_index, int
frame_rate)
00057     {
00058         renderAllFrames(begin_frame_index, end_frame_index);
00059         std::string ffmpeg_render_command = "ffmpeg -framerate " + std::to_string(frame_rate) + "
-pattern_type glob -i '" + save_directory + "/*.png' -c:v libx264 -pix_fmt yuv420p " +
output_file_name;
00060         std::system(ffmpeg_render_command.c_str());
00061     }
00063     void exportFrame(int index)
00064     {
00065         matplotlib::vector_2d Up = np::convert_to_matplotlib(this->u[index]);
00066         std::ofstream outfile;
00067         outfile.open(save_directory + "/frame_" + format_num(index) + ".csv");
00068         for (std::size_t i = 0; i < Up.size(); i++)
00069         {
00070             for (std::size_t j = 0; j < Up[i].size(); j++)
00071             {
00072                 outfile << Up[i][j];
00073                 if (j != Up[i].size() - 1)
00074                     outfile << ",";
00075             }
00076             outfile << "\n";
00077         }
00078         outfile.close();
00079     }
00080
00082     void exportAllFrames(int begin_frame_index, int end_frame_index)
00083     {
00084         for (int i = begin_frame_index; i < end_frame_index; i++)
00085         {
00086             exportFrame(i);
00087         }
00088     }
00089
00091     void setSaveDirectory(std::string save_directory)
00092     {
00093         this->save_directory = save_directory;
00094     }
00095
00096     private:
00097         std::string format_num(int num, int length = 8)
00098         {
00099             std::string str_num = std::to_string(num);
00100
00101             int str_length = str_num.length();
00102             for (int i = 0; i < length - str_length; i++)
00103                 str_num = "0" + str_num;
00104             return str_num;
00105         }
00106
00107         boost::multi_array<double, 3> u;
00108         matplotlib::vector_2d Xp;
00109         matplotlib::vector_2d Zp;
00110         int num_levels;
00111         int nt;
00112         std::vector<double> levels;
00113         std::string save_directory = "output";
00114     };
00115
00116 }
00117 #endif

```

## 11.11 wave\_solver\_with\_animation.cpp

```

00001 #include <boost/multi_array.hpp>
00002 #include <boost/array.hpp>
00003 #include "CustomLibraries/np.hpp"
00004 #include "CustomLibraries/np_to_matplotlib.hpp"
00005 #include "CustomLibraries/wavePlotter.hpp"
00006 #include <matplotlib/matplotlib.h>
00007 #include <cassert>
00008 #include <iostream>
00009 #include <sstream>
00010
00011 #include "CoreAlgorithm/helper_func.hpp"
00012 #include "CoreAlgorithm/coefficient.hpp"
00013 #include "CoreAlgorithm/source.hpp"
00014 #include "CoreAlgorithm/computational.hpp"
00015 #include "CoreAlgorithm/solver.hpp"
00016
00017 int main()

```



```

00018 {
00019     // Define the constants for the simulation
00020
00021     // Number of x and z grid points
00022     int nx = 100;
00023     int nz = 100;
00024     // Number of time steps
00025     int nt = 1000;
00026
00027     // Differentiation values
00028     double dx = 0.01;
00029     double dz = 0.01;
00030     double dt = 0.001;
00031
00032     // Define the domain
00033     double xmin = 0.0;
00034     double xmax = nx * dx;
00035     double zmin = 0.0;
00036     double zmax = nz * dz;
00037     double tmin = 0.0;
00038     double tmax = nt * dt;
00039
00040     // Define the source parameters
00041     double f_M = 10.0;
00042     double amp = 1e0;
00043     double shift = 0.1;
00044
00045     // Source location
00046     int source_is = 50;
00047     int source_js = 50;
00048
00049     // Create the source
00050     boost::multi_array<double, 3> f = waveSimCore::ricker(source_is, source_js, f_M, amp, shift, tmin,
tmax, nt, nx, nz);
00051
00052     // Create the velocity profile
00053     double r = 150.0;
00054     boost::multi_array<double, 2> vel = waveSimCore::get_profile(xmin, xmax, zmin, zmax, nx, nz, r);
00055
00056     // Solve the wave equation
00057     boost::multi_array<double, 3> u = waveSimCore::wave_solver(vel, dt, dx, dz, nt, nx, nz, f);
00058
00059     // Define the number of different levels for the contour plot
00060     int num_levels = 100;
00061     // Create the levels for the contour plot based on the min and max values of u
00062     double min_u = np::min(u);
00063     double max_u = np::max(u);
00064     std::vector<double> levels = matplotlib::linspace(min_u, max_u, num_levels);
00065
00066     // Create the x and z axis for the contour plot and convert them to matplotlib format
00067     boost::multi_array<double, 1> x = np::linspace(xmin, xmax, nx);
00068     boost::multi_array<double, 1> z = np::linspace(zmin, zmax, nz);
00069     const boost::multi_array<double, 1> axis[2] = {x, z};
00070     std::vector<boost::multi_array<double, 2>> XcZ = np::meshgrid(axis, false, np::xy);
00071
00072     matplotlib::vector_2d Xp = np::convert_to_matplot(XcZ[0]);
00073     matplotlib::vector_2d Zp = np::convert_to_matplot(XcZ[1]);
00074
00075     // Create the plotter object and animate the results
00076     wavePlotter::Plotter my_plotter(u, Xp, Zp, num_levels, nt);
00077
00078     // If you want to render a specific frame, use this:
00079     // my_plotter.renderFrame(int frame_index);
00080
00081     // Renders the entire animation from start_frame to end_frame
00082     int start_frame = 20;
00083     int end_frame = nt - 1;
00084     int fps = 30;
00085     my_plotter.animate("example-wave.mp4", start_frame, end_frame, fps);
00086
00087     // The animation will be saved in .
00088     // Frames will be saved to ./output
00089 }

```

## 11.12 main.cpp

