

Autonomous Underwater Vehicle: A Surveillance Protocol

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Preface

This project is an attempt at combining all of my major skills into creating a simulation, imaging, perception and control pipeline for Autonomous Underwater Vehicles (AUV). As such, creating this project involves creating a number of pipelines.

The first pipeline is the signal simulation pipeline. The signal simulation pipeline involves sea-floor point-cloud creation and simulating the signals received by the sensor arrays of the AUV. The signals recorded by the sensor-arrays on the AUV contains information from the surrounding environment. The imaging pipeline performs certain operations on the recorded signals to obtain acoustic images of the surrounding environment. To that end, this pipeline involves the topics of signal processing, linear algebra, signals and systems.

As such, the second pipeline is the imaging pipeline. The inputs to the imaging pipeline is the signals recorded by the different sensor-arrays of the AUV, in addition to the parameters of the AUV and its components. This pipeline involves match-filtering, focussing and beamforming operations to create acoustic images of the surrounding environment. Depending on the number of ULAs present, the imaging pipeline is responsible for creating multiple acoustic images in real-time. Thus, this pipeline involves the topics of Digital Signal Processing, Match-Filtering, Estimation and Detection Theory and so on.

The images created by the imaging pipeline are fed to the perception-to-control pipeline. This pipeline takes in the image formed created from the ULA signals, parameters of AUV and its components, and some historical data, it provides instructions regarding the movement of the AUV. The mapping from the inputs to the controls is called policy. Learning policies is a core part of reinforcement learning. Thus, this pipeline mainly involves the topics of reinforcement learning. And since we'll be using convolutional neural nets and transformers for learning the policies, this pipeline involves a significant amount of machine and deep learning.

The final result is an AUV that is primarily trained to map an area of the sea-floor in a constant surveillance mode. The RL-trained policy will also be trained to deal with different kinds of sea-floor terrains: those containing hills, valleys, and path-obstructing features. Due to the resource constrained nature of the marine vessel, we also prioritize efficient policies in the policy-training pipeline.

The project is currently written in C++. And since there is non-trivial amount of training and adaptive features in the pipelines, we'll be using LibTorch (the C++ API of PyTorch) to enable computation graphs, backpropagation and thereby, learning in our AUV pipeline. However, for the sections where a computation graph is not required we will be writing templated STL code.

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Part I

AUV Components & Setup

Chapter 1

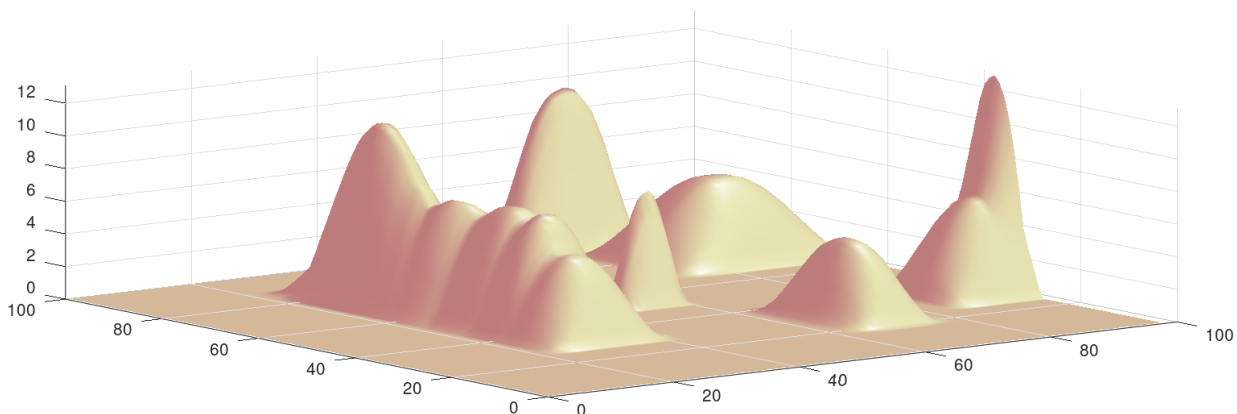
Underwater Environment

Overview

All physical matter in this framework is represented using point-clouds. Thus, the sea-floor also is represented using a number of 3D points. In addition to the coordinates, the points also have the additional property of “reflectivity”. It is the impulse response of that point.

Sea-floors in real-life are rarely flat. They often contain valleys, mountains, hills and much richer geographical features. Thus, training an agent to function in such environments call for the creation of similar structures in our simulations.

To simplify things, we shall take a more constrained and structured approach. We start by creating different classes of structures and produce instantiations of those structures on the sea-floor. These structures are defined in such a way that the shape and size can be parameterized to enable creation of random sea-floors.



1.1 Underwater Hills

The most basic approach to creating this is to create a flat seafloor, where all the points have the same height. While this is a good place to start, it is good to bring in some realism to the seafloor. To that end, we shall have some rolling hills as the sea-floor. Each “hill ”

is created using the method outlined in Algorithm 1. The method involves deciding the location of the hills, the dimension of the hills and then designing a hill by combining an exponential function and a cosine function. We're aiming to essentially produce gaussian-looking sea-floor hills. After the creation, this becomes the set of points representing the lowest set of points in the overall seafloor structure.

Algorithm 1 Hill Creation

```

1: Input: Mean vector  $\mathbf{m}$ , Dimension vector  $\mathbf{d}$ , 2D points  $\mathbf{P}$ 
2: Output: Updated  $\mathbf{P}$  with hill heights
3:  $\text{num\_hills} \leftarrow \text{numel}(\mathbf{m}_x)$ 
4:  $H \leftarrow$  Zeros tensor of size  $(1, \text{numel}(\mathbf{P}_x))$ 
5: for  $i = 1$  to  $\text{num\_hills}$  do
6:    $x_{\text{norm}} \leftarrow \frac{\frac{\pi}{2}(\mathbf{P}_x - \mathbf{m}_x[i])}{\mathbf{d}_x[i]}$ 
7:    $y_{\text{norm}} \leftarrow \frac{\frac{\pi}{2}(\mathbf{P}_y - \mathbf{m}_y[i])}{\mathbf{d}_y[i]}$ 
8:    $h_x \leftarrow \cos(x_{\text{norm}}) \cdot e^{\frac{|x_{\text{norm}}|}{10}}$ 
9:    $h_y \leftarrow \cos(y_{\text{norm}}) \cdot e^{\frac{|y_{\text{norm}}|}{10}}$ 
10:   $h \leftarrow \mathbf{d}_z[i] \cdot h_x \cdot h_y$ 
11:  Apply boundary conditions:
12:  if  $x_{\text{norm}} > \frac{\pi}{2}$  or  $x_{\text{norm}} < -\frac{\pi}{2}$  or  $y_{\text{norm}} > \frac{\pi}{2}$  or  $y_{\text{norm}} < -\frac{\pi}{2}$  then
13:     $h \leftarrow 0$ 
14:  end if
15:   $H \leftarrow H + h$ 
16: end for
17:  $\mathbf{P} \leftarrow \text{concatenate}([\mathbf{P}, H])$ 

```

1.2 Scatterer Definition

The sea-floor is represented by a single object of the class ScattererClass.

```

1  /*=====
2  Class Declaration
3  -----*/
4  template <typename T>
5  class ScattererClass
6  {
7  public:
8      // members
9      std::vector<std::vector<T>> coordinates;
10     std::vector<T> reflectivity;
11
12     // Constructor
13     ScattererClass() {}
14
15     // Constructor
16     ScattererClass(std::vector<std::vector<T>> coordinates_arg,
17                    std::vector<T> reflectivity_arg):
18         coordinates(std::move(coordinates_arg)),
19         reflectivity(std::move(reflectivity_arg)) {}
20
21     // Save to CSV

```



```

22     void save_to_csv();
23 };

```

1.3 Sea-Floor Setup Script

Following is the function that will setup the sea-floor script.

```

1  void fSeaFloorSetup(
2      ScattererClass<double>& scatterers
3  ){
4
5      // auto save_files {false};
6      const auto save_files {false};
7      const auto hill_creation_flag {true};
8
9      // sea-floor bounds
10     auto bed_width {100.00};
11     auto bed_length {100.00};
12
13     // creating tensors for coordinates and reflectivity
14     vector<vector<double>> box_coordinates;
15     vector<double> box_reflectivity;
16
17     // scatter density
18     // auto bed_width_density {static_cast<double>( 10.00)};
19     // auto bed_length_density {static_cast<double>( 10.00)};
20     auto bed_width_density {static_cast<double>( 5.00)};
21     auto bed_length_density {static_cast<double>( 5.00)};
22
23     // setting up coordinates
24     auto xpoints {svr::linspace<double>(
25         0.00,
26         bed_width,
27         bed_width * bed_width_density
28     )};
29     auto ypoints {svr::linspace<double>(
30         0.00,
31         bed_length,
32         bed_length * bed_length_density
33     )};
34     if(save_files) fWriteVector(xpoints, "../csv-files/xpoints.csv"); // verified
35     if(save_files) fWriteVector(ypoints, "../csv-files/ypoints.csv"); // verified
36
37     // creating mesh
38     auto [xgrid, ygrid] = meshgrid(std::move(xpoints), std::move(ypoints));
39     if(save_files) fWriteMatrix(xgrid, "../csv-files/xgrid.csv"); // verified
40     if(save_files) fWriteMatrix(ygrid, "../csv-files/ygrid.csv"); // verified
41
42     // reshaping
43     auto X {reshape(xgrid, xgrid.size()*xgrid[0].size())};
44     auto Y {reshape(ygrid, ygrid.size()*ygrid[0].size())};
45     if(save_files) fWriteVector(X, "../csv-files/X.csv"); // verified
46     if(save_files) fWriteVector(Y, "../csv-files/Y.csv"); // verified
47
48     // creating heights of scatterers
49     if(hill_creation_flag){

```

```

50
51 // setting up hill parameters
52 auto num_hills {10};
53
54 // setting up placement of hills
55 auto points2D {concatenate<0>(X, Y)}; // verified
56 auto min2D {min<1, double>(points2D)}; // verified
57 auto max2D {max<1, double>(points2D)}; // verified
58 auto hill_2D_center {min2D + \
59 rand({2, num_hills}) * (max2D - min2D)}; // verified
60
61 // setup: hill-dimensions
62 auto hill_dimensions_min {transpose(vector<double>{5, 5, 2})}; // verified
63 auto hill_dimensions_max {transpose(vector<double>{30, 30, 10})}; // verified
64 auto hill_dimensions {hill_dimensions_min + \
65 rand({3, num_hills}) * (hill_dimensions_max -
66 hill_dimensions_min)}; // verified
67
68 // function-call: hill-creation function
69 fCreateHills(hill_2D_center,
70 hill_dimensions,
71 points2D);
72
73 // setting up floor reflectivity
74 auto floorScatter_reflectivity {std::vector<double>(Y.size(), 1.00)};
75
76 // populating the values of the incoming argument
77 scatterers.coordinates = std::move(points2D);
78 scatterers.reflectivity = std::move(floorScatter_reflectivity);
79
80 else{
81
82 // assigning flat heights
83 auto Z {std::vector<double>(Y.size(), 0)};
84
85 // setting up floor coordinates
86 auto floorScatter_coordinates {concatenate<0>(X, Y, Z)};
87 auto floorScatter_reflectivity {std::vector<double>(Y.size(), 1)};
88
89 // populating the values of the incoming argument
90 scatterers.coordinates = std::move(floorScatter_coordinates);
91 scatterers.reflectivity = std::move(floorScatter_reflectivity);
92
93 }
94
95 // printing status
96 std::cout << format("> Finished Sea-Floor Setup \n");
97 }

```

Chapter 2

Transmitter

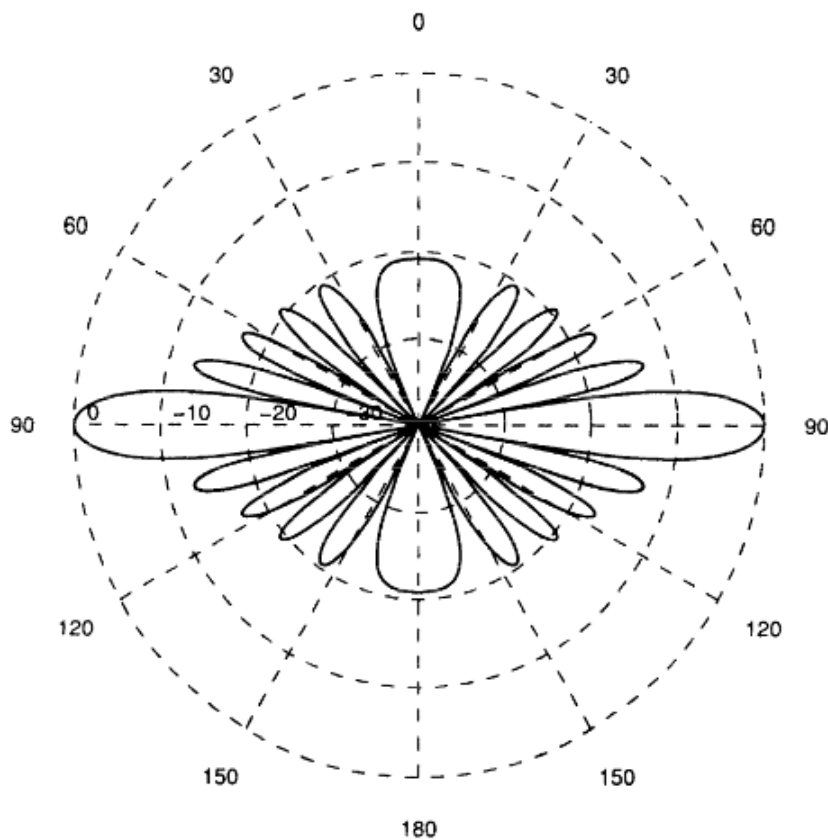


Figure 2.1: Beampattern of a Transmission Uniform Linear Array

Overview

Probing systems are those systems that send out a signal, listen to the reflection and infer qualitative and quantitative qualities of the environment, matter or object, it was trying to infer information about. The transmitter is one of the most fundamental components of probing systems. As the name suggests, the transmitter is the equipment responsible for sending out the probing signal into the medium.

A transmitter is any device or circuit that converts information into a signal and sends it out onto some media like air, cable, water or space. The components of a transmitter are usually as follows

1. Input: Information containing signal such as voice, data, video etc
2. Process: Encode/modulate the information onto a carrier signal, which can be electromagnetic wave or mechanical wave.
3. Transmission: The signal is then transmitted onto the media with electro-mechanical equipment.

Transmitters are of many kinds. But the ones that we will be considering will be directed transmitters, which means that these transmitters have an associated beampattern. To the uninitiated, this means that the power of the transmitted signal is not transmitted in all directions equally. A beampattern is a graphical representation of the power received by an ideal receiver when placed at different angles.

Transmitters made out of a linear-array of individual transmitters use beamforming to “direct” the major power of the transmitter. These kind of systems have well studied beampatterns which can be utilized in our simulations. These kind of studies and inculcating that in our pipelines produce accurate signal simulation pipelines. For now, we stick to a very simple model of a transmitter. We assume that the transmitter sends out the power equally into a particular cone from the AUV position.

2.1 Transmission Signal

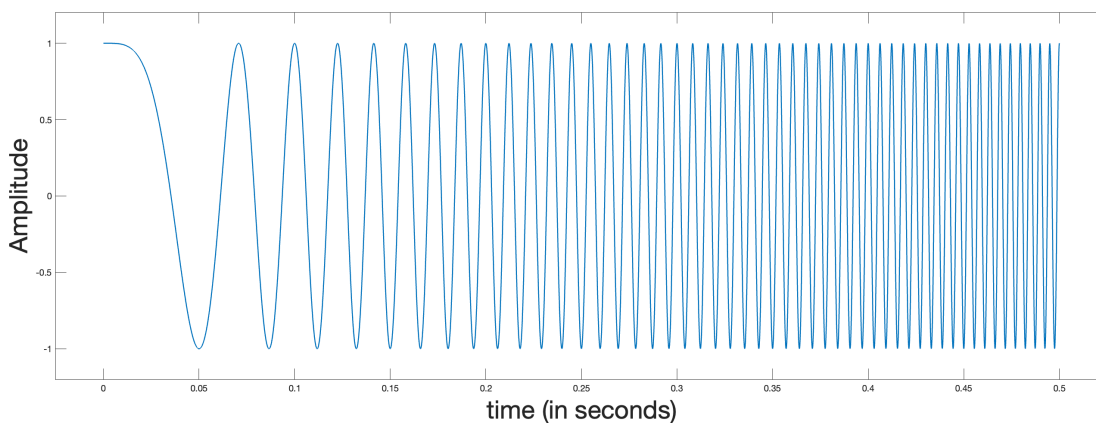


Figure 2.2: Linear Frequency Modulated Wave

The resolution of any probing system is fundamentally tied to the signal bandwidth. A higher bandwidth corresponds to finer resolution $\frac{\text{speed-of-sounds}}{2 \cdot \text{bandwidth}}$. Thus, for perfect resolution, an infinite bandwidth is in order. However, infinite bandwidth is impossible for obvious reasons: hardware limitations, spectral regulations, energy limitations and so on.

This is where Linear Frequency Modulation (LFM), also called a “chirp,” becomes valuable. An LFM signal linearly sweeps a limited bandwidth over a relatively long duration. This technique spreads the signal’s energy in time while retaining the resolution benefits of

the bandwidth. After matched filtering (or pulse compression), we essentially produce pulses corresponding to a base-band LFM of same bandwidth. Overall, LFM is a practical compromise between finite bandwidth and desired performance.

One of the best parts about the resolution depending only on the bandwidth is that it allows us to deploy techniques that would help us improve SNRs without virtually increasing the bandwidth at all. Much of the noise in submarine environments are in and around the baseband region (around frequency, 0). Since resolution depends purely on bandwidth, and LFM can be transmitted at a carrier-frequency, this means that processing the returns after low-pass filtering and basebanding allows us to get rid of the submarine noise, since they do not occupy the same frequency-coefficients. The end-result, thus, is improved SNR compared to use baseband LFM.

Due to all of these advantages, LFM waves are ubiquitous in probing systems, from sonar to radar. Thus, for this project too, the transmitter will be using LFM waves as probing signals, to probe the surrounding submarine environment.

2.2 Transmitter Class Definition

The transmitter is represented by a single object of the class TransmitterClass.

```

1  template <typename T>
2  class TransmitterClass{
3  public:
4
5      // A shared pointer to the configuration object
6      std::shared_ptr<svr::AUVParameters> config_ptr;
7
8      // physical/intrinsic properties
9      std::vector<T>    location;           // location tensor
10     std::vector<T>    pointing_direction; // pointing direction
11
12     // basic parameters
13     std::vector<T>    signal;             // transmitted signal (LFM)
14     T                  azimuthal_angle;   // transmitter's azimuthal pointing direction
15     T                  elevation_angle;   // transmitter's elevation pointing direction
16     T                  azimuthal_beamwidth; // azimuthal beamwidth of transmitter
17     T                  elevation_beamwidth; // elevation beamwidth of transmitter
18     T                  range;             // a parameter used for spotlight mode.
19
20     // transmitted signal attributes
21     T                  f_low;             // lowest frequency of LFM
22     T                  f_high;           // highest frequency of LFM
23     T                  fc;               // center frequency of LFM
24     T                  bandwidth;        // bandwidth of LFM
25     T                  speed_of_sound {1500}; // speed of sound
26
27     // shadowing properties
28     int                azimuthQuantDensity; // quantization of angles along the
29     azimuth            elevationQuantDensity; // quantization of angles along the
30     elevation          rangeQuantSize;       // range-cell size when shadowing
31     T                  azimuthShadowThreshold; // azimuth thresholding
32     T                  elevationShadowThreshold; // elevation thresholding

```

```

33
34 // shadowing related
35 std::vector<T> checkbox; // box indicating whether a scatter for a
    range-angle pair has been found
36 std::vector<std::vector<std::vector<T>>> finalScatterBox; // a 3D tensor where the
    third dimension represnets the vector length
37 std::vector<T> finalReflectivityBox; // to store the reflectivity
38
39 // constructor
40 TransmitterClass() = default;
41
42 // Deleting copy constructors/assignment
43 TransmitterClass(const TransmitterClass& other) = delete;
44 TransmitterClass& operator=(TransmitterClass& other) = delete;
45
46 // Creating move-constructor and move-assignment
47 TransmitterClass(TransmitterClass&& other) = default;
48 TransmitterClass& operator=(TransmitterClass&& other) = default;
49
50 // member-functions
51 auto updatePointingAngle(std::vector<T> AUV_pointing_vector);
52 auto subset_scatterers(const ScattererClass<T>& seafloor,

```

2.3 Transmitter Setup Scripts

The following script shows the setup-script

```

1  template <
2      typename T,
3      typename = std::enable_if_t<
4          std::is_same_v<T, double> ||
5          std::is_same_v<T, float>
6      >
7  >
8  void fTransmitterSetup(
9      TransmitterClass<T>& transmitter_fls,
10     TransmitterClass<T>& transmitter_portside,
11     TransmitterClass<T>& transmitter_starboard
12 ){
13     // Setting up transmitter
14     T sampling_frequency {160e3}; // sampling frequency
15     T f1 {50e3}; // first frequency of LFM
16     T f2 {70e3}; // second frequency of LFM
17     T fc {(f1 + f2)/2.00}; // finding center-frequency
18     T bandwidth {std::abs(f2 - f1)}; // bandwidth
19     T pulselength {5e-2}; // time of recording
20
21     // building LFM
22     auto timearray {svr::linspace<T>(
23         0.00,
24         pulselength,
25         std::floor(pulselength * sampling_frequency)
26     )};
27     auto K {f2 - f1/pulselength}; // calculating frequency-slope
28     auto Signal {cos(2 * std::numbers::pi * \
29         (f1 + K*timearray) * \

```

```

30         timearray)}};           // frequency at each time-step, with f1
                                   = 0
31
32 // Setting up transmitter
33 auto location                    {std::vector<T>(3, 0)};           // location of
    transmitter
34 T azimuthal_angle_fls           {0};                             // initial
    pointing direction
35 T azimuthal_angle_port          {90};                             // initial
    pointing direction
36 T azimuthal_angle_starboard     {-90};                            // initial
    pointing direction
37
38 T elevation_angle               {-60};                             // initial
    pointing direction
39
40 T azimuthal_beamwidth_fls        {20};                             // azimuthal
    beamwidth of the signal cone
41 T azimuthal_beamwidth_port      {20};                             // azimuthal
    beamwidth of the signal cone
42 T azimuthal_beamwidth_starboard {20};                             // azimuthal
    beamwidth of the signal cone
43
44 T elevation_beamwidth_fls        {20};                             // elevation
    beamwidth of the signal cone
45 T elevation_beamwidth_port      {20};                             // elevation
    beamwidth of the signal cone
46 T elevation_beamwidth_starboard {20};                             // elevation
    beamwidth of the signal cone
47
48 int azimuthQuantDensity          {10}; // number of points, a degree is split
    into quantization density along azimuth (used for shadowing)
49 int elevationQuantDensity        {10}; // number of points, a degree is split
    into quantization density along elevation (used for shadowing)
50 T rangeQuantSize                 {10}; // the length of a cell (used for
    shadowing)
51
52 T azimuthShadowThreshold          {1}; // azimuth threshold (in degrees)
53 T elevationShadowThreshold        {1}; // elevation threshold (in degrees)
54
55
56 // transmitter-fls
57 transmitter_fls.location          = location;                     // Assigning
    location
58 transmitter_fls.signal            = Signal;                       // Assigning
    signal
59 transmitter_fls.azimuthal_angle   = azimuthal_angle_fls;         // assigning
    azimuth angle
60 transmitter_fls.elevation_angle   = elevation_angle;              // assigning
    elevation angle
61 transmitter_fls.azimuthal_beamwidth = azimuthal_beamwidth_fls;   // assigning
    azimuth-beamwidth
62 transmitter_fls.elevation_beamwidth = elevation_beamwidth_fls;   // assigning
    elevation-beamwidth
63 // updating quantization densities
64 transmitter_fls.azimuthQuantDensity = azimuthQuantDensity;       // assigning
    azimuth quant density
65 transmitter_fls.elevationQuantDensity = elevationQuantDensity;    // assigning
    elevation quant density

