`lintrans`

by Dyson Dyson

Centre Name: The Duston School
Centre Number: 27220
Candidate Number: 9065

Built from `820a6f2-dirty`

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1 Analysis

One of the topics in the A Level Further Maths course is linear transformations, as represented by matrices. This is a topic all about how vectors move and get transformed in the plane. It's a topic that lends itself exceedingly well to visualization, but students often find it hard to visualize this themselves, and there is a considerable lack of good tools to provide visual intuition on the subject. There is the YouTube series *Essence of Linear Algebra* by 3blue1brown[21], which is excellent, but I couldn't find any good interactive visualizations.

My solution is to develop a desktop application that will allow the user to define 2×2 matrices and view these matrices and compositions thereof as linear transformations of a 2D plane. This will give students a way to get to grips with linear transformations in a more hands-on way, and will give teachers the ability to easily and visually show concepts like the determinant and invariant lines.

1.1 Computational Approach

This solution is particularly well suited to a computational approach since it is entirely focussed on visualizing transformations, which require complex mathematics to properly display. It will also have lots of settings to allow the user to configure aspects of the visualization. As previously mentioned, visualizing transformations in one's own head is difficult, so a piece of software to do it would be very valuable to teachers and learners, but current solutions are considerably lacking.

My solution will make use of abstraction by allowing the user to define a set of matrices which they can use in expressions. This allows them to use a matrix multiple times and they don't have to keep track of any of the numbers. All the actual processing and mathematics happens behind the scenes and the user never has to worry about it - they just compose their defined matrices into transformations. This abstraction allows the user to focus on exploring the transformations themselves without having to do any actual computations. This will make learning the subject much easier, as they will able to gain a visual intuition for linear transformations without worrying about computation until after they've built up that intuition.

I will also employ decomposition and modularization by breaking the project down into many smaller parts, such as one module to keep track of defined matrices, one module to validate and parse matrix expressions, one module for the main GUI, as well as sub-modules for the widgets and dialog boxes, etc. This decomposition allows for simpler project design, easier code maintenance (since module coupling is kept to a minimum, so bugs are isolated in their modules), inheritance of classes to reduce code repetition, and unit testing to inform development. I also intend this unit testing to be automated using GitHub Actions.

Selection will also be used widely in the application. The GUI will provide many settings for visualization, and these settings will need to be checked when rendering the transformation. For example, the user will have the option to render the determinant, so I will need to check this setting on every render cycle and only render the determinant parallelogram if the user has enabled that option. The app will have many options for visualization, which will be useful in learning, but if all these options were being rendered at the same time, then there would be too much information for the user to properly process, so I will let the user configure these display options to their liking and only render the things they want to be rendered.

Validation will also be prevalent because the matrix expressions will need to follow a strict format, which will be validated. The buttons to render and animate the matrix will only be clickable when the given expression is valid, so I will need to check this and update the buttons every time the text in the text box is changed. I will also need to parse matrix expressions so that I can evaluate them properly. All this validation ensures that crashes due to malformed input are practically impossible, and makes the user's life easier since they don't need to worry about if their input is in the right format - the app will tell them.

I will also make use of iteration, primarily in animation. I will have to re-calculate positions and

values to render everything for every frame of the animation and this will likely be done with a simple `for` loop. A `for` loop will allow me to just loop over every frame and use the counter variable as a way to measure how far through the animation we are on each frame. This is preferable to a `while` loop, since that would require me to keep track of which frame we're on with a separate variable.

Finally, the core of the application is visualization, so that will definitely be used a lot. I will have to calculate positions of points and lines based on given matrices, and when animating, I will also have to calculate these matrices based on the current frame. Then I will have to use the rendering capabilities of the GUI framework that I choose to render these calculated points and lines onto a widget, which will form the viewport of the main GUI. I may also have to convert between coordinate systems. I will have the origin in the middle with positive x going to the right and positive y going up, but I may need to convert that to standard computer graphics coordinates with the origin in the top left, positive x going to the right, and positive y going down. This visualization of linear transformations is the core component of the app and is the primary feature, so it is incredibly important.

1.2 Stakeholders

Stakeholders for my app include A Level Further Maths students and teachers, who learn and teach linear transformations respectively. They will be able to provide useful input as to what they would like to see in the app, and they can provide feedback on what they like and what I can add or improve. I already know from experience that linear transformations are tricky to visualize and a computer-based visualization would be useful. My stakeholders agreed with this. Multiple teachers said that a desktop app that could render and animate linear transformations would be useful in a classroom environment and students said that it would be helpful to have something that they could play around with at home and use to get to grips with matrices and linear transformations. They also said that an online version would probably be easier to use, but I have absolutely no experience in web development and I'm much more comfortable making a desktop app.

Some teachers also suggested that it would be useful to have an option to save and load sets of matrices. This would allow them to have a single save file containing some matrices, and then just load this file to use for demonstrations in the classroom. This would probably be quite easy to implement. I could just wrap all the relevant information into one object and use Python's `pickle` module to save the binary data to a file, and then load this data back into the app in a similar way.

My stakeholders agreed that being able to see incremental animation - where, for example, we apply matrix **A** to the current scene, pause, and then apply matrix **B** - would be beneficial. This would be a good demonstration of matrix multiplication being non-commutative. **AB** is not always equal to **BA**. Being able to see this in terms of animating linear transformations would be good for learning.

They also agreed that a tutorial on using the software would be useful, so I plan to implement this through an online written tutorial hosted with GitHub Pages, and perhaps a video tutorial as well. This would make the app much easier to use for people who have never seen it before. It wouldn't be a lesson on the maths itself, but just a guide on how to use the software.

1.3 Research on existing solutions

There are actually quite a few web apps designed to help visualize 2D linear transformations but many of them are hard to use and lacking many features.

1.3.1 MIT 'Matrix Vector' Mathlet

Arguably the best app that I found was an MIT 'Mathlet' - a simple web app designed to help visualize a maths concept. This one is called 'Matrix Vector'[22] and allows the user to drag an input vector

around the plane and see the corresponding output vector, transformed by a matrix that the user can define, although this definition is finicky since it involves sliders rather than keyboard input.

This app fails in two crucial ways in my opinion. It doesn't show the basis vectors or let the user drag them around, and the user can only define and therefore visualize a single matrix at once. This second problem was common among every solution I found, so I won't mention it again, but it is a big issue in my opinion and my app will allow for multiple matrices. I like the idea of having a draggable input vector and rendering its output, so I will probably have this feature in my app, but I also want the ability to define multiple matrices and be able to drag the basis vectors to visually define a matrix. Being able to drag the basis vectors will help build intuition, so I think this would greatly benefit the app.

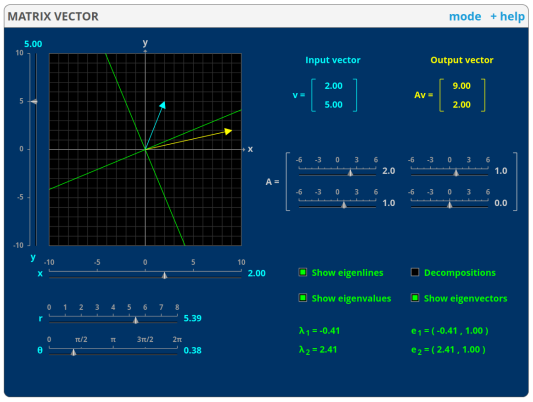


Figure 1.3.1: The MIT 'Matrix Vector' Mathlet

However, in the comments on this Mathlet, a user called 'David S. Bruce' suggested that the Mathlet should display the basis vectors, to which a user called 'hrm' (who I assume to be the 'H. Miller' to whom the copyright of the whole website is accredited) replied saying that this Mathlet is primarily focussed on eigenvectors, that it is perhaps badly named, and that displaying the basis vectors 'would make a good focus for a second Mathlet about 2×2 matrices'. This Mathlet does not exist. But I do like the idea of showing the eigenvectors and eigenlines, so I will definitely have that in my app. Showing the invariant lines or lack thereof will help with learning, since these are often hard to visualize.

1.3.2 Linear Transformation Visualizer

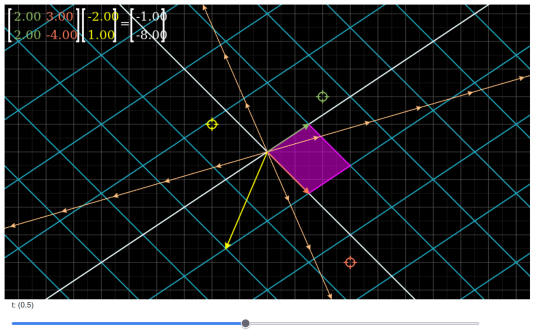


Figure 1.3.2: 'Linear Transformation Visualizer' halfway through an animation

Another web app that I found was one simply called 'Linear Transformation Visualizer' by Shad Sharma[53]. This one was similarly inspired by 3blue1brown's YouTube series. This app has the ability to render input and output vectors and eigenlines, but it can also render the determinant parallelogram; it allows the user to drag the basis vectors; and it has the option to snap vectors to the background grid, which is quite useful. It also implements a simple form of animation where the tips of the vectors move in straight lines from where they start to where they end, and the animation is controlled by dragging a slider labelled t. This isn't particularly intuitive.

I really like the vectors snapping to the grid, the input and output vectors, and rendering the determinant. This app also renders positive and negative determinants in different colours, which is really nice - I intend to use that idea in my own app, since it helps create understanding about negative determinants in terms of orientation changes. However, I think that the animation system here is flawed and not very easy to use. My animation will likely be a button, which just triggers an animation, rather than a slider. I also don't like the way vector dragging is handled. If you click anywhere on the grid, then the closest vector target (the final position of the target's associated vector) snaps to that location. I think it would be more intuitive to have to drag the vector from its current location to where you want it. This was also a problem with the MIT Mathlet.

1.3.3 Desmos app

One of the solutions I found was a Desmos app[7], which was quite hard to use and arguably overcomplicated. Desmos is not designed for this kind of thing - it's designed to graph pure mathematical functions - and it shows here. However, this app brings some really interesting ideas to the table, mainly functions. This app allows you to define custom functions and view them before and after the transformation. This is achieved by treating the functions parametrically as the set of points $(t, f(t))$ and then transforming each coordinate by the given matrix to get a new coordinate.