```

00001 #include <iostream>
00002 #include <string>
00003 #include "ExternalLibraries/cxxopts.hpp"
00004
00005 #include <boost/multi_array.hpp>
00006 #include <boost/array.hpp>
00007 #include "CustomLibraries/np.hpp"

```

```

00008 #include "CustomLibraries/np_to_matplot.hpp"
00009 #include "CustomLibraries/wavePlotter.hpp"
00010 #include <matplot/matplot.h>
00011 #include <cassert>
00012 #include <sstream>
00013
00014 #include "CoreAlgorithm/helper_func.hpp"
00015 #include "CoreAlgorithm/coeff.hpp"
00016 #include "CoreAlgorithm/source.hpp"
00017 #include "CoreAlgorithm/computational.hpp"
00018 #include "CoreAlgorithm/solver.hpp"
00019
00020 // Command line arguments
00021 cxxopts::Options options("WaveSimPP", "A wave propagation simulator written in C++.");
00022 int main(int argc, char *argv[])
00023 {
00024     // Parse command line arguments
00025     options.add_options() ("d,debug", "Enable debugging",
00026         cxxopts::value<bool>()->default_value("false"));
00027     options.add_options() ("animate", "Render an animation at the end",
00028         cxxopts::value<bool>()->default_value("true"));
00029     options.add_options() ("render", "Render each of the frames at the end",
00030         cxxopts::value<bool>()->default_value("false"));
00031     options.add_options() ("export", "Export the data to a series of csv files",
00032         cxxopts::value<bool>()->default_value("false"));
00033     options.add_options() ("o,output_dir", "Output directory path",
00034         cxxopts::value<std::string>()->default_value("output"));
00035     options.add_options() ("output_filename", "Output filename",
00036         cxxopts::value<std::string>()->default_value("output.mp4"));
00037     options.add_options() ("framerate", "Framerate of output video",
00038         cxxopts::value<int>()->default_value("30"));
00039     options.add_options() ("v,verbose", "Verbose output",
00040         cxxopts::value<bool>()->default_value("false"));
00041     options.add_options() ("source_i", "Source i position",
00042         cxxopts::value<int>()->default_value("50"));
00043     options.add_options() ("source_j", "Source j position",
00044         cxxopts::value<int>()->default_value("50"));
00045     options.add_options() ("nt", "Number of time steps", cxxopts::value<int>()->default_value("1000"));
00046     options.add_options() ("nx", "Number of x steps", cxxopts::value<int>()->default_value("100"));
00047     options.add_options() ("nz", "Number of z steps", cxxopts::value<int>()->default_value("100"));
00048     options.add_options() ("dt", "Time step size", cxxopts::value<double>()->default_value("0.001"));
00049     options.add_options() ("dx", "x step size", cxxopts::value<double>()->default_value("0.01"));
00050     options.add_options() ("dz", "z step size", cxxopts::value<double>()->default_value("0.01"));
00051     options.add_options() ("f,frequency", "Frequency of source",
00052         cxxopts::value<double>()->default_value("10.0"));
00053     options.add_options() ("a,amplitude", "Amplitude of source",
00054         cxxopts::value<double>()->default_value("1.0"));
00055     options.add_options() ("s,shift", "Shift of source",
00056         cxxopts::value<double>()->default_value("0.1"));
00057     options.add_options() ("r,radius", "Radius of velocity profile",
00058         cxxopts::value<double>()->default_value("150.0"));
00059     options.add_options() ("l,num_levels", "Number of levels in the filled contour plot",
00060         cxxopts::value<int>()->default_value("100"));
00061     options.add_options() ("h,help", "Print help");
00062     cxxopts::ParseResult result;
00063     try
00064     {
00065         result = options.parse(argc, argv);
00066     }
00067     catch (const cxxopts::exceptions::exception &e)
00068     {
00069         std::cerr << "WaveSimPP: " << e.what() << '\n';
00070         std::cerr << "usage: WaveSimPP [options] ...\n";
00071         return EXIT_FAILURE;
00072     }
00073     if (result.count("help"))
00074     {
00075         std::cout << options.help({"", "Group"}) << std::endl;
00076         return true;
00077     }
00078
00079     // Define the constants for the simulation
00080
00081     // Number of x and z grid points
00082     int nx = result["nx"].as<int>();
00083
00084     int nz = result["nz"].as<int>();
00085     // Number of time steps
00086     int nt = result["nt"].as<int>();
00087
00088     // Differentiation values
00089     double dx = result["dx"].as<double>();
00090     double dz = result["dz"].as<double>();
00091     double dt = result["dt"].as<double>();
00092
00093     // Define the domain

```