```

```

66 transmitter_fls.rangeQuantSize          = rangeQuantSize;          // assigning
    range-quantization
67 transmitter_fls.azimuthShadowThreshold = azimuthShadowThreshold; //
    azimuth-threshold in shadowing
68 transmitter_fls.elevationShadowThreshold = elevationShadowThreshold; //
    elevation-threshold in shadowing
69 // signal related
70 transmitter_fls.f_low                   = f1;          // assigning lower frequency
71 transmitter_fls.f_high                  = f2;          // assigning higher frequency
72 transmitter_fls.fc                     = fc;          // assigning center frequency
73 transmitter_fls.bandwidth               = bandwidth;   // assigning bandwidth
74
75
76 // transmitter-portside
77 transmitter_portside.location           = location;     // Assigning
    location
78 transmitter_portside.signal             = Signal;       // Assigning
    signal
79 transmitter_portside.azimuthal_angle    = azimuthal_angle_port; // assigning
    azimuth angle
80 transmitter_portside.elevation_angle    = elevation_angle; // assigning
    elevation angle
81 transmitter_portside.azimuthal_beamwidth = azimuthal_beamwidth_port; // assigning
    azimuth-beamwidth
82 transmitter_portside.elevation_beamwidth = elevation_beamwidth_port; // assigning
    elevation-beamwidth
83 // updating quantization densities
84 transmitter_portside.azimuthQuantDensity = azimuthQuantDensity; // assigning
    azimuth quant density
85 transmitter_portside.elevationQuantDensity = elevationQuantDensity; // assigning
    elevation quant density
86 transmitter_portside.rangeQuantSize      = rangeQuantSize; // assigning
    range-quantization
87 transmitter_portside.azimuthShadowThreshold = azimuthShadowThreshold; //
    azimuth-threshold in shadowing
88 transmitter_portside.elevationShadowThreshold = elevationShadowThreshold; //
    elevation-threshold in shadowing
89 // signal related
90 transmitter_portside.f_low               = f1;          // assigning
    lower frequency
91 transmitter_portside.f_high              = f2;          // assigning
    higher frequency
92 transmitter_portside.fc                 = fc;          // assigning
    center frequency
93 transmitter_portside.bandwidth           = bandwidth;   // assigning
    bandwidth
94
95
96 // transmitter-starboard
97 transmitter_starboard.location           = location;     //
    assigning location
98 transmitter_starboard.signal             = Signal;       //
    assigning signal
99 transmitter_starboard.azimuthal_angle    = azimuthal_angle_starboard; //
    assigning azimuthal signal
100 transmitter_starboard.elevation_angle    = elevation_angle;
101 transmitter_starboard.azimuthal_beamwidth = azimuthal_beamwidth_starboard;
102 transmitter_starboard.elevation_beamwidth = elevation_beamwidth_starboard;
103 // updating quantization densities

```



```
104 transmitter_starboard.azimuthQuantDensity    = azimuthQuantDensity;    //
      assigning azimuth-quant-density
105 transmitter_starboard.elevationQuantDensity  = elevationQuantDensity;
106 transmitter_starboard.rangeQuantSize         = rangeQuantSize;
107 transmitter_starboard.azimuthShadowThreshold = azimuthShadowThreshold;
108 transmitter_starboard.elevationShadowThreshold = elevationShadowThreshold;
109 // signal related
110 transmitter_starboard.f_low                   = f1;                        //
      assigning lower frequency
111 transmitter_starboard.f_high                  = f2;                        //
      assigning higher frequency
112 transmitter_starboard.fc                     = fc;                        //
      assigning center frequency
113 transmitter_starboard.bandwidth               = bandwidth;                //
      assigning bandwidth
114 }
115 }
```

Chapter 3

Uniform Linear Array

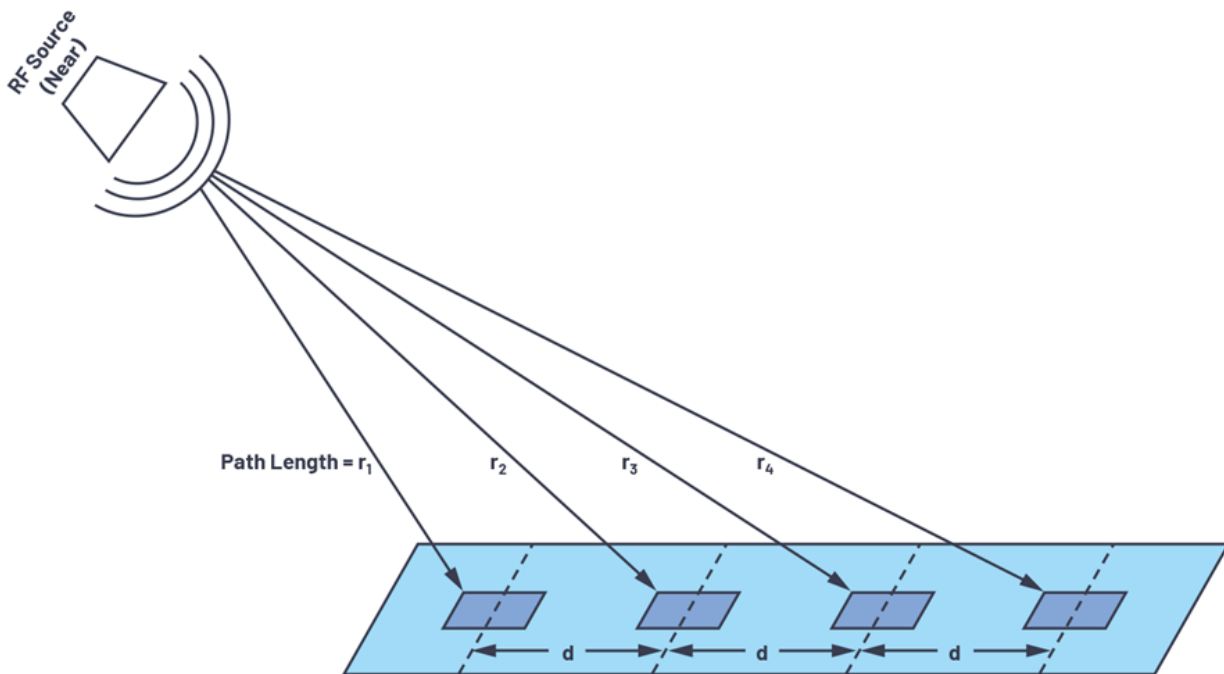


Figure 3.1: Uniform Linear Array

Overview

A Uniform Linear Array (ULA) is a common antenna or sensor configuration in which multiple elements are arranged in a straight line with equal spacing between adjacent elements. This geometry simplifies both the analysis and implementation of array signal processing techniques. In a ULA, each element receives a version of the incoming signal that differs only in phase, depending on the angle of arrival. This phase difference can be exploited to steer the array's beam in a desired direction (beamforming) or to estimate the direction of arrival (DOA) of multiple sources. The equal spacing also leads to a regular phase progression across the elements, which makes the array's response mathematically tractable and allows the use of tools like the discrete Fourier transform (DFT) to analyze spatial frequency content.

The performance of a ULA depends on the number of elements and their spacing. The spacing is typically chosen to be half the wavelength of the signal to avoid spatial aliasing, also called grating lobes, which can introduce ambiguities in DOA estimation. Increasing the number of elements improves the array's angular resolution and directivity, meaning it can better distinguish closely spaced sources and focus energy more narrowly. ULAs are widely used in radar, sonar, wireless communications, and microphone arrays due to their simplicity, predictable behavior, and compatibility with well-established signal processing algorithms. Their linear structure also makes them easier to implement in hardware compared to more complex array geometries like circular or planar arrays.

3.1 ULA Class Definition

The following is the class used to represent the uniform linear array

```

1  template <typename T>
2  class ULAClass
3  {
4  public:
5      // intrinsic parameters
6      std::size_t          num_sensors;                // number of
           sensors
7      T                    inter_element_spacing;      // space between
           sensors
8      std::vector<std::vector<T>> coordinates;          // coordinates
           of each sensor
9      T                    sampling_frequency;          // sampling
           frequency of the sensors
10     T                    recording_period;            // recording
           period of the ULA
11     std::vector<T>        location;                   // location of
           first coordinate
12
13     // derived
14     std::vector<T>        sensor_direction;
15     std::vector<std::vector<T>> signal_matrix;
16     std::size_t          num_samples;
17
18     // decimation related
19     int                   decimation_factor;          // the new
           decimation factor
20     T                    post_decimation_sampling_frequency; // the new
           sampling frequency
21     std::vector<T>        lowpass_filter_coefficients_for_decimation; //
           filter-coefficients for filtering
22
23     // imaging related
24     T range_resolution; // theoretical range-resolution =  $\frac{c}{2B}$ 
25     T azimuthal_resolution; // theoretical azimuth-resolution =
            $\frac{\lambda}{(N-1) \cdot \text{inter-element-distance}}$ 
26     T range_cell_size; // the range-cell quanta we're choosing for
           efficiency trade-off
27     T azimuth_cell_size; // the azimuth quanta we're choosing
28     std::vector<T> azimuth_centers; // tensor containing the azimuth centers
29     std::vector<T> range_centers; // tensor containing the range-centers
30     int frame_size; // the frame-size corresponding to a range cell in a
           decimated signal matrix

```

```

31
32     std::vector<std::vector<complex<T>>> mulFFTMMatrix; // the matrix containing the
        delays for each-element as a slot
33     std::vector<complex<T>> matchFilter; // torch tensor containing the
        match-filter
34     int num_buffer_zeros_per_frame; // number of zeros we're adding
        per frame to ensure no-rotation
35     std::vector<std::vector<T>> beamformedImage; // the beamformed image
36     std::vector<std::vector<T>> cartesianImage; // the cartesian version of
        beamformed image
37
38     // Decimating Related
39     std::vector<std::complex<T>> basebanding_signal;
40
41     // Artificial acoustic-image related
42     std::vector<std::vector<T>> currentArtificialAcousticImage; // acoustic image
        directly produced
43
44
45     // Basic Constructor
46     ULAClass() = default;
47
48     // constructor
49     ULAClass(const int num_sensors_arg,
50               const auto inter_element_spacing_arg,
51               const auto& coordinates_arg,
52               const auto& sampling_frequency_arg,
53               const auto& recording_period_arg,
54               const auto& location_arg,
55               const auto& signalMatrix_arg,
56               const auto& lowpass_filter_coefficients_for_decimation_arg):
57         num_sensors(num_sensors_arg),
58         inter_element_spacing(inter_element_spacing_arg),
59         coordinates(std::move(coordinates_arg)),
60         sampling_frequency(sampling_frequency_arg),
61         recording_period(recording_period_arg),
62         location(std::move(location_arg)),
63         signal_matrix(std::move(signalMatrix_arg)),
64         lowpass_filter_coefficients_for_decimation(std::move(lowpass_filter_coefficients_for_decima
65     {
66
67         // calculating ULA direction
68         sensor_direction = std::vector<T>{coordinates[1][0] - coordinates[0][0],
69                                           coordinates[1][1] - coordinates[0][1],
70                                           coordinates[1][2] - coordinates[0][2]};
71
72         // normalizing
73         auto norm_value_temp {std::norm(std::inner_product(sensor_direction.begin(),
74                                                             sensor_direction.end(),
75                                                             sensor_direction.begin(),
76                                                             0.00))};
77
78         // dividing
79         if (norm_value_temp != 0) {sensor_direction = sensor_direction /
            norm_value_temp;}
80
81     }
82
83     // // deleting copy constructor/assignment

```

```

84 // ULAClass<T>(const ULAClass<T>& other)           = delete;
85 // ULAClass<T>& operator=(const ULAClass<T>& other) = delete;
86 ULAClass<T>(ULAClass<T>&& other)                   = delete;
87 ULAClass<T>& operator=(const ULAClass<T>& other)    = default;
88
89 // member-functions
90 void buildCoordinatesBasedOnLocation();
91 void buildCoordinatesBasedOnLocation(const std::vector<T>& new_location);

```

3.2 ULA Setup Scripts

The following script shows the setup-script for Uniform Linear Arrays

```

1  template <
2      typename T,
3      typename = std::enable_if_t<
4          std::is_same_v<T, double> ||
5          std::is_same_v<T, float>
6      >
7  >
8  void fULASetup(
9      ULAClass<T>&    ula_fls,
10     ULAClass<T>&    ula_portside,
11     ULAClass<T>&    ula_starboard)
12 {
13     // setting up ula
14     auto num_sensors      {static_cast<int>(32)};           // number of sensors
15     T    sampling_frequency {static_cast<T>(160e3)};        // sampling frequency
16     T    inter_element_spacing {1500/(2*sampling_frequency)}; // space between
17         samples
18     T    recording_period {10e-2};                         // sampling-period
19     auto num_samples      {static_cast<std::size_t>(
20         std::ceil(
21             sampling_frequency * recording_period
22         )
23     )};
24
25     // building the direction for the sensors
26     auto ULA_direction      {std::vector<T>({-1, 0, 0})};
27     auto ULA_direction_norm {norm(ULA_direction)};
28     if (ULA_direction_norm != 0) {ULA_direction = ULA_direction/ULA_direction_norm;}
29     ULA_direction          = ULA_direction * inter_element_spacing;
30
31     // building coordinates for sensors
32     auto ULA_coordinates    {
33         transpose(ULA_direction) * \
34         svr::linspace<double>(
35             0.00,
36             num_sensors -1,
37             num_sensors)
38     };
39
40     // coefficients of decimation filter
41     auto lowpassfiltercoefficients {std::vector<T>{0.0000, 0.0000, 0.0000, 0.0000,
42         0.0000, 0.0000, 0.0001, 0.0003, 0.0006, 0.0015, 0.0030, 0.0057, 0.0100, 0.0163,
43         0.0251, 0.0364, 0.0501, 0.0654, 0.0814, 0.0966, 0.1093, 0.1180, 0.1212, 0.1179,

```

```

0.1078, 0.0914, 0.0699, 0.0451, 0.0192, -0.0053, -0.0262, -0.0416, -0.0504,
-0.0522, -0.0475, -0.0375, -0.0239, -0.0088, 0.0057, 0.0179, 0.0263, 0.0303,
0.0298, 0.0253, 0.0177, 0.0086, -0.0008, -0.0091, -0.0153, -0.0187, -0.0191,
-0.0168, -0.0123, -0.0065, -0.0004, 0.0052, 0.0095, 0.0119, 0.0125, 0.0112,
0.0084, 0.0046, 0.0006, -0.0031, -0.0060, -0.0078, -0.0082, -0.0075, -0.0057,
-0.0033, -0.0006, 0.0019, 0.0039, 0.0051, 0.0055, 0.0050, 0.0039, 0.0023, 0.0005,
-0.0012, -0.0025, -0.0034, -0.0036, -0.0034, -0.0026, -0.0016, -0.0004, 0.0007,
0.0016, 0.0022, 0.0024, 0.0023, 0.0018, 0.0011, 0.0003, -0.0004, -0.0011,
-0.0015, -0.0016, -0.0015}};

```

```

41
42 // assigning values
43 ula_fls.num_sensors                = num_sensors;
44 ula_fls.inter_element_spacing      = inter_element_spacing;
45 ula_fls.coordinates                = ULA_coordinates;
46 ula_fls.sampling_frequency         = sampling_frequency;
47 ula_fls.recording_period           = recording_period;
48 ula_fls.sensor_direction           = ULA_direction;
49 ula_fls.lowpass_filter_coefficients_for_decimation = lowpassfiltercoefficients;
50 ula_fls.num_samples                = num_samples;
51
52
53 // assigning values
54 ula_portside.num_sensors            = num_sensors;
55 ula_portside.inter_element_spacing  = inter_element_spacing;
56 ula_portside.coordinates            = ULA_coordinates;
57 ula_portside.sampling_frequency     = sampling_frequency;
58 ula_portside.recording_period       = recording_period;
59 ula_portside.sensor_direction       = ULA_direction;
60 ula_portside.lowpass_filter_coefficients_for_decimation = lowpassfiltercoefficients;
61 ula_portside.num_samples            = num_samples;
62
63
64 // assigning values
65 ula_starboard.num_sensors           = num_sensors;
66 ula_starboard.inter_element_spacing = inter_element_spacing;
67 ula_starboard.coordinates           = ULA_coordinates;
68 ula_starboard.sampling_frequency    = sampling_frequency;
69 ula_starboard.recording_period      = recording_period;
70 ula_starboard.sensor_direction      = ULA_direction;
71 ula_starboard.lowpass_filter_coefficients_for_decimation = lowpassfiltercoefficients;
72 ula_starboard.num_samples           = num_samples;
73 }

```

Chapter 4

Autonomous Underwater Vehicle

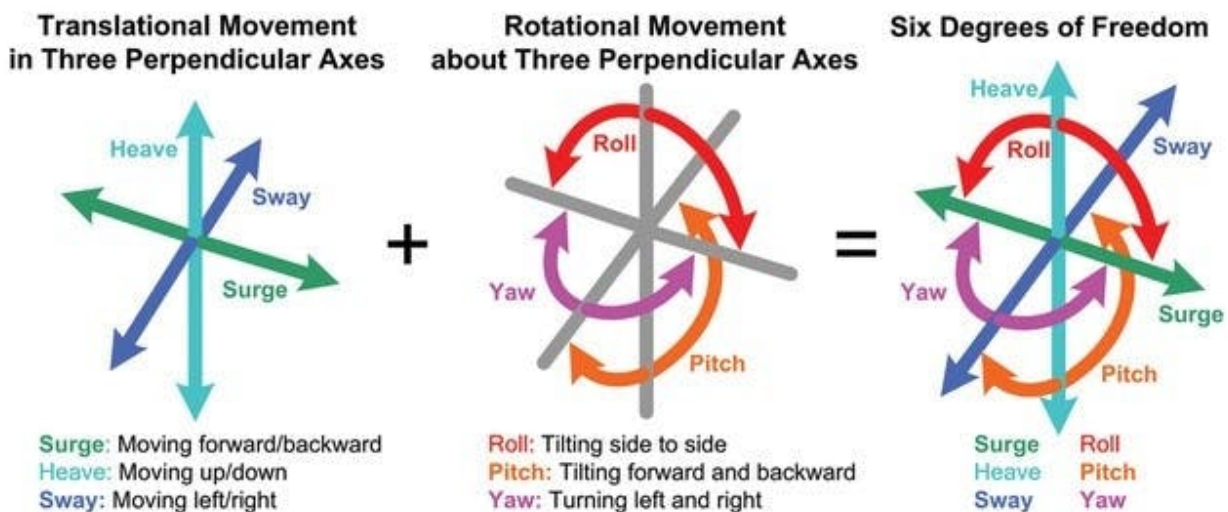


Figure 4.1: AUV degrees of freedom

Overview

Autonomous Underwater Vehicles (AUVs) are robotic systems designed to operate underwater without direct human control. They navigate and perform missions independently using onboard sensors, processors, and preprogrammed instructions. They are widely used in oceanographic research, environmental monitoring, offshore engineering, and military applications. AUVs can vary in size from small, portable vehicles for shallow water surveys to large, torpedo-shaped platforms capable of deep-sea exploration. Their autonomy allows them to access environments that are too dangerous, remote, or impractical for human divers or tethered vehicles.

The navigation and sensing systems of AUVs are critical to their performance. They typically use a combination of inertial measurement units (IMUs), Doppler velocity logs

(DVLs), pressure sensors, magnetometers, and sometimes acoustic positioning systems to estimate their position and orientation underwater. Since GPS signals do not penetrate water, AUVs must rely on these onboard sensors and occasional surfacing for GPS fixes. They are often equipped with sonar systems, cameras, or other scientific instruments to collect data about the seafloor, water column, or underwater structures. Advanced AUVs can also implement adaptive mission planning and obstacle avoidance, enabling them to respond to changes in the environment in real time.

The applications of AUVs are diverse and expanding rapidly. In scientific research, they are used for mapping the seafloor, studying marine life, and monitoring oceanographic parameters such as temperature, salinity, and currents. In the commercial sector, AUVs inspect pipelines, subsea infrastructure, and offshore oil platforms. Military and defense applications include mine countermeasure operations and underwater surveillance. The development of AUVs continues to focus on increasing endurance, improving autonomy, enhancing sensor payloads, and reducing costs, making them a key technology for exploring and understanding the underwater environment efficiently and safely.

4.1 AUV Class Definition

The following is the class used to represent the uniform linear array

```

1  template <
2      typename T,
3      typename = std::enable_if_t<std::is_floating_point_v<T>>
4  >
5  class AUVClass{
6  public:
7
8      // Intrinsic attributes
9      std::vector<T>    location;           // location of vessel
10     std::vector<T>    velocity;           // velocity of the vessel
11     std::vector<T>    acceleration;       // acceleration of vessel
12     std::vector<T>    pointing_direction; // AUV's pointing direction
13
14     // uniform linear-arrays
15     ULAClass<T>        ULA_fls;           // front-looking SONAR ULA
16     ULAClass<T>        ULA_portside;      // mounted ULA [object of class, ULAClass]
17     ULAClass<T>        ULA_starboard;     // mounted ULA [object of class, ULAClass]
18
19     // transmitters
20     TransmitterClass<T> transmitter_fls;   // transmitter for front-looking SONAR
21     TransmitterClass<T> transmitter_portside; // portside transmitter
22     TransmitterClass<T> transmitter_starboard; // starboard transmitter
23
24     // derived or dependent attributes
25     std::vector<std::vector<T>> signalMatrix_1; // matrix containing the
26     signals obtained from ULA_1
27     std::vector<std::vector<T>> largeSignalMatrix_1; // matrix holding signal of
28     synthetic aperture
29     std::vector<std::vector<T>> beamformedLargeSignalMatrix; // each column is the
30     beamformed signal at each stop-hop
31
32     // plotting mode
33     bool plottingmode; // to suppress plotting associated with classes

```



```

31
32 // spotlight mode related
33 std::vector<std::vector<T>> absolute_coords_patch_cart; // cartesian coordinates of
    patch
34
35 // Synthetic Aperture Related
36 std::vector<std::vector<T>> ApertureSensorLocations; // sensor locations of
    aperture
37
38 // functions
39 void syncComponentAttributes();
40 void init(
41     svr::ThreadPool& thread_pool,
42     svr::FFTPlanUniformPoolHandle<T, std::complex<T>>& fph_match_filter,
43     svr::IFFTPPlanUniformPoolHandle<std::complex<T>, T>& ifph_match_filter);
44 void simulate_signal(
45     const ScattererClass<T>& seafloor,
46     svr::ThreadPool& thread_pool,
47     svr::FFTPlanUniformPoolHandle<T, std::complex<T>>& fft_pool_handle,
48     svr::IFFTPPlanUniformPoolHandle<std::complex<T>, T>& ifft_pool_handle);
49 void subset_scatterers(
50     const ScattererClass<T>& seafloor,
51     svr::ThreadPool& thread_pool,
52     std::vector<std::size_t>& fls_scatterer_indices,

```

4.2 AUV Setup Scripts

The following script shows the setup-script for Uniform Linear Arrays

```

1 template <
2     typename T,
3     typename = std::enable_if_t<
4         std::is_same_v<T, double> ||
5         std::is_same_v<T, float>
6     >
7 >
8 void fAUVSetup(AUVClass<T>& auv) {
9
10     // building properties for the auv
11     auto location {std::vector<T>{0, 50, 30}}; // starting location
12     auto velocity {std::vector<T>{5, 0, 0}}; // starting velocity
13     auto pointing_direction {std::vector<T>{1, 0, 0}}; // pointing direction
14
15     // assigning
16     auv.location = std::move(location); // assigning location
17     auv.velocity = std::move(velocity); // assigning velocity
18     auv.pointing_direction = std::move(pointing_direction); // assigning pointing
        direction
19
20     // signaling end
21     std::cout << format("> Completed AUV-setup\n");
22
23 }

```

Part II

Signal Simulation Pipeline

Chapter 5

Signal Simulation

Overview

The signal simulation pipeline is the pipeline responsible for simulating/modeling the signals sampled by the ULA-sensors under a real sub-marine environment. This chapter, and the subsequent ones, deal with the assumptions, mathematics, physics and code that goes into the design and creation of the pipeline.

A disclaimer that goes without saying is that signal-simulation is a world of its own. There's a reason that comsol, flexcompute and other numerical-simulation based companies exist. To write a signal simulation, from scratch, while these entities exist, and to make any case that this competes with those, would be flirting with delusion.

To that end, we don't write general-purpose signal simulation pipeline. However, the effort in the signal-simulator direction is purely for application-specific reasons. This is something I can talk about. One of the major in-house signal simulation pipelines yours truly developed at Naval Physical and Oceanographic Laboratory did just that. The aim of that pipeline was not to re-invent the wheel. But to create one that existed at the right speed-fidelity trade-off that the institute operated in. The pipeline created during my time there had several toggles corresponding to the different information to consider during simulation. The more information pertaining to the environment, is involved, the higher the compute and time required. Thus, mid-to-high fidelity pipelines often involve writing well-tuned GPU-supported C++ (think, CUDA). And this is important when you have pipelines downstream whose outputs depend on the signal accuracy, and by association, signal simulator fidelity.

To that end, understanding what this pipeline is not, is perhaps just as important as what it is. The core priority of this signal simulator pipeline is to produce signals for navigation. Navigation does not require high-accuracy signals owing to the very simple fact that decisions made from high-accuracy signals and low-accuracy signals tend to be the same as long as environment-topology information is not lost. To grossly oversimplify what I mean by that, the outcome of your driving doesn't change whether you have high-definition LIDAR mapping the surrounding environment to the millimeter level or if you're just driving with your eyes. Thus fidelity of simulator is not a priority and I will not be putting in the kind of effort I put in at NPOL, for this reason (also because I don't want OPSEC to be

mad).

To put it simply, the signal simulation pipeline is quite trivial as far as signal simulators are concerned. But it'll work perfectly for our purposes. And thus, we'll be choosing the simplest of systems and one I like to call, "the EE engineer's best friend": the infamous Linear Time Invariant systems.