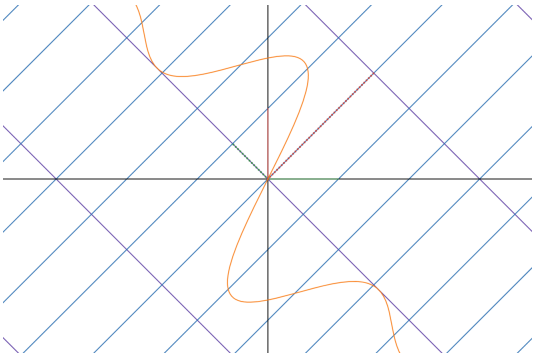


Figure 1.3.3: The Desmos app halfway through an animation, rendering $f(x) = \frac{\sin^2 x}{x}$ in orange

Desmos does this for every point and then renders the resulting transformed function parametrically. This is a really interesting technique and idea, but I'm not going to use it in my app. I don't think arbitrary functions fit with the linearity of the whole app, and I don't think it's necessary. It's just overcomplicating things, and rendering it on a widget would be tricky, because I'd have to render every point myself, possibly using something like OpenGL. It's just not worth implementing.

Additionally, this Desmos app makes things quite hard to see. It's hard to tell where any of the vectors are - they just get lost in the sea of grid lines. This image also hides some of the extra information. For instance, this image doesn't show the original function $f(x) = \frac{\sin^2 x}{x}$, only the transformed version. This app easily gets quite cluttered. I will give my vectors arrowheads to make them easily identifiable amongst the grid lines.

1.3.4 Visualizing Linear Transformations

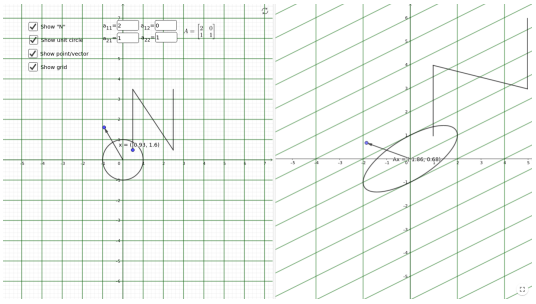


Figure 1.3.4: The GeoGebra applet rendering its default matrix

The last solution that I want to talk about is a GeoGebra applet simply titled 'Visualizing Linear Transformations'[24]. This applet has input and output vectors, original and transformed grid lines, a unit circle, and the letter N. It allows the user to define a matrix as 4 numbers and view the aforementioned N (which the user can translate to anywhere on the grid), the unit circle, the input/output vectors, and the grid lines. It also has the input vector snapping to integer coordinates, but that's a standard part of GeoGebra.

I've already talked about most of these features but the thing I wanted to talk about here is the N. I don't particularly want the letter N to be a prominent part of my own app, but I really like the idea of being able to define a custom polygon and see how that polygon gets transformed by a given transformation. I think that would really help with building intuition and it shouldn't be too hard to implement.

1.4 Essential features

The primary aim of this application is to visualize linear transformations, so this will obviously be the centre of the app and an essential feature. I will have a widget which can render a background grid and a second version of the grid, transformed according to a user-defined matrix expression. This is necessary because it is the entire purpose of the app. It's designed to visualize linear transformations and would be completely useless without this visual component. I will give the user the ability to render a custom matrix expression containing matrices they have previously defined, as well as reset the canvas to the default identity matrix transformation. This will obviously require an input box to enter the expression, a render button, a reset button, and various dialog boxes to define matrices in different ways. I want the user to be able to define a matrix as a set of 4 numbers, and by dragging the basis vectors i and j. These dialogs will allow the user to define new matrices to be used in expressions, and having multiple ways to do it will make it easier, and will aid learning.

Another essential feature is animation. I want the user to be able to smoothly animate between matrices. I see two options for how this could work. If **C** is the matrix for the currently displayed transformation, and **T** is the matrix for the target transformation, then we could either animate from **C** to **T** or we could animate from **C** to **TC**. I would probably call these transitional and applicative animation respectively. Perhaps I'll give the user the option to choose which animation method they want to use. I might even have an option for sequential animation, where the user can define a sequence of matrices, perhaps separated with commas or semicolons, and the app will animate through the sequence, applying one at a time. Sequential animation would be nice, but is not crucial.

Either way, animation is used in most of the alternative solutions that I found, and it's a great way to build intuition, by allowing students to watch the transformation happen in real time. Compared to simply rendering the transformations, animating them would profoundly benefit learning, and since that's the main aim of the project, I think animation is a necessary part of the app.

Something that I thought was a big problem in every alternative solution I found was the fact that the user could only visualize a single matrix at once. I see this as a fatal flaw and I will allow the user to define 25 different matrices (all capital letters except **I** for the identity matrix) and use all of them in expressions. This will allow teachers to define multiple matrices and then just change the expression to demonstrate different concepts rather than redefine a new transformation every time. It will also make things easier for students as it will allow them to visualize compositions of different matrix transformations without having to do any computations themselves.

Additionally, being able to show information on the currently displayed matrix is an essential tool for learning. Rendering things like the determinant parallelogram and the invariant lines of the transformation will greatly assist with learning and building understanding, so I think that having the option to render these attributes of the currently displayed transformation is necessary for success.

1.5 Limitations

The main limitation in this app is likely to be drawing grid lines. Most transformations will be fine but in some cases, the app will be required to draw potentially thousands of grid lines on the canvas and this will probably cause noticeable lag, especially in the animations. I will have to artificially limit the number of grid lines that can be drawn on the screen. This won't look fantastic, because it means that the grid lines will only extend a certain distance from the origin, but it's an inherent limitation of computers. Perhaps if I was using a faster, compiled language like C++ rather than Python, this processing would happen faster and I could render more grid lines, but it's impossible to render all the grid lines and any implementation of this idea must limit them for performance.

An interesting limitation is that I don't think I'll implement panning. I suspect that I'll have to convert between coordinate systems and having the origin in the centre of the canvas will probably make the code much simpler. Also, linear transformations always leave the origin fixed, so always having it in the centre of the canvas seems thematically appropriate. Panning is certainly an option - the Desmos solution in §1.3.3 and GeoGebra solution in §1.3.4 both allow panning as a default part

of Desmos and GeoGebra respectively, for example - but I don't think I'll implement it myself. I just don't think it's worth it.

I'm also not going to do any work with 3D linear transformations. 3D transformations are often harder to visualize and thus it would make sense to target them in an app like this, designed to help with learning and intuition, but 3D transformations are also harder to code. I would have to use a full graphics package rather than a simple widget, and I think it would be too much work for this project and I wouldn't be able to do it in the time frame. It's definitely a good idea, but I'm currently incapable of creating an app like that.

There are other limitations inherent to matrices. For instance, it's impossible to take an inverse of a singular matrix. There's nothing I can do about that without rewriting most of mathematics. Matrices can also only represent linear transformations. There's definitely a market for an app that could render any arbitrary transformation from $\mathbb{R}^2 \to \mathbb{R}^2$ - I know I'd want an app like that - but matrices can only represent linear transformations, so those are the only kind of transformations that I'll be looking at with this project.

1.6 Hardware and software requirements

1.6.1 Hardware

Hardware requirements for the project are the same between the release and development environments and they're quite simple. I expect the app to require a processor with at least 1 GHz clock speed, roughly 100MB free disk space, and about 1 GB of available RAM. The processor and RAM requirements are needed by the Python runtime and mainly by Qt5 - the GUI library I'll be using. The 100MB of disk space is just for the executable binary that I'll compile for the public release. The code itself is less than 1 MB, but the compiled binary has to package all the dependencies and the entire CPython runtime to allow it to run on systems that don't have that, so the file size is much bigger.

I will also require that the user has a monitor that is at least 1920×1080 pixels in resolution. This isn't necessarily required, because the app will likely run in a smaller window, but a HD monitor is highly recommended. This allows the user to go fullscreen if they want to, and it gives them enough resolution to easily see everything in the app. A large, wall-mounted screen is also highly recommended for use in the classroom, although this is common among schools.

I will also require a keyboard with all standard Latin alphabet characters. This is because the matrices are defined as uppercase Latin letters. Any UK or US keyboard will suffice for this. The app will also require a mouse with at least one button. I don't intend to have right click do anything, so only the primary mouse button is required, although getting a single button mouse to actually work on modern computers is probably quite a challenge. A separate mouse is not strictly required - a laptop trackpad is equally sufficient.

1.6.2 Software

Software requirements differ slightly between release and development, although everything that the release environment requires is also required by the development environment. I will require a modern operating system - namely Windows 10 or later, macOS 10.9 'Mavericks'[1] or later, or any modern Linux distro[2]. Basically, it just requires an operating system that is compatible with Python 3.8 or higher as well as Qt5, since I'll be using these in the project. Of course, Qt5 will need to be installed on the user's computer, although it's standard pretty much everywhere these days.

[1] Python 3.8 or higher won't compile on any earlier versions of macOS[40]

[2] Specifying a Linux version is practically impossible. Python 3.8 or higher is available in many package repositories, but all modern Python versions will compile on any modern distro. Qt5 is available in many package repositories and can be compiled on any `x86` or `x86_64` generic Linux machine with `gcc` version 5 or later[43]

Python won't actually be required for the end user, because I will be compiling the app into a standalone binary executable for release, and this binary will contain the required Python runtime and dependencies. However, if the user wishes to download and run the source code themself, then they will need Python 3.8 or higher and the package dependencies: `numpy`, `nptyping`, and `pyqt5`. These can be automatically installed with the command `python -m pip install -r requirements.txt` from the root of the repository, although the whole project will be an installable Python package, so using `pip install -e .` will be preferred.

`numpy` is a maths library that allows for fast matrix maths; `nptyping` is used by `mypy` for type-checking and isn't actually a runtime dependency but the imports in the `typing` module fail if it's not installed at runtime[3]; and `pyqt5` is a library that just allows interop between Python and Qt5, which is originally a C++ library.

In the development environment, I use PyCharm for actually writing my code, and I use a virtual environment to isolate my project dependencies. There are also some development dependencies listed in the file `dev_requirements.txt`. They are: `mypy`, `pyqt5-stubs`, `flake8`, `pycodestyle`, `pydocstyle`, and `pytest`. `mypy` is a static type checker[4]; `pyqt5-stubs` is a collection of type annotations for the PyQt5 API for `mypy` to use; `flake8`, `pycodestyle`, and `pydocstyle` are all linters; and `pytest` is a unit testing framework. I use these libraries to make sure my code is good quality and actually working properly during development.

1.7 Success criteria

The main aim of the app is to help teach students about linear transformations. As such, the primary measure of success will be letting teachers get to grips with the app and then asking if they would use it in the classroom or recommend it to students to use at home.