```

00080     double xmin = 0.0;
00081     double xmax = nx * dx;
00082     double zmin = 0.0;
00083     double zmax = nz * dz;
00084     double tmin = 0.0;
00085     double tmax = nt * dt;
00086
00087     // Define the source parameters
00088     double f_M = result["frequency"].as<double>();
00089     double amp = result["amplitude"].as<double>();
00090     double shift = result["shift"].as<double>();
00091
00092     // Source location
00093     int source_is = result["source_i"].as<int>();
00094     int source_js = result["source_j"].as<int>();
00095     // Create the source
00096     boost::multi_array<double, 3> f = waveSimCore::ricker(source_is, source_js, f_M, amp, shift, tmin,
tmax, nt, nx, nz);
00097
00098     // Create the velocity profile
00099     double r = result["radius"].as<double>();
00100
00101     boost::multi_array<double, 2> vel = waveSimCore::get_profile(xmin, xmax, zmin, zmax, nx, nz, r);
00102
00103     // Solve the wave equation
00104     boost::multi_array<double, 3> u = waveSimCore::wave_solver(vel, dt, dx, dz, nt, nx, nz, f);
00105
00106     // Define the number of different levels for the contour plot
00107     int num_levels = result["num_levels"].as<int>();
00108     // Create the levels for the contour plot based on the min and max values of u
00109     double min_u = np::min(u);
00110     double max_u = np::max(u);
00111     std::vector<double> levels = matplotlib::linspace(min_u, max_u, num_levels);
00112
00113     // Create the x and z axis for the contour plot and convert them to matplotlib format
00114     boost::multi_array<double, 1> x = np::linspace(xmin, xmax, nx);
00115     boost::multi_array<double, 1> z = np::linspace(zmin, zmax, nz);
00116     const boost::multi_array<double, 1> axis[2] = {x, z};
00117     std::vector<boost::multi_array<double, 2> XcZ = np::meshgrid(axis, false, np::xy);
00118
00119     matplotlib::vector_2d Xp = np::convert_to_matplot(XcZ[0]);
00120     matplotlib::vector_2d Zp = np::convert_to_matplot(XcZ[1]);
00121
00122     // Create the plotter object and animate the results
00123     wavePlotter::Plotter my_plotter(u, Xp, Zp, num_levels, nt);
00124     my_plotter.setSaveDirectory(result["output_filename"].as<std::string>());
00125
00126     // If you want to render a specific frame, use this:
00127     // my_plotter.renderFrame(int frame_index);
00128
00129     // Renders the entire animation from start_frame to end_frame
00130     int start_frame = 0;
00131     int end_frame = nt;
00132     int fps = result["framerate"].as<int>();
00133     if (result["export"].as<bool>())
00134     {
00135         my_plotter.renderAllFrames(start_frame, end_frame);
00136     }
00137     else if (result["animate"].as<bool>())
00138     {
00139         my_plotter.animate(result["output_filename"].as<std::string>(), start_frame, end_frame, fps);
00140     }
00141     else
00142     {
00143         my_plotter.renderAllFrames(start_frame, end_frame);
00144     }
00145 }

```

## 11.13 Benchmarks.cpp

```

00001 //
00002 // Created by Yan Cheng on 12/2/22.
00003 //
00004
00005 #include <boost/multi_array.hpp>
00006 #include <boost/array.hpp>
00007 #include "CustomLibraries/np.hpp"
00008 #include "CustomLibraries/np_to_matplot.hpp"
00009 #include "CustomLibraries/wavePlotter.hpp"
00010 #include <matplotlib/matplotlib.h>
00011 #include <cassert>
00012 #include <iostream>
00013 #include <sstream>

```