Part III

Imaging Pipeline

Part IV

Perception & Control Pipeline

Appendix A

Application Specific Tools

A.1 CSV File-Writes

```
1 #pragma once
2 /*=====
3 writing the contents of a vector a csv-file
4 -----*/
5 template <typename T>
6 void fWriteVector(const vector<T>&          inputvector,
7                  const string&            filename){
8
9     // opening a file
10    std::ofstream fileobj(filename);
11    if (!fileobj) {return;}
12
13    // writing the real parts in the first column and the imaginary parts int he second
14    // column
15    if constexpr(std::is_same_v<T, std::complex<double>> ||
16                  std::is_same_v<T, std::complex<float>> ||
17                  std::is_same_v<T, std::complex<long double>>){
18        for(int i = 0; i<inputvector.size(); ++i){
19            // adding entry
20            fileobj << inputvector[i].real() << "+" << inputvector[i].imag() << "i";
21
22            // adding delimiter
23            if(i!=inputvector.size()-1) {fileobj << ",";}
24            else {fileobj << "\n";}
25        }
26    }
27    else{
28        for(int i = 0; i<inputvector.size(); ++i){
29            fileobj << inputvector[i];
30            if(i!=inputvector.size()-1) {fileobj << ",";}
31            else {fileobj << "\n";}
32        }
33    }
34
35    // return
36    return;
37 }
38 /*=====
```

```

38  writing the contents of a matrix to a csv-file
39  -----*/
40  template <typename T>
41  auto fWriteMatrix(const std::vector<std::vector<T>> inputMatrix,
42                  const string filename){
43
44      // opening a file
45      std::ofstream fileobj(filename);
46
47      // writing
48      if (fileobj){
49          for(int i = 0; i<inputMatrix.size(); ++i){
50              for(int j = 0; j<inputMatrix[0].size(); ++j){
51                  fileobj << inputMatrix[i][j];
52                  if (j!=inputMatrix[0].size()-1) {fileobj << ",";}
53                  else {fileobj << "\n";}
54              }
55          }
56      }
57      else{
58          cout << format("File-write to {} failed\n", filename);
59      }
60  }
61
62  /*=====
63  writing complex-matrix to a csv-file
64  -----*/
65  template <>
66  auto fWriteMatrix(const std::vector<std::vector<std::complex<double>>> inputMatrix,
67                  const string filename){
68
69      // opening a file
70      std::ofstream fileobj(filename);
71
72      // writing
73      if (fileobj){
74          for(int i = 0; i<inputMatrix.size(); ++i){
75              for(int j = 0; j<inputMatrix[0].size(); ++j){
76                  fileobj << inputMatrix[i][j].real() << "+" << inputMatrix[i][j].imag() <<
77                      "i";
78                  if (j!=inputMatrix[0].size()-1) {fileobj << ",";}
79                  else {fileobj << "\n";}
80              }
81          }
82      }
83      else{
84          cout << format("File-write to {} failed\n", filename);
85      }
86  }

```

A.2 Thread-Pool

```

1  #pragma once
2  namespace svr {
3      class ThreadPool {
4      public:

```



```

5      // Members
6      boost::asio::thread_pool      thread_pool;      // the pool
7      std::vector<std::future<void>> future_vector;    // futures to wait on
8
9      // Special-Members
10     ThreadPool(std::size_t num_threads) : thread_pool(num_threads) {}
11     ThreadPool(const ThreadPool& other)    = delete;
12     ThreadPool& operator=(ThreadPool& other) = delete;
13
14     // Member-functions
15     void converge();
16     template <typename F> void push_back(F&& func);
17     void shutdown();
18
19 private:
20     template<typename F>
21     std::future<void> _wrap_task(F&& func) {
22         std::promise<void> p;
23         auto f = p.get_future();
24
25         boost::asio::post(thread_pool,
26             [func = std::forward<F>(func), p = std::move(p)]() mutable {
27                 func();
28                 p.set_value();
29             });
30
31         return f;
32     }
33 };
34
35 /*=====
36 Member-Function: Add new task to the pool
37 -----*/
38 template <typename F>
39 void ThreadPool::push_back(F&& func)
40 {
41     future_vector.push_back(_wrap_task(std::forward<F>(func)));
42 }
43 /*=====
44 Member-Function: waiting until all the assigned work is done
45 -----*/
46 void ThreadPool::converge()
47 {
48     for (auto &fut : future_vector) fut.get();
49     future_vector.clear();
50 }
51 /*=====
52 Member-Function: Shutting things down
53 -----*/
54 void ThreadPool::shutdown()
55 {
56     thread_pool.join();
57 }
58
59 }

```

A.3 FFTPlanClass

```

1  #pragma once
2
3  namespace svr    {
4
5      template <typename T>
6      concept FFTPlanClassSourceDestinationType = \
7          std::is_floating_point_v<T> ||
8          (
9              std::is_class_v<T> &&
10             std::is_floating_point_v<typename T::value_type>
11         );
12     template <
13         FFTPlanClassSourceDestinationType sourceType,
14         FFTPlanClassSourceDestinationType destinationType
15     >
16     class FFTPlanClass
17     {
18     public:
19
20         // Members
21         std::size_t    nfft_        {std::numeric_limits<std::size_t>::max()};
22         fftw_complex*  in_          {nullptr};
23         fftw_complex*  out_         {nullptr};
24         fftw_plan      plan_        {nullptr};
25
26         /*=====
27         Destructor
28         -----*/
29         ~FFTPlanClass()
30         {
31             if(plan_ != nullptr) {fftw_destroy_plan(    plan_);}
32             if(in_   != nullptr) {fftw_free(            in_);}
33             if(out_  != nullptr) {fftw_free(            out_);}
34         }
35         /*=====
36         Default Constructor
37         -----*/
38         FFTPlanClass() = default;
39         /*=====
40         Constructor
41         -----*/
42         FFTPlanClass(const std::size_t  nfft)
43         {
44
45             // allocating nfft
46             this->nfft_ = nfft;
47
48             // allocating input-region
49             in_   = reinterpret_cast<fftw_complex*>(
50                 fftw_malloc(nfft_ * sizeof(fftw_complex))
51             );
52             out_  = reinterpret_cast<fftw_complex*>(
53                 fftw_malloc(nfft_ * sizeof(fftw_complex))
54             );
55             if(!in_ || !out_) {throw std::runtime_error("FILE: FFTPlanClass.hpp |
56                 CLASS: FFTPlanClass | REPORT: in-out allocation failed");}
57
58             // creating plan
59             plan_ = fftw_plan_dft_1d(

```

```

59         static_cast<int>(nfft_),
60         in_,
61         out_,
62         FFTW_FORWARD,
63         FFTW_MEASURE
64     );
65     if(!plan_) {throw std::runtime_error("FILE: FFTPlanClass.hpp |
66         CLASS: FFTPlanClass | REPORT: plan-creation failed");}
67 }
68 /*=====
69 Copy Constructor
70 -----*/
71 FFTPlanClass(const FFTPlanClass& other)
72 {
73     // copying nfft
74     nfft_ = other.nfft_;
75     cout << format("\t\t FFTPlanClass(const FFTPlanClass& other) | nfft_ =
76         {}\n", nfft_);
77
78     // allocating input-region
79     in_ = reinterpret_cast<fftw_complex*>(
80         fftw_malloc(nfft_ * sizeof(fftw_complex))
81     );
82     out_ = reinterpret_cast<fftw_complex*>(
83         fftw_malloc(nfft_ * sizeof(fftw_complex))
84     );
85     if(!in_ || !out_) {throw std::runtime_error("FILE: FFTPlanClass.hpp |
86         CLASS: FFTPlanClass | REPORT: in-out allocation failed");}
87
88     // copying input-region and output-region
89     std::memcpy(in_, other.in_, nfft_ * sizeof(fftw_complex));
90     std::memcpy(out_, other.out_, nfft_ * sizeof(fftw_complex));
91
92     // creating plan
93     plan_ = fftw_plan_dft_1d(
94         static_cast<int>(nfft_),
95         in_,
96         out_,
97         FFTW_FORWARD,
98         FFTW_MEASURE
99     );
100     if(!plan_) {throw std::runtime_error("FILE: FFTPlanClass.hpp |
101         CLASS: FFTPlanClass | REPORT: plan-creation failed");}
102 }
103 /*=====
104 Copy Assignment
105 -----*/
106 FFTPlanClass& operator=(const FFTPlanClass& other)
107 {
108     // handling self-assignment
109     if (this == &other) {return *this;}
110
111     // cleaning-up existing resources
112     if(plan_ != nullptr) {fftw_destroy_plan( plan_);}
113     if(in_ != nullptr) {fftw_free( in_);}
114     if(out_ != nullptr) {fftw_free( out_);}
115
116     // allocating input-region and output-region
117     nfft_ = other.nfft_;

```

```

114         in_      = reinterpret_cast<fftw_complex*>(
115             fftw_malloc(nfft_ * sizeof(fftw_complex))
116         );
117         out_     = reinterpret_cast<fftw_complex*>(
118             fftw_malloc(nfft_ * sizeof(fftw_complex))
119         );
120         if(!in_ || !out_) {throw std::runtime_error("FILE: FFTPlanClass.hpp |
121             CLASS: FFTPlanClass | FUNCTION: Copy-Assignment | REPORT: in-out
122             allocation failed");}
123
124         // copying contents
125         cout << format("\t\t FFTPlanClass& operator=(const FFTPlanClass& other) |
126             nfft_ = {} \n", nfft_);
127         std::memcpy(in_, other.in_, nfft_ * sizeof(fftw_complex));
128         std::memcpy(out_, other.out_, nfft_ * sizeof(fftw_complex));
129
130         // creating engine
131         plan_ = fftw_plan_dft_id(
132             static_cast<int>(nfft_),
133             in_,
134             out_,
135             FFTW_FORWARD,
136             FFTW_MEASURE
137         );
138         if(!plan_) {throw std::runtime_error("FILE: FFTPlanClass.hpp | CLASS:
139             FFTPlanClass | FUNCTION: Copy-Assignment | REPORT: plan-creation
140             failed");}
141
142         // returning
143         return *this;
144     }
145     /*=====
146     Move Constructor
147     -----*/
148     FFTPlanClass(FFTPlanClass&& other)
149     :   nfft_(      other.nfft_),
150         in_(        other.in_),
151         out_(       other.out_),
152         plan_(      other.plan_)
153     {
154         // resetting the others
155         other.nfft_ = 0;
156         other.in_   = nullptr;
157         other.out_  = nullptr;
158         other.plan_ = nullptr;
159     }
160     /*=====
161     Move Assignment
162     -----*/
163     FFTPlanClass& operator=(FFTPlanClass&& other)
164     {
165         // self-assignment check
166         if (this == &other) {return *this;}
167
168         // cleaning up existing resources
169         if(plan_ != nullptr) {fftw_destroy_plan(    plan_);}
170         if(in_   != nullptr) {fftw_free(           in_);}
171         if(out_  != nullptr) {fftw_free(           out_);}

```

```

168 // Copying-values and changing pointers
169 nfft_ = other.nfft_;
170 cout << format("\t\t FFTPlanClass's MOVE assignment | nfft_ = {}\n",
171               nfft_);
172 in_ = other.in_;
173 out_ = other.out_;
174 plan_ = other.plan_;
175
176 // resetting source-members
177 other.nfft_ = 0;
178 other.in_ = nullptr;
179 other.out_ = nullptr;
180 other.plan_ = nullptr;
181
182 // returning
183 return *this;
184 }
185 /*=====
186 Running fft
187 -----*/
188 std::vector<destinationType>
189 fft(const std::vector<sourceType>& input_vector)
190 {
191     // throwing an error
192     if (input_vector.size() > nfft_){
193         cout << format("input_vector.size() = {}, nfft_ = {}\n",
194                       input_vector.size(),
195                       nfft_);
196         throw std::runtime_error("FILE: FFTPlanClass.hpp | CLASS: FFTPlanClass
197                                   | FUNCTION: fft() | REPORT: input-vector size is greater than
198                                   NFFT");
199     }
200
201     // copying inputs
202     for(std::size_t index = 0; index < input_vector.size(); ++index)
203     {
204         if constexpr(
205             std::is_floating_point_v<sourceType>
206         ){
207             in_[index][0] = input_vector[index];
208             in_[index][1] = 0;
209         }
210         else if constexpr(
211             std::is_same_v<sourceType, std::complex<float>> ||
212             std::is_same_v<sourceType, std::complex<double>>
213         ){
214             in_[index][0] = input_vector[index].real();
215             in_[index][1] = input_vector[index].imag();
216         }
217     }
218
219     // executing fft
220     fftw_execute(plan_);
221
222     // copying results to output-vector
223     std::vector<destinationType> output_vector(nfft_);
224     for(std::size_t index = 0; index < nfft_; ++index){
225         if constexpr(

```

```

224         std::is_same_v<destinationType, std::complex<float>> ||
225         std::is_same_v<destinationType, std::complex<double>>
226     ){
227         output_vector[index] = destinationType(
228             out_[index][0],
229             out_[index][1]
230         );
231     }
232     else if constexpr(
233         std::is_floating_point_v<destinationType>
234     ){
235         output_vector[index] = static_cast<destinationType>(
236             std::sqrt(
237                 std::pow(out_[index][0], 2) + \
238                 std::pow(out_[index][1], 2)
239             )
240         );
241     }
242 }
243
244 // returning output
245 return std::move(output_vector);
246 }
247 /*=====
248 Running fft - balanced
249 -----*/
250 std::vector<destinationType>
251 fft_l2_conserved(const std::vector<sourceType>& input_vector)
252 {
253     // throwing an error
254     if (input_vector.size() > nfft_)
255         throw std::runtime_error("FILE: FFTPlanClass.hpp | CLASS: FFTPlanClass
256                                     | FUNCTION: fft() | REPORT: input-vector size is greater than
257                                     NFFT");
258
259     // copying inputs
260     for(std::size_t index = 0; index < input_vector.size(); ++index)
261     {
262         if constexpr(
263             std::is_floating_point_v<sourceType>
264         ){
265             in_[index][0] = input_vector[index];
266             in_[index][1] = 0;
267         }
268         else if constexpr(
269             std::is_same_v<sourceType, std::complex<float>> ||
270             std::is_same_v<sourceType, std::complex<double>>
271         ){
272             in_[index][0] = input_vector[index].real();
273             in_[index][1] = input_vector[index].imag();
274         }
275     }
276
277     // executing fft
278     fftw_execute(plan_);
279
280     // copying results to output-vector
281     std::vector<destinationType> output_vector(nfft_);
282     for(std::size_t index = 0; index < nfft_; ++index)

```

```

281     {
282         if constexpr(
283             std::is_same_v< destinationType, std::complex<double> > ||
284             std::is_same_v< destinationType, std::complex<float> >
285         ){
286             output_vector[index] = destinationType(
287                 out_[index][0] * (1.00 / std::sqrt(nfft_)),
288                 out_[index][1] * (1.00 / std::sqrt(nfft_))
289             );
290         }
291         else if constexpr(
292             std::is_floating_point_v<destinationType>
293         ){
294             output_vector[index] = destinationType(
295                 std::sqrt(
296                     std::pow(out_[index][0] * (1.00 / std::sqrt(nfft_)), 2) + \
297                     std::pow(out_[index][1] * (1.00 / std::sqrt(nfft_)), 2)
298                 )
299             );
300         }
301     }
302
303     // returning output
304     return std::move(output_vector);
305 }
306 };
307 }

```

A.4 IFFTPlanClass

```

1  #pragma once
2  namespace svr {
3
4      template <typename T>
5      concept IFFTPlanClassSourceDestinationType = \
6          std::is_floating_point_v<T> ||
7          (
8              std::is_class_v<T> &&
9              std::is_floating_point_v<typename T::value_type>
10         );
11     template <
12         IFFTPlanClassSourceDestinationType sourceType,
13         IFFTPlanClassSourceDestinationType destinationType
14     >
15     class IFFTPlanClass
16     {
17     public:
18         std::size_t      nfft_;
19         fftw_complex*    in_;
20         fftw_complex*    out_;
21         fftw_plan        plan_;
22
23         /*=====
24         Destructor
25         -----*/
26         ~IFFTPlanClass()

```

```

27     {
28         if(plan_ != nullptr) {fftw_destroy_plan(    plan_);}
29         if(in_  != nullptr) {fftw_free(            in_);}
30         if(out_ != nullptr) {fftw_free(            out_);}
31     }
32     /*=====
33     Constructor
34     -----*/
35     IFFTPlanClass(const std::size_t nfft): nfft_(nfft)
36     {
37         // allocating space
38         in_  = reinterpret_cast<fftw_complex*>(fftw_malloc(nfft_ *
39             sizeof(fftw_complex)));
40         out_ = reinterpret_cast<fftw_complex*>(fftw_malloc(nfft_ *
41             sizeof(fftw_complex)));
42         if(!in_ || !out_) {throw std::runtime_error("in_, out_ creation
43             failed");}
44
45         // creating plan
46         plan_ = fftw_plan_dft_1d(
47             static_cast<int>(nfft_),
48             in_,
49             out_,
50             FFTW_BACKWARD,
51             FFTW_MEASURE
52         );
53         if(!plan_) {throw std::runtime_error("File: FFTPlanClass.hpp |
54             Class: IFFTPlanClass | report: plan-creation failed");}
55     }
56     /*=====
57     Copy Constructor
58     -----*/
59     IFFTPlanClass(const IFFTPlanClass&    other)
60     {
61         // allocating space
62         nfft_ = other.nfft_;
63         in_  = reinterpret_cast<fftw_complex*>(fftw_malloc(nfft_ *
64             sizeof(fftw_complex)));
65         out_ = reinterpret_cast<fftw_complex*>(fftw_malloc(nfft_ *
66             sizeof(fftw_complex)));
67         if (!in_ || !out_) {throw std::runtime_error("FILE: FFTPlanClass.hpp |
68             Class: IFFTPlanClass | Function: Copy-Constructor | Report: in-out
69             plan creation failed");}
70
71         // copying contents
72         std::memcpy(in_,  other.in_, nfft_ * sizeof(fftw_complex));
73         std::memcpy(out_, other.out_, nfft_ * sizeof(fftw_complex));
74
75         // creating a new plan since its more of an engine
76         plan_ = fftw_plan_dft_1d(
77             static_cast<int>(nfft_),
78             in_,
79             out_,
80             FFTW_BACKWARD,
81             FFTW_MEASURE
82         );
83         if(!plan_) {throw std::runtime_error("FILE: FFTPlanClass.hpp | Class:
84             IFFTPlanClass | Function: Copy-Constructor | Report: plan-creation
85             failed");}

```



```

76
77 }
78 /*=====
79 Copy Assignment
80 -----*/
81 IFFTPlanClass& operator=(const IFFTPlanClass& other)
82 {
83     // handling self-assignment
84     if(this == &other) {return *this;}
85
86     // cleaning up existing resources
87     if(plan_ != nullptr) {fftw_destroy_plan(    plan_);}
88     if(in_  != nullptr) {fftw_free(            in_);}
89     if(out_ != nullptr) {fftw_free(            out_);}
90
91     // allocating space
92     nfft_ = other.nfft_;
93     in_   = reinterpret_cast<fftw_complex*>(fftw_malloc(nfft_ *
94         sizeof(fftw_complex)));
95     out_  = reinterpret_cast<fftw_complex*>(fftw_malloc(nfft_ *
96         sizeof(fftw_complex)));
97     if (!in_ || !out_) {throw std::runtime_error("FILE: FFTPlanClass.hpp |
98         Class: IFFTPlanClass | Function: Copy-Constructor | Report: in-out
99         plan creation failed");}
100
101     // copying contents
102     std::memcpy(in_, other.in_, nfft_ * sizeof(fftw_complex));
103     std::memcpy(out_, other.out_, nfft_ * sizeof(fftw_complex));
104
105     // creating a new plan since its more of an engine
106     plan_ = fftw_plan_dft_1d(
107         static_cast<int>(nfft_),
108         in_,
109         out_,
110         FFTW_BACKWARD,
111         FFTW_MEASURE
112     );
113     if(!plan_) {throw std::runtime_error("FILE: FFTPlanClass.hpp | Class:
114         IFFTPlanClass | Function: Copy-Constructor | Report: plan-creation
115         failed");}
116
117     // returning
118     return *this;
119 }
120 /*=====
121 Move Constructor
122 -----*/
123 IFFTPlanClass(IFFTPlanClass&& other) noexcept
124 :   nfft_( other.nfft_),
125     in_(   other.in_),
126     out_(  other.out_),
127     plan_( other.plan_)
128 {
129     // resetting the source object
130     other.nfft_ = 0;
131     other.in_   = nullptr;
132     other.out_  = nullptr;
133     other.plan_ = nullptr;

```

```

129     }
130     /*=====
131     Move-Assignment
132     -----*/
133     IFFTPlanClass& operator=(IFFTPlanClass&& other) noexcept
134     {
135         // self-assignment check
136         if(this == &other)    {return *this;}
137
138         // cleaning up existing
139         if(plan_ != nullptr) {fftw_destroy_plan(    plan_);}
140         if(in_  != nullptr)  {fftw_free(           in_);}
141         if(out_ != nullptr)  {fftw_free(           out_);}
142
143         // Copying values and changing pointers
144         nfft_    =  other.nfft_;
145         in_      =  other.in_;
146         out_     =  other.out_;
147         plan_    =  other.plan_;
148
149         // resetting the source-object
150         other.nfft_ = 0;
151         other.in_   = nullptr;
152         other.out_  = nullptr;
153         other.plan_ = nullptr;
154
155         // returning
156         return *this;
157     }
158     /*=====
159     Running
160     -----*/
161     std::vector<destinationType>
162     ifft(const std::vector<sourceType>& input_vector)
163     {
164         // throwing an error
165         if (input_vector.size() > nfft_)
166             throw std::runtime_error("File: FFTPlanClass | Class: IFFTPlanClass |
167                                     Function: ifft() | Report: size of vector > nfft ");
168
169         // copy input into fftw buffer
170         for(std::size_t index = 0; index < nfft_; ++index)
171         {
172             if constexpr(
173                 std::is_same_v<    sourceType, std::complex<double> > ||
174                 std::is_same_v<    sourceType, std::complex<float> >
175             ){
176                 in_[index][0] = input_vector[index].real();
177                 in_[index][1] = input_vector[index].imag();
178             }
179             else if constexpr(
180                 std::is_floating_point_v< sourceType >
181             ){
182                 in_[index][0] = input_vector[index];
183                 in_[index][1] = 0;
184             }
185         }
186
187         // execute ifft

```

```

187     fftw_execute(plan_);
188
189     // normalize output
190     std::vector<destinationType> output_vector(nfft_);
191     for(std::size_t index = 0; index < nfft_; ++index){
192         if constexpr(
193             std::is_floating_point_v< destinationType >
194         ){
195             output_vector[index] =
196                 static_cast<destinationType>(out_[index][0]/nfft_);
197         }
198         else if constexpr(
199             std::is_same_v< destinationType, std::complex<double> > ||
200             std::is_same_v< destinationType, std::complex<float> >
201         ){
202             output_vector[index][0] = destinationType(
203                 out_[index][0]/nfft_,
204                 out_[index][1]/nfft_
205             );
206         }
207     }
208
209     // returning
210     return std::move(output_vector);
211 }
212
213 /*=====
214 Running - proper bases change
215 -----*/
216
217 std::vector<destinationType>
218 ifft_l2_conserved(const std::vector<sourceType>& input_vector)
219 {
220     // throwing an error
221     if (input_vector.size() > nfft_)
222         throw std::runtime_error("File: FFTPlanClass | Class: IFFTPlanClass |
223             Function: ifft() | Report: size of vector > nfft ");
224
225     // copy input into fftw buffer
226     for(std::size_t index = 0; index < nfft_; ++index)
227     {
228         if constexpr(
229             std::is_same_v< sourceType, std::complex<double> > ||
230             std::is_same_v< sourceType, std::complex<float> >
231         ){
232             in_[index][0] = input_vector[index].real();
233             in_[index][1] = input_vector[index].imag();
234         }
235         else if constexpr(
236             std::is_floating_point_v<sourceType>
237         ){
238             in_[index][0] = input_vector[index];
239             in_[index][1] = 0;
240         }
241     }
242
243     // execute ifft
244     fftw_execute(plan_);
245
246     // normalize output
247     std::vector<destinationType> output_vector(nfft_);

```

```

244     for(std::size_t index = 0; index < nfft_; ++index)
245     {
246         if constexpr(
247             std::is_floating_point_v<destinationType>
248         ){
249             output_vector[index] =
250                 static_cast<destinationType>(out_[index][0] *
251                     1.00/std::sqrt(nfft_));
252         }
253         else if constexpr(
254             std::is_same_v< destinationType, std::complex<double> > ||
255             std::is_same_v< destinationType, std::complex<float> >
256         ){
257             output_vector[index][0] = destinationType(
258                 out_[index][0] * 1.00/std::sqrt(nfft_),
259                 out_[index][1] * 1.00/std::sqrt(nfft_)
260             );
261         }
262     }
263     // returning
264     return std::move(output_vector);
265 }
266 }

```

A.5 FFT Plan Pool

```

1  #pragma once
2  namespace svr {
3
4      template <
5          typename sourceType,
6          typename destinationType,
7          typename = std::enable_if_t<
8              std::is_same_v<sourceType, double> &&
9              std::is_same_v<destinationType, std::complex<double>>
10          >
11      >
12      class FFTPlanUniformPool {
13      public:
14          /*=====
15          Handle to Plan
16          -----*/
17          struct AccessPairs
18          {
19              /*=====
20              Members
21              -----*/
22              svr::FFTPlanClass<sourceType, destinationType>& plan;
23              std::unique_lock<std::mutex> lock;
24
25              /*=====
26              Special Members
27              -----*/
28              AccessPairs() = delete;