Additionally, the app must fulfil some basic requirements:

1. It must allow the user to define multiple matrices in at least two different ways (numerically and visually)
2. It must be able to validate arbitrary matrix expressions
3. It must be able to parse any valid matrix expression
4. It must be able to render any valid matrix expression
5. It must be able to animate from **I** to any valid matrix expression
6. It must be able to apply a matrix expression to the current scene and animate this (animate from **C** to **TC**, and perhaps do sequential animation)
7. It must be able to display information about the currently rendered transformation (determinant, eigenlines, etc.)
8. It must be able to save and load sessions (defined matrices, display settings, etc.)
9. It must allow the user to define and transform arbitrary polygons

Defining multiple matrices is a feature that I thought was lacking from every other solution I researched, and I think it would make the app much easier to use, so I think it's necessary for success. Validating matrix expressions is necessary because if the user tries to render an expression that doesn't make sense, has an undefined matrix, or contains the inverse of a singular matrix, then we have to disallow that or else the app will crash.

Visualizing matrix expressions as linear transformations is the core part of the app, so basic rendering of them is definitely a requirement for success. Animating these expressions is also a pretty crucial

[3] These `nptyping` imports are needed for type annotations all over the code base, so factoring them out is not feasible

[4] Python has weak, dynamic typing with optional type annotations but `mypy` enforces these static type annotations

part of the app, so I would consider this necessary for success. Displaying the information of a matrix transformation is also very useful for building understanding, so I would consider this needed to succeed.

Saving and loading isn't strictly necessary for success, but it is a standard part of many apps, so will likely be expected by users, and it will benefit the app by allowing teachers to plan lessons in advance and save the matrices they've defined for that lesson to be loaded later.

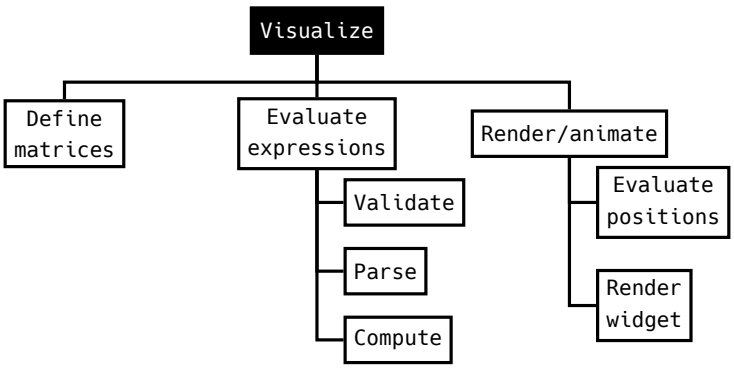
Transforming polygons is the lowest priority item on this list and will likely be implemented last, but it would definitely benefit learning. I wouldn't consider it necessary for success, but it would be very good to include, and it's certainly a feature that I want to have.

If the majority of teachers would use and/or recommend the app and it meets all of these points, then I will consider the app as a whole to be a success.

2 Design

2.1 Problem decomposition

I have decomposed the problem of visualization as follows:



Defining matrices is key to visualization because we need to have matrices to actually visualize. This is a key part of the app, and the user will be able to define multiple separate matrices numerically and visually using the GUI.

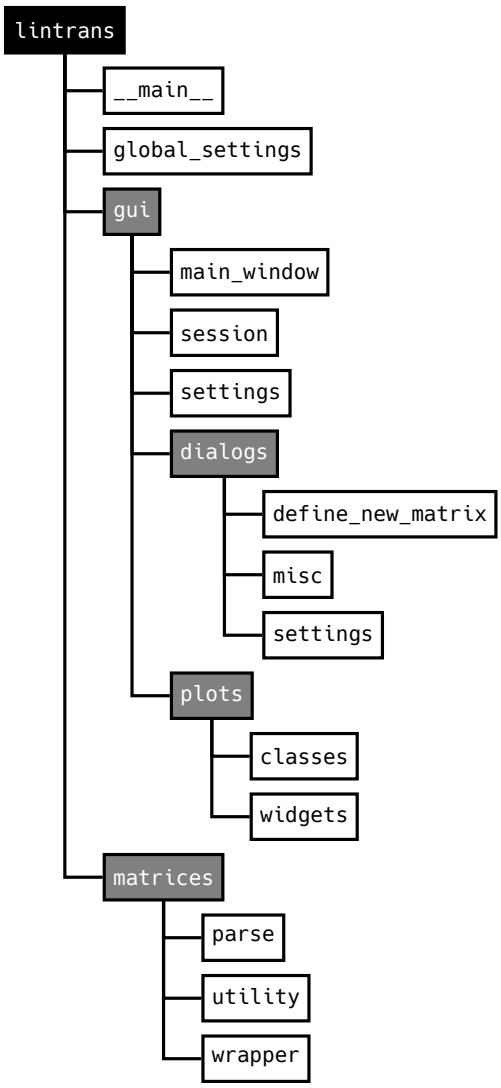
Evaluating expressions is another key part of the app and can be further broken down into validating, parsing, and computing the value. Validating an expression simply consists of checking that it adheres to a set of syntax rules for matrix expressions, and that it only contains matrices which have already been defined. Parsing consists of breaking an expression down into tokens, which are then much easier to evaluate. Computing the expression with these tokens is then just a series of simple operations, which will produce a final matrix at the end.

Rendering and animating will likely be the largest part in reality, but I've only decomposed it into simple blocks here. Evaluating positions involves evaluating the matrix expression that the user has input and using the columns of the resultant matrix to find the new positions of the basis vectors, and then extrapolating this for the rest of the plane. Rendering onto the widget is likely to be quite complicated and framework-dependent, so I've abstracted away the details for brevity here. Rendering will involve using the previously calculated values to render grid lines and vectors. Animating will probably be a `for` loop which just renders slightly different matrices onto the widget and sleeps momentarily between frames.

I have deliberately broken this problem down into parts that can be easily translated into modules in my eventual coded solution. This is simply to ease the design and development process, since now I already know my basic project structure. This problem could've been broken down into the parts that the user will directly interact with, but that would be less useful to me when actually starting development, since I would then have to decompose the problem differently to write the actual code.

2.2 Structure of the solution

I have decomposed my solution like so:



The `lintrans` node is simply the root of the whole project. `__main__` is the Python way to make the project executable as `python -m lintrans` on the command line. For release, I will package it into a standalone binary executable, using this module as the entry point.

The `global_settings` module will define a `GlobalSettings` singleton class. This class will manage global settings and variables - things like where to save sessions by default, etc. I'm not entirely sure what I want to put in here, but I expect that I'll want global settings in the future. Having this class will allow me to easily read and write these settings to a file to have them persist between sessions.

`matrices` is the package that will allow the user to define, validate, parse, evaluate, and use matrices. The `matrices.parse` module will contain functions to validate matrix expressions - likely using regular expressions - and functions to parse matrix expressions. It will not know which matrices are defined, so validation will be naïve and evaluation will be in the `matrices.wrapper` module. This `wrapper` module will contain a `MatrixWrapper` class, which will hold a dictionary of matrix names and values. It is this class which will have aware validation - making sure that all the matrices used in an expression are actually defined in the wrapper - as well the ability to evaluate matrix expressions, in addition to its basic behaviour of setting and getting matrices by name. There will also be a `matrices.utility` module, which will contain some simple functions for simple functionality. Functions like `create_rotation_matrix()`, which will generate a rotation matrix from an angle using the formula $\begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix}$.

`gui` is the package that will contain all the frontend code for everything GUI-related. `gui.main_window` is the module that will define the `LintransMainWindow` class, which will act as the main window of the application and have an instance of `MatrixWrapper` to keep track of which matrices are defined and allow for evaluation of matrix expressions. It will also have methods for rendering and animating matrix expressions, which will be connected to buttons in the GUI. The most important part of the main window is the viewport, which will be discussed shortly. This module will also contain a simple `main()` function to instantiate and launch the application GUI.

The `gui.session` module will contain functions to save and load a session from a file. A session will consist of the `MatrixWrapper`, along with perhaps the display settings and maybe some other things. I know that saving the wrapper will be essential, but I'll see what else should be saved as the project evolves.

The `gui.settings` module will contain a `DisplaySettings` dataclass[5] that will represent the settings for visualizing transformations. The viewport class will have an instance of this class and check against it when rendering things. The user will be able to open a dialog to change these display settings, which will update the main window's instance of this class.

The `gui.dialogs` subpackage will contain modules with different dialog classes. It will have a `gui.dialogs.define_new_matrices` module, which will have a `DefineDialog` abstract superclass. It will then contain classes that inherit from this superclass and provide dialogs for defining new matrices visually,

[5]This is the Python equivalent of a `struct` or `record` in other languages

numerically, and as an expression in terms of other matrices. Additionally, it will contain a `gui.dialogs.settings` module, which will provide a `SettingsDialog` superclass and a `DisplaySettingsDialog` class, which will allow the user to configure the aforementioned display settings. It may also have a `GlobalSettingsDialog` class in the future, which would similarly allow the user to configure the app's global settings through a dialog. This will only be implemented once I've actually got global settings to configure.

The `gui.dialogs.misc` module will contain small miscellaneous dialog boxes - things like the about box which are very simple and don't need a dedicated module.

The `gui.plots` subpackage will have a `gui.plots.classes` module and a `gui.plots.widgets` module. The `classes` module will have the abstract superclasses `BackgroundPlot` and `VectorGridPlot`. The former will provide helper methods to convert between coordinate systems and draw the background grid, while the latter will provide helper methods to draw transformations and their components. It will have `point_i` and `point_j` attributes and will provide methods to draw the transformed version of the grid, the vectors and their arrowheads, the eigenlines of the transformation, etc. These methods can then be called from the Qt5 `paintEvent` handler which will be declared abstract and must therefore be implemented by all subclasses.

The `gui.plots.widgets` module will have the classes `VisualizeTransformationWidget` and `DefineVisuallyWidget`, which will both inherit from `VectorGridPlot`. They will both implement their own `paintEvent` handler to actually draw the respective widgets, and `DefineVisuallyWidget` will also implement handlers for mouse events, allowing the user to drag around the basis vectors.

I also want the user to be able to define arbitrary polygons and view their transformations. I imagine this polygon definition will happen in a separate dialog, but I don't know where that's going to fit just yet. I'll probably have the widget in `gui.plots.widgets`, but possibly elsewhere.

2.3 Algorithm design

The project will have many algorithms and a lot of them will be related to drawing transformations on the canvas itself, but almost all of the algorithms will evolve over time. In this section, I will present pseudocode for some of the most interesting parts of the project. The real implementations may be different from these initial plans.