```

00014 #include <chrono>
00015
00016 #include "CoreAlgorithm/helper_func.hpp"
00017 #include "CoreAlgorithm/coeff.hpp"
00018 #include "CoreAlgorithm/source.hpp"
00019 #include "CoreAlgorithm/computational.hpp"
00020 #include "CoreAlgorithm/solver.hpp"
00021
00022 void benchmark_solver()
00023 {
00024     int nx = 101;
00025     int nz = 101;
00026     int nt = 750;
00027
00028     double dx = 10;
00029     double dz = 10;
00030     double dt = 0.001;
00031
00032     double xmin = 0.0;
00033     double xmax = nx * dx;
00034     double zmin = 0.0;
00035     double zmax = nz * dz;
00036     double tmin = 0.0;
00037     double tmax = nt * dt;
00038
00039     double f_M = 10.0;
00040     double amp = 1e0;
00041     double shift = 0.1;
00042
00043     boost::multi_array<double, 3> f = waveSimCore::ricker(50, 50, f_M, amp, shift, tmin, tmax, nt, nx,
00044 nz);
00045
00046     double r = 150.0;
00047     boost::multi_array<double, 2> vel = waveSimCore::get_profile(xmin, xmax, zmin, zmax, nx, nz, r);
00048     auto start = std::chrono::high_resolution_clock::now();
00049     boost::multi_array<double, 3> u = waveSimCore::wave_solver(vel, dt, dx, dz, nt, nx, nz, f);
00050     auto stop = std::chrono::high_resolution_clock::now();
00051     auto duration = std::chrono::duration_cast<std::chrono::microseconds>(stop - start);
00052     std::cout << "Time taken by the solving function: " << duration.count() << " microseconds" <<
00053     std::endl;
00054 }
00055
00056 void benchmark_gradient()
00057 {
00058     int size_x = 100;
00059     int size_y = 100;
00060     int size_z = 100;
00061     int size_t = 10;
00062     double dx = 0.1;
00063     double dy = 0.1;
00064     double dz = 0.1;
00065     double dt = 0.1;
00066     int axis[4] = {size_x, size_y, size_z, size_t};
00067     boost::multi_array<double, 4> nd_array = np::zeros<double>(axis);
00068     auto start = std::chrono::high_resolution_clock::now();
00069     auto grad = np::gradient(nd_array, {dx, dy, dz, dt});
00070     auto stop = std::chrono::high_resolution_clock::now();
00071     auto duration = std::chrono::duration_cast<std::chrono::microseconds>(stop - start);
00072     std::cout << "Time taken by the gradient function: " << duration.count() << " microseconds" <<
00073     std::endl;
00074 }
00075
00076 int main()
00077 {
00078     benchmark_solver();
00079     benchmark_gradient();
00080 }

```

## 11.14 CoreTests.cpp

```

00001 //
00002 // Created by Yan Cheng on 12/2/22.
00003 //
00004
00005 #include <boost/multi_array.hpp>
00006 #include <boost/array.hpp>
00007 #include "CustomLibraries/np.hpp"
00008 #include "CustomLibraries/np_to_matplotlib.hpp"
00009 #include "CustomLibraries/wavePlotter.hpp"
00010 #include <matplotlib/matplotlib.h>
00011 #include <cassert>
00012 #include <iostream>
00013 #include <sstream>

```

```

00014
00015 #include "CoreAlgorithm/helper_func.hpp"
00016 #include "CoreAlgorithm/coeff.hpp"
00017 #include "CoreAlgorithm/source.hpp"
00018 #include "CoreAlgorithm/computational.hpp"
00019 #include "CoreAlgorithm/solver.hpp"
00020
00021 std::string format_num(int num, int length = 8)
00022 {
00023     std::string str_num = std::to_string(num);
00024
00025     int str_length = str_num.length();
00026     for (int i = 0; i < length - str_length; i++)
00027         str_num = "0" + str_num;
00028     return str_num;
00029 }
00030
00031 void test_()
00032 {
00033     int num_levels = 100;
00034     int nx = 100;
00035     int nz = 100;
00036     int nt = 1000;
00037
00038     double dx = 0.01;
00039     double dz = 0.01;
00040     double dt = 0.001;
00041
00042     double xmin = 0.0;
00043     double xmax = nx * dx;
00044     double zmin = 0.0;
00045     double zmax = nz * dz;
00046     double tmin = 0.0;
00047     double tmax = nt * dt;
00048
00049     double f_M = 10.0;
00050     double amp = 1e0;
00051     double shift = 0.1;
00052
00053     boost::multi_array<double, 3> f = waveSimCore::ricker(50, 50, f_M, amp, shift, tmin, tmax, nt, nx,
00054 nz);
00055
00056     double r = 150.0;
00057     boost::multi_array<double, 2> vel = waveSimCore::get_profile(xmin, xmax, zmin, zmax, nx, nz, r);
00058
00059     boost::multi_array<double, 3> u = waveSimCore::wave_solver(vel, dt, dx, dz, nt, nx, nz, f);
00060     double min_u = np::min(u);
00061     double max_u = np::max(u);
00062     std::cout << "min_u = " << min_u << " max_u = " << max_u << "\n";
00063     std::vector<double> levels = matplotlib::linspace(min_u, max_u, num_levels);
00064     std::cout << u[20][10][10] << "\n";
00065
00066     // boost::multi_array<double, 2> u20(boost::extents[nx][nz]);
00067     // for (int i = 0; i < nx; i++)
00068     // {
00069     //     for (int j = 0; j < nz; j++)
00070     //     {
00071     //         u20[i][j] = u[10][i][j];
00072     //         std::cout << u20[i][j] << " ";
00073     //     }
00074     //     std::cout << "\n";
00075     // }
00076     // std::cout << "\n";
00077
00078     boost::multi_array<double, 1> x = np::linspace(xmin, xmax, nx);
00079     boost::multi_array<double, 1> z = np::linspace(zmin, zmax, nz);
00080     const boost::multi_array<double, 1> axis[2] = {x, z};
00081     std::vector<boost::multi_array<double, 2> XcZ = np::meshgrid(axis, false, np::xy);
00082
00083     matplotlib::vector_2d Xp = np::convert_to_matplot(XcZ[0]);
00084     matplotlib::vector_2d Zp = np::convert_to_matplot(XcZ[1]);
00085     // matplotlib::contourf(Xp, Zp, vel, levels, "", num_levels);
00086     // matplotlib::show();
00087
00088     wavePlotter::Plotter my_plotter(u, Xp, Zp, num_levels, nt);
00089     // my_plotter.exportAllFrames(0, nt - 1);
00090     my_plotter.animate("output-test.mp4", 20, nt - 1, 30);
00091
00092     // for (int i = 10; i < nt - 1; i++)
00093     // {
00094     //     matplotlib::vector_2d Up = np::convert_to_matplot(u[i]);
00095     //     matplotlib::contourf(Xp, Zp, Up, levels);
00096     //     matplotlib::save("output/contourf_" + format_num(i) + ".png");
00097     // }
00098 }
00099 int main()

```