```

```

29     AccessPairs(
30         svr::FFTPlanClass<sourceType, destinationType>& plan_arg,
31         std::mutex& plan_mutex
32     ) : plan(plan_arg), lock(plan_mutex) {}
33     AccessPairs(
34         svr::FFTPlanClass<sourceType, destinationType>& plan_arg,
35         std::unique_lock<std::mutex>&& lock_arg
36     ): plan(plan_arg), lock(std::move(lock_arg)) {}
37     AccessPairs(const AccessPairs& other) = delete;
38     AccessPairs& operator=(const AccessPairs& other) = delete;
39     AccessPairs(AccessPairs&& other) = delete;
40     AccessPairs& operator=(AccessPairs&& other) = delete;
41 };
42
43 /*=====
44 Core Members
45 -----*/
46 std::vector<svr::FFTPlanClass<sourceType, destinationType>> plans;
47 std::vector<std::mutex> mutexes;
48
49 /*=====
50 Special-Members
51 -----*/
52 FFTPlanUniformPool() = default;
53 FFTPlanUniformPool(const std::size_t num_plans,
54                     const std::size_t nfft)
55 {
56     // reserving space
57     plans.reserve(num_plans);
58     for(auto i = 0; i < num_plans; ++i){
59         plans.emplace_back(nfft);
60     }
61
62     // creating a vector of mutexes
63     mutexes = std::move(std::vector<std::mutex>(num_plans));
64 }
65 FFTPlanUniformPool(const FFTPlanUniformPool& other) = delete;
66 FFTPlanUniformPool& operator=(const FFTPlanUniformPool& other) = delete;
67 FFTPlanUniformPool(FFTPlanUniformPool&& other) = default;
68 FFTPlanUniformPool& operator=(FFTPlanUniformPool&& other) = default;
69
70 /*=====
71 Function to fetch a plan
72 > searches for a free-plan
73 > if found, locks the plan
74 > return the handle to the plan
75 -----*/
76 AccessPairs fetch_plan() {
77     const int num_rounds = 12;
78     for (int round = 0; round < num_rounds; ++round) {
79         for (int i = 0; i < mutexes.size(); ++i) {
80
81             std::unique_lock<std::mutex> curr_lock(
82                 mutexes[i],
83                 std::try_to_lock
84             );
85             if (curr_lock.owns_lock())
86                 return AccessPairs(plans[i], std::move(curr_lock));
87

```

```

88     }
89 }
90 throw std::runtime_error(
91     "FILE: FFTPlanPoolClass.hpp | CLASS: FFTPlanUniformPool | FUNCTION:
92     fetch_plan() | "
93     "Report: No plans available despite num_rounds rounds of searching");
94 };
95 }

```

A.6 IFFT Plan Pool

```

1  #pragma once
2
3  /*=====
4  Dependencies
5  -----*/
6
7  namespace svr {
8
9      template <
10         typename sourceType,
11         typename destinationType,
12         typename = std::enable_if_t<
13             std::is_same_v<sourceType, std::complex<double>>&&
14             std::is_same_v<destinationType, double>
15         >
16     >
17     class IFFTPlanUniformPool
18     {
19     public:
20         /*=====
21         Structure used for interfacing to plans
22         -----*/
23         struct AccessPairs
24         {
25             /*=====
26             Core Members
27             -----*/
28             svr::IFFTPlanClass<sourceType, destinationType>& plan;
29             std::unique_lock<std::mutex> lock;
30
31             /*=====
32             Special Members
33             -----*/
34             AccessPairs() = delete;
35             AccessPairs(
36                 svr::IFFTPlanClass<sourceType, destinationType>& plan_arg,
37                 std::mutex& plan_mutex_arg
38             ): plan(plan_arg), lock(plan_mutex_arg) {}
39             AccessPairs(
40                 svr::IFFTPlanClass<sourceType, destinationType>& plan_arg,
41                 std::unique_lock<std::mutex>&& lock_arg
42             ): plan(plan_arg), lock(std::move(lock_arg)) {}
43             AccessPairs(const AccessPairs& other) = delete;
44             AccessPairs& operator=(const AccessPairs& other) = delete;

```

```

45         AccessPairs(AccessPairs&& other)                = delete;
46         AccessPairs& operator=(AccessPairs&& other)      = delete;
47     };
48
49     /*=====
50     Core Members
51     -----*/
52     std::vector< svr::IFFTPlanClass<sourceType, destinationType> > plans;
53     std::vector< std::mutex > mutexes;
54
55     /*=====
56     Special Members
57     -----*/
58     IFFTPlanUniformPool() = default;
59     IFFTPlanUniformPool(const std::size_t num_plans,
60                         const std::size_t nfft)
61     {
62         // reserving space
63         plans.reserve(num_plans);
64         for(auto i = 0; i < num_plans; ++i)
65             plans.emplace_back(nfft);
66
67         // creating vector of mutexes
68         mutexes = std::vector<std::mutex>(num_plans);
69     }
70     IFFTPlanUniformPool(const IFFTPlanUniformPool& other) = delete;
71     IFFTPlanUniformPool& operator=(const IFFTPlanUniformPool& other) = delete;
72     IFFTPlanUniformPool(IFFTPlanUniformPool&& other) = default;
73     IFFTPlanUniformPool& operator=(IFFTPlanUniformPool&& other) = default;
74
75     /*=====
76     Member-Functions
77     -----*/
78     AccessPairs fetch_plan()
79     {
80         // setting the number of rounds to take
81         const int num_rounds {12};
82
83         // performing rounds
84         for(auto round = 0; round < num_rounds; ++round)
85         {
86             // going through vector mutexes
87             for(auto i = 0; i < mutexes.size(); ++i)
88             {
89                 // trying to lock current mutex
90                 std::unique_lock<std::mutex> curr_lock(mutexes[i],
91                                                         std::try_to_lock);
92
93                 // if our lock contains the mutex, returning the plan and lock
94                 if (curr_lock.owns_lock())
95                     return AccessPairs(plans[i], std::move(curr_lock));
96             }
97         }
98
99         // throwing error
100         throw std::runtime_error("FILE: IFFTPlanPoolClass.hpp | CLASS:
101                                 IFFTPlanUniformPool | REPORT: COULDN'T FIND ANY AVAILABLE PLANS");

```

102 }

A.7 FFT Plan Pool Handle

```

1  #pragma once
2
3  /*=====
4  Dependencies
5  -----*/
6  #include "FFTPlanPoolClass.hpp"
7
8  namespace svr
9  {
10     template <
11         typename    sourceType,
12         typename    destinationType,
13         typename    =    std::enable_if_t<
14             std::is_same_v<    sourceType, double >    &&
15             std::is_same_v<    destinationType, std::complex<double> >
16         >
17     >
18     struct FFTPlanUniformPoolHandle
19     {
20         /*=====
21         Core Members
22         -----*/
23         svr::FFTPlanUniformPool<sourceType, destinationType> uniform_pool;
24         std::mutex                                          mutex;
25         std::size_t                                        num_plans;
26         std::size_t                                        nfft;
27
28         /*=====
29         Special Member-functions
30         -----*/
31         FFTPlanUniformPoolHandle()    =    default;
32         FFTPlanUniformPoolHandle(const std::size_t num_plans_arg,
33                                 const std::size_t nfft_arg)
34             :    uniform_pool(num_plans_arg, nfft_arg),
35                 num_plans(num_plans_arg),
36                 nfft(nfft_arg)    {}
37         FFTPlanUniformPoolHandle(const FFTPlanUniformPoolHandle& other)    =    delete;
38         FFTPlanUniformPoolHandle& operator=(const FFTPlanUniformPoolHandle& other) =
39             delete;
40         FFTPlanUniformPoolHandle(FFTPlanUniformPoolHandle&& other)    =    default;
41         FFTPlanUniformPoolHandle& operator=(FFTPlanUniformPoolHandle&& other) = default;
42
43         /*=====
44         Member Functions
45         -----*/
46         auto    lock()
47         {
48             return std::unique_lock<std::mutex>(this->mutex);
49         }
50     };

```


A.8 IFFT Plan Pool Handle

```

1  #pragma once
2
3  /*=====
4  Dependencies
5  -----*/
6  #include "IFFTPlanPoolClass.hpp"
7
8
9  namespace svr
10 {
11     template <
12         typename sourceType,
13         typename destinationType,
14         typename = std::enable_if_t<
15             std::is_same_v< sourceType, std::complex<double> > &&
16             std::is_same_v< destinationType, double >
17         >
18     >
19     struct IFFTPlanUniformPoolHandle
20     {
21         /*=====
22         Members
23         -----*/
24         IFFTPlanUniformPool< sourceType,
25                             destinationType >      uniform_pool;
26         std::mutex                mutex;
27         std::size_t               num_plans;
28         std::size_t               nfft;
29
30         /*=====
31         Special Member Functions
32         -----*/
33         IFFTPlanUniformPoolHandle() = default;
34         IFFTPlanUniformPoolHandle(const std::size_t num_plans_arg,
35                                   const std::size_t nfft_arg)
36             : uniform_pool(      num_plans_arg, nfft_arg),
37               num_plans(      num_plans_arg),
38               nfft(      nfft_arg) {}
39         IFFTPlanUniformPoolHandle(const IFFTPlanUniformPoolHandle& other) = delete;
40         IFFTPlanUniformPoolHandle& operator=(const IFFTPlanUniformPoolHandle& other) =
41             delete;
42         IFFTPlanUniformPoolHandle(IFFTPlanUniformPoolHandle&& other) = delete;
43         IFFTPlanUniformPoolHandle& operator=(IFFTPlanUniformPoolHandle&& other) = delete;
44
45         /*=====
46         Member Functions
47         -----*/
48         auto lock()
49         {
50             return std::unique_lock<std::mutex>(this->mutex);
51         }
52     };
53 }
```

Appendix B

General Purpose Templated Functions

B.1 abs

```
1 #pragma once
2 /*=====
3 Dependencies
4 -----*/
5 #include <vector>    // for vectors
6 #include <algorithm> // for std::transform
7
8 /*=====
9 y = abs(vector)
10 -----*/
11 template <typename T>
12 auto abs(const std::vector<T>& input_vector)
13 {
14     // creating canvas
15     auto canvas {input_vector};
16
17     // calculating abs
18     std::transform(canvas.begin(),
19                   canvas.end(),
20                   canvas.begin(),
21                   [](auto& argx){return std::abs(argx);});
22
23     // returning
24     return std::move(canvas);
25 }
26 /*=====
27 y = abs(matrix)
28 -----*/
29 template <typename T>
30 auto abs(const std::vector<std::vector<T>> input_matrix)
31 {
32     // creating canvas
33     auto canvas {input_matrix};
34
35     // applying element-wise abs
36     std::transform(input_matrix.begin(),
37                   input_matrix.end(),
38                   input_matrix.begin(),
```

```

39         [](auto& argx){return std::abs(argx);});
40
41     // returning
42     return std::move(canvas);
43 }

```

B.2 Boolean Comparators

```

1  #pragma once
2  /*=====
3  -----*/
4  template <typename T, typename U>
5  auto operator<(const std::vector<T>& input_vector,
6                const U scalar)
7  {
8      // creating canvas
9      auto canvas {std::vector<bool>(input_vector.size())};
10
11     // transforming
12     std::transform(input_vector.begin(), input_vector.end(),
13                   canvas.begin(),
14                   [&scalar](const auto& argx){
15                       return argx < static_cast<T>(scalar);
16                   });
17
18     // returning
19     return std::move(canvas);
20 }
21 /*=====
22 -----*/
23 template <typename T, typename U>
24 auto operator<=(const std::vector<T>& input_vector,
25                const U scalar)
26 {
27     // creating canvas
28     auto canvas {std::vector<bool>(input_vector.size())};
29
30     // transforming
31     std::transform(input_vector.begin(), input_vector.end(),
32                   canvas.begin(),
33                   [&scalar](const auto& argx){
34                       return argx <= static_cast<T>(scalar);
35                   });
36
37     // returning
38     return std::move(canvas);
39 }
40 // =====
41 template <typename T, typename U>
42 auto operator>(const std::vector<T>& input_vector,
43               const U scalar)
44 {
45     // creating canvas
46     auto canvas {std::vector<bool>(input_vector.size())};
47
48     // transforming

```

```

49     std::transform(input_vector.begin(), input_vector.end(),
50                   canvas.begin(),
51                   [&scalar](const auto& argx){
52                       return argx > static_cast<T>(scalar);
53                   });
54
55     // returning
56     return std::move(canvas);
57 }
58 /*=====
59 -----*/
60 template <typename T, typename U>
61 auto operator>=(const std::vector<T>& input_vector,
62               const U scalar)
63 {
64     // creating canvas
65     auto canvas {std::vector<bool>(input_vector.size())};
66
67     // transforming
68     std::transform(input_vector.begin(), input_vector.end(),
69                   canvas.begin(),
70                   [&scalar](const auto& argx){
71                       return argx >= static_cast<T>(scalar);
72                   });
73
74     // returning
75     return std::move(canvas);
76 }

```

B.3 Concatenate Functions

```

1  #pragma once
2  /*=====
3  input = [vector, vector],
4  output = [vector]
5  -----*/
6  template <std::size_t axis, typename T>
7  auto concatenate(const std::vector<T>& input_vector_A,
8                 const std::vector<T>& input_vector_B) -> std::enable_if_t<axis == 1,
9                 std::vector<T> >
10 {
11     // creating canvas vector
12     auto num_elements {input_vector_A.size() + input_vector_B.size()};
13     auto canvas {std::vector<T>(num_elements, (T)0) };
14
15     // filling up the canvas
16     std::copy(input_vector_A.begin(), input_vector_A.end(),
17               canvas.begin());
18     std::copy(input_vector_B.begin(), input_vector_B.end(),
19               canvas.begin()+input_vector_A.size());
20
21     // moving it back
22     return std::move(canvas);
23 }
24 /*=====

```

```

25 input = [vector, vector],
26 output = [matrix]
27 -----*/
28 template <std::size_t axis, typename T>
29 auto concatenate(const std::vector<T>& input_vector_A,
30                 const std::vector<T>& input_vector_B) -> std::enable_if_t<axis == 0,
31                 std::vector<std::vector<T>> >
32 {
33     // throwing error dimensions
34     if (input_vector_A.size() != input_vector_B.size())
35         std::cerr << "concatenate:: incorrect dimensions \n";
36
37     // creating canvas
38     auto canvas {std::vector<std::vector<T>>>(
39         2, std::vector<T>(input_vector_A.size())
40     )};
41
42     // filling up the dimensions
43     std::copy(input_vector_A.begin(), input_vector_A.end(), canvas[0].begin());
44     std::copy(input_vector_B.begin(), input_vector_B.end(), canvas[1].begin());
45
46     // moving it back
47     return std::move(canvas);
48 }
49 /*=====
50 input = [vector, vector, vector],
51 output = [matrix]
52 -----*/
53 template <std::size_t axis, typename T>
54 auto concatenate(const std::vector<T>& input_vector_A,
55                 const std::vector<T>& input_vector_B,
56                 const std::vector<T>& input_vector_C) -> std::enable_if_t<axis == 0,
57                 std::vector<std::vector<T>> >
58 {
59     // throwing error dimensions
60     if (input_vector_A.size() != input_vector_B.size() ||
61         input_vector_A.size() != input_vector_C.size())
62         std::cerr << "concatenate:: incorrect dimensions \n";
63
64     // creating canvas
65     auto canvas {std::vector<std::vector<T>>>(
66         3, std::vector<T>(input_vector_A.size())
67     )};
68
69     // filling up the dimensions
70     std::copy(input_vector_A.begin(), input_vector_A.end(), canvas[0].begin());
71     std::copy(input_vector_B.begin(), input_vector_B.end(), canvas[1].begin());
72     std::copy(input_vector_C.begin(), input_vector_C.end(), canvas[2].begin());
73
74     // moving it back
75     return std::move(canvas);
76 }
77 /*=====
78 input = [matrix, vector],
79 output = [matrix]
80 -----*/
81 template <std::size_t axis, typename T>

```

```

82 auto concatenate(const std::vector<std::vector<T>>& input_matrix,
83                 const std::vector<T>          input_vector) -> std::enable_if_t<axis
                        == 0, std::vector<std::vector<T>>> >
84 {
85     // creating canvas
86     auto canvas {input_matrix};
87
88     // adding to the canvas
89     canvas.push_back(input_vector);
90
91     // returning
92     return std::move(canvas);
93 }

```

B.4 Conjugate

```

1  #pragma once
2  namespace svr {
3      /*=====
4      y = svr::conj(vector);
5      -----*/
6      template <typename T>
7      auto conj(const std::vector<T>& input_vector)
8      {
9          // creating canvas
10         auto canvas {std::vector<T>(input_vector.size())};
11
12         // calculating conjugates
13         std::for_each(canvas.begin(), canvas.end(),
14             [](auto& argx){argx = std::conj(argx);});
15
16         // returning
17         return std::move(canvas);
18     }
19 }

```

B.5 Convolution

```

1  #pragma once
2  namespace svr {
3
4      /*=====
5      1D convolution of two vectors
6      > implemented through fft
7      -----*/
8      template <typename T1, typename T2>
9      auto conv1D(const std::vector<T1>& input_vector_A,
10                 const std::vector<T2>& input_vector_B)
11      {
12          // resulting type
13          using T3 = decltype(std::declval<T1>() * std::declval<T2>());
14
15          // creating canvas
16          auto canvas_length {input_vector_A.size() + input_vector_B.size() - 1};

```

```

17
18 // calculating fft of two arrays
19 auto fft_A {svr::fft(input_vector_A, canvas_length)};
20 auto fft_B {svr::fft(input_vector_B, canvas_length)};
21
22 // element-wise multiplying the two matrices
23 auto fft_AB {fft_A * fft_B};
24
25 // finding inverse FFT
26 auto convolved_result {ifft(fft_AB)};
27
28 // returning
29 return std::move(convolved_result);
30 }
31
32 template <>
33 auto conv1D(const std::vector<double>& input_vector_A,
34            const std::vector<double>& input_vector_B)
35 {
36 // creating canvas
37 auto canvas_length {input_vector_A.size() + input_vector_B.size() - 1};
38
39 // calculating fft of two arrays
40 auto fft_A {svr::fft(input_vector_A, canvas_length)};
41 auto fft_B {svr::fft(input_vector_B, canvas_length)};
42
43 // element-wise multiplying the two matrices
44 auto fft_AB {fft_A * fft_B};
45
46 // finding inverse FFT
47 auto convolved_result {ifft(fft_AB)};
48
49 // returning
50 return std::move(convolved_result);
51 }
52
53 /*=====
54 1D convolution of two vectors
55 > implemented through fft
56 -----*/
57 template <typename T1, typename T2>
58 auto conv1D_fftw(const std::vector<T1>& input_vector_A,
59                 const std::vector<T2>& input_vector_B)
60 {
61 // resulting type
62 using T3 = decltype(std::declval<T1>() * std::declval<T2>());
63
64 // creating canvas
65 auto canvas_length {input_vector_A.size() + input_vector_B.size() - 1};
66
67 // calculating fft of two arrays
68 auto fft_A {svr::fft(input_vector_A, canvas_length)};
69 auto fft_B {svr::fft(input_vector_B, canvas_length)};
70
71 // element-wise multiplying the two matrices
72 auto fft_AB {fft_A * fft_B};
73
74 // finding inverse FFT
75 auto convolved_result {svr::ifft(fft_AB, fft_AB.size())};

```

```

76
77     // returning
78     return std::move(convolved_result);
79 }
80
81 /*=====
82 Long-signal Conv1D
83 improvements:
84 > make an inplace version of this
85 -----*/
86 template <std::size_t L, typename T>
87 auto conv1D_long(const std::vector<T>& input_vector_A,
88                 const std::vector<T>& input_vector_B)
89 {
90     // fetching dimensions
91     const auto maxlength = {std::max(input_vector_A.size(),
92                                     input_vector_B.size())};
93     const auto filter_size = {std::min(input_vector_A.size(),
94                                     input_vector_B.size())};
95     const auto block_size = {L + filter_size - 1};
96     const auto num_blocks = {2 + static_cast<std::size_t>(
97         (maxlength - block_size)/L
98     )};
99
100    // obtaining references
101    const auto& large_vector = {input_vector_A.size() >= input_vector_B.size() ? \
102                                input_vector_A      : input_vector_B};
103    const auto& small_vector = {input_vector_A.size() < input_vector_B.size() ? \
104                                input_vector_A      : input_vector_B};
105
106    // setup
107    auto starting_index = {static_cast<std::size_t>(0)};
108    auto ending_index = {static_cast<std::size_t>(0)};
109    auto length_left_to_fill = {ending_index - starting_index};
110    auto canvas = {std::vector<double>(block_size, 0)};
111    auto finaloutput = {std::vector<double>(maxlength, 0)};
112    auto block_conv_output_size = {L + 2 * filter_size - 2};
113    auto block_conv_output = {std::vector<double>(block_conv_output_size, 0)};
114
115    // block-wise processing
116    for(auto bid = 0; bid < num_blocks; ++bid)
117    {
118        // estimating indices
119        starting_index = L*bid;
120        ending_index = std::min(starting_index + block_size - 1, maxlength -
121                                1);
122        length_left_to_fill = ending_index - starting_index;
123
124        // copying to the common-block
125        std::copy(large_vector.begin() + starting_index,
126                  large_vector.begin() + ending_index + 1,
127                  canvas.begin());
128
129        // performing convolution
130        block_conv_output = svr::conv1D_fftw(canvas,
131                                              small_vector);
132
133        // discarding edges and writing values
134        std::copy(block_conv_output.begin() + filter_size-2,

```



```

134         block_conv_output.begin() + filter_size-2 +
            std::min(static_cast<int>(L-1),
                static_cast<int>(length_left_to_fill)) + 1,
135         finaloutput.begin()+starting_index);
136     }
137
138     // returning
139     return std::move(finaloutput);
140
141 }
142
143 /*=====
144 Long-signal Conv1D with FFT Plan
145 improvements:
146 > make an inplace version of this
147 -----*/
148 template <
149     typename T,
150     std::enable_if_t<
151         std::is_floating_point_v<T>
152     >
153 auto conv1D_long_prototype(
154     const std::vector<T>& input_vector_A,
155     const std::vector<T>& input_vector_B,
156     svr::FFTPlanClass<T, std::complex<T>>& fft_plan,
157     svr::IFFTPPlanClass<std::complex<T>, T>& ifft_plan
158 )
159 {
160     // Error checks
161     if (fft_plan.nfft_ != ifft_plan.nfft_)
162         throw std::runtime_error("fft_plan.nfft_ != ifft_plan.nfft_");
163
164     // fetching references to large-signal and small-signal
165     const auto& large_signal_original {
166         input_vector_A.size() >= input_vector_B.size() ?
167         input_vector_A : input_vector_B
168     };
169     const auto& small_signal {
170         input_vector_A.size() < input_vector_B.size() ?
171         input_vector_A : input_vector_B
172     };
173
174     // copying
175     auto large_signal {std::vector<double>(
176         input_vector_A.size() + input_vector_B.size() - 1
177     )};
178     std::copy(large_signal_original.begin(),
179         large_signal_original.end(),
180         large_signal.begin());;
181
182     // calculating parameters
183     const auto signal_size {large_signal_original.size()};
184     const auto filter_size {small_signal.size()};
185     const auto input_signal_block_size {fft_plan.nfft_ + 1 - filter_size};
186     if (input_signal_block_size <= 0)
187         throw std::runtime_error("input_signal_block_size <= 0 ");
188     const auto block_output_length {fft_plan.nfft_};
189     const auto num_blocks {static_cast<int>(
190         1 + std::ceil((signal_size + filter_size - 2)/input_signal_block_size)

```

```

191     )
192 };
193 const auto final_output_size {signal_size + filter_size - 1};
194 const auto useful_sample_length {block_output_length - (filter_size - 1)
    - (filter_size - 1)};
195
196 // parameters for re-use
197 auto start_index {static_cast<int>(0)};
198 auto end_index {static_cast<int>(0)};
199 auto output_start_index {static_cast<int>(0)};
200
201 // calculating fft(filter)
202 auto filter_zero_padded {std::vector<double>(block_output_length, 0.0)};
203 std::copy(small_signal.begin(), small_signal.end(), filter_zero_padded.begin());
204 auto filter_FFT {fft_plan.fft(filter_zero_padded)};
205
206 // allocating space for storing input-blocks
207 auto signal_block_zero_padded {std::vector<double>(block_output_length, 0.0)};
208 auto fftw_output {std::vector<double>()};
209 auto conv_output {std::vector<double>()};
210 auto finaloutput {std::vector<double>(final_output_size, 0.0)};
211
212 // going through the values
213 svr::Timer timer("fft-loop");
214 for(auto i = 0; i<num_blocks; ++i){
215
216     // calculating bounds
217     auto analytical_start {
218         (i*static_cast<int>(input_signal_block_size)) -
219         (static_cast<int>(filter_size) - 1)
220     };
221     auto analytical_end {(i+1)*input_signal_block_size - 1};
222     start_index = std::max(
223         static_cast<int>(0), static_cast<int>(analytical_start)
224     );
225     end_index = std::min(
226         static_cast<int>(signal_size-1), static_cast<int>(analytical_end)
227     ); // [start-index, end-index)
228
229     // copying values
230     signal_block_zero_padded = std::move(std::vector<double>(block_output_length,
231         0.0));
232     std::copy(large_signal.begin() + start_index,
233         large_signal.begin() + end_index + 1,
234         signal_block_zero_padded.begin() + start_index - analytical_start);
235
236     // performing ifft(fft(x) * fft(y))
237     fftw_output = ifft_plan.ifft(
238         fft_plan.fft(signal_block_zero_padded) * filter_FFT
239     );
240
241     // trimming away the first parts (since partial)
242     conv_output = std::vector<double>(fftw_output.begin() + filter_size -
243         1, fftw_output.end());
244
245     // writing to final-output
246     std::copy(conv_output.begin(), conv_output.end(), finaloutput.begin() +
247         output_start_index);
248     output_start_index += conv_output.size();