The `lintrans.matrices.utility` module will look roughly like this:

```
import numpy as np // Python import

// Create a matrix representing a rotation (anticlockwise) by the given angle
function create_rotation_matrix(angle: float, degrees: bool = True) -> MatrixType
    if (degrees) then
        rad = np.deg2rad(angle MOD 360)
    else
        rad = angle MOD (2 * np.pi)
    endif

    return np.array([
        [np.cos(rad), -1 * np.sin(rad)],
        [np.sin(rad), np.cos(rad)]
    ])
endfunction
```

And the `lintrans.matrices.wrapper` module will look like this:

```
import re
import numpy as np

// The `.utility` syntax means that the utility module is next to this one in the tree
from .utility import create_rotation_matrix
```

```

class MatrixWrapper
    // This is a hashmap from string to matrices, but the matrices might be null
    private matrices: Dict[string, Optional[MatrixType]]

    public procedure new()
        matrices = {
            "A": null, "B": null, "C": null, "D": null,
            "E": null, "F": null, "G": null, "H": null,
            "I": np.eye(2),  // I is always defined as the identity matrix
            "J": null, "K": null, "L": null, "M": null,
            "N": null, "O": null, "P": null, "Q": null,
            "R": null, "S": null, "T": null, "U": null,
            "V": null, "W": null, "X": null, "Y": null,
            "Z": null
        }
    endprocedure

    // This is a Python "magic method", which enable syntax like `wrapper['A']` to get the matrix A
    public function getitem(name: string) -> Optional[MatrixType]
        // If it is a simple name, it will just be fetched from the dictionary. If the name is ``rot(x)``, with
        // a given angle in degrees, then we return a new matrix representing a rotation by that angle

        // Return a new rotation matrix
        match = re.match(r"^rot\((-?\d*\.?\d*)\)$", name)
        if (match != null) then
            return create_rotation_matrix(float(match.group(1)))
        endif

        if (!matrices.contains(name)) then
            raise NameError(f'Unrecognised matrix name "{name}"')
        endif

        return matrices[name]
    endfunction

    // Again, this is Python magic. This one allows assignments like `wrapper['A'] = my_matrix`
    public procedure setitem(name: string, new_matrix: Optional[MatrixType])
        // If new_matrix is null, then that effectively unsets the matrix name.

        if (name == "I" OR !matrices.contains(name)) then
            raise NameError("Matrix name is illegal")
        endif

        if (new_matrix == null) then
            matrices[name] = null
            return
        endif

        if (!is_matrix_type(new_matrix)) then
            raise TypeError("Matrix must be a 2x2 NumPy array")
        endif

        // All matrices must have float entries
        a = float(new_matrix[0][0])
        b = float(new_matrix[0][1])
        c = float(new_matrix[1][0])
        d = float(new_matrix[1][1])

        matrices[name] = np.array([[a, b], [c, d]])
    endprocedure
endclass
```

The `lintrans.gui.plots.classes` module will contain the following utility functions:

```
from PyQt5.QtGui import QPainter
from PyQt5.QtWidgets import QWidget

const DEFAULT_GRID_SPACING: int = 85

// This class will act as a baseclass for the viewport and visual defintion dialog.
```

```
// They will both use different subclasses of this class to visualize things on a grid.
// Canvas coordinates are the coordinates that Qt5 uses internally. These are standard
// computer graphics coordinates, with (0, 0) in the top left, positive x to the right,
// and positive y going down.
class BackgroundPlot extends QWidget
    private grid_spacing: int

    public procedure new()
        super.new()

        grid_spacing = DEFAULT_GRID_SPACING
    endprocedure

    // Return the canvas coordinates of the grid origin (centre)
    private function canvas_origin() -> (int, int):
        // width() and height() come from QWidget. They get the total width or height of the widget
        return (width() DIV 2, height() DIV 2)
    endfunction

    // Convert an x coordinate from grid coords to canvas coords so it can be drawn
    private function canvas_x(self, x: float) -> int
        return int(canvas_origin()[0] + x * grid_spacing)
    endfunction

    // Convert an x coordinate from grid coords to canvas coords so it can be drawn
    private function canvas_y(self, y: float) -> int
        return int(canvas_origin()[1] - y * grid_spacing)
    endfunction

    // Convert a coordinate from grid coords to canvas coords
    private function canvas_coords(x: float, y: float) -> (int, int)
        return (canvas_x(x), canvas_y(y))
    endfunction

    // Find the grid coordinates of the top right corner. We use the top right because
    // both coordinates will be positive
    private function grid_corner() -> (float, float)
        // Again, width() and height() come from QWidget
        return (width() / (2 * grid_spacing), height() / (2 * grid_spacing))
    endfunction

    // Convert a coordinate from canvas coords to grid coords
    private function grid_coords(x: int, y: int) -> (float, float)
        return (
            (x - canvas_origin[0]) / grid_spacing,
            (-y + canvas_origin[1]) / grid_spacing
        )
    endfunction

    // Draw the background grid. This method is meant to be used by subclasses when
    // they paint their whole scene
    private function draw_background(painter: QPainter)
        // Draw equally spaced vertical lines, starting in the middle and going out
        // We loop uo to half the width because we draw one line on each side of the axis per iteration
        for (int x = width() DIV 2 + grid_spacing; x < width(); x += grid_spacing)
            painter.drawLine((x, 0), (x, height()))
            painter.drawLine((width() - x, 0), (width() - x, height()))
        next x

        // Now do the same for horizontal lines
        for (int y = height() DIV 2 + grid_spacing; y < height(); x += grid_spacing)
            painter.drawLine((0, y), (width(), y))
            painter.drawLine((0, height() - y), (width(), height() - y))
        next y

        // Now draw the axes
        painter.drawLine((width() DIV 2, 0), (width() DIV 2, height()))
        painter.drawLine((0, height() DIV 2), (width(), height() DIV 2))
    endfunction
endclass
```

These modules handle the creation, storage, and use of matrices. Their implementations are deliber-

ately simple, since they don't have to do much. I will eventually extend the `MatrixWrapper` class to allow strings as matrices, so they can be defined as expressions, but this is unnecessary for now. It will simply be more conditions in `__getitem__` and `__setitem__` and a method to evaluate expressions.

Parsing matrix expressions will be quite tricky and I don't really know how I'm going to do it. I think it will be possible with regular expressions, since I won't support nested expressions at first. But adding support for nested expressions may require something more complicated. I will have a function to validate a matrix expression, which can definitely be done with regular expressions, and I'll have another public function to parse matrix expressions, although this one may use some private functions to implement it properly.

I'm not sure on any algorithms yet, but here's the full BNF specification for matrix expressions (including nested expressions):

```
1  expression        ::=  [ "-" ] matrices { ( "+" | "-" ) matrices };
2  matrices          ::=  matrix { matrix };
3  matrix            ::=  [ real_number ] matrix_identifier [ index ] | "(" expression ")";
4  matrix_identifier ::=  "A" .. "Z" | "rot(" [ "-" ] real_number ")";
5  index             ::=  "^{" index_content "}" | "^" index_content;
6  index_content     ::=  [ "-" ] integer_not_zero | "T";
7
8  digit_no_zero     ::=  "1" | "2" | "3" | "4" | "5" | "6" | "7" | "8" | "9";
9  digit             ::=  "0" | digit_no_zero;
10 digits            ::=  digit | digits digit;
11 integer_not_zero  ::=  digit_no_zero [ digits ];
12 real_number       ::=  ( integer_not_zero [ "." digits ] | "0" "." digits );
```

Obviously the data structure returned by the parser is very important. I have decided to use `list[list[tuple[str, str, str]]]`. Each tuple represents a real number multiplier, a matrix identifier, and an index. The multiplier and index may be empty strings. These tuples are contained in lists which represent matrices to be multiplied together, in order. Those lists are contained in a top level list, which represents multiplication groups which should be summed.

This type makes the structure of the input clear, and makes it very easy for the `MatrixWrapper` to evaluate a parsed expression.

2.4 Usability features

My main concern in terms of usability is colour. In the 3blue1brown videos on linear algebra, red and green are used for the basis vectors, but these colours are often hard to distinguish in most common forms of colour blindness. The most common form is deuteranopia[58], which makes red and green look incredibly similar. I will use blue and red for my basis vectors. These colours are easy to distinguish for people with deuteranopia and protanopia - the two most common forms of colour blindness. Tritanopia makes it harder to distinguish blue and yellow, but my colour scheme is still be accessible for people with tritanopia, as red and blue are very distinct in this form of colour blindness.

I will probably use green for the eigenvectors and eigenlines, which will be hard to distinguish from the red basis vector for people with red-green colour blindness, but I think that the basis vectors and eigenvectors/eigenlines will look physically different enough from each other that the colour shouldn't be too much of a problem. Additionally, I will use a tool called Color Oracle[28] to make sure that my app is accessible to people with different forms of colour blindness[6].

Another solution would be to have one default colour scheme, and allow the user to change the colour scheme to something more accessible for colour blind people, but I don't see the point in this. I think it's easier for colour blind people to just have the main colour scheme be accessible, and it's not really an inconvenience to non-colour blind people, so I think this is the best option.

[6] I actually had to clone a fork of this project[1] to get it working on Ubuntu 20.04 and adapt it slightly to create a working `jar` file[2]

The layout of my app will be self-consistent and follow standard conventions. I will have a menu bar at the top of the main window for actions like saving and loading, as well as accessing the tutorial (which will also be accessible by pressing `F1` at any point) and documentation. The dialogs will always have the confirm button in the bottom right and the cancel button just to the left of that. They will also have the matrix name drop-down on the left. This consistency will make the app easier to learn and understand.

I will also have hotkeys for everything that can have hotkeys - buttons, checkboxes, etc. This makes my life easier, since I'm used to having hotkeys for everything, and thus makes the app faster to test because I don't need to click everything. This also makes things easier for other people like me, who prefer to stay at the keyboard and not use the mouse. Obviously a mouse will be required for things like dragging basis vectors and polygon vertices, but hotkeys will be available wherever possible to help people who don't like using the mouse or find it difficult.

2.5 Variables and validation

The most important variables in the project will be instance attributes on the `LintransMainWindow` class. It will have a `MatrixWrapper` instance, a `DisplaySettings` instance, and most importantly, a `VisualizeTransformationWidget` instance. These will handle the matrices and various settings respectively. Having these as instance attributes allows them to be referenced from any method in the class, and Qt5 uses lots of slots (basically callback methods) and handlers, so it's good to be able to access the attributes I need right there rather than having to pass them around from method to method.