```

00100 {
00101     test_();
00102 }

```

## 11.15 MatPlotTest.cpp

```

00001 #include <matplot/matplot.h>
00002 #include <thread>
00003 #include "boost/multi_array.hpp"
00004 #include "boost/array.hpp"
00005 #include "CustomLibraries/np.hpp"
00006 #include "CustomLibraries/np_to_matplot.hpp"
00007
00008 using namespace matplot;
00009 void test_simple_plot()
00010 {
00011     std::vector<double> x = linspace(-2 * pi, 2 * pi);
00012     std::vector<double> y = linspace(0, 4 * pi);
00013     auto [X, Y] = meshgrid(x, y);
00014     vector_2d Z =
00015         transform(X, Y, [](double x, double y)
00016             { return sin(x) + cos(y); });
00017     contourf(X, Y, Z, 10);
00018
00019     show();
00020 }
00021
00022 void test_conversion()
00023 {
00024     boost::multi_array<double, 1> x = np::linspace(0, 1, 100);
00025     boost::multi_array<double, 1> y = np::linspace(0, 1, 100);
00026     // x = np::pow(x, 2.0);
00027     // y = np::pow(y, 3.0);
00028
00029     const boost::multi_array<double, 1> axis[2] = {x, y};
00030     std::vector<boost::multi_array<double, 2>> XcY = np::meshgrid(axis, false, np::xy);
00031
00032     double dx, dy;
00033     dx = 1.0 / 100.0;
00034     dy = 1.0 / 100.0;
00035
00036     boost::multi_array<double, 2> f = np::pow(XcY[0], 2.0) + XcY[0] * np::pow(XcY[1], 1.0);
00037
00038     // g.push_back(np::gradient(XcY[0], {dx, dy}));
00039     // g.push_back(np::gradient(XcY[1], {dx, dy}));
00040     std::vector<boost::multi_array<double, 2>> gradf = np::gradient(f, {dx, dy});
00041     matplot::vector_2d Xp = np::convert_to_matplot(XcY[0]);
00042     matplot::vector_2d Yp = np::convert_to_matplot(XcY[1]);
00043     matplot::vector_2d X = matplot::meshgrid(linspace(0, 1, 100), linspace(0, 1, 100)).first;
00044     matplot::vector_2d Y = matplot::meshgrid(linspace(0, 1, 100), linspace(0, 1, 100)).second;
00045
00046     matplot::vector_2d Z = np::convert_to_matplot(gradf[1]);
00047     std::cout << "X.size() = " << X.size() << std::endl;
00048     std::cout << "Y.size() = " << Y.size() << std::endl;
00049     std::cout << "Z.size() = " << Z.size() << std::endl;
00050     for (size_t i = 0; i < X.size(); i++)
00051     {
00052         for (size_t j = 0; j < X[i].size(); j++)
00053         {
00054             std::cout << "X[" << i << "][" << j << "] = " << X[i][j] << " | XP[" << i << "][" << j << "] = " <<
00055             Xp[i][j] << " | YP[" << i << "][" << j << "] = " << Yp[i][j] << std::endl;
00056         }
00057     }
00058     contourf(Xp, Yp, Z, 10);
00059     show();
00060 }
00061 int main()
00062 {
00063     // test_simple_plot();
00064     test_conversion();
00065     return 0;
00066 }

```

## 11.16 variadic.cpp