```

```

245     }
246
247 }
248
249 /*=====
250 Long-signal Conv1D with FFT-Plan-Pool
251 -----*/
252 template <
253     typename T,
254     typename = std::enable_if_t<
255         std::is_same_v<T, double> ||
256         std::is_same_v<T, float>
257     >
258 >
259 auto conv_per_plan(
260     const int i,
261     const int& input_signal_block_size,
262     const int& filter_size,
263     const int& block_output_length,
264     const std::vector<T>& large_signal,
265     std::vector<T> signal_block_zero_padded,
266     svr::FFTPlanUniformPoolHandle<T, std::complex<T>>& fft_pool_handle,
267     svr::IFFTPlanUniformPoolHandle<std::complex<T>, T>& ifft_pool_handle,
268     const std::vector<std::complex<T>>& filter_FFT,
269     std::vector<T> fftw_output,
270     std::vector<T> conv_output,
271     std::vector<T>& output_vector,
272     std::mutex& output_vector_mutex,
273     const auto& signal_size
274 )
275 {
276
277     // calculating bounds
278     auto analytical_start {
279         (i*static_cast<int>(input_signal_block_size)) -
280         (static_cast<int>(filter_size) - 1)
281     };
282     auto analytical_end { (i+1)*input_signal_block_size - 1 };
283     auto start_index = std::max(
284         static_cast<int>(0), static_cast<int>(analytical_start)
285     );
286     auto end_index = std::min(
287         static_cast<int>(signal_size-1), static_cast<int>(analytical_end)
288     ); // [start-index, end-index]
289
290     // copying values
291     signal_block_zero_padded = std::move(std::vector<double>(block_output_length,
292         0.0));
293     std::copy(
294         large_signal.begin() + start_index,
295         large_signal.begin() + end_index + 1,
296         signal_block_zero_padded.begin() + start_index - analytical_start
297     );
298
299     // fetching an fft and IFFT plan
300     auto fph_lock {fft_pool_handle.lock()};
301     auto ifph_lock {ifft_pool_handle.lock()};
302     auto fft_pair {fft_pool_handle.uniform_pool.fetch_plan()};
303     auto ifft_pair {ifft_pool_handle.uniform_pool.fetch_plan()};

```

```

302
303 // performing ifft(fft(x) * filter-FFT)
304 fftw_output = ifft_pair.plan.ifft_l2_conservd(
305     fft_pair.plan.fft_l2_conservd(signal_block_zero_padded) * filter_FFT
306 );
307
308 // trimming away the first parts (since partial)
309 conv_output = std::vector<T>(
310     fftw_output.begin() + filter_size - 1,
311     fftw_output.end()
312 );
313
314 // writing to final-output
315 auto output_start_index = i * (block_output_length - (filter_size - 1));
316 std::lock_guard<std::mutex> output_lock(output_vector_mutex);
317 std::copy(
318     conv_output.begin(), conv_output.end(),
319     output_vector.begin() + output_start_index
320 );
321 }
322
323
324 template <
325     typename T,
326     typename = std::enable_if_t<
327         std::is_same_v<T, double> ||
328         std::is_same_v<T, float>
329     >
330 >
331 auto conv1D_long_FFTPlanPool(
332     const std::vector<T>& input_vector_A,
333     const std::vector<T>& input_vector_B,
334     svr::FFTPlanUniformPoolHandle<T, std::complex<T>>& fft_pool_handle,
335     svr::IFFTPlanUniformPoolHandle<std::complex<T>, T>& ifft_pool_handle
336 )
337 {
338     // Error checks
339     if (fft_pool_handle.nfft != ifft_pool_handle.nfft)
340         throw std::runtime_error("FILE: svr_conv.hpp | FUNCTION:
341             conv1D_long_FFTPlanPool | Report: the pool-handles are for different
342             nffts");
343
344     // fetching references to the large signal and small signal
345     const auto& large_signal_original {
346         input_vector_A.size() >= input_vector_B.size() ?
347         input_vector_A : input_vector_B
348     };
349     const auto& small_signal {
350         input_vector_A.size() < input_vector_B.size() ?
351         input_vector_A : input_vector_B
352     };
353
354     // copying
355     auto large_signal {std::vector<double>(
356         input_vector_A.size() + input_vector_B.size() - 1
357     )};
358     std::copy(large_signal_original.begin(),
359         large_signal_original.end(),
360         large_signal.begin());

```

```

359
360 // calculating some parameters
361 const auto signal_size {large_signal_original.size()};
362 const auto filter_size {small_signal.size()};
363 const auto input_signal_block_size {
364     fft_pool_handle.nfft + 1 - filter_size
365 };
366
367 // throwing an error if nfft < filter-size
368 if (fft_pool_handle.nfft < filter_size)
369     throw std::runtime_error("FILE: svr_conv.hpp | FUNCTION:
370         conv1D_long_FFTPlanPool | REPORT: filter is bigger than nfft");
371
372 // throwing an error if number of useful samples is less than zero
373 if (input_signal_block_size <= 0)
374     throw std::runtime_error("FILE: svr_conv.hpp | FUNCTION:
375         conv1D_long_FFTPlanPool | REPORT: input_signal_block_size = 0");
376
377 const auto block_output_length {fft_pool_handle.nfft};
378 const auto num_blocks {static_cast<int>((
379     1 + std::ceil((signal_size + filter_size - 2) / input_signal_block_size)
380 ));
381 const auto final_output_size {signal_size + filter_size - 1};
382 const auto useful_sample_length {
383     block_output_length - (filter_size - 1) - (filter_size - 1)
384 };
385
386 // parameters for re-use
387 auto start_index {static_cast<int>(0)};
388 auto end_index {static_cast<int>(0)};
389 auto output_start_index {static_cast<int>(0)};
390
391 // calculating fft(filter)
392 auto filter_zero_padded {std::vector<double>(block_output_length, 0.0)};
393 std::copy(small_signal.begin(), small_signal.end(), filter_zero_padded.begin());
394 auto fph_lock0 {fft_pool_handle.lock()};
395 auto curr_plan_pair {fft_pool_handle.uniform_pool.fetch_plan()};
396 auto pool_num_plans {fft_pool_handle.num_plans};
397 fph_lock0.unlock();
398 auto filter_FFT {
399     curr_plan_pair.plan.fft(
400         filter_zero_padded
401     )
402 };
403 curr_plan_pair.lock.unlock();
404
405 // allocating space for storing input-blocks
406 auto signal_block_zero_padded {std::vector<T>(block_output_length, 0.0)};
407 auto fftw_output {std::vector<T>()};
408 auto conv_output {std::vector<T>()};
409 auto output_vector {std::vector<T>(final_output_size, 0.0)};
410 auto output_vector_mutex {std::mutex()};
411
412 // creating boost
413 svr::ThreadPool local_pool(pool_num_plans);
414
415 // going through the values
416 for(auto i = 0; i < num_blocks; ++i)

```

```

416     {
417         local_pool.push_back(
418             [
419                 i,
420                 &input_signal_block_size,
421                 &filter_size,
422                 &block_output_length,
423                 &large_signal,
424                 signal_block_zero_padded,
425                 &fft_pool_handle,
426                 &ifft_pool_handle,
427                 &filter_FFT,
428                 fftw_output,
429                 conv_output,
430                 &output_vector,
431                 &output_vector_mutex,
432                 &signal_size
433             ]{
434                 conv_per_plan<T>(
435                     i,
436                     std::ref(input_signal_block_size),
437                     std::ref(filter_size),
438                     std::ref(block_output_length),
439                     std::ref(large_signal),
440                     signal_block_zero_padded,
441                     fft_pool_handle,
442                     ifft_pool_handle,
443                     filter_FFT,
444                     fftw_output,
445                     conv_output,
446                     std::ref(output_vector),
447                     output_vector_mutex,
448                     signal_size
449                 );
450             }
451         );
452     }
453     local_pool.converge();
454
455     // returning final output
456     return std::move(output_vector);
457     // return output_vector;
458 }
459
460 /*=====
461 Short-conv1D
462 -----*/
463 template <typename T1,
464           typename T2>
465 auto conv1D_short(const std::vector<T1>& input_vector_A,
466                  const std::vector<T2>& input_vector_B)
467 {
468     // resulting type
469     using T3 = decltype(std::declval<T1>() * std::declval<T2>());
470
471     // creating canvas
472     auto canvas_length = {input_vector_A.size() + input_vector_B.size() - 1};
473
474     // calculating fft of two arrays

```

```

475     auto    fft_A      {svr::fft(input_vector_A, canvas_length)};
476     auto    fft_B      {svr::fft(input_vector_B, canvas_length)};
477
478     // element-wise multiplying the two matrices
479     auto    fft_AB      {fft_A *  fft_B};
480
481     // finding inverse FFT
482     auto    convolved_result  {ifft(fft_AB)};
483
484     // returning
485     // return std::move(convolved_result);
486     return convolved_result;
487
488 }
489
490
491 /*=====
492 1D Convolution of a matrix and a vector
493 -----*/
494 template    <typename T>
495 auto    conv1D(const    std::vector<std::vector<T>>& input_matrix,
496                const    std::vector<T>&                input_vector,
497                const    std::size_t&                    dim)
498 {
499     // getting dimensions
500     const auto&    num_rows_matrix    {input_matrix.size()};
501     const auto&    num_cols_matrix    {input_matrix[0].size()};
502     const auto&    num_elements_vector {input_vector.size()};
503
504     // creating canvas
505     auto    canvas    {std::vector<std::vector<T>>()};
506
507     // creating output based on dim
508     if (dim == 1)
509     {
510         // performing convolutions row by row
511         for(auto    row = 0; row < num_rows_matrix; ++row)
512         {
513             cout << format("\t\t row = {}/{}\n", row, num_rows_matrix);
514             auto bruh {conv1D(input_matrix[row], input_vector)};
515             auto bruh_real {svr::real(std::move(bruh))};
516
517             canvas.push_back(
518                 svr::real(
519                     std::move(bruh_real)
520                 )
521             );
522         }
523     }
524     else{
525         std::cerr << "svr_conv.hpp | conv1D | yet to be implemented \n";
526     }
527
528     // returning
529     return std::move(canvas);
530
531 }
532
533 }

```

B.6 Coordinate Change

```

1  #pragma once
2  namespace svr {
3      /*=====
4      y = cart2sph(vector)
5      -----*/
6      template <typename T>
7      auto cart2sph(const std::vector<T>& cartesian_vector){
8
9          // splatting the point onto xy-plane
10         auto xysplat {cartesian_vector};
11         xysplat[2] = 0;
12
13         // finding splat lengths
14         auto xysplat_lengths {norm(xysplat)};
15
16         // finding azimuthal and elevation angles
17         auto azimuthal_angles {svr::atan2(xysplat[1],
18                                           xysplat[0]) \
19                               * 180.00/std::numbers::pi};
20         auto elevation_angles {svr::atan2(cartesian_vector[2],
21                                           xysplat_lengths) \
22                               * 180.00/std::numbers::pi};
23         auto rho_values {norm(cartesian_vector)};
24
25         // creating tensor to send back
26         auto spherical_vector {std::vector<T>{azimuthal_angles,
27                                               elevation_angles,
28                                               rho_values}};
29
30         // moving it back
31         return std::move(spherical_vector);
32     }
33     /*=====
34     y = cart2sph(vector)
35     -----*/
36     template <typename T>
37     auto cart2sph_inplace(std::vector<T>& cartesian_vector){
38
39         // splatting the point onto xy-plane
40         auto xysplat {cartesian_vector};
41         xysplat[2] = 0;
42
43         // finding splat lengths
44         auto xysplat_lengths {norm(xysplat)};
45
46         // finding azimuthal and elevation angles
47         auto azimuthal_angles {svr::atan2(xysplat[1], xysplat[0]) *
48                                     180.00/std::numbers::pi};
49         auto elevation_angles {svr::atan2(cartesian_vector[2],
50                                           xysplat_lengths) * 180.00/std::numbers::pi};
51         auto rho_values {norm(cartesian_vector)};
52
53         // creating tesnor
54         cartesian_vector[0] = azimuthal_angles;
55         cartesian_vector[1] = elevation_angles;
56         cartesian_vector[2] = rho_values;
57     }

```



```

57  /*=====
58  y = cart2sph(input_matrix, dim)
59  -----*/
60  template <typename T>
61  auto cart2sph(const std::vector<std::vector<T>>& input_matrix,
62                const std::size_t axis)
63  {
64      // fetching dimensions
65      const auto& num_rows {input_matrix.size()};
66      const auto& num_cols {input_matrix[0].size()};
67
68      // checking the axis and dimensions
69      if (axis == 0 && num_rows != 3) {std::cerr << "cart2sph: incorrect num-elements
70          \n";}
71      if (axis == 1 && num_cols != 3) {std::cerr << "cart2sph: incorrect num-elements
72          \n";}
73
74      // creating canvas
75      auto canvas {std::vector<std::vector<T>>(
76          num_rows,
77          std::vector<T>(num_cols, 0)
78      )};
79
80      // if axis = 0, performing operation column-wise
81      if(axis == 0)
82      {
83          for(auto col = 0; col < num_cols; ++col)
84          {
85              // fetching current column
86              auto curr_column {std::vector<T>({input_matrix[0][col],
87                  input_matrix[1][col],
88                  input_matrix[2][col]})};
89
90              // performing inplace transformation
91              cart2sph_inplace(curr_column);
92
93              // storing it back
94              canvas[0][col] = curr_column[0];
95              canvas[1][col] = curr_column[1];
96              canvas[2][col] = curr_column[2];
97          }
98      }
99      // if axis == 1, performing operations row-wise
100      else if(axis == 0)
101      {
102          std::cerr << "cart2sph: yet to be implemented \n";
103      }
104      else
105      {
106          std::cerr << "cart2sph: yet to be implemented \n";
107      }
108
109      // returning
110      return std::move(canvas);
111  }
112  // =====
113  template <typename T>

```

```

114 auto sph2cart(const std::vector<T> spherical_vector){
115
116     // creating cartesian vector
117     auto cartesian_vector {std::vector<T>(spherical_vector.size(), 0)};
118
119     // populating
120     cartesian_vector[0] = spherical_vector[2] * \
121         cos(spherical_vector[1] * std::numbers::pi / 180.00) * \
122         cos(spherical_vector[0] * std::numbers::pi / 180.00);
123     cartesian_vector[1] = spherical_vector[2] * \
124         cos(spherical_vector[1] * std::numbers::pi / 180.00) * \
125         sin(spherical_vector[0] * std::numbers::pi / 180.00);
126     cartesian_vector[2] = spherical_vector[2] * \
127         sin(spherical_vector[1] * std::numbers::pi / 180.00);
128
129     // returning
130     return std::move(cartesian_vector);
131 }
132 }

```

B.7 Cosine

```

1 #pragma once
2 /*=====
3 y = cos(input_vector)
4 -----*/
5 template <typename T>
6 auto cos(const std::vector<T>& input_vector)
7 {
8     // created canvas
9     auto canvas {input_vector};
10
11     // calling the function
12     std::transform(input_vector.begin(), input_vector.end(),
13         canvas.begin(),
14         [](auto& argx){return std::cos(argx);});
15
16     // returning the output
17     return std::move(canvas);
18 }
19 /*=====
20 y = cosd(input_vector)
21 -----*/
22 template <typename T>
23 auto cosd(const std::vector<T> input_vector)
24 {
25     // created canvas
26     auto canvas {input_vector};
27
28     // calling the function
29     std::transform(input_vector.begin(),
30         input_vector.end(),
31         input_vector.begin(),
32         [](const auto& argx){return std::cos(argx * 180.00/std::numbers::pi);});
33
34     // returning the output

```

```

35     return std::move(canvas);
36 }

```

B.8 Data Structures

```

1  struct TreeNode {
2      int val;
3      TreeNode *left;
4      TreeNode *right;
5      TreeNode() : val(0), left(nullptr), right(nullptr) {}
6      TreeNode(int x) : val(x), left(nullptr), right(nullptr) {}
7      TreeNode(int x, TreeNode *left, TreeNode *right) : val(x), left(left), right(right)
8          {}
9  };
10
11 struct ListNode {
12     int val;
13     ListNode *next;
14     ListNode() : val(0), next(nullptr) {}
15     ListNode(int x) : val(x), next(nullptr) {}
16     ListNode(int x, ListNode *next) : val(x), next(next) {}
17 };

```

B.9 Editing Index Values

```

1  #pragma once
2  /*=====
3  Matlab's equivalent of A[A < 0.5] = 0
4  -----*/
5  template <typename T, typename U>
6  auto edit(std::vector<T>&                input_vector,
7           const std::vector<bool>&        bool_vector,
8           const U                        scalar)
9  {
10     // throwing an error
11     if (input_vector.size() != bool_vector.size())
12         std::cerr << "edit: incompatible size\n";
13
14     // overwriting input-vector
15     std::transform(input_vector.begin(), input_vector.end(),
16                   bool_vector.begin(),
17                   input_vector.begin(),
18                   [&scalar](auto& argx, auto argy){
19                       if (argy == true) {return static_cast<T>(scalar);}
20                       else {return argx;}
21                   });
22
23     // no-returns since in-place
24 }
25
26 /*=====
27 accumulate version of edit, instead of just placing values
28 */

```

```

29 Things to add
30 - ensuring template only accepts int, std::size_t and similar for T2
31 - bring in histogram method to ensure SIMD
32 -----*/
33 template <typename T1,
34           typename T2>
35 auto edit_accumulate(std::vector<T1>& input_vector,
36                     const std::vector<T2>& indices_to_edit,
37                     const std::vector<T1>& new_values)
38 {
39     // certain checks
40     if (indices_to_edit.size() != new_values.size())
41         std::cerr << "svr::edit | edit_accumulate | size-disparity occurred \n";
42
43     // going through each and accumulating
44     for(auto i = 0; i < input_vector.size(); ++i){
45         const auto target_index {static_cast<std::size_t>(indices_to_edit[i])}; //
46         const auto new_value {new_values[i]};
47         if (target_index < input_vector.size()){
48             input_vector[target_index] = input_vector[target_index] + new_value;
49         }
50         else{
51             // std::cout << "warning: FILE: svr_edit.hpp | FUNCTION: edit_accumulate |
52             // REPORT: index out of bounds";
53         }
54     }
55     // no-return since in-place
56 }

```

B.10 Equality

```

1 #pragma once
2 /*=====
3 -----*/
4 template <typename T, typename U>
5 auto operator==(const std::vector<T>& input_vector,
6                const U& scalar)
7 {
8     // setting up canvas
9     auto canvas {std::vector<bool>(input_vector.size())};
10
11     // writing to canvas
12     std::transform(input_vector.begin(), input_vector.end(),
13                   canvas.begin(),
14                   [&scalar](const auto& argx){
15                       return argx == scalar;
16                   });
17
18     // returning
19     return std::move(canvas);
20 }

```

B.11 Exponentiate

```

1  #pragma once
2
3  namespace svr {
4      /*=====
5      y = exp(vector)
6      -----*/
7      template <typename T>
8      auto exp(const std::vector<T>& input_vector)
9      {
10         // creating canvas
11         auto canvas {input_vector};
12
13         // transforming
14         std::transform(canvas.begin(), canvas.end(),
15                        canvas.begin(),
16                        [](auto& argx){return std::exp(argx);});
17
18         // returning
19         return std::move(canvas);
20     }
21     /*=====
22     y = exp(matrix)
23     -----*/
24     template <
25         typename sourceType,
26         typename destinationType,
27         typename = std::enable_if_t<
28             std::is_arithmetic_v<sourceType>
29         >
30     >
31     auto exp(
32         const std::vector<std::vector<sourceType>> input_matrix
33     )
34     {
35         // fetching dimensions
36         const auto& num_rows {input_matrix.size()};
37         const auto& num_cols {input_matrix[0].size()};
38
39         // creating canvas
40         auto canvas {std::vector<std::vector<destinationType>>(
41             num_rows,
42             std::vector<destinationType>(num_cols)
43         )};
44
45         // writing to each entry
46         for(auto row = 0; row < num_rows; ++row)
47             std::transform(
48                 input_matrix[row].begin(), input_matrix[row].end(),
49                 canvas[row].begin(),
50                 [](const auto& argx){
51                     return std::exp(argx);
52                 }
53             );
54
55         // returning
56         return std::move(canvas);
57     }
58     /*=====
59     Aim: Exponentiating complex matrices with general floating types

```

```

60 -----*/
61 template <
62     typename T,
63     typename = std::enable_if_t<
64         std::is_floating_point_v<T>
65     >
66 >
67 auto exp(
68     const std::vector<std::vector<std::complex<T>>> input_matrix
69 )
70 {
71     // fetching dimensions
72     const auto& num_rows {input_matrix.size()};
73     const auto& num_cols {input_matrix[0].size()};
74
75     // creating canvas
76     auto canvas {std::vector<std::vector<std::complex<T>>>(
77         num_rows,
78         std::vector<std::complex<T>>(num_cols)
79     )};
80
81     // writing to each entry
82     for(auto row = 0; row < num_rows; ++row)
83         std::transform(
84             input_matrix[row].begin(), input_matrix[row].end(),
85             canvas[row].begin(),
86             [](const auto& argx){
87                 return std::exp(argx);
88             }
89         );
90
91     // returning
92     return std::move(canvas);
93 }
94
95 }

```

B.12 FFT

```

1  #pragma once
2  namespace svr {
3      /*=====
4      For type-deductions
5      -----*/
6      template <typename T>
7      struct fft_result_type;
8
9      // specializations
10     template <> struct fft_result_type<double>{
11         using type = std::complex<double>;
12     };
13     template <> struct fft_result_type<std::complex<double>>{
14         using type = std::complex<double>;
15     };
16     template <> struct fft_result_type<float>{
17         using type = std::complex<float>;

```

```

18 };
19 template <> struct fft_result_type<std::complex<float>>>{
20     using type = std::complex<float>;
21 };
22
23 template <typename T>
24 using fft_result_t = typename fft_result_type<T>::type;
25
26 /*=====
27 y = fft(x, nfft)
28     > calculating n-point dft where n-value is explicit
29 -----*/
30 template<typename T>
31 auto fft(const std::vector<T>& input_vector,
32         const size_t nfft)
33 {
34     // throwing an error
35     if (nfft < input_vector.size()) {std::cerr << "size-mismatch\n";}
36     if (nfft <= 0) {std::cerr << "size-mismatch\n";}
37
38     // fetching data-type
39     using RType = fft_result_t<T>;
40     using baseType = std::conditional_t<std::is_same_v<T, std::complex<double>>,
41                                         double,
42                                         T>;
43
44     // canvas instantiation
45     std::vector<RType> canvas(nfft);
46     auto nfft_sqrt = {static_cast<RType>(std::sqrt(nfft))};
47     auto finaloutput = {std::vector<RType>(nfft, 0)};
48
49     // calculating index by index
50     for(int frequency_index = 0; frequency_index<nfft; ++frequency_index){
51         RType accumulate_value;
52         for(int signal_index = 0; signal_index < input_vector.size(); ++signal_index){
53             accumulate_value += \
54                 static_cast<RType>(input_vector[signal_index]) * \
55                 static_cast<RType>(std::exp(-1.00 * std::numbers::pi * \
56                                         (static_cast<baseType>(frequency_index)/static_cast<baseType>(nfft) * \
57                                         static_cast<baseType>(signal_index))));
58         }
59         finaloutput[frequency_index] = accumulate_value / nfft_sqrt;
60     }
61
62     // returning
63     return std::move(finaloutput);
64 }
65
66 /*=====
67 y = fft(std::vector<double> nfft) // specialization
68 -----*/
69 #include <fftw3.h> // for fft
70 template <>
71 auto fft(const std::vector<double>& input_vector,
72         const std::size_t nfft)
73 {
74     if (nfft < input_vector.size())
75         throw std::runtime_error("nfft must be >= input_vector.size()");