The `MatrixWrapper` class will have a dictionary of names and matrices. The names will be single letters[7] and the matrices will be of type `MatrixType`. This will be a custom type alias representing a 2×2 `numpy` array of floats. When setting the values for these matrices, I will have to manually check the types. This is because Python has weak typing, and if we got, say, an integer in place of a matrix, then operations would fail when trying to evaluate a matrix expression, and the program would crash. To prevent this, we have to validate the type of every matrix when it's set. I have chosen to use a dictionary here because it makes accessing a matrix by its name easier. We don't have to check against a list of letters and another list of matrices, we just index into the dictionary.

The settings dataclasses will have instance attributes for each setting. Most of these will be booleans, since they will be simple binary options like *Show determinant*, which will be represented with checkboxes in the GUI. The `DisplaySettings` dataclass will also have an attribute of type `int` representing the time in milliseconds to pause during animations.

The `DefineDialog` superclass have a `MatrixWrapper` instance attribute, which will be a parameter in the constructor. When `LintransMainWindow` spawns a definition dialog (which subclasses `DefineDialog`), it will pass in a copy of its own `MatrixWrapper` and connect the `accepted` signal for the dialog. The slot (method) that this signal is connected to will get called when the dialog is closed with the *Confirm* button[8]. This allows the dialog to mutate its own `MatrixWrapper` object and then the main window can copy that mutated version back into its own instance attribute when the user confirms the change. This reduces coupling and makes everything easier to reason about and debug, as well as reducing the number of bugs, since the classes will be independent of each other. In another language, I could pass a pointer to the wrapper and let the dialog mutate it directly, but this is potentially dangerous, and Python doesn't have pointers anyway.

Validation will also play a very big role in the application. The user will be able to enter matrix expressions and these must be validated. I will define a BNF schema and either write my own RegEx or use that BNF to programmatically generate a RegEx. Every matrix expression input will be checked against it. This is to ensure that the matrix wrapper can actually evaluate the expression. If we didn't validate the expression, then the parsing would fail and the program could crash. I've chosen to use a RegEx here rather than any other option because it's the simplest. Creating a RegEx

[7] I would make these `char` but Python only has a `str` type for strings

[8] Actually when the dialog calls `.accept()`. The `Confirm` button is actually connected to a method which first takes the info and updates the instance `MatrixWrapper`, and then calls `.accept()`

can be difficult, especially for complicated patterns, but it's then easier to use it. Also, Python can compile a RegEx pattern, which makes it much faster to match against, so I will compile the pattern at initialization time and just compare expressions against that pre-compiled pattern, since we know it won't change at runtime.

Additionally, the buttons to render and animate the current matrix expression will only be enabled when the expression is valid. Textboxes in Qt5 emit a `textChanged` signal, which can be connected to a slot. This is just a method that gets called whenever the text in the textbox is changed, so I can use this method to validate the input and update the buttons accordingly. An empty string will count as invalid, so the buttons will be disabled when the box is empty.

I will also apply this matrix expression validation to the textbox in the dialog which allows the user to define a matrix as an expression involving other matrices, and I will validate the input in the numeric definition dialog to make sure that all the inputs are floats. Again, this is to prevent crashes, since a matrix with non-number values in it will likely crash the program.

2.6 Iterative test data

There is a Python library called `pytest`, which can be used to run unit tests[25]. Unit tests are automatic tests that I can run whenever I like[59]. I can also set these up to be run automatically by using GitHub Actions[17]. Doing this will make it easy to test my code, because I can write separate testing code which makes sure that all my backend functions work as intended. This testing code is easy to run, and can be run automatically after every change, so I know that my changes won't break previous behaviour. All the unit testing code is in appendix B.

Additionally, `pytest` supports doctests[26], which are unit tests written in the source code documentation[39]. These tests are typically small, simple examples used to demonstrate how to use a function to an end user of the API (in this case, me). It is important to tests these examples to verify that the API is always correctly documented. I will use a few doctests for important functions, but I will mainly focus on unit tests.

In unit tests, I will test the validation, parsing, and generation of rotation matrices from an angle. I will also unit test the utility functions for the GUI, such as `is_valid_float()`, which is needed to verify input when defining a matrix visually. I will not be testing the GUI in unit tests, since this is almost impossible to do automatically. Instead, I will have to regularly test the GUI manually; mostly defining matrices, thinking about what I expect them to look like, and then making sure they look like that. I don't see a way around this limitation. I will make my backend unit tests very thorough, but testing the GUI can only be done manually.

For the validation of matrix expressions, I will have data like the following:

Valid	Invalid
`"A"`	`""`
`"AB"`	`"A^"`
`"-3.4A"`	`"rot()"`
`"A^2"`	`"A^{2"`
`"A^T"`	`"^12"`
`"A^{-1}"`	`"A^3.2"`
`"rot(45)"`	`"A^B"`
`"3A^{12}"`	`".A"`
`"2B^2+A^TC^{-1}"`	`"--A"`
`"3.5A^{4}5.6rot(19.2)^T-B^{-1}4.1C^5"`	`"A--B"`

This list is not exhaustive, mostly to save space and time, but the full unit testing code is included in appendix B.

The invalid expressions presented here have been chosen to be almost valid, but not quite. They are

edge cases. I will also test blatantly invalid expressions like `"This is a matrix expression"` to make sure the validation works.

Here's an example of some test data for parsing:

Input	Expected
`"A"`	`[[("", "A", "")]]`
`"AB"`	`[[("", "A", ""), ("", "B", "")]]`
`"2A+B^2"`	`[[("2", "A", ""), ("", "B", "2")]]`
`"3A^T2.4B^{-1}-C"`	`[[("3", "A", "T"), ("2.4", "B", "-1")], [("-1", "C", "")]]`

The parsing output is pretty verbose and this table doesn't have enough space for most of the more complicated inputs, so here's a monster one:

```
"2.14A^{3} 4.5rot(14.5)^-1 + 8.5B^T 5.97C^14 - 3.14D^{-1} 6.7E^T"
```

which should parse to give:

```
[[("2.14", "A", "3"), ("4.5", "rot(14.5)", "-1")], [("8.5", "B", "T"), ("5.97", "C", "14")],
                        [("-3.14", "D", "-1"), ("6.7", "E", "T")]]
```

Any invalid expression will also raise a `MatrixParseError`, so I will check every invalid input previously mentioned and make sure it raises the appropriate error.

Again, this section is brief to save space and time. All unit tests are included in appendix B.

2.7 Post-development test data

I will test all parts of the program to evaluate how well I have met the success criteria outlined in §1.7. See §4 for the tests themselves.

3 Development

Please note, throughout this section, every code snippet will have two comments at the top. The first is the git commit hash that the snippet was taken from[9]. The second comment is the file name. The line numbers of the snippet reflect the line numbers of the file from where the snippet was taken. After a certain point, I introduced copyright comments at the top of every file. These are always omitted here.

3.1 Matrices backend

3.1.1 `MatrixWrapper` class

The first real part of development was creating the `MatrixWrapper` class. It needs a simple instance dictionary to be created in the constructor, and it needs a way of accessing the matrices. I decided to use Python's `__getitem__()` and `__setitem__()` special methods[38] to allow indexing into a `MatrixWrapper` object like `wrapper['M']`. This simplifies using the class.

```python
# 29ec1fedbf307e3b7ca731c4a381535fec899b0b
# src/lintrans/matrices/wrapper.py

"""A module containing a simple MatrixWrapper class to wrap matrices and context."""

import numpy as np

from lintrans.typing import MatrixType


class MatrixWrapper:
    """A simple wrapper class to hold all possible matrices and allow access to them."""

    def __init__(self):
        """Initialise a MatrixWrapper object with a matrices dict."""
        self._matrices: dict[str, MatrixType | None] = {
            'A': None, 'B': None, 'C': None, 'D': None,
            'E': None, 'F': None, 'G': None, 'H': None,
            'I': np.eye(2),  # I is always defined as the identity matrix
            'J': None, 'K': None, 'L': None, 'M': None,
            'N': None, 'O': None, 'P': None, 'Q': None,
            'R': None, 'S': None, 'T': None, 'U': None,
            'V': None, 'W': None, 'X': None, 'Y': None,
            'Z': None
        }

    def __getitem__(self, name: str) -> MatrixType | None:
        """Get the matrix with `name` from the dictionary.

        Raises:
            KeyError:
                If there is no matrix with the given name
        """
        return self._matrices[name]

    def __setitem__(self, name: str, new_matrix: MatrixType) -> None:
        """Set the value of matrix `name` with the new_matrix.

        Raises:
            ValueError:
                If `name` isn't a valid matrix name
        """
        name = name.upper()

        if name == 'I' or name not in self._matrices:
            raise NameError('Matrix name must be a capital letter and cannot be "I"')
```

[9] A history of all commits can be found in the GitHub repository[3]

```
44
45              self._matrices[name] = new_matrix
```

This code is very simple. The constructor (`__init__()`) creates a dictionary of matrices which all start out as having no value, except the identity matrix **I**. The `__getitem__()` and `__setitem__()` methods allow the user to easily get and set matrices just like a dictionary, and `__setitem__()` will raise an error if the name is invalid. This is a very early prototype, so it doesn't validate the type of whatever the user is trying to assign it to yet. This validation will come later.

I could make this class subclass `dict`, since it's basically just a dictionary at this point, but I want to extend it with much more functionality later, so I chose to handle the dictionary stuff myself.