```

00001 #include "boost/multi_array.hpp"
00002 #include "boost/array.hpp"
00003 #include "CustomLibraries/np.hpp"

```

```

00004 #include <cassert>
00005 #include <iostream>
00006
00007 void test_gradient()
00008 {
00009     // Create a 4D array that is 3 x 4 x 2 x 1
00010     typedef boost::multi_array<double, 4>::index index;
00011     boost::multi_array<double, 4> A(boost::extents[3][4][2][1]);
00012
00013     // Assign values to the elements
00014     int values = 0;
00015     for (index i = 0; i != 3; ++i)
00016         for (index j = 0; j != 4; ++j)
00017             for (index k = 0; k != 2; ++k)
00018                 for (index l = 0; l != 1; ++l)
00019                     A[i][j][k][l] = values++;
00020
00021     // Verify values
00022     int verify = 0;
00023     for (index i = 0; i != 3; ++i)
00024         for (index j = 0; j != 4; ++j)
00025             for (index k = 0; k != 2; ++k)
00026                 for (index l = 0; l != 1; ++l)
00027                     assert(A[i][j][k][l] == verify++);
00028
00029     double dx, dy, dz, dt;
00030     dx = 1.0;
00031     dy = 1.0;
00032     dz = 1.0;
00033     dt = 1.0;
00034     std::vector<boost::multi_array<double, 4> my_arrays = np::gradient(A, {dx, dy, dz, dt});
00035
00036     boost::multi_array<double, 1> x = np::linspace(0, 1, 5);
00037     std::vector<boost::multi_array<double, 1> gradf = np::gradient(x, {1.0});
00038     for (int i = 0; i < 5; i++)
00039     {
00040         std::cout << gradf[0][i] << ", ";
00041     }
00042     std::cout << "\n";
00043     // np::print(std::cout, my_arrays[0]);
00044 }
00045
00046 void test_meshgrid()
00047 {
00048     boost::multi_array<double, 1> x = np::linspace(0, 1, 5);
00049     boost::multi_array<double, 1> y = np::linspace(0, 1, 5);
00050     boost::multi_array<double, 1> z = np::linspace(0, 1, 5);
00051     boost::multi_array<double, 1> t = np::linspace(0, 1, 5);
00052     const boost::multi_array<double, 1> axis[4] = {x, y, z, t};
00053     std::vector<boost::multi_array<double, 4> my_arrays = np::meshgrid(axis, false, np::xy);
00054     // np::print(std::cout, my_arrays[0]);
00055     int nx = 3;
00056     int ny = 2;
00057     boost::multi_array<double, 1> x2 = np::linspace(0, 1, nx);
00058     boost::multi_array<double, 1> y2 = np::linspace(0, 1, ny);
00059     const boost::multi_array<double, 1> axis2[2] = {x2, y2};
00060     std::vector<boost::multi_array<double, 2> my_arrays2 = np::meshgrid(axis2, false, np::xy);
00061     std::cout << "xv\n";
00062     for (int i = 0; i < ny; i++)
00063     {
00064         for (int j = 0; j < nx; j++)
00065         {
00066             std::cout << my_arrays2[0][i][j] << " ";
00067         }
00068         std::cout << "\n";
00069     }
00070     std::cout << "yv\n";
00071     for (int i = 0; i < ny; i++)
00072     {
00073         for (int j = 0; j < nx; j++)
00074         {
00075             std::cout << my_arrays2[1][i][j] << " ";
00076         }
00077         std::cout << "\n";
00078     }
00079 }
00080
00081 void test_complex_operations()
00082 {
00083     int nx = 3;
00084     int ny = 2;
00085     boost::multi_array<double, 1> x = np::linspace(0, 1, nx);
00086     boost::multi_array<double, 1> y = np::linspace(0, 1, ny);
00087     const boost::multi_array<double, 1> axis[2] = {x, y};
00088     std::vector<boost::multi_array<double, 2> my_arrays = np::meshgrid(axis, false, np::xy);
00089     boost::multi_array<double, 2> A = np::sqrt(my_arrays[0]);
00090     std::cout << "sqrt\n";

```