```

```

76     if (nfft <= 0)
77         throw std::runtime_error("nfft must be > 0");
78
79     // FFTW real-to-complex output
80     std::vector<std::complex<double>> output(nfft);
81
82     // Allocate input (double) and output (fftw_complex) arrays
83     double* in      = reinterpret_cast<double*>(
84         fftw_malloc(sizeof(double) * nfft)
85     );
86     fftw_complex* out = reinterpret_cast<fftw_complex*>(
87         fftw_malloc(sizeof(fftw_complex) * (nfft/2 + 1))
88     );
89
90     // Copy input and zero-pad if needed
91     for (std::size_t i = 0; i < nfft; ++i) {
92         in[i] = (i < input_vector.size()) ? input_vector[i] : 0.0;
93     }
94
95     // Create FFTW plan and execute
96     fftw_plan plan = fftw_plan_dft_r2c_1d(
97         static_cast<int>(nfft), in, out, FFTW_ESTIMATE
98     );
99     fftw_execute(plan);
100
101     // Copy FFTW output to std::vector<std::complex<double>>
102     for (std::size_t i = 0; i < nfft/2 + 1; ++i) {
103         output[i] = std::complex<double>(out[i][0], out[i][1]);
104     }
105     // Optional: fill remaining bins with zeros to match full nfft size
106     for (std::size_t i = nfft/2 + 1; i < nfft; ++i) {
107         output[i] = std::complex<double>(0.0, 0.0);
108     }
109
110     // Cleanup
111     fftw_destroy_plan(plan);
112     fftw_free(in);
113     fftw_free(out);
114
115     // filling up the other half of the output
116     const auto halfpoint {static_cast<std::size_t>(nfft/2)};
117     std::transform(
118         output.begin() + 1,          // first half (skip DC)
119         output.begin() + halfpoint, // end of first half
120         output.rbegin(),             // start writing from last element backward (skip
            Nyquist)
121         [](const auto& x) { return std::conj(x); }
122     );
123
124     // returning
125     return std::move(output);
126 }
127
128
129 /*=====
130 y = ifft(x, nfft)
131 -----*/
132 template<typename T>
133 auto ifft(const std::vector<T>& input_vector)

```



```

134 {
135     // fetching data-type
136     using RType = fft_result_t<T>;
137     using baseType = std::conditional_t<std::is_same_v<T, std::complex<double>>,
138                                     double,
139                                     T>;
140
141     // setup
142     auto nfft = {input_vector.size()};
143
144     // canvas instantiation
145     std::vector<RType> canvas(nfft);
146     auto nfft_sqrt = {static_cast<RType>(std::sqrt(nfft))};
147     auto finaloutput = {std::vector<RType>(nfft, 0)};
148
149     // calculating index by index
150     for(int frequency_index = 0; frequency_index < nfft; ++frequency_index){
151         RType accumulate_value;
152         for(int signal_index = 0; signal_index < input_vector.size(); ++signal_index){
153             accumulate_value += \
154                 static_cast<RType>(input_vector[signal_index]) * \
155                 static_cast<RType>(std::exp(1.00 * std::numbers::pi * \
156                                     (static_cast<baseType>(frequency_index)/static_cast<baseType>(nfft) * \
157                                     static_cast<baseType>(signal_index))));
158         }
159         finaloutput[frequency_index] = accumulate_value / nfft_sqrt;
160     }
161
162     // returning
163     return std::move(finaloutput);
164 }
165
166 /*=====
167 x = ifft(std::vector<std::complex<double>> spectrum, nfft)
168 -----*/
169 #include <fftw3.h>
170 #include <vector>
171 #include <complex>
172 #include <stdexcept>
173
174 auto ifft(const std::vector<std::complex<double>>& input_vector,
175          const std::size_t nfft)
176 {
177     if (nfft <= 0)
178         throw std::runtime_error("nfft must be > 0");
179     if (input_vector.size() != nfft)
180         throw std::runtime_error("input spectrum must be of size nfft");
181
182     // Output: real-valued time-domain sequence
183     std::vector<double> output(nfft);
184
185     // Allocate FFTW input/output
186     fftw_complex* in = reinterpret_cast<fftw_complex*>(
187         fftw_malloc(sizeof(fftw_complex) * (nfft/2 + 1))
188     );
189     double* out = reinterpret_cast<double*>(
190         fftw_malloc(sizeof(double) * nfft)
191     );

```

```

192
193 // Copy *only* the first nfft/2+1 bins (rest are redundant due to symmetry)
194 for (std::size_t i = 0; i < nfft/2 + 1; ++i) {
195     in[i][0] = input_vector[i].real();
196     in[i][1] = input_vector[i].imag();
197 }
198
199 // Create inverse FFTW plan
200 fftw_plan plan = fftw_plan_dft_c2r_1d(
201     static_cast<int>(nfft),
202     in,
203     out,
204     FFTW_ESTIMATE
205 );
206
207 fftw_execute(plan);
208
209 // Normalize by nfft (FFTW leaves IFFT unscaled)
210 for (std::size_t i = 0; i < nfft; ++i) {
211     output[i] = out[i] / static_cast<double>(nfft);
212 }
213
214 // Cleanup
215 fftw_destroy_plan(plan);
216 fftw_free(in);
217 fftw_free(out);
218
219 return output;
220 }
221
222
223
224 }

```

B.13 Flipping Containers

```

1 #pragma once
2 namespace svr {
3     /*=====
4     Mirror image of a vector
5     -----*/
6     template <typename T>
7     auto fliplr(const std::vector<T>& input_vector)
8     {
9         // creating canvas
10        auto canvas {input_vector};
11
12        // rewriting
13        std::reverse(canvas.begin(), canvas.end());
14
15        // returning
16        return std::move(canvas);
17    }
18 }

```

B.14 Indexing

```

1  #pragma once
2  namespace svr {
3      /*=====
4      y = index(vector, mask)
5
6      template <
7          typename T1,
8          typename T2,
9          typename = std::enable_if_t<
10              (std::is_arithmetic_v<T1> ||
11               std::is_same_v<T1, std::complex<float>> > ||
12               std::is_same_v<T1, std::complex<double>> >) &&
13               std::is_integral_v<T2>
14          >
15      >
16      -----*/
17      template <typename T1,
18              typename T2,
19              typename = std::enable_if_t<std::is_arithmetic_v<T1> ||
20                                          std::is_same_v<T1, std::complex<float>> > ||
21                                          std::is_same_v<T1, std::complex<double>> >
22                                          >
23          >
24      auto index(const std::vector<T1>& input_vector,
25                const std::vector<T2>& indices_to_sample)
26      {
27          // creating canvas
28          auto canvas {std::vector<T1>(indices_to_sample.size(), 0)};
29
30          // copying the associated values
31          for(int i = 0; i < indices_to_sample.size(); ++i){
32              auto source_index {indices_to_sample[i]};
33              if(source_index < input_vector.size()){
34                  canvas[i] = input_vector[source_index];
35              }
36              else{
37                  // cout << "warning: Some chosen samples are out of bounds. svr::index |
38                      source_index !< input_vector.size()\n";
39              }
40          }
41
42          // returning
43          return std::move(canvas);
44      }
45      /*=====
46      y = index(matrix, mask, dim)
47      -----*/
48      template <
49          typename T1,
50          typename T2,
51          typename = std::enable_if_t<
52              (std::is_same_v<T1, double> || std::is_same_v<T1, float>) &&
53              (std::is_same_v<T2, int> || std::is_same_v<T2, std::size_t>)
54          >
55      >
56      auto index(const std::vector<std::vector<T1>>& input_matrix,
```

```

57         const std::vector<T2>&      indices_to_sample,
58         const std::size_t&          dim)
59     {
60         // fetching dimensions
61         const auto& num_rows_matrix {input_matrix.size()};
62         const auto& num_cols_matrix {input_matrix[0].size()};
63
64         // creating canvas
65         auto canvas {std::vector<std::vector<T1>>>()};
66
67         // if indices are row-indices
68         if (dim == 0){
69
70             // initializing canvas
71             canvas = std::vector<std::vector<T1>>>(
72                 num_rows_matrix,
73                 std::vector<T1>(indices_to_sample.size())
74             );
75
76             // filling the canvas
77             auto destination_index {0};
78             std::for_each(
79                 indices_to_sample.begin(), indices_to_sample.end(),
80                 [&](const auto& col){
81                     for(auto row = 0; row < num_rows_matrix; ++row){
82                         if (col <= input_matrix[0].size()){
83                             canvas[row][destination_index] = input_matrix[row][col];
84                         }
85                     }
86                     ++destination_index;
87                 });
88         }
89         else if(dim == 1){
90             // initializing canvas
91             canvas = std::vector<std::vector<T1>>>(
92                 indices_to_sample.size(),
93                 std::vector<T1>(num_cols_matrix)
94             );
95
96             // filling the canvas
97             #pragma omp parallel for
98             for(auto row = 0; row < canvas.size(); ++row){
99                 auto destination_col {0};
100                 std::for_each(indices_to_sample.begin(), indices_to_sample.end(),
101                     [&row,
102                     &input_matrix,
103                     &destination_col,
104                     &canvas](const auto& source_col){
105                         canvas[row][destination_col++] =
106                             input_matrix[row][source_col];
107                     });
108             }
109         }
110         else {
111             std::cerr << "svr_index | this dim is not implemented \n";
112         }
113
114         // moving it back
115         return std::move(canvas);

```

```

115     }
116 }

```

B.15 Linspace

```

1  /*=====
2  Dependencies
3  -----*/
4  #pragma once
5  #include <vector>
6  #include <complex>
7
8  namespace svr {
9      /*=====
10     in-place
11     -----*/
12     template <typename T>
13     auto linspace(
14         auto&          input,
15         const auto      startvalue,
16         const auto      endvalue,
17         const auto      numpoints
18     ) -> void
19     {
20         auto stepsize = static_cast<T>(endvalue - startvalue)/static_cast<T>(numpoints-1);
21         for(int i = 0; i<input.size(); ++i) {input[i] = startvalue + i*stepsize;}
22     };
23     /*=====
24     in-place
25     -----*/
26     template <typename T>
27     auto linspace(
28         std::vector<std::complex<T>>& input,
29         const auto                    startvalue,
30         const auto                    endvalue,
31         const auto                    numpoints
32     ) -> void
33     {
34         auto stepsize = static_cast<T>(endvalue - startvalue)/static_cast<T>(numpoints-1);
35         for(int i = 0; i<input.size(); ++i) {
36             input[i] = startvalue + static_cast<T>(i)*stepsize;
37         }
38     };
39     /*=====
40     -----*/
41     template <
42         typename T,
43         typename = std::enable_if_t<
44             std::is_arithmetic_v<T> ||
45             std::is_same_v<T, std::complex<float>> > ||
46             std::is_same_v<T, std::complex<double>> >
47         >
48     >
49     auto linspace(
50         const T      startvalue,
51         const T      endvalue,

```

```

52     const    std::size_t    numpoints
53 )
54 {
55     std::vector<T> input(numpoints);
56     auto stepsize = static_cast<T>(endvalue - startvalue)/static_cast<T>(numpoints-1);
57     for(int i = 0; i<input.size(); ++i) {input[i] = startvalue +
58         static_cast<T>(i)*stepsize;}
59     return std::move(input);
60 };
61 /*=====
62 -----*/
63 template <typename T, typename U>
64 auto linspace(
65     const    T            startvalue,
66     const    U            endvalue,
67     const    std::size_t    numpoints
68 )
69 {
70     std::vector<double> input(numpoints);
71     auto stepsize = static_cast<double>(endvalue -
72         startvalue)/static_cast<double>(numpoints-1);
73     for(int i = 0; i<input.size(); ++i) {input[i] = startvalue + i*stepsize;}
74     return std::move(input);
75 };
76 }

```

B.16 Max

```

1  #pragma once
2  /*=====
3  maximum along dimension 1
4  -----*/
5  template <std::size_t axis, typename T>
6  auto max(const std::vector<std::vector<T>>& input_matrix) -> std::enable_if_t<axis
7  == 1, std::vector<std::vector<T>> >
8  {
9      // setting up canvas
10     auto canvas
11         {std::vector<std::vector<T>>(input_matrix.size(),std::vector<T>(1))};
12
13     // filling up the canvas
14     for(auto row = 0; row < input_matrix.size(); ++row)
15         canvas[row][0] = *(std::max_element(input_matrix[row].begin(),
16             input_matrix[row].end()));
17
18     // returning
19     return std::move(canvas);
20 }

```

B.17 Meshgrid

```

1  /*=====
2  Dependencies
3  -----*/

```

```

4  #pragma once
5  #include <vector> // for std::vector
6  #include <utility> // for std::pair
7  #include <complex> // for std::complex
8
9
10 /*=====
11 mesh-grid when working with l-values
12 -----*/
13 template <typename T>
14 auto meshgrid(const std::vector<T>& x,
15               const std::vector<T>& y)
16 {
17
18     // creating and filling x-grid
19     std::vector<std::vector<T>> xcanvas(y.size(), std::vector<T>(x.size(), 0));
20     for(auto row = 0; row < y.size(); ++row)
21         std::copy(x.begin(), x.end(), xcanvas[row].begin());
22
23     // creating and filling y-grid
24     std::vector<std::vector<T>> ycanvas(y.size(), std::vector<T>(x.size(), 0));
25     for(auto col = 0; col < x.size(); ++col)
26         for(auto row = 0; row < y.size(); ++row)
27             ycanvas[row][col] = y[row];
28
29     // returning
30     return std::move(std::pair{xcanvas, ycanvas});
31
32 }
33 /*=====
34 meshgrid when working with r-values
35 -----*/
36 template <typename T>
37 auto meshgrid(std::vector<T>&& x,
38               std::vector<T>&& y)
39 {
40
41     // creating and filling x-grid
42     std::vector<std::vector<T>> xcanvas(y.size(), std::vector<T>(x.size(), 0));
43     for(auto row = 0; row < y.size(); ++row)
44         std::copy(x.begin(), x.end(), xcanvas[row].begin());
45
46     // creating and filling y-grid
47     std::vector<std::vector<T>> ycanvas(y.size(), std::vector<T>(x.size(), 0));
48     for(auto col = 0; col < x.size(); ++col)
49         for(auto row = 0; row < y.size(); ++row)
50             ycanvas[row][col] = y[row];
51
52     // returning
53     return std::move(std::pair{xcanvas, ycanvas});
54
55 }

```

B.18 Minimum

```

1  #pragma once

```

```

2  /*=====
3  minimum along dimension 1
4  -----*/
5  template <std::size_t axis, typename T>
6  auto min(const std::vector<std::vector<T>>& input_matrix) -> std::enable_if_t<axis ==
    1, std::vector<std::vector<T>>> >
7  {
8      // creating canvas
9      auto canvas
        {std::vector<std::vector<T>>(input_matrix.size(),std::vector<T>(1))};
10
11     // storing the values
12     for(auto row = 0; row < input_matrix.size(); ++row)
13         canvas[row][0] = *(std::min_element(input_matrix[row].begin(),
            input_matrix[row].end()));
14
15     // returning the value
16     return std::move(canvas);
17 }

```

B.19 Norm

```

1  #pragma once
2  /*=====
3  calculating norm for vector
4  -----*/
5  template <typename T>
6  auto norm(const std::vector<T>& input_vector)
7  {
8      return std::sqrt(
9          std::inner_product(
10             input_vector.begin(), input_vector.end(),
11             input_vector.begin(),
12             (T)0
13         )
14     );
15 }
16 /*=====
17 Calculating norm of a complex-vector
18 -----*/
19 template <>
20 auto norm(const std::vector<std::complex<double>>& input_vector)
21 {
22     return std::sqrt(
23         std::inner_product(
24             input_vector.begin(), input_vector.end(),
25             input_vector.begin(),
26             static_cast<double>(0),
27             std::plus<double>(),
28             [](const auto& argx,
29                const auto& argy){
30                 return static_cast<double>(
31                     (argx * std::conj(argy)).real()
32                 );
33             })
34     )

```



```

35     );
36
37 }
38 /*=====
39 -----*/
40 template <typename T>
41 auto norm(const std::vector<std::vector<T>>& input_matrix,
42          const std::size_t dim)
43 {
44     // creating canvas
45     auto canvas {std::vector<std::vector<T>>()};
46     const auto& num_rows_matrix {input_matrix.size()};
47     const auto& num_cols_matrix {input_matrix[0].size()};
48
49     // along dim 0
50     if(dim == 0)
51     {
52         // allocate canvas
53         canvas = std::vector<std::vector<T>>(
54             1,
55             std::vector<T>(input_matrix[0].size())
56         );
57
58         // performing norm
59         auto accumulate_vector {std::vector<T>(input_matrix[0].size())};
60
61         // going through each row
62         for(auto row = 0; row < num_rows_matrix; ++row)
63         {
64             std::transform(input_matrix[row].begin(), input_matrix[row].end(),
65                             accumulate_vector.begin(),
66                             accumulate_vector.begin(),
67                             [](const auto& argx, auto& argy){
68                                 return argx*argx + argy;
69                             });
70         }
71
72         // calculating element-wise square root
73         std::for_each(accumulate_vector.begin(), accumulate_vector.end(),
74                       [](auto& argx){
75                           argx = std::sqrt(argx);
76                       });
77
78         // moving to the canvas
79         canvas[0] = std::move(accumulate_vector);
80     }
81     else if (dim == 1)
82     {
83         // allocating space in the canvas
84         canvas = std::vector<std::vector<T>>(
85             input_matrix[0].size(),
86             std::vector<T>(1, 0)
87         );
88
89         // going through each column
90         for(auto row = 0; row < num_cols_matrix; ++row){
91             canvas[row][0] = norm(input_matrix[row]);
92         }
93

```

```

94     }
95     else
96     {
97         std::cerr << "norm(matrix, dim): dimension operation not defined \n";
98     }
99
100    // returning
101    return std::move(canvas);
102 }
103
104
105
106 /*
107 Templates to create
108 - matrix and norm-axis
109 - axis instantiated std::vector<T>
110 */

```

B.20 Division

```

1  #pragma once
2  /*=====
3  element-wise division with scalars
4  -----*/
5  template <typename T>
6  auto operator/(const std::vector<T>& input_vector,
7                const T& input_scalar)
8  {
9      // creating canvas
10     auto canvas {input_vector};
11
12     // filling canvas
13     std::transform(canvas.begin(), canvas.end(),
14                   canvas.begin(),
15                   [&input_scalar](const auto& argx){
16                       return static_cast<double>(argx) /
17                          static_cast<double>(input_scalar);
18                   });
19
20     // returning value
21     return std::move(canvas);
22 }
23 /*=====
24 element-wise division with scalars
25 -----*/
26 template <typename T>
27 auto operator/=(const std::vector<T>& input_vector,
28                const T& input_scalar)
29 {
30     // creating canvas
31     auto canvas {input_vector};
32
33     // filling canvas
34     std::transform(canvas.begin(), canvas.end(),
35                   canvas.begin(),
36                   [&input_scalar](const auto& argx){

```

```

36         return static_cast<double>(argx) /
37            static_cast<double>(input_scalar);
38     });
39
40     // returning value
41     return std::move(canvas);
42 }
43
44 //=====
45 element-wise with matrix
46 -----*/
47
48 template <
49     typename T,
50     typename = std::enable_if_t<
51         std::is_floating_point_v<T>
52     >
53 >
54 auto operator/((const std::vector<std::vector<T>>& input_matrix,
55                const T scalar)
56 {
57     // fetching matrix-dimensions
58     const auto& num_rows_matrix {input_matrix.size()};
59     const auto& num_cols_matrix {input_matrix[0].size()};
60
61     // creating canvas
62     auto canvas {std::vector<std::vector<T>>>(
63         num_rows_matrix,
64         std::vector<T>(num_cols_matrix)
65     )};
66
67     // dividing with values
68     for(auto row = 0; row < num_rows_matrix; ++row){
69         std::transform(input_matrix[row].begin(), input_matrix[row].end(),
70             canvas[row].begin(),
71             [&scalar](const auto& argx){
72                 return argx/scalar;
73             });
74     }
75
76     // returning values
77     return std::move(canvas);
78 }
79
80 template <
81     typename numeratorComplexType,
82     typename denominatorType,
83     typename = std::enable_if_t<
84         std::is_floating_point_v< numeratorComplexType> &&
85         std::is_arithmetic_v< denominatorType>
86     >
87 >
88 auto operator/((
89     const std::vector<std::vector<std::complex<numeratorComplexType>>>& input_matrix,
90     const denominatorType input_scalar
91 )
92 {
93     // fetching matrix-dimensions
94     const auto& num_rows_matrix {input_matrix.size()};
95     const auto& num_cols_matrix {input_matrix[0].size()};
96
97     // creating canvas

```

```

94     auto    canvas    {std::vector<std::vector<std::complex<numeratorComplexType>>>(
95         num_rows_matrix,
96         std::vector<std::complex<numeratorComplexType>>(num_cols_matrix)
97     )};
98
99     // dividing with values
100    for(auto row = 0; row < num_rows_matrix; ++row){
101        std::transform(
102            input_matrix[row].begin(), input_matrix[row].end(),
103            canvas[row].begin(),
104            [&input_scalar](const auto& argx){
105                return argx /
106                    static_cast<std::complex<numeratorComplexType>>(input_scalar);
107            });
108    }
109
110    // returning values
111    return std::move(canvas);
112 }
113
114 /*=====
115 y = std::vector<std::complex<T>> / T
116 -----*/
117
118 template <
119     typename T,
120     typename = std::enable_if_t<
121         std::is_floating_point_v<T>
122     >
123 >
124 auto operator/(
125     const std::vector<std::complex<T>>& input_vector,
126     const T input_scalar
127 )
128 {
129     // creating canvas
130     auto canvas {std::vector<std::complex<T>>(input_vector.size())};
131
132     // filling the canvas
133     std::transform(
134         input_vector.begin(), input_vector.end(),
135         canvas.begin(),
136         [&input_scalar](const auto& argx){
137             return argx/static_cast<std::complex<T>>(input_scalar);
138         });
139
140     // returning
141     return std::move(canvas);
142 }

```

B.21 Addition

```

1 #pragma once
2 /*=====
3 y = vector + vector
4 -----*/
5 template <typename T>

```

```

6  std::vector<T> operator+(const std::vector<T>& a,
7                          const std::vector<T>& b)
8  {
9      // Identify which is bigger
10     const auto& big = (a.size() > b.size()) ? a : b;
11     const auto& small = (a.size() > b.size()) ? b : a;
12
13     std::vector<T> result = big; // copy the bigger one
14
15     // Add elements from the smaller one
16     for (size_t i = 0; i < small.size(); ++i) {
17         result[i] += small[i];
18     }
19
20     return result;
21 }
22 /*=====
23 -----*/
24 // y = vector + vector
25 template <typename T>
26 std::vector<T>& operator+=(std::vector<T>& a,
27                          const std::vector<T>& b) {
28
29     const auto& small = (a.size() < b.size()) ? a : b;
30     const auto& big = (a.size() < b.size()) ? b : a;
31
32     // If b is bigger, resize 'a' to match
33     if (a.size() < b.size()) {a.resize(b.size());}
34
35     // Add elements
36     for (size_t i = 0; i < small.size(); ++i) {a[i] += b[i];}
37
38     // returning elements
39     return a;
40 }
41 // =====
42 // y = matrix + matrix
43 template <typename T>
44 std::vector<std::vector<T>> operator+(const std::vector<std::vector<T>>& a,
45                                     const std::vector<std::vector<T>>& b)
46 {
47     // fetching dimensions
48     const auto& num_rows_A = {a.size()};
49     const auto& num_cols_A = {a[0].size()};
50     const auto& num_rows_B = {b.size()};
51     const auto& num_cols_B = {b[0].size()};
52
53     // choosing the three different metrics
54     if (num_rows_A != num_rows_B && num_cols_A != num_cols_B){
55         cout << format("a.dimensions = [{},{}, b.shape = [{},{},{}\n",
56                        num_rows_A, num_cols_A,
57                        num_rows_B, num_cols_B);
58         std::cerr << "dimensions don't match\n";
59     }
60
61     // creating canvas
62     auto canvas = {std::vector<std::vector<T>>(
63         std::max(num_rows_A, num_rows_B),
64         std::vector<T>(std::max(num_cols_A, num_cols_B), (T)0.00)

```

```

65     });
66
67     // performing addition
68     if (num_rows_A == num_rows_B && num_cols_A == num_cols_B){
69         for(auto row = 0; row < num_rows_A; ++row){
70             std::transform(a[row].begin(), a[row].end(),
71                             b[row].begin(),
72                             canvas[row].begin(),
73                             std::plus<T>());
74         }
75     }
76     else if(num_rows_A == num_rows_B){
77
78         // if number of columns are different, check if one of the cols are one
79         const auto min_num_cols {std::min(num_cols_A, num_cols_B)};
80         if (min_num_cols != 1) {std::cerr<< "Operator+: unable to broadcast\n";}
81         const auto max_num_cols {std::max(num_cols_A, num_cols_B)};
82
83         // using references to tag em differently
84         const auto& big_matrix {num_cols_A > num_cols_B ? a : b};
85         const auto& small_matrix {num_cols_A < num_cols_B ? a : b};
86
87         // Adding to canvas
88         for(auto row = 0; row < canvas.size(); ++row){
89             std::transform(big_matrix[row].begin(), big_matrix[row].end(),
90                             canvas[row].begin(),
91                             [&small_matrix,
92                             &row](const auto& argx){
93                                     return argx + small_matrix[row][0];
94                                 });
95         }
96     }
97     else if(num_cols_A == num_cols_B){
98
99         // check if the smallest column-number is one
100        const auto min_num_rows {std::min(num_rows_A, num_rows_B)};
101        if(min_num_rows != 1) {std::cerr << "Operator+ : unable to broadcast\n";}
102        const auto max_num_rows {std::max(num_rows_A, num_rows_B)};
103
104        // using references to differentiate the two matrices
105        const auto& big_matrix {num_rows_A > num_rows_B ? a : b};
106        const auto& small_matrix {num_rows_A < num_rows_B ? a : b};
107
108        // adding to canvas
109        for(auto row = 0; row < canvas.size(); ++row){
110            std::transform(big_matrix[row].begin(), big_matrix[row].end(),
111                            small_matrix[0].begin(),
112                            canvas[row].begin(),
113                            [](const auto& argx, const auto& argy){
114                                return argx + argy;
115                            });
116        }
117    }
118    else {
119        std::cerr << "operator+: yet to be implemented \n";
120    }
121
122    // returning
123    return std::move(canvas);