I then had to write unit tests for this class, and I chose to do all my unit tests using a framework called `pytest`.

```
# 29ec1fedbf307e3b7ca731c4a381535fec899b0b
# tests/test_matrix_wrapper.py

"""Test the MatrixWrapper class."""

import numpy as np
import pytest
from lintrans.matrices import MatrixWrapper

valid_matrix_names = 'ABCDEFGHJKLMNOPQRSTUVWXYZ'
test_matrix = np.array([[1, 2], [4, 3]])


@pytest.fixture
def wrapper() -> MatrixWrapper:
    """Return a new MatrixWrapper object."""
    return MatrixWrapper()


def test_get_matrix(wrapper) -> None:
    """Test MatrixWrapper.__getitem__()."""
    for name in valid_matrix_names:
        assert wrapper[name] is None

    assert (wrapper['I'] == np.array([[1, 0], [0, 1]])).all()


def test_get_name_error(wrapper) -> None:
    """Test that MatrixWrapper.__getitem__() raises a KeyError if called with an invalid name."""
    with pytest.raises(KeyError):
        _ = wrapper['bad name']
        _ = wrapper['123456']
        _ = wrapper['Th15 Is an 1nV@l1D n@m3']
        _ = wrapper['abc']


def test_set_matrix(wrapper) -> None:
    """Test MatrixWrapper.__setitem__()."""
    for name in valid_matrix_names:
        wrapper[name] = test_matrix
        assert (wrapper[name] == test_matrix).all()


def test_set_identity_error(wrapper) -> None:
    """Test that MatrixWrapper.__setitem__() raises a NameError when trying to assign to I."""
    with pytest.raises(NameError):
        wrapper['I'] = test_matrix


def test_set_name_error(wrapper) -> None:
    """Test that MatrixWrapper.__setitem__() raises a NameError when trying to assign to an invalid name."""
    with pytest.raises(NameError):
        wrapper['bad name'] = test_matrix
        wrapper['123456'] = test_matrix
```

```
52          wrapper['Th15 Is an 1nV@l1D n@m3'] = test_matrix
53          wrapper['abc'] = test_matrix
```

```
(lintrans) dyson@Harold-Ubuntu:~/repos/lintrans [main *]
$ pytest -v
========================================= test session starts ==========================================
platform linux -- Python 3.11.0, pytest-7.2.1, pluggy-1.0.0 -- /home/dyson/temp/lintrans/venv/bin/python
cachedir: .pytest_cache
rootdir: /home/dyson/temp/lintrans, configfile: pyproject.toml, testpaths: tests
collected 5 items

tests/test_matrix_wrapper.py::test_get_matrix PASSED                                          [ 20%]
tests/test_matrix_wrapper.py::test_get_name_error PASSED                                      [ 40%]
tests/test_matrix_wrapper.py::test_set_matrix PASSED                                          [ 60%]
tests/test_matrix_wrapper.py::test_set_identity_error PASSED                                  [ 80%]
tests/test_matrix_wrapper.py::test_set_name_error PASSED                                      [100%]

========================================== 5 passed in 0.27s ===========================================
```

Figure 3.1.1: Running `pytest` with the new tests

These tests are quite simple and just ensure that the expected behaviour works the way it should, and that the correct errors are raised when they should be. It verifies that matrices can be assigned, that every valid name works, and that the identity matrix $\mathbf{I}$ cannot be assigned to.

The function decorated with `@pytest.fixture` allows functions to use a parameter called `wrapper` and `pytest` will automatically call this function and pass it as that parameter. It just saves on code repetition.

3.1.2 Rudimentary parsing and evaluating

This first thing I did here was improve the `__setitem__()` and `__getitem__()` methods to validate input and easily get transposes and simple rotation matrices.

```
# f89fc9fd8d5917d07557fc50df3331123b55ad6b
# src/lintrans/matrices/wrapper.py
```

```
11  class MatrixWrapper:
...
60      def __setitem__(self, name: str, new_matrix: MatrixType) -> None:
61          """Set the value of matrix `name` with the new_matrix.
62
63          :param str name: The name of the matrix to set the value of
64          :param MatrixType new_matrix: The value of the new matrix
65          :rtype: None
66
67          :raises NameError: If the name isn't a valid matrix name or is 'I'
68          """
69          if name not in self._matrices.keys():
70              raise NameError('Matrix name must be a single capital letter')
71
72          if name == 'I':
73              raise NameError('Matrix name cannot be "I"')
74
75          # All matrices must have float entries
76          a = float(new_matrix[0][0])
77          b = float(new_matrix[0][1])
78          c = float(new_matrix[1][0])
79          d = float(new_matrix[1][1])
80
81          self._matrices[name] = np.array([[a, b], [c, d]])
```

In this method, I'm now casting all the values to floats. This is very simple validation, since this cast will raise `ValueError` if it fails to cast the value to a float. I should've declared `:raises ValueError:` in the docstring, but this was an oversight at the time.

```python
# f89fc9fd8d5917d07557fc50df3331123b55ad6b
# src/lintrans/matrices/wrapper.py

class MatrixWrapper:
...
    def __getitem__(self, name: str) -> Optional[MatrixType]:
        """Get the matrix with the given name.

        If it is a simple name, it will just be fetched from the dictionary.
        If the name is followed with a 't', then we will return the transpose of the named matrix.
        If the name is 'rot()', with a given angle in degrees, then we return a new rotation matrix with that angle.

        :param str name: The name of the matrix to get
        :returns: The value of the matrix (may be none)
        :rtype: Optional[MatrixType]

        :raises NameError: If there is no matrix with the given name
        """
        # Return a new rotation matrix
        match = re.match(r'rot\((\d+)\)', name)
        if match is not None:
            return create_rotation_matrix(float(match.group(1)))

        # Return the transpose of this matrix
        match = re.match(r'([A-Z])t', name)
        if match is not None:
            matrix = self[match.group(1)]

            if matrix is not None:
                return matrix.T
            else:
                return None

        if name not in self._matrices:
            raise NameError(f'Unrecognised matrix name "{name}"')

        return self._matrices[name]

```

This `__getitem__()` method now allows for easily accessing transposes and rotation matrices by checking input with regular expressions. This makes getting matrices easier and thus makes evaluating full expressions simpler.

The `create_rotation_matrix()` method is also defined in this file and just uses the $\begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix}$ formula from before:

```python
# f89fc9fd8d5917d07557fc50df3331123b55ad6b
# src/lintrans/matrices/wrapper.py

def create_rotation_matrix(angle: float) -> MatrixType:
    """Create a matrix representing a rotation by the given number of degrees anticlockwise.

    :param float angle: The number of degrees to rotate by
    :returns MatrixType: The resultant rotation matrix
    """
    rad = np.deg2rad(angle)
    return np.array([
        [np.cos(rad), -1 * np.sin(rad)],
        [np.sin(rad), np.cos(rad)]
    ])
```

At this stage, I also implemented a simple parser and evaluator using regular expressions. It's not great and it's not very flexible, but it can evaluate simple expressions.

```python
# f89fc9fd8d5917d07557fc50df3331123b55ad6b
# src/lintrans/matrices/wrapper.py
```

```
11  class MatrixWrapper:
...
83      def parse_expression(self, expression: str) -> MatrixType:
84          """Parse a given expression and return the matrix for that expression.
85
86          Expressions are written with standard LaTeX notation for exponents. All whitespace is ignored.
87
88          Here is documentation on syntax:
89              A single matrix is written as 'A'.
90              Matrix A multiplied by matrix B is written as 'AB'
91              Matrix A plus matrix B is written as 'A+B'
92              Matrix A minus matrix B is written as 'A-B'
93              Matrix A squared is written as 'A^2'
94              Matrix A to the power of 10 is written as 'A^10' or 'A^{10}'
95              The inverse of matrix A is written as 'A^-1' or 'A^{-1}'
96              The transpose of matrix A is written as 'A^T' or 'At'
97
98          :param str expression: The expression to be parsed
99          :returns MatrixType: The matrix result of the expression
100
101         :raises ValueError: If the expression is invalid, such as an empty string
102         """
103         if expression == '':
104             raise ValueError('The expression cannot be an empty string')
105
106         match = re.search(r'[^-+A-Z^{}rot()\d.]', expression)
107         if match is not None:
108             raise ValueError(f'Invalid character "{match.group(0)}"')
109
110         # Remove all whitespace in the expression
111         expression = re.sub(r'\s', '', expression)
112
113         # Wrap all exponents and transposition powers with {}
114         expression = re.sub(r'(?<=\^)(-?\d+|T)(?=[^}]|$)', r'{\g<0>}', expression)
115
116         # Replace all subtractions with additions, multiplied by -1
117         expression = re.sub(r'(?<=.)-(?=[A-Z])', '+-1', expression)
118
119         # Replace a possible leading minus sign with -1
120         expression = re.sub(r'^-(?=[A-Z])', '-1', expression)
121
122         # Change all transposition exponents into lowercase
123         expression = expression.replace('^{T}', 't')
124
125         # Split the expression into groups to be multiplied, and then we add those groups at the end
126         # We also have to filter out the empty strings to reduce errors
127         multiplication_groups = [x for x in expression.split('+') if x != '']
128
129         # Start with the 0 matrix and add each group on
130         matrix_sum: MatrixType = np.array([[0., 0.], [0., 0.]])
131
132         for group in multiplication_groups:
133             # Generate a list of tuples, each representing a matrix
134             # These tuples are (the multiplier, the matrix (with optional
135             # 't' at the end to indicate a transpose), the exponent)
136             string_matrices: list[tuple[str, str, str]]
137
138             # The generate tuple is (multiplier, matrix, full exponent, stripped exponent)
139             # The full exponent contains ^{}, so we ignore it
140             # The multiplier and exponent might be '', so we have to set them to '1'
141             string_matrices = [(t[0] if t[0] != '' else '1', t[1], t[3] if t[3] != '' else '1')
142                                for t in re.findall(r'(-?\d*\.?\d*)([A-Z]t?|rot\(\d+\))(\^{(-?\d+|T)})?', group)]
143
144             # This list is a list of tuple, where each tuple is (a float multiplier,
145             # the matrix (gotten from the wrapper's __getitem__()), the integer power)
146             matrices: list[tuple[float, MatrixType, int]]
147             matrices = [(float(t[0]), self[t[1]], int(t[2])) for t in string_matrices]
148
149             # Process the matrices and make actual MatrixType objects
150             processed_matrices: list[MatrixType] = [t[0] * np.linalg.matrix_power(t[1], t[2]) for t in matrices]
151
152             # Add this matrix product to the sum total
153             matrix_sum += reduce(lambda m, n: m @ n, processed_matrices)
```

```
154
155             return matrix_sum
```

I think the comments in the code speak for themselves, but we basically split the expression up into groups to be added, and then for each group, we multiply every matrix in that group to get its value, and then add all these values together at the end.

This code is objectively bad. At the time of writing, it's now quite old, so I can say that. This code has no real error handling, and line 127 introduces the glaring error that `'A++B'` is now a valid expression because we disregard empty strings. Not to mention the fact that the method is called `parse_expression()` but actually evaluates an expression. All these issues will be fixed in the future, but this was the first implementation of matrix evaluation, and it does the job decently well.