```

00091     for (int i = 0; i < ny; i++)
00092     {
00093         for (int j = 0; j < nx; j++)
00094         {
00095             std::cout << A[i][j] << " ";
00096         }
00097         std::cout << "\n";
00098     }
00099     std::cout << "\n";
00100     float a = 100.0;
00101     float sqa = np::sqrt(a);
00102     std::cout << "sqrt of " << a << " is " << sqa << "\n";
00103     std::cout << "exp\n";
00104     boost::multi_array<double, 2> B = np::exp(my_arrays[0]);
00105     for (int i = 0; i < ny; i++)
00106     {
00107         for (int j = 0; j < nx; j++)
00108         {
00109             std::cout << B[i][j] << " ";
00110         }
00111         std::cout << "\n";
00112     }
00113
00114     std::cout << "Power\n";
00115     boost::multi_array<double, 1> x2 = np::linspace(1, 3, nx);
00116     boost::multi_array<double, 1> y2 = np::linspace(1, 3, ny);
00117     const boost::multi_array<double, 1> axis2[2] = {x2, y2};
00118     std::vector<boost::multi_array<double, 2> my_arrays2 = np::meshgrid(axis2, false, np::xy);
00119     boost::multi_array<double, 2> C = np::pow(my_arrays2[1], 2.0);
00120     for (int i = 0; i < ny; i++)
00121     {
00122         for (int j = 0; j < nx; j++)
00123         {
00124             std::cout << C[i][j] << " ";
00125         }
00126         std::cout << "\n";
00127     }
00128 }
00129
00130 void test_equal()
00131 {
00132     boost::multi_array<double, 1> x = np::linspace(0, 1, 5);
00133     boost::multi_array<double, 1> y = np::linspace(0, 1, 5);
00134     boost::multi_array<double, 1> z = np::linspace(0, 1, 5);
00135     boost::multi_array<double, 1> t = np::linspace(0, 1, 5);
00136     const boost::multi_array<double, 1> axis[4] = {x, y, z, t};
00137     std::vector<boost::multi_array<double, 4> my_arrays = np::meshgrid(axis, false, np::xy);
00138     boost::multi_array<double, 1> x2 = np::linspace(0, 1, 5);
00139     boost::multi_array<double, 1> y2 = np::linspace(0, 1, 5);
00140     boost::multi_array<double, 1> z2 = np::linspace(0, 1, 5);
00141     boost::multi_array<double, 1> t2 = np::linspace(0, 1, 5);
00142     const boost::multi_array<double, 1> axis2[4] = {x2, y2, z2, t2};
00143     std::vector<boost::multi_array<double, 4> my_arrays2 = np::meshgrid(axis2, false, np::xy);
00144     std::cout << "equality test:\n";
00145     std::cout << (bool)(my_arrays == my_arrays2) << "\n";
00146 }
00147 void test_basic_operations()
00148 {
00149     int nx = 3;
00150     int ny = 2;
00151     boost::multi_array<double, 1> x = np::linspace(0, 1, nx);
00152     boost::multi_array<double, 1> y = np::linspace(0, 1, ny);
00153     const boost::multi_array<double, 1> axis[2] = {x, y};
00154     std::vector<boost::multi_array<double, 2> my_arrays = np::meshgrid(axis, false, np::xy);
00155
00156     std::cout << "basic operations:\n";
00157
00158     std::cout << "addition:\n";
00159     boost::multi_array<double, 2> A = my_arrays[0] + my_arrays[1];
00160
00161     for (int i = 0; i < ny; i++)
00162     {
00163         for (int j = 0; j < nx; j++)
00164         {
00165             std::cout << A[i][j] << " ";
00166         }
00167         std::cout << "\n";
00168     }
00169
00170     std::cout << "multiplication:\n";
00171     boost::multi_array<double, 2> B = my_arrays[0] * my_arrays[1];
00172
00173     for (int i = 0; i < ny; i++)
00174     {
00175         for (int j = 0; j < nx; j++)
00176         {
00177             std::cout << B[i][j] << " ";

```