```

```

124 }
125 /*=====
126 y = vector + scalar
127 -----*/
128 template <typename T>
129 auto operator+(const std::vector<T>& input_vector,
130               const T scalar)
131 {
132     // creating canvas
133     auto canvas {input_vector};
134
135     // adding scalar to the canvas
136     std::transform(canvas.begin(), canvas.end(),
137                   canvas.begin(),
138                   [&scalar](auto& argx){return argx + scalar;});
139
140     // returning canvas
141     return std::move(canvas);
142 }
143 /*=====
144 y = scalar + vector
145 -----*/
146 template <typename T>
147 auto operator+(const T scalar,
148               const std::vector<T>& input_vector)
149 {
150     // creating canvas
151     auto canvas {input_vector};
152
153     // adding scalar to the canvas
154     std::transform(canvas.begin(), canvas.end(),
155                   canvas.begin(),
156                   [&scalar](auto& argx){return argx + scalar;});
157
158     // returning canvas
159     return std::move(canvas);
160 }

```

B.22 Multiplication (Element-wise)

```

1  #pragma once
2  /*=====
3  y = scalar * vector
4  -----*/
5  template <typename T>
6  auto operator*(
7      const T scalar,
8      const std::vector<T>& input_vector
9  )
10 {
11     // creating canvas
12     auto canvas {input_vector};
13     // performing operation
14     std::for_each(canvas.begin(), canvas.end(),
15                   [&scalar](auto& argx){argx = argx * scalar;});
16     // returning

```

```

17     return std::move(canvas);
18 }
19 /*=====
20 y = scalar * vector
21 -----*/
22 template <
23     typename T1,
24     typename T2,
25     typename = std::enable_if_t<
26         !std::is_same_v<std::decay_t<T1>, std::vector<T2> > &&
27         std::is_arithmetic_v<T1>
28     >
29 >
30 auto operator*(const T1 scalar,
31               const vector<T2>& input_vector)
32 {
33     // fetching final-type
34     using T3 = decltype(std::declval<T1>() * std::declval<T2>());
35
36     // creating canvas
37     auto canvas = {std::vector<T3>(input_vector.size())};
38
39     // multiplying
40     std::transform(
41         input_vector.begin(), input_vector.end(),
42         canvas.begin(),
43         [&scalar](auto& argx){
44             return static_cast<T3>(scalar) * static_cast<T3>(argx);
45         });
46
47     // returning
48     return std::move(canvas);
49 }
50 /*=====
51 y = scalar * vecotor (subset init)
52 -----*/
53 template <
54     typename T,
55     typename = std::enable_if_t<
56         std::is_floating_point_v<T>
57     >
58 >
59 auto operator*(
60     const std::complex<T> scalar,
61     const std::vector<T>& input_vector
62 )
63 {
64     // creating canvas
65     auto canvas = {std::vector<std::complex<T>>(
66         input_vector.size()
67     )};
68
69     // copying to canvas
70     std::transform(
71         input_vector.begin(), input_vector.end(),
72         canvas.begin(),
73         [&scalar](const auto& argx){
74             return scalar * static_cast<std::complex<T>>(argx);
75         });

```



```

76     );
77
78     // moving it back
79     return std::move(canvas);
80 }
81 /*=====
82 y = vector * scalar
83 -----*/
84 template <typename T>
85 auto operator*(const std::vector<T>& input_vector,
86               const T scalar)
87 {
88     // creating canvas
89     auto canvas {input_vector};
90     // multiplying
91     std::for_each(canvas.begin(), canvas.end(),
92                 [&scalar](auto& argx){
93         argx = argx * scalar;
94     });
95     // returning
96     return std::move(canvas);
97 }
98 /*=====
99 y = vector * vector
100 -----*/
101 template <typename T>
102 auto operator*(const std::vector<T>& input_vector_A,
103               const std::vector<T>& input_vector_B)
104 {
105     // throwing error: size-disparity
106     if (input_vector_A.size() != input_vector_B.size()) {std::cerr << "operator*: size
107         disparity \n";}
108
109     // creating canvas
110     auto canvas {input_vector_A};
111
112     // element-wise multiplying
113     std::transform(input_vector_B.begin(), input_vector_B.end(),
114                   canvas.begin(),
115                   canvas.begin(),
116                   [](const auto& argx, const auto& argy){
117       return argx * argy;
118     });
119
120     // moving it back
121     return std::move(canvas);
122 }
123 /*=====
124 y = vecotr * vector
125 -----*/
126 template <
127     typename T1,
128     typename T2,
129     typename = std::enable_if_t<
130         std::is_arithmetic_v<T1> &&
131         std::is_arithmetic_v<T2>
132     >
133 auto operator*(const std::vector<T1>& input_vector_A,

```

```

134         const      std::vector<T2>&  input_vector_B)
135     {
136
137         // checking size disparity
138         if (input_vector_A.size() != input_vector_B.size())
139             std::cerr << "operator*: error, size-disparity \n";
140
141         // figuring out resulting data type
142         using T3    = decltype(std::declval<T1>() * std::declval<T2>());
143
144         // creating canvas
145         auto  canvas    {std::vector<T3>(input_vector_A.size())};
146
147         // performing multiplications
148         std::transform(input_vector_A.begin(), input_vector_A.end(),
149                        input_vector_B.begin(),
150                        canvas.begin(),
151                        [](const auto&      argx,
152                          const auto&      argy){
153                            return static_cast<T3>(argx) * static_cast<T3>(argy);
154                        });
155
156         // returning
157         return std::move(canvas);
158     }
159 }
160 /*=====
161 y = vector * complex_vector
162 -----*/
163 template <
164     typename T,
165     typename = std::enable_if_t<
166         std::is_floating_point_v<T>
167     >
168 >
169 auto operator*(
170     const std::vector<T>&      input_vector_A,
171     const std::vector<std::complex<T>>& input_vector_B
172 )
173 {
174     // checking size issue
175     if (input_vector_A.size() != input_vector_B.size())
176         throw std::runtime_error(
177             "FILE: svr_operator_star.hpp | FUNCTION: operator* | REPORT: error disparity
178             in the two input-vectors"
179         );
180
181     // creating canvas
182     auto  canvas    {std::vector<std::complex<T>>( input_vector_A.size() )};
183
184     // filling up the canvas
185     std::transform(
186         input_vector_B.begin(), input_vector_B.end(),
187         input_vector_A.begin(),
188         canvas.begin(),
189         [](const auto& argx, const auto& argy){
190             return argx + static_cast<std::complex<T>>(argy);
191         });

```

```

192
193     // moving it back
194     return std::move(canvas);
195 }
196 /*=====
197 y = complex_vector * vector
198 -----*/
199 template <
200     typename T,
201     typename = std::enable_if_t<
202         std::is_floating_point_v<T>
203     >
204 >
205 auto operator*(
206     const std::vector<std::complex<T>>& input_vector_A,
207     const std::vector<T>& input_vector_B
208 )
209 {
210     // enforcing size
211     if (input_vector_A.size() != input_vector_B.size())
212         throw std::runtime_error(
213             "FILE: svr_operator_star.hpp | FUNCTION: operator* overload"
214         );
215
216     // creating canvas
217     auto canvas {std::vector<std::complex<T>>(input_vector_A.size())};
218
219     // filling values
220     std::transform(
221         input_vector_A.begin(), input_vector_A.end(),
222         input_vector_B.begin(),
223         canvas.begin(),
224         [](const auto& argx, const auto& argy){
225             return argx * static_cast<std::complex<T>>(argy);
226         }
227     );
228
229     // returning
230     return std::move(canvas);
231 }
232 /*=====
233 y = complex-vector * complex-vector
234 -----*/
235 template <
236     typename T,
237     typename = std::enable_if_t<
238         std::is_floating_point_v<T>
239     >
240 >
241 auto operator*(
242     const std::vector<std::complex<T>> input_vector_A,
243     const std::vector<std::complex<T>> input_vector_B
244 )
245 {
246     // checking size
247     if (input_vector_A.size() != input_vector_B.size())
248         throw std::runtime_error(
249             "FILE: svr_operator_star.hpp | FUNCTION: operator*(complex-vector,
                complex-vector)"

```

```

250     );
251
252     // creating canvas
253     auto canvas {std::vector<std::complex<T>>(input_vector_A.size())};
254
255     // filling canvas
256     std::transform(
257         input_vector_A.begin(), input_vector_A.end(),
258         input_vector_B.begin(),
259         canvas.begin(),
260         [](const auto& argx, const auto& argy){
261             return argx * argy;
262         }
263     );
264
265     // returning values
266     return std::move(canvas);
267 }
268 // scalar * matrix =====
269 template <typename T>
270 auto operator*(const T scalar,
271               const std::vector<std::vector<T>>& inputMatrix)
272 {
273     std::vector<std::vector<T>> temp {inputMatrix};
274     for(int i = 0; i<inputMatrix.size(); ++i){
275         std::transform(inputMatrix[i].begin(),
276                       inputMatrix[i].end(),
277                       temp[i].begin(),
278                       [&scalar](T x){return scalar * x;});
279     }
280     return std::move(temp);
281 }
282 /*=====
283 y = matrix * scalar
284 -----*/
285 template <typename T>
286 auto operator*(const std::vector<std::vector<T>>& input_matrix,
287               const T scalar)
288 {
289     // fetching matrix dimensions
290     const auto& num_rows_matrix {input_matrix.size()};
291     const auto& num_cols_matrix {input_matrix[0].size()};
292
293     // creating canvas
294     auto canvas {std::vector<std::vector<T>>(
295         num_rows_matrix,
296         std::vector<T>(num_cols_matrix)
297     )};
298
299     // storing the values
300     for(auto row = 0; row < num_rows_matrix; ++row)
301         std::transform(input_matrix[row].begin(), input_matrix[row].end(),
302                       canvas[row].begin(),
303                       [&scalar](const auto& argx){
304                           return argx * scalar;
305                       });
306
307     // returning
308     return std::move(canvas);

```

```

309 }
310 /*=====
311 y = matrix * matrix
312 -----*/
313 template <typename T>
314 auto operator*(const std::vector<std::vector<T>>& A,
315               const std::vector<std::vector<T>>& B) -> std::vector<std::vector<T>>
316 {
317     // Case 1: element-wise multiplication
318     if (A.size() == B.size() && A[0].size() == B[0].size()) {
319         std::vector<std::vector<T>> C(A.size(), std::vector<T>(A[0].size()));
320         for (std::size_t row = 0; row < A.size(); ++row) {
321             std::transform(A[row].begin(), A[row].end(),
322                           B[row].begin(),
323                           C[row].begin(),
324                           [](const auto& x, const auto& y){ return x * y; });
325         }
326         return C;
327     }
328
329     // Case 2: broadcast column vector
330     else if (A.size() == B.size() && B[0].size() == 1) {
331         std::vector<std::vector<T>> C(A.size(), std::vector<T>(A[0].size()));
332         for (std::size_t row = 0; row < A.size(); ++row) {
333             std::transform(A[row].begin(), A[row].end(),
334                           C[row].begin(),
335                           [&](const auto& x){ return x * B[row][0]; });
336         }
337         return C;
338     }
339
340     // case 3: when second matrix contains just one row
341     // case 4: when first matrix is just one column
342     // case 5: when second matrix is just one column
343
344     // Otherwise, invalid
345     else {
346         throw std::runtime_error("operator* dimension mismatch");
347     }
348 }
349 /*=====
350 y = scalar * matrix
351 -----*/
352 template <typename T1, typename T2>
353 auto operator*(const T1 scalar,
354               const std::vector<std::vector<T2>>& inputMatrix)
355 {
356     std::vector<std::vector<T2>> temp {inputMatrix};
357     for(int i = 0; i<inputMatrix.size(); ++i){
358         std::transform(inputMatrix[i].begin(),
359                       inputMatrix[i].end(),
360                       temp[i].begin(),
361                       [&scalar](T2 x){return static_cast<T2>(scalar) * x;});
362     }
363     return temp;
364 }
365 /*=====
366 matrix-multiplication
367 -----*/

```

```

368 template <typename T1, typename T2>
369 auto matmul(const std::vector<std::vector<T1>>& matA,
370             const std::vector<std::vector<T2>>& matB)
371 {
372
373     // throwing error
374     if (matA[0].size() != matB.size()) {std::cerr << "dimension-mismatch \n";}
375
376     // getting result-type
377     using ResultType = decltype(std::declval<T1>() * std::declval<T2>() + \
378                                std::declval<T1>() * std::declval<T2>());
379
380     // creating aliases
381     auto finalnumrows {matA.size()};
382     auto finalnumcols {matB[0].size()};
383
384     // creating placeholder
385     auto rowcolproduct = [&](auto rowA, auto colB){
386         ResultType temp {0};
387         for(int i = 0; i < matA.size(); ++i) {temp +=
388             static_cast<ResultType>(matA[rowA][i]) +
389             static_cast<ResultType>(matB[i][colB]);}
390         return temp;
391     };
392
393     // producing row-column combinations
394     std::vector<std::vector<ResultType>> finaloutput(finalnumrows,
395                                                     std::vector<ResultType>(finalnumcols));
396     for(int row = 0; row < finalnumrows; ++row){for(int col = 0; col < finalnumcols;
397                                                     ++col){finaloutput[row][col] = rowcolproduct(row, col);}}
398
399     // returning
400     return finaloutput;
401 }
402
403 /*=====
404 y = matrix * vector
405 -----*/
406
407 template <
408     typename T,
409     typename = std::enable_if_t<
410         std::is_arithmetic_v<T>
411     >
412 >
413 auto operator*(const std::vector<std::vector<T>>& input_matrix,
414               const std::vector<T>& input_vector)
415 {
416     // fetching dimensions
417     const auto& num_rows_matrix {input_matrix.size()};
418     const auto& num_cols_matrix {input_matrix[0].size()};
419     const auto& num_rows_vector {1};
420     const auto& num_cols_vector {input_vector.size()};
421     const auto& max_num_rows {num_rows_matrix > num_rows_vector ? \
422                               num_rows_matrix : num_rows_vector};
423     const auto& max_num_cols {num_cols_matrix > num_cols_vector ? \
424                               num_cols_matrix : num_cols_vector};
425
426     // creating canvas
427     auto canvas {std::vector<std::vector<T>>(
428         max_num_rows,

```

```

423     std::vector<T>(max_num_cols, 0)
424 });
425
426 // multiplying column matrix with row matrix
427 if (num_cols_matrix == 1 && num_rows_vector == 1){
428
429     // writing to canvas
430     for(auto row = 0; row < max_num_rows; ++row)
431         for(auto col = 0; col < max_num_cols; ++col)
432             canvas[row][col] = input_matrix[row][0] * input_vector[col];
433 }
434 /*=====
435 Multiplying each row with the input-vector
436 -----*/
437 else if(
438     num_cols_matrix == num_cols_vector &&
439     num_rows_vector == 1
440 )
441 {
442     // writing to canvas
443     for(auto row = 0; row < max_num_rows; ++row)
444         std::transform(
445             input_matrix[row].begin(), input_matrix[row].end(),
446             input_vector.begin(),
447             canvas[row].begin(),
448             [](const auto& argx, const auto& argy){return argx * argy;}
449         );
450 }
451 else
452 {
453     std::cerr << "Operator*: [matrix, vector] | not implemented \n";
454 }
455
456 // returning
457 return std::move(canvas);
458
459 }
460 /*=====
461 complex-matrix * vector
462 -----*/
463 template <
464     typename T,
465     typename = std::enable_if_t<
466         std::is_floating_point_v<T>
467     >
468 >
469 auto operator*(
470     const std::vector<std::vector<std::complex<T>>>& input_matrix,
471     const std::vector<T>& input_vector
472 )
473 {
474     // fetching dimensions
475     const auto num_rows_matrix {input_matrix.size()};
476     const auto num_cols_matrix {input_matrix[0].size()};
477     const auto num_rows_vector {static_cast<std::size_t>(1)};
478     const auto num_cols_vector {input_vector.size()};
479
480     // throwing an error
481     if (num_cols_matrix != num_cols_vector)

```

```

482     throw std::runtime_error(
483         "FILE: svr_operator_star.hpp | FUNCTION: operator*(complex-matrix, vector)"
484     );
485
486     // creating canvas
487     auto canvas {std::vector<std::vector<std::complex<T>>>(
488         num_rows_matrix,
489         std::vector<std::complex<T>>(num_cols_matrix)
490     )};
491
492     // performing operations
493     for(auto row = 0; row < num_rows_matrix; ++row)
494         std::transform(
495             input_matrix[row].begin(), input_matrix[row].end(),
496             input_vector.begin(),
497             canvas[row].begin(),
498             [](const auto& argx, const auto& argy){
499                 return argx * static_cast<std::complex<T>>(argy);
500             }
501         );
502
503     // returning the final output
504     return std::move(canvas);
505
506 }
507 /*=====
508 matrix * complex-vector
509 -----*/
510 template <
511     typename T,
512     typename = std::enable_if_t<
513         std::is_floating_point_v<T>
514     >
515 >
516 auto operator*(
517     const std::vector<std::vector<T>>& input_matrix,
518     const std::vector<std::complex<T>>& input_vector
519 )
520 {
521     // fetching dimensions
522     const auto num_rows_matrix {input_matrix.size()};
523     const auto num_cols_matrix {input_matrix[0].size()};
524     const auto num_rows_vector {static_cast<std::size_t>(1)};
525     const auto num_cols_vector {input_vector.size()};
526
527     // fetching dimension mismatch
528     if (num_cols_matrix != num_cols_vector){
529         cout << format("input_matrix.shape = [{}, {}], input_vector.shape = [{}, {}]\n",
530             num_rows_matrix, num_cols_matrix, 1, num_cols_vector);
531         throw std::runtime_error(
532             "FILE: svr_operator_star.hpp | FUNCTION: operator*(input-matrix,
533                 complex-vector)"
534         );
535     }
536
537     // creating canvas
538     auto canvas {std::vector<std::vector<std::complex<T>>>(
539         num_rows_matrix,

```



```

539     std::vector<std::complex<T>>>(
540         num_cols_matrix
541     )
542 });
543
544 // filling the values
545 for(auto row = 0; row < num_rows_matrix; ++row)
546     std::transform(
547         input_matrix[row].begin(), input_matrix[row].end(),
548         input_vector.begin(),
549         canvas[row].begin(),
550         [](const auto& argx, const auto& argy){
551             return static_cast<std::complex<T>>>(argx) * argy;
552         }
553     );
554
555 // returning final-output
556 return std::move(canvas);
557 }
558 /*=====
559 scalar operators
560 -----*/
561 auto operator*(const std::complex<double> complexscalar,
562               const double doublescalar){
563     return complexscalar * static_cast<std::complex<double>>>(doublescalar);
564 }
565 auto operator*(const double doublescalar,
566               const std::complex<double> complexscalar){
567     return complexscalar * static_cast<std::complex<double>>>(doublescalar);
568 }
569 auto operator*(const std::complex<double> complexscalar,
570               const int scalar){
571     return complexscalar * static_cast<std::complex<double>>>(scalar);
572 }
573 auto operator*(const int scalar,
574               const std::complex<double> complexscalar){
575     return complexscalar * static_cast<std::complex<double>>>(scalar);
576 }

```

B.23 Subtraction

```

1  #pragma once
2  /*=====
3  y = vector - scalar
4  -----*/
5  template <typename T>
6  auto operator-(const std::vector<T>& a,
7               const T scalar){
8     std::vector<T> temp(a.size());
9     std::transform(a.begin(),
10                  a.end(),
11                  temp.begin(),
12                  [scalar](T x){return (x - scalar);});
13     return std::move(temp);
14 }
15 /*=====

```

```

16 y = vector - vector
17 -----*/
18 template <typename T>
19 auto operator-(const std::vector<T>& input_vector_A,
20               const std::vector<T>& input_vector_B)
21 {
22     // throwing error
23     if (input_vector_A.size() != input_vector_B.size())
24         std::cerr << "operator-(vector, vector): size disparity\n";
25
26     // creating canvas
27     const auto& num_cols {input_vector_A.size()};
28     auto canvas {std::vector<T>()};
29
30     // performing operations
31     std::transform(input_vector_A.begin(), input_vector_A.begin(),
32                   input_vector_B.begin(),
33                   canvas.begin(),
34                   [](const auto& argx, const auto& argy){
35                       return argx - argy;
36                   });
37
38     // return
39     return std::move(canvas);
40 }
41 /*=====
42 y = matrix - matrix
43 -----*/
44 template <typename T>
45 auto operator-(const std::vector<std::vector<T>>& input_matrix_A,
46               const std::vector<std::vector<T>>& input_matrix_B)
47 {
48     // fetching dimensions
49     const auto& num_rows_A {input_matrix_A.size()};
50     const auto& num_cols_A {input_matrix_A[0].size()};
51     const auto& num_rows_B {input_matrix_B.size()};
52     const auto& num_cols_B {input_matrix_B[0].size()};
53
54     // creating canvas
55     auto canvas {std::vector<std::vector<T>>()};
56
57     // if both matrices are of equal dimensions
58     if (num_rows_A == num_rows_B && num_cols_A == num_cols_B)
59     {
60         // copying one to the canvas
61         canvas = input_matrix_A;
62
63         // subtracting
64         for(auto row = 0; row < num_rows_B; ++row)
65             std::transform(canvas[row].begin(), canvas[row].end(),
66                           input_matrix_B[row].begin(),
67                           canvas[row].begin(),
68                           [](auto& argx, const auto& argy){
69                               return argx - argy;
70                           });
71     }
72     // column broadcasting (case 1)
73     else if (num_rows_A == num_rows_B && num_cols_B == 1)
74     {

```

```

75     // copying canvas
76     canvas = input_matrix_A;
77
78     // subtracting
79     for(auto row = 0; row < num_rows_A; ++row){
80         std::transform(canvas[row].begin(), canvas[row].end(),
81                         canvas[row].begin(),
82                         [&input_matrix_B,
83                          &row](auto& argx){
84                             return argx - input_matrix_B[row][0];
85                         });
86     }
87 }
88 else{
89     std::cerr << "operator-: not implemented for this case \n";
90 }
91
92 // returning
93 return std::move(canvas);
94 }

```

B.24 Printing Containers

```

1  #pragma once
2  /*=====
3  -----*/
4  template<typename T>
5  void fPrintVector(const vector<T> input){
6      for(auto x: input) cout << x << ", ";
7      cout << endl;
8  }
9
10 template<typename T>
11 void fpv(vector<T> input){
12     for(auto x: input) cout << x << ", ";
13     cout << endl;
14 }
15 /*=====
16 -----*/
17 template<typename T>
18 void fPrintMatrix(const std::vector<std::vector<T>> input_matrix){
19     for(const auto& row: input_matrix)
20         cout << format("{}\n", row);
21 }
22 /*=====
23 -----*/
24 template <typename T>
25 void fPrintMatrix(const string& input_string,
26                  const std::vector<std::vector<T>> input_matrix){
27     cout << format("{} = \n", input_string);
28     for(const auto& row: input_matrix)
29         cout << format("{}\n", row);
30 }
31 /*=====
32 -----*/
33 template<typename T, typename T1>

```

```

34 void fPrintHashMap(unordered_map<T, T1> input){
35     for(auto x: input){
36         cout << format("[{} , {}] | ", x.first, x.second);
37     }
38     cout << endl;
39 }
40 /*=====
41 -----*/
42 void fPrintBinaryTree(TreeNode* root){
43     // sending it back
44     if (root == nullptr) return;
45
46     // printing
47     PRINTLINE
48     cout << "root->val = " << root->val << endl;
49
50     // calling the children
51     fPrintBinaryTree(root->left);
52     fPrintBinaryTree(root->right);
53
54     // returning
55     return;
56 }
57
58 /*=====
59 -----*/
60 void fPrintLinkedList(ListNode* root){
61     if (root == nullptr) return;
62     cout << root->val << " -> ";
63     fPrintLinkedList(root->next);
64     return;
65 }
66 /*=====
67 -----*/
68 template<typename T>
69 void fPrintContainer(T input){
70     for(auto x: input) cout << x << ", ";
71     cout << endl;
72     return;
73 }
74 /*=====
75 -----*/
76 template <typename T>
77 auto size(std::vector<std::vector<T>> inputMatrix){
78     cout << format("[{} , {}]\n",
79         inputMatrix.size(),
80         inputMatrix[0].size());
81 }
82 /*=====
83 -----*/
84 template <typename T>
85 auto size(const std::string& inputstring,
86     const std::vector<std::vector<T>>& inputMatrix){
87     cout << format("{} = [{} , {}]\n",
88         inputstring,
89         inputMatrix.size(),
90         inputMatrix[0].size());
91 }