I then implemented several tests for this parsing.

```
# 60e0c713b244e097bab8ee0f71142b709fde1a8b
# tests/test_matrix_wrapper_parse_expression.py

1   """Test the MatrixWrapper parse_expression() method."""
2
3   import numpy as np
4   from numpy import linalg as la
5   import pytest
6   from lintrans.matrices import MatrixWrapper
7
8
9   @pytest.fixture
10  def wrapper() -> MatrixWrapper:
11      """Return a new MatrixWrapper object with some preset values."""
12      wrapper = MatrixWrapper()
13
14      root_two_over_two = np.sqrt(2) / 2
15
16      wrapper['A'] = np.array([[1, 2], [3, 4]])
17      wrapper['B'] = np.array([[6, 4], [12, 9]])
18      wrapper['C'] = np.array([[-1, -3], [4, -12]])
19      wrapper['D'] = np.array([[13.2, 9.4], [-3.4, -1.8]])
20      wrapper['E'] = np.array([
21          [root_two_over_two, -1 * root_two_over_two],
22          [root_two_over_two, root_two_over_two]
23      ])
24      wrapper['F'] = np.array([[-1, 0], [0, 1]])
25      wrapper['G'] = np.array([[np.pi, np.e], [1729, 743.631]])
26
27      return wrapper
28
29
30  def test_simple_matrix_addition(wrapper: MatrixWrapper) -> None:
31      """Test simple addition and subtraction of two matrices."""
32
33      # NOTE: We assert that all of these values are not None just to stop mypy complaining
34      # These values will never actually be None because they're set in the wrapper() fixture
35      # There's probably a better way  do this, because this method is a bit of a bdoge, but this works for now
36      assert wrapper['A'] is not None and wrapper['B'] is not None and wrapper['C'] is not None and \
37          wrapper['D'] is not None and wrapper['E'] is not None and wrapper['F'] is not None and \
38          wrapper['G'] is not None
39
40      assert (wrapper.parse_expression('A+B') == wrapper['A'] + wrapper['B']).all()
41      assert (wrapper.parse_expression('E+F') == wrapper['E'] + wrapper['F']).all()
42      assert (wrapper.parse_expression('G+D') == wrapper['G'] + wrapper['D']).all()
43      assert (wrapper.parse_expression('C+C') == wrapper['C'] + wrapper['C']).all()
44      assert (wrapper.parse_expression('D+A') == wrapper['D'] + wrapper['A']).all()
45      assert (wrapper.parse_expression('B+C') == wrapper['B'] + wrapper['C']).all()
46
47
48  def test_simple_two_matrix_multiplication(wrapper: MatrixWrapper) -> None:
49      """Test simple multiplication of two matrices."""
50      assert wrapper['A'] is not None and wrapper['B'] is not None and wrapper['C'] is not None and \
51             wrapper['D'] is not None and wrapper['E'] is not None and wrapper['F'] is not None and \
```

```
            wrapper['G'] is not None

    assert (wrapper.parse_expression('AB') == wrapper['A'] @ wrapper['B']).all()
    assert (wrapper.parse_expression('BA') == wrapper['B'] @ wrapper['A']).all()
    assert (wrapper.parse_expression('AC') == wrapper['A'] @ wrapper['C']).all()
    assert (wrapper.parse_expression('DA') == wrapper['D'] @ wrapper['A']).all()
    assert (wrapper.parse_expression('ED') == wrapper['E'] @ wrapper['D']).all()
    assert (wrapper.parse_expression('FD') == wrapper['F'] @ wrapper['D']).all()
    assert (wrapper.parse_expression('GA') == wrapper['G'] @ wrapper['A']).all()
    assert (wrapper.parse_expression('CF') == wrapper['C'] @ wrapper['F']).all()
    assert (wrapper.parse_expression('AG') == wrapper['A'] @ wrapper['G']).all()


def test_identity_multiplication(wrapper: MatrixWrapper) -> None:
    """Test that multiplying by the identity doesn't change the value of a matrix."""
    assert wrapper['A'] is not None and wrapper['B'] is not None and wrapper['C'] is not None and \
           wrapper['D'] is not None and wrapper['E'] is not None and wrapper['F'] is not None and \
           wrapper['G'] is not None

    assert (wrapper.parse_expression('I') == wrapper['I']).all()
    assert (wrapper.parse_expression('AI') == wrapper['A']).all()
    assert (wrapper.parse_expression('IA') == wrapper['A']).all()
    assert (wrapper.parse_expression('GI') == wrapper['G']).all()
    assert (wrapper.parse_expression('IG') == wrapper['G']).all()

    assert (wrapper.parse_expression('EID') == wrapper['E'] @ wrapper['D']).all()
    assert (wrapper.parse_expression('IED') == wrapper['E'] @ wrapper['D']).all()
    assert (wrapper.parse_expression('EDI') == wrapper['E'] @ wrapper['D']).all()
    assert (wrapper.parse_expression('IEIDI') == wrapper['E'] @ wrapper['D']).all()
    assert (wrapper.parse_expression('EI^3D') == wrapper['E'] @ wrapper['D']).all()


def test_simple_three_matrix_multiplication(wrapper: MatrixWrapper) -> None:
    """Test simple multiplication of two matrices."""
    assert wrapper['A'] is not None and wrapper['B'] is not None and wrapper['C'] is not None and \
           wrapper['D'] is not None and wrapper['E'] is not None and wrapper['F'] is not None and \
           wrapper['G'] is not None

    assert (wrapper.parse_expression('ABC') == wrapper['A'] @ wrapper['B'] @ wrapper['C']).all()
    assert (wrapper.parse_expression('ACB') == wrapper['A'] @ wrapper['C'] @ wrapper['B']).all()
    assert (wrapper.parse_expression('BAC') == wrapper['B'] @ wrapper['A'] @ wrapper['C']).all()
    assert (wrapper.parse_expression('EFG') == wrapper['E'] @ wrapper['F'] @ wrapper['G']).all()
    assert (wrapper.parse_expression('DAC') == wrapper['D'] @ wrapper['A'] @ wrapper['C']).all()
    assert (wrapper.parse_expression('GAE') == wrapper['G'] @ wrapper['A'] @ wrapper['E']).all()
    assert (wrapper.parse_expression('FAG') == wrapper['F'] @ wrapper['A'] @ wrapper['G']).all()
    assert (wrapper.parse_expression('GAF') == wrapper['G'] @ wrapper['A'] @ wrapper['F']).all()


def test_matrix_inverses(wrapper: MatrixWrapper) -> None:
    """Test the inverses of single matrices."""
    assert wrapper['A'] is not None and wrapper['B'] is not None and wrapper['C'] is not None and \
           wrapper['D'] is not None and wrapper['E'] is not None and wrapper['F'] is not None and \
           wrapper['G'] is not None

    assert (wrapper.parse_expression('A^{-1}') == la.inv(wrapper['A'])).all()
    assert (wrapper.parse_expression('B^{-1}') == la.inv(wrapper['B'])).all()
    assert (wrapper.parse_expression('C^{-1}') == la.inv(wrapper['C'])).all()
    assert (wrapper.parse_expression('D^{-1}') == la.inv(wrapper['D'])).all()
    assert (wrapper.parse_expression('E^{-1}') == la.inv(wrapper['E'])).all()
    assert (wrapper.parse_expression('F^{-1}') == la.inv(wrapper['F'])).all()
    assert (wrapper.parse_expression('G^{-1}') == la.inv(wrapper['G'])).all()

    assert (wrapper.parse_expression('A^-1') == la.inv(wrapper['A'])).all()
    assert (wrapper.parse_expression('B^-1') == la.inv(wrapper['B'])).all()
    assert (wrapper.parse_expression('C^-1') == la.inv(wrapper['C'])).all()
    assert (wrapper.parse_expression('D^-1') == la.inv(wrapper['D'])).all()
    assert (wrapper.parse_expression('E^-1') == la.inv(wrapper['E'])).all()
    assert (wrapper.parse_expression('F^-1') == la.inv(wrapper['F'])).all()
    assert (wrapper.parse_expression('G^-1') == la.inv(wrapper['G'])).all()


def test_matrix_powers(wrapper: MatrixWrapper) -> None:
    """Test that matrices can be raised to integer powers."""
```

```
125         assert wrapper['A'] is not None and wrapper['B'] is not None and wrapper['C'] is not None and \
126                wrapper['D'] is not None and wrapper['E'] is not None and wrapper['F'] is not None and \
127                wrapper['G'] is not None
128
129         assert (wrapper.parse_expression('A^2') == la.matrix_power(wrapper['A'], 2)).all()
130         assert (wrapper.parse_expression('B^4') == la.matrix_power(wrapper['B'], 4)).all()
131         assert (wrapper.parse_expression('C^{12}') == la.matrix_power(wrapper['C'], 12)).all()
132         assert (wrapper.parse_expression('D^12') == la.matrix_power(wrapper['D'], 12)).all()
133         assert (wrapper.parse_expression('E^8') == la.matrix_power(wrapper['E'], 8)).all()
134         assert (wrapper.parse_expression('F^{-6}') == la.matrix_power(wrapper['F'], -6)).all()
135         assert (wrapper.parse_expression('G^-2') == la.matrix_power(wrapper['G'], -2)).all()
```

```
(lintrans) dyson@Harold-Ubuntu:~/repos/lintrans [main *]
$ pytest -v
========================================= test session starts =========================================
platform linux -- Python 3.11.0, pytest-7.2.1, pluggy-1.0.0 -- /home/dyson/temp/lintrans/venv/bin/python
cachedir: .pytest_cache
rootdir: /home/dyson/temp/lintrans, configfile: pyproject.toml, testpaths: tests
collected 12 items

tests/test_matrix_wrapper_parse_expression.py::test_simple_matrix_addition PASSED                  [  8%]
tests/test_matrix_wrapper_parse_expression.py::test_simple_two_matrix_multiplication PASSED        [ 16%]
tests/test_matrix_wrapper_parse_expression.py::test_identity_multiplication PASSED                 [ 25%]
tests/test_matrix_wrapper_parse_expression.py::test_simple_three_matrix_multiplication PASSED      [ 33%]
tests/test_matrix_wrapper_parse_expression.py::test_matrix_inverses PASSED                         [ 41%]
tests/test_matrix_wrapper_parse_expression.py::test_matrix_powers PASSED                           [ 50%]
tests/test_matrix_wrapper_setitem_and_getitem.py::test_get_matrix PASSED                           [ 58%]
tests/test_matrix_wrapper_setitem_and_getitem.py::test_get_name_error PASSED                       [ 66%]
tests/test_matrix_wrapper_setitem_and_getitem.py::test_set_matrix PASSED                           [ 75%]
tests/test_matrix_wrapper_setitem_and_getitem.py::test_set_identity_error PASSED                   [ 83%]
tests/test_matrix_wrapper_setitem_and_getitem.py::test_set_name_error PASSED                       [ 91%]
tests/test_matrix_wrapper_setitem_and_getitem.py::test_set_type_error PASSED                       [100%]

========================================== 12 passed in 0.35s =========================================
```

Figure 3.1.2: Running `pytest` with the new tests

These test lots of simple expressions, but don't test any more complicated expressions, nor do they test any validation, mostly because validation doesn't really exist at this point. `'A++B'` is still a valid expression and is equivalent to `'A+B'`.