```

00178     }
00179     std::cout << "\n";
00180 }
00181 double coeff = 3;
00182 boost::multi_array<double, 1> t = np::linspace(0, 1, nx);
00183 boost::multi_array<double, 1> t_time_3 = coeff * t;
00184 boost::multi_array<double, 1> t_time_2 = 2.0 * t;
00185 std::cout << "t_time_3: ";
00186 for (int j = 0; j < nx; j++)
00187 {
00188     std::cout << t_time_3[j] << " ";
00189 }
00190 std::cout << "\n";
00191 std::cout << "t_time_2: ";
00192 for (int j = 0; j < nx; j++)
00193 {
00194     std::cout << t_time_2[j] << " ";
00195 }
00196 std::cout << "\n";
00197 }
00198
00199 void test_zeros()
00200 {
00201     int nx = 3;
00202     int ny = 2;
00203     int dimensions[] = {ny, nx};
00204     boost::multi_array<double, 2> A = np::zeros<double>(dimensions);
00205     std::cout << "zeros:\n";
00206     for (int i = 0; i < ny; i++)
00207     {
00208         for (int j = 0; j < nx; j++)
00209         {
00210             std::cout << A[i][j] << " ";
00211         }
00212         std::cout << "\n";
00213     }
00214 }
00215
00216 void test_min_max()
00217 {
00218     int nx = 24;
00219     int ny = 5;
00220     boost::multi_array<double, 1> x = np::linspace(0, 10, nx);
00221     boost::multi_array<double, 1> y = np::linspace(-1, 1, ny);
00222     const boost::multi_array<double, 1> axis[2] = {x, y};
00223     std::vector<boost::multi_array<double, 2> my_array = np::meshgrid(axis, false, np::xy);
00224     std::cout << "min: " << np::min(my_array[0]) << "\n";
00225     std::cout << "max: " << np::max(my_array[1]) << "\n";
00226     std::cout << "max simple: " << np::max(1.0, 2.0, 3.0, 4.0, 5.0) << "\n";
00227     std::cout << "min simple: " << np::min(1, -2, 3, -4, 5) << "\n";
00228 }
00229
00230 void test_toy_problem()
00231 {
00232     boost::multi_array<double, 1> x = np::linspace(0, 1, 100);
00233     boost::multi_array<double, 1> y = np::linspace(0, 1, 100);
00234     // x = np::pow(x, 2.0);
00235     // y = np::pow(y, 3.0);
00236
00237     const boost::multi_array<double, 1> axis[2] = {x, y};
00238     std::vector<boost::multi_array<double, 2> XcY = np::meshgrid(axis, false, np::xy);
00239
00240     double dx, dy;
00241     dx = 1.0 / 100.0;
00242     dy = 1.0 / 100.0;
00243
00244     boost::multi_array<double, 2> f = np::pow(XcY[0], 2.0) + XcY[0] * np::pow(XcY[1], 1.0);
00245
00246     // g.push_back(np::gradient(XcY[0], {dx, dy}));
00247     // g.push_back(np::gradient(XcY[1], {dx, dy}));
00248     std::vector<boost::multi_array<double, 2> gradf = np::gradient(f, {dx, dy});
00249     // auto [gradfx_x, gradfx_y] = np::gradient(f, {dx, dy});
00250
00251     int i, j;
00252     i = 10;
00253     j = 20;
00254     std::cout << "df/dx of f(x,y) = x^2 + xy at x = " << x[i] << " and y = " << y[j] << " is equal to " <<
    gradf[0][i][j];
00255
00256     std::cout << "\n";
00257 }
00258
00259 void test_abs()
00260 {
00261     int nx = 4;
00262     int ny = 4;
00263     boost::multi_array<double, 1> x = np::linspace(-1, 1, nx);

```

```

00264     boost::multi_array<double, 1> y = np::linspace(-1, 1, ny);
00265     const boost::multi_array<double, 1> axis[2] = {x, y};
00266     std::vector<boost::multi_array<double, 2>> XcY = np::meshgrid(axis, false, np::xy);
00267     boost::multi_array<double, 2> abs_f = np::abs(XcY[0]);
00268     std::cout << "abs_f: \n";
00269     for (int i = 0; i < ny; i++)
00270     {
00271         for (int j = 0; j < nx; j++)
00272         {
00273             std::cout << abs_f[i][j] << " ";
00274         }
00275         std::cout << "\n";
00276     }
00277 }
00278
00279 void test_slice()
00280 {
00281     int nx = 4;
00282     int ny = 4;
00283     boost::multi_array<double, 1> x = np::linspace(-1, 1, nx);
00284     boost::multi_array<double, 1> y = np::linspace(-1, 1, ny);
00285     const boost::multi_array<double, 1> axis[2] = {x, y};
00286     std::vector<boost::multi_array<double, 2>> XcY = np::meshgrid(axis, false, np::xy);
00287     boost::multi_array<double, 2> f = np::pow(XcY[0], 2.0) + XcY[0] * np::pow(XcY[1], 1.0);
00288     std::cout << "f: \n";
00289     for (int i = 0; i < ny; i++)
00290     {
00291         for (int j = 0; j < nx; j++)
00292         {
00293             std::cout << f[i][j] << " ";
00294         }
00295         std::cout << "\n";
00296     }
00297     std::cout << "f[0]: \n";
00298     boost::multi_array<double, 1> f_slice = np::slice(f, 0);
00299     for (int i = 0; i < nx; i++)
00300     {
00301         std::cout << f_slice[i] << " ";
00302     }
00303     std::cout << "\n";
00304
00305     std::cout << "f[1]: \n";
00306     f_slice = np::slice(f, 1);
00307     for (int i = 0; i < ny; i++)
00308     {
00309         std::cout << f_slice[i] << " ";
00310     }
00311     std::cout << "\n";
00312 }
00313
00314 int main()
00315 {
00316     test_gradient();
00317     test_meshgrid();
00318     test_complex_operations();
00319     test_equal();
00320     test_basic_operations();
00321     test_zeros();
00322     test_min_max();
00323     test_abs();
00324     test_toy_problem();
00325     test_slice();
00326 }

```