```

B.25 Random Number Generation

```

1  #pragma once
2  /*=====
3  -----*/
4  template <typename T>
5  auto rand(const T min,
6            const T max) {
7      static std::random_device rd; // Seed
8      static std::mt19937 gen(rd()); // Mersenne Twister generator
9      std::uniform_real_distribution<> dist(min, max);
10     return dist(gen);
11 }
12 /*=====
13 -----*/
14 template <typename T>
15 auto rand(const T min,
16           const T max,
17           const std::size_t numelements)
18 {
19     static std::random_device rd; // Seed
20     static std::mt19937 gen(rd()); // Mersenne Twister generator
21     std::uniform_real_distribution<> dist(min, max);
22
23     // building the finaloutput
24     vector<T> finaloutput(numelements);
25     for(int i = 0; i<finaloutput.size(); ++i) {finaloutput[i] =
26         static_cast<T>(dist(gen));}
27
28     return finaloutput;
29 }
30 /*=====
31 -----*/
32 template <typename T>
33 auto rand(const T argmin,
34           const T argmax,
35           const std::vector<int> dimensions)
36 {
37     // throwing an error if dimension is greater than two
38     if (dimensions.size() > 2) {std::cerr << "dimensions are too high\n";}
39
40     // creating random engine
41     static std::random_device rd; // Seed
42     static std::mt19937 gen(rd()); // Mersenne Twister generator
43     std::uniform_real_distribution<> dist(argmin, argmax);
44
45     // building the finaloutput
46     vector<vector<T>> finaloutput;
47     for(int i = 0; i<dimensions[0]; ++i){
48         vector<T> temp;
49         for(int j = 0; j<dimensions[1]; ++j) {temp.push_back(dist(gen));}
50         // cout << format("\t\t temp = {}\n", temp);
51
52         finaloutput.push_back(temp);
53     }
54
55     // returning the finaloutput
56     return finaloutput;

```

```

57 }
58 }
59 /*=====
60 -----*/
61 auto rand(const std::vector<int> dimensions)
62 {
63     using ReturnType = double;
64
65     // throwing an error if dimension is greater than two
66     if (dimensions.size() > 2) {std::cerr << "dimensions are too high\n";}
67
68     // creating random engine
69     static std::random_device rd; // Seed
70     static std::mt19937 gen(rd()); // Mersenne Twister generator
71     std::uniform_real_distribution<> dist(0.00, 1.00);
72
73     // building the finaloutput
74     vector<vector<ReturnType>> finaloutput;
75     for(int i = 0; i<dimensions[0]; ++i){
76         vector<ReturnType> temp;
77         for(int j = 0; j<dimensions[1]; ++j) {temp.push_back(dist(gen));}
78         finaloutput.push_back(std::move(temp));
79     }
80
81     // returning the finaloutput
82     return std::move(finaloutput);
83 }
84 }
85 /*=====
86 -----*/
87 template <typename T>
88 auto rand_complex_double(const T argmin,
89                          const T argmax,
90                          const std::vector<int>& dimensions)
91 {
92
93     // throwing an error if dimension is greater than two
94     if (dimensions.size() > 2) {std::cerr << "dimensions are too high\n";}
95
96     // creating random engine
97     static std::random_device rd; // Seed
98     static std::mt19937 gen(rd()); // Mersenne Twister generator
99     std::uniform_real_distribution<> dist(argmin, argmax);
100
101     // building the finaloutput
102     vector<vector<complex<double>>> finaloutput;
103     for(int i = 0; i<dimensions[0]; ++i){
104         vector<complex<double>> temp;
105         for(int j = 0; j<dimensions[1]; ++j)
106             {temp.push_back(static_cast<double>(dist(gen)));}
107         finaloutput.push_back(std::move(temp));
108     }
109
110     // returning the finaloutput
111     return finaloutput;
112 }

```

B.26 Reshape

```

1  #pragma once
2
3  /*=====
4  reshaping a matrix into another matrix
5  -----*/
6  template <std::size_t M, std::size_t N, typename T>
7  auto reshape(const std::vector<std::vector<T>>& input_matrix){
8
9      // verifying size stuff
10     if (M*N != input_matrix.size() * input_matrix[0].size())
11         std::cerr << "Dimensions are quite different\n";
12
13     // creating canvas
14     auto canvas {std::vector<std::vector<T>>(
15         M, std::vector<T>(N, (T)0)
16     )};
17
18     // writing to canvas
19     size_t tid {0};
20     size_t target_row {0};
21     size_t target_col {0};
22     for(auto row = 0; row<input_matrix.size(); ++row){
23         for(auto col = 0; col < input_matrix[0].size(); ++col){
24             tid = row * input_matrix[0].size() + col;
25             target_row = tid/N;
26             target_col = tid%N;
27             canvas[target_row][target_col] = input_matrix[row][col];
28         }
29     }
30
31     // moving it back
32     return std::move(canvas);
33 }
34 /*=====
35 reshaping a matrix into a vector
36 -----*/
37 template<std::size_t M, typename T>
38 auto reshape(const std::vector<std::vector<T>>& input_matrix){
39
40     // checking element-count validity
41     if (M != input_matrix.size() * input_matrix[0].size())
42         std::cerr << "Number of elements differ\n";
43
44     // creating canvas
45     auto canvas {std::vector<T>(M, 0)};
46
47     // filling canvas
48     for(auto row = 0; row < input_matrix.size(); ++row)
49         for(auto col = 0; col < input_matrix[0].size(); ++col)
50             canvas[row * input_matrix.size() + col] = input_matrix[row][col];
51
52     // moving it back
53     return std::move(canvas);
54 }
55 /*=====
56 Matrix to matrix
57 -----*/

```

```

58 template<typename T>
59 auto reshape(const std::vector<std::vector<T>>& input_matrix,
60             const std::size_t M,
61             const std::size_t N){
62
63     // checking element-count validity
64     if ( M * N != input_matrix.size() * input_matrix[0].size())
65         std::cerr << "Number of elements differ\n";
66
67     // creating canvas
68     auto canvas {std::vector<std::vector<T>>>(
69         M, std::vector<T>(N, (T)0)
70     )};
71
72     // writing to canvas
73     size_t tid {0};
74     size_t target_row {0};
75     size_t target_col {0};
76     for(auto row = 0; row<input_matrix.size(); ++row){
77         for(auto col = 0; col < input_matrix[0].size(); ++col){
78             tid = row * input_matrix[0].size() + col;
79             target_row = tid/N;
80             target_col = tid%N;
81             canvas[target_row][target_col] = input_matrix[row][col];
82         }
83     }
84
85     // moving it back
86     return std::move(canvas);
87 }
88 /*=====
89 converting a matrix into a vector
90 -----*/
91 template<typename T>
92 auto reshape(const std::vector<std::vector<T>>& input_matrix,
93             const size_t M){
94
95     // checking element-count validity
96     if (M != input_matrix.size() * input_matrix[0].size())
97         std::cerr << "Number of elements differ\n";
98
99     // creating canvas
100    auto canvas {std::vector<T>(M, 0)};
101
102    // filling canvas
103    for(auto row = 0; row < input_matrix.size(); ++row)
104        for(auto col = 0; col < input_matrix[0].size(); ++col)
105            canvas[row * input_matrix.size() + col] = input_matrix[row][col];
106
107    // moving it back
108    return std::move(canvas);
109 }

```

B.27 Summing with containers

```
1 #pragma once
```



```

2  /*=====
3  -----*/
4  template <std::size_t axis, typename T>
5  auto sum(const std::vector<T>& input_vector) -> std::enable_if_t<axis == 0,
        std::vector<T>>
6  {
7      // returning the input as is
8      return input_vector;
9  }
10 /*=====
11 -----*/
12 template <std::size_t axis, typename T>
13 auto sum(const std::vector<std::vector<T>>& input_matrix) -> std::enable_if_t<axis == 0,
        std::vector<T>>
14 {
15     // creating canvas
16     auto canvas {std::vector<T>(input_matrix[0].size(), 0)};
17
18     // filling up the canvas
19     for(auto row = 0; row < input_matrix.size(); ++row)
20         std::transform(input_matrix[row].begin(), input_matrix[row].end(),
21                         canvas.begin(),
22                         canvas.begin(),
23                         [](auto& argx, auto& argy){return argx + argy;});
24
25     // returning
26     return std::move(canvas);
27 }
28
29 /*=====
30 -----*/
31 template <std::size_t axis, typename T>
32 auto sum(const std::vector<std::vector<T>>& input_matrix) -> std::enable_if_t<axis == 1,
        std::vector<std::vector<T>>>
33 {
34     // creating canvas
35     auto canvas {std::vector<std::vector<T>>(input_matrix.size(),
36                                             std::vector<T>(1, 0.00))};
37
38     // filling up the canvas
39     for(auto row = 0; row < input_matrix.size(); ++row)
40         canvas[row][0] = std::accumulate(input_matrix[row].begin(),
41                                           input_matrix[row].end(),
42                                           static_cast<T>(0));
43
44     // returning
45     return std::move(canvas);
46 }
47
48 /*=====
49 -----*/
50 template <std::size_t axis, typename T>
51 auto sum(const std::vector<T>& input_vector_A,
52         const std::vector<T>& input_vector_B) -> std::enable_if_t<axis == 0,
        std::vector<T>>
53 {
54     // setup
55     const auto& num_cols_A {input_vector_A.size()};
56     const auto& num_cols_B {input_vector_B.size()};

```

```

57
58 // throwing errors
59 if (num_cols_A != num_cols_B) {std::cerr << "sum: size disparity\n";}
60
61 // creating canvas
62 auto canvas {input_vector_A};
63
64 // summing up
65 std::transform(input_vector_B.begin(), input_vector_B.end(),
66               canvas.begin(),
67               canvas.begin(),
68               std::plus<T>());
69
70 // returning
71 return std::move(canvas);
72 }

```

B.28 Tangent

```

1 #pragma once
2 namespace svr {
3     /*=====
4     y = tan-inverse(input_vector_A/input_vector_B)
5     -----*/
6     template <typename T>
7     auto atan2(const std::vector<T> input_vector_A,
8               const std::vector<T> input_vector_B)
9     {
10         // throw error
11         if (input_vector_A.size() != input_vector_B.size())
12             std::cerr << "atan2: size disparity\n";
13
14         // create canvas
15         auto canvas {std::vector<T>(input_vector_A.size(), 0)};
16
17         // performing element-wise atan2 calculation
18         std::transform(input_vector_A.begin(), input_vector_A.end(),
19                       input_vector_B.begin(),
20                       canvas.begin(),
21                       [](const auto& arg_a,
22                         const auto& arg_b){
23
24                             return std::atan2(arg_a, arg_b);
25                         });
26
27         // moving things back
28         return std::move(canvas);
29     }
30     /*=====
31     y = tan-inverse(a/b)
32     -----*/
33     template <typename T>
34     auto atan2(T scalar_A,
35               T scalar_B)
36     {
37         return std::atan2(scalar_A, scalar_B);

```

```

38     }
39 }

```

B.29 Tiling Operations

```

1  #pragma once
2  namespace svr {
3      /*=====
4      tiling a vector
5      -----*/
6      template <typename T>
7      auto tile(const std::vector<T>& input_vector,
8                const std::vector<size_t>& mul_dimensions){
9
10         // creating canvas
11         const std::size_t& num_rows {1 * mul_dimensions[0]};
12         const std::size_t& num_cols {input_vector.size() * mul_dimensions[1]};
13         auto canvas {std::vector<std::vector<T>>(
14             num_rows,
15             std::vector<T>(num_cols, 0)
16         )};
17
18         // writing
19         std::size_t source_row;
20         std::size_t source_col;
21
22         for(std::size_t row = 0; row < num_rows; ++row){
23             for(std::size_t col = 0; col < num_cols; ++col){
24                 source_row = row % 1;
25                 source_col = col % input_vector.size();
26                 canvas[row][col] = input_vector[source_col];
27             }
28         }
29
30         // returning
31         return std::move(canvas);
32     }
33     /*=====
34     tiling a matrix
35     -----*/
36     template <typename T>
37     auto tile(const std::vector<std::vector<T>>& input_matrix,
38               const std::vector<size_t>& mul_dimensions){
39
40         // creating canvas
41         const std::size_t& num_rows {input_matrix.size() * mul_dimensions[0]};
42         const std::size_t& num_cols {input_matrix[0].size() * mul_dimensions[1]};
43         auto canvas {std::vector<std::vector<T>>(
44             num_rows,
45             std::vector<T>(num_cols, 0)
46         )};
47
48         // writing
49         std::size_t source_row;
50         std::size_t source_col;
51

```

```

52     for(std::size_t row = 0; row < num_rows; ++row){
53         for(std::size_t col = 0; col < num_cols; ++col){
54             source_row = row % input_matrix.size();
55             source_col = col % input_matrix[0].size();
56             canvas[row][col] = input_matrix[source_row][source_col];
57         }
58     }
59
60     // returning
61     return std::move(canvas);
62 }
63 }

```

B.30 Transpose

```

1  #pragma once
2  /*=====
3  -----*/
4  template <typename T>
5  auto transpose(const std::vector<T>& input_vector){
6
7      // creating canvas
8      auto canvas {std::vector<std::vector<T>>{
9          input_vector.size(),
10         std::vector<T>(1)
11     }};
12
13     // filling canvas
14     for(auto i = 0; i < input_vector.size(); ++i){
15         canvas[i][0] = input_vector[i];
16     }
17
18     // moving it back
19     return std::move(canvas);
20 }

```

B.31 Masking

```

1  #pragma once
2  namespace svr {
3      /*=====
4      y = input_vector[mask == 1]
5      -----*/
6      template <typename T,
7              typename = std::enable_if_t< std::is_arithmetic_v<T>          ||
8              std::is_same_v<T, std::complex<double>> ||
9              std::is_same_v<T, std::complex<float>>
10              >
11              >
12      auto mask(const std::vector<T>& input_vector,
13              const std::vector<bool>& mask_vector)
14      {
15          // checking dimensionality issues
16          if (input_vector.size() != mask_vector.size())

```

```

17         std::cerr << "mask(vector, mask): incompatible size \n";
18
19     // creating canas
20     auto num_trues {std::count(mask_vector.begin(),
21                               mask_vector.end(),
22                               true)};
23     auto canvas {std::vector<T>(num_trues)};
24
25     // copying values
26     auto destination_index {0};
27     for(auto i = 0; i < input_vector.size(); ++i)
28         if (mask_vector[i] == true)
29             canvas[destination_index++] = input_vector[i];
30
31     // returning output
32     return std::move(canvas);
33 }
34 /*=====
35 -----*/
36 template <typename T>
37 auto mask(const std::vector<std::vector<T>>& input_matrix,
38           const std::vector<bool> mask_vector)
39 {
40     // fetching dimensions
41     const auto& num_rows_matrix {input_matrix.size()};
42     const auto& num_cols_matrix {input_matrix[0].size()};
43     const auto& num_cols_vector {mask_vector.size()};
44
45     // error-checking
46     if (num_cols_matrix != num_cols_vector)
47         std::cerr << "mask(matrix, bool-vector): size disparity";
48
49     // building canvas
50     auto num_trues {std::count(mask_vector.begin(),
51                               mask_vector.end(),
52                               true)};
53     auto canvas {std::vector<std::vector<T>>(
54                 num_rows_matrix,
55                 std::vector<T>(num_cols_vector, 0)
56             )};
57
58     // writing values
59     #pragma omp parallel for
60     for(auto row = 0; row < num_rows_matrix; ++row){
61         auto destination_index {0};
62         for(auto col = 0; col < num_cols_vector; ++col)
63             if(mask_vector[col] == true)
64                 canvas[row][destination_index++] = input_matrix[row][col];
65     }
66
67     // returning
68     return std::move(canvas);
69 }
70 /*=====
71 Fetch Indices corresponding to mask true's
72 -----*/
73 auto mask_indices(const std::vector<bool>& mask_vector)
74 {
75     // creating canvas

```

```

76     auto    num_trues {std::count(mask_vector.begin(), mask_vector.end(),
77                                   true)};
78     auto    canvas    {std::vector<std::size_t>(num_trues)};
79
80     // building canvas
81     auto    destination_index {0};
82     for(auto i = 0; i < mask_vector.size(); ++i)
83         if (mask_vector[i] == true)
84             canvas[destination_index++] = i;
85
86     // returning
87     return std::move(canvas);
88 }
89 }

```

B.32 Resetting Containers

```

1  #pragma once
2  namespace svr {
3      /*=====
4      Variadic version of resetting
5      -----*/
6      template <typename T, typename... Rest>
7      void reset(std::vector<T>& first_vector, Rest&... rest_vectors) {
8          // Reset the first vector
9          std::vector<T>().swap(first_vector);
10
11         // Recursively reset the remaining vectors
12         if constexpr (sizeof...(rest_vectors) > 0) {
13             reset(rest_vectors...);
14         }
15     }
16 }

```

B.33 Element-wise squaring

```

1  #pragma once
2  namespace svr {
3      /*=====
4      Element-wise squaring vector
5      -----*/
6      template <typename T,
7                typename = std::enable_if_t<std::is_arithmetic_v<T>>
8                >
9      auto square(const std::vector<T>& input_vector)
10     {
11         // creating canvas
12         auto canvas {std::vector<T>(input_vector.size())};
13
14         // performing calculations
15         std::transform(input_vector.begin(), input_vector.end(),
16                        canvas.begin(),
17                        [](const auto& argx){
18                            return argx * argx;
19                        });
20     }
21 }

```

```

19         });
20
21         // moving it back
22         return std::move(canvas);
23     }
24     /*=====
25     Element-wise squaring vector (in-place)
26     -----*/
27     template <typename T,
28             typename = std::enable_if_t<std::is_arithmetic_v<T>>
29             >
30     void square_inplace(std::vector<T>& input_vector)
31     {
32         // performing operations
33         std::transform(input_vector.begin(), input_vector.end(),
34                        input_vector.begin(),
35                        [](auto& argx){
36                            return argx * argx;
37                        });
38     }
39     /*=====
40     Element-wise squaring a matrix
41     -----*/
42     template <typename T>
43     auto square(const std::vector<std::vector<T>>& input_matrix)
44     {
45         // fetching dimensions
46         const auto& num_rows {input_matrix.size()};
47         const auto& num_cols {input_matrix[0].size()};
48
49         // creating canvas
50         auto canvas {std::vector<std::vector<T>>>(
51             num_rows,
52             std::vector<T>(num_cols, 0)
53         )};
54
55         // going through each row
56         #pragma omp parallel for
57         for(auto row = 0; row < num_rows; ++row)
58             std::transform(input_matrix[row].begin(), input_matrix[row].end(),
59                            canvas[row].begin(),
60                            [](const auto& argx){
61                                return argx * argx;
62                            });
63
64         // returning
65         return std::move(canvas);
66     }
67     /*=====
68     Squaring for scalars
69     -----*/
70     template <typename T>
71     auto square(const T& scalar) {return scalar * scalar;}
72 }

```

B.34 Flooring

```

1 namespace svr {
2     /*=====
3     element-wise flooring of a vector-contents
4     -----*/
5     template <typename T>
6     auto floor(const std::vector<T>& input_vector)
7     {
8         // creating canvas
9         auto canvas {std::vector<T>(input_vector.size())};
10
11        // filling the canvas
12        std::transform(input_vector.begin(), input_vector.end(),
13                       canvas.begin(),
14                       [](const auto& argx){
15                           return std::floor(argx);
16                       });
17
18        // returning
19        return std::move(canvas);
20    }
21    /*=====
22    element-wise flooring of a vector-contents (in-place)
23    -----*/
24    template <typename T>
25    auto floor_inplace(std::vector<T>& input_vector)
26    {
27        // rewriting the contents
28        std::transform(input_vector.begin(), input_vector.end(),
29                       input_vector.begin(),
30                       [](auto& argx){
31                           return std::floor(argx);
32                       });
33    }
34    /*=====
35    element-wise flooring of matrix-contents
36    -----*/
37    template <typename T>
38    auto floor(const std::vector<std::vector<T>>& input_matrix)
39    {
40        // fetching dimensions
41        const auto& num_rows_matrix {input_matrix.size()};
42        const auto& num_cols_matrix {input_matrix[0].size()};
43
44        // creating canvas
45        auto canvas {std::vector<std::vector<T>>(
46            num_rows_matrix,
47            std::vector<T>(num_cols_matrix)
48        )};
49
50        // writing contents
51        for(auto row = 0; row < num_rows_matrix; ++row)
52            std::transform(input_matrix[row].begin(), input_matrix[row].end(),
53                           canvas[row].begin(),
54                           [](const auto& argx){
55                               return std::floor(argx);
56                           });
57
58        // returning contents
59        return std::move(canvas);

```



```

60 }
61
62 /*=====
63 element-wise flooring of matrix-contents (in-place)
64 -----*/
65 template <typename T>
66 auto floor_inplace(std::vector<std::vector<T>>& input_matrix)
67 {
68     // performing operations
69     for(auto row = 0; row < input_matrix.size(); ++row)
70         std::transform(input_matrix[row].begin(), input_matrix[row].end(),
71                        input_matrix[row].begin(),
72                        [](auto& argx){
73                            return std::floor(argx);
74                        });
75 }
76 }

```

B.35 Squeeze

```

1 namespace svr {
2     template <typename T>
3     auto squeeze(const std::vector<std::vector<T>>& input_matrix)
4     {
5         // fetching dimensions
6         const auto& num_rows_matrix {input_matrix.size()};
7         const auto& num_cols_matrix {input_matrix[0].size()};
8
9         // check if any dimension is 1
10        if (num_rows_matrix == 0 || num_cols_matrix == 0)
11            std::cerr << "at least one dimension should be 1";
12
13        auto final_length {std::max(num_rows_matrix, num_cols_matrix)};
14
15        // creating canvas
16        auto canvas {std::vector<T>(final_length)};
17
18        // building canvas
19        if (num_rows_matrix == 1)
20        {
21            // filling canvas
22            std::copy(input_matrix[0].begin(), input_matrix[0].end(),
23                    canvas.begin());
24        }
25        else if (num_cols_matrix == 1)
26        {
27            // filling canvas
28            std::transform(input_matrix.begin(), input_matrix.end(),
29                           canvas.begin(),
30                           [](const auto& argx){
31                               return argx[0];
32                           });
33        }
34
35        // returning
36        return std::move(canvas);

```

```

37     }
38 }

```

B.36 Tensor Initializations

```

1 namespace svr {
2     /*=====
3     -----*/
4     template <typename T>
5     auto zeros(const std::array<std::size_t, 2> input_dimensions)
6     {
7         // create canvas
8         auto canvas {std::vector<std::vector<T>>(
9             input_dimensions[0],
10            std::vector<T>(input_dimensions[1], 0)
11        )};
12
13        // returning
14        return std::move(canvas);
15    }
16 }

```

B.37 Real part

```

1 #pragma once
2 namespace svr {
3
4     /*=====
5     For type-deductions
6     -----*/
7     template <typename T>
8     struct real_result_type;
9
10    template <> struct real_result_type<std::complex<double>>{
11        using type = double;
12    };
13    template <> struct real_result_type<std::complex<float>>{
14        using type = float;
15    };
16    template <> struct real_result_type<double> {
17        using type = double;
18    };
19    template <> struct real_result_type<float>{
20        using type = float;
21    };
22
23    template <typename T>
24    using real_result_t = typename real_result_type<T>::type;
25
26    /*=====
27    Element-wise real() of a vector
28    -----*/
29    template <typename T>
30    auto real(const std::vector<T>& input_vector)

```

```

31 {
32     // figure out base-type
33     using TCanvas = real_result_t<T>;
34
35     // creating canvas
36     auto canvas = std::vector<TCanvas>(
37         input_vector.size()
38     );
39
40     // storing values
41     std::transform(input_vector.begin(), input_vector.end(),
42                   canvas.begin(),
43                   [](const auto& argx){
44                       return std::real(argx);
45                   });
46
47     // returning
48     return std::move(canvas);
49 }
50 }

```

B.38 Imaginary part

```

1  #pragma once
2  namespace svr {
3
4      /*=====
5      For type-deductions
6      -----*/
7      template <typename T>
8      struct imag_result_type;
9
10     template <> struct imag_result_type<std::complex<double>>{
11         using type = double;
12     };
13     template <> struct imag_result_type<std::complex<float>>{
14         using type = float;
15     };
16     template <> struct imag_result_type<double> {
17         using type = double;
18     };
19     template <> struct imag_result_type<float>{
20         using type = float;
21     };
22
23     template <typename T>
24     using imag_result_t = typename imag_result_type<T>::type;
25
26     /*=====
27     -----*/
28     template <typename T>
29     auto imag(const std::vector<T>& input_vector)
30     {
31         // figure out base-type
32         using TCanvas = imag_result_t<T>;
33

```

```
34     // creating canvas
35     auto canvas {std::vector<TCanvas>(
36         input_vector.size()
37     )};
38
39     // storing values
40     std::transform(input_vector.begin(), input_vector.end(),
41                   canvas.begin(),
42                   [](const auto& argx){
43                       return std::imag(argx);
44                   });
45
46     // returning
47     return std::move(canvas);
48 }
49 }
```