3.1.3 Simple matrix expression validation

My next major step was to implement proper parsing, but I procrastinated for a while and first implemented proper validation.

```
# 39b918651f60bc72bc19d2018075b24a6fc3af17
# src/lintrans/_parse/matrices.py

9   def compile_valid_expression_pattern() -> Pattern[str]:
10      """Compile the single regular expression that will match a valid matrix expression."""
11      digit_no_zero = '[123456789]'
12      digits = '\\d+'
13      integer_no_zero = '-?' + digit_no_zero + '(' + digits + ')?'
14      real_number = f'({integer_no_zero}(\\.{digits})?|-?0?\\.{digits})'
15
16      index_content = f'({integer_no_zero}|T)'
17      index = f'(\\^\\{{{index_content}\\}}|\\^{index_content}|t)'
18      matrix_identifier = f'([A-Z]|rot\\({real_number}\\))'
19      matrix = '(' + real_number + '?' + matrix_identifier + index + '?)'
20      expression = f'{matrix}+((\\+|-){matrix}+)*'
21
22      return re.compile(expression)
23
24
25  # This is an expensive pattern to compile, so we compile it when this module is initialized
26  valid_expression_pattern = compile_valid_expression_pattern()
```

```
27
28
29  def validate_matrix_expression(expression: str) -> bool:
30      """Validate the given matrix expression.
31
32      This function simply checks the expression against a BNF schema. It is not
33      aware of which matrices are actually defined in a wrapper. For an aware
34      version of this function, use the MatrixWrapper().is_valid_expression() method.
35
36      Here is the schema for a valid expression given in a version of BNF:
37
38          expression        ::=  matrices { ( "+" | "-" ) matrices };
39          matrices          ::=  matrix { matrix };
40          matrix            ::=  [ real_number ] matrix_identifier [ index ];
41          matrix_identifier ::=  "A" .. "Z" | "rot(" real_number ")";
42          index             ::=  "^{" index_content "}" | "^" index_content | "t";
43          index_content     ::=  integer_not_zero | "T";
44
45          digit_no_zero     ::=  "1" | "2" | "3" | "4" | "5" | "6" | "7" | "8" | "9";
46          digit             ::=  "0" | digit_no_zero;
47          digits            ::=  digit | digits digit;
48          integer_not_zero  ::=  [ "-" ] digit_no_zero [ digits ];
49          real_number       ::=  ( integer_not_zero [ "." digits ] | [ "-" ] [ "0" ] "." digits );
50
51      :param str expression: The expression to be validated
52      :returns bool: Whether the expression is valid according to the schema
53      """
54      match = valid_expression_pattern.match(expression)
55      return expression == match.group(0) if match is not None else False
```

Here, I'm using a BNF schema to programmatically generate a regular expression. I use a function to generate this pattern and assign it to a variable when the module is initialized. This is because the pattern compilation is expensive and it's more efficient to compile the pattern once and then just use it in the `validate_matrix_expression()` function.

I also created a method `is_valid_expression()` in `MatrixWrapper`, which just validates a given expression. It uses the aforementioned `validate_matrix_expression()` and also checks that every matrix referenced in the expression is defined in the wrapper.

```
# 39b918651f60bc72bc19d2018075b24a6fc3af17
# src/lintrans/matrices/wrapper.py

12  class MatrixWrapper:
...
99      def is_valid_expression(self, expression: str) -> bool:
100         """Check if the given expression is valid, using the context of the wrapper.
101
102         This method calls _parse.validate_matrix_expression(), but also ensures
103         that all the matrices in the expression are defined in the wrapper.
104
105         :param str expression: The expression to validate
106         :returns bool: Whether the expression is valid according the schema
107         """
108         # Get rid of the transposes to check all capital letters
109         expression = re.sub(r'\^T', 't', expression)
110         expression = re.sub(r'\^{T}', 't', expression)
111
112         # Make sure all the referenced matrices are defined
113         for matrix in {x for x in expression if re.match('[A-Z]', x)}:
114             if self[matrix] is None:
115                 return False
116
117         return _parse.validate_matrix_expression(expression)
```

I then implemented some simple tests to make sure the function works with valid and invalid expressions.

```
# a0fb029f7da995803c24ee36e7e8078e5621f676
```

```python
# tests/_parse/test_parse_and_validate_expression.py

"""Test the _parse.matrices module validation and parsing."""

import pytest
from lintrans._parse import validate_matrix_expression

valid_inputs: list[str] = [
    'A', 'AB', '3A', '1.2A', '-3.4A', 'A^2', 'A^-1', 'A^{-1}',
    'A^12', 'A^T', 'A^{5}', 'A^{T}', '4.3A^7', '9.2A^{18}',

    'rot(45)', 'rot(12.5)', '3rot(90)',
    'rot(135)^3', 'rot(51)^T', 'rot(-34)^-1',

    'A+B', 'A+2B', '4.3A+9B', 'A^2+B^T', '3A^7+0.8B^{16}',
    'A-B', '3A-4B', '3.2A^3-16.79B^T', '4.752A^{17}-3.32B^{36}',
    'A--1B', '-A', '--1A'

    '3A4B', 'A^TB', 'A^{T}B', '4A^6B^3',
    '2A^{3}4B^5', '4rot(90)^3', 'rot(45)rot(13)',
    'Arot(90)', 'AB^2', 'A^2B^2', '8.36A^T3.4B^12',

    '3.5A^{4}5.6rot(19.2)^T-B^{-1}4.1C^5',
]

invalid_inputs: list[str] = [
    '', 'rot()', 'A^', 'A^1.2', 'A^{3.4}', '1,2A', 'ro(12)', '5', '12^2',
    '^T', '^{12}', 'A^{13', 'A^3}', 'A^A', '^2', 'A--B', '--A'

    'This is 100% a valid matrix expression, I swear'
]


@pytest.mark.parametrize('inputs,output', [(valid_inputs, True), (invalid_inputs, False)])
def test_validate_matrix_expression(inputs: list[str], output: bool) -> None:
    """Test the validate_matrix_expression() function."""
    for inp in inputs:
        assert validate_matrix_expression(inp) == output
```

```
(lintrans) dyson@Harold-Ubuntu:~/repos/lintrans [main *]
$ pytest -v
============================================= test session starts ==============================================
platform linux -- Python 3.11.0, pytest-7.2.1, pluggy-1.0.0 -- /home/dyson/temp/lintrans/venv/bin/python
cachedir: .pytest_cache
rootdir: /home/dyson/temp/lintrans, configfile: pyproject.toml, testpaths: tests
collected 18 items

tests/_parse/test_parse_and_validate_expression.py::test_validate_matrix_expression[inputs0-True] PASSED        [  5%]
tests/_parse/test_parse_and_validate_expression.py::test_validate_matrix_expression[inputs1-False] PASSED       [ 11%]
tests/matrices/test_rotation_matrices.py::test_create_rotation_matrix PASSED                                    [ 16%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_simple_matrix_addition PASSED                   [ 22%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_simple_two_matrix_multiplication PASSED         [ 27%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_identity_multiplication PASSED                  [ 33%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_simple_three_matrix_multiplication PASSED       [ 38%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_matrix_inverses PASSED                          [ 44%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_matrix_powers PASSED                            [ 50%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_matrix_transpose PASSED                         [ 55%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_rotation_matrices PASSED                        [ 61%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_value_errors PASSED                             [ 66%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_get_matrix PASSED                               [ 72%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_get_name_error PASSED                           [ 77%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_set_matrix PASSED                               [ 83%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_set_identity_error PASSED                       [ 88%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_set_name_error PASSED                           [ 94%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_set_type_error PASSED                           [100%]

============================================== 18 passed in 0.31s ==============================================
```

Figure 3.1.3: Running `pytest` with the new tests

Here, we test some valid data, some definitely invalid data, and some edge cases. At this stage, `'A--1B'` was considered a valid expression. This was a quirk of the validator at the time, but I fixed it later. This should obviously be an invalid expression, especially since `'A--B'` is considered invalid, but `'A--1B'` is valid.

The `@pytest.mark.parametrize` decorator on line 32 means that `pytest` will run one test for valid

inputs, and then another test for invalid inputs, and these will count as different tests. This makes it easier to see which tests failed and then debug the app.

While I was adding tests, I added new doctests for the `MatrixWrapper` class and `create_rotation_matrix()` function.

```python
# 6db1a1a1b3deaa30b1a8d23bb66ff738a3f212d2
# src/lintrans/matrices/wrapper.py

class MatrixWrapper:
    """A simple wrapper class to hold all possible matrices and allow access to them.

    The contained matrices can be accessed with square bracket notation.

    :Example:

    >>> wrapper = MatrixWrapper()
    >>> wrapper['I']
    array([[1., 0.],
           [0., 1.]])
    >>> wrapper['M']  # Returns None
    >>> wrapper['M'] = np.array([[1, 2], [3, 4]])
    >>> wrapper['M']
    array([[1., 2.],
           [3., 4.]])

    Methods:
        is_valid_expression(expression: str) -> bool:
            Check if the given expression is valid, using the context of the wrapper.

        evaluate_expression(expression: str) -> MatrixType:
            Evaluate a given expression and return the matrix for that expression.
    """
```

```python
# e79664861434059eb2b27a38310a140e00c6432b
# src/lintrans/matrices/wrapper.py

def create_rotation_matrix(angle: float, degrees: bool = True) -> MatrixType:
    """Create a matrix representing a rotation by the given angle (anticlockwise).

    :Example:

    >>> create_rotation_matrix(30)
    array([[ 0.8660254, -0.5      ],
           [ 0.5      ,  0.8660254]])
    >>> create_rotation_matrix(45)
    array([[ 0.70710678, -0.70710678],
           [ 0.70710678,  0.70710678]])
    >>> create_rotation_matrix(np.pi / 3, degrees=False)
    array([[ 0.5      , -0.8660254],
           [ 0.8660254,  0.5      ]])

    :param float angle: The angle to rotate anticlockwise by
    :param bool degrees: Whether to interpret the angle as degrees (True) or radians (False)
    :returns MatrixType: The resultant rotation matrix
    """
```

```
(lintrans) dyson@Harold-Ubuntu:~/repos/lintrans [main *=]
$ pytest --doctest-modules src/ -v
========================================= test session starts ==========================================
platform linux -- Python 3.11.0, pytest-7.2.1, pluggy-1.0.0 -- /home/dyson/temp/lintrans/venv/bin/python
cachedir: .pytest_cache
rootdir: /home/dyson/temp/lintrans, configfile: pyproject.toml
collected 2 items

src/lintrans/matrices/wrapper.py::lintrans.matrices.wrapper.MatrixWrapper PASSED                  [ 50%]
src/lintrans/matrices/wrapper.py::lintrans.matrices.wrapper.create_rotation_matrix PASSED         [100%]

========================================== 2 passed in 0.28s ===========================================
```

Figure 3.1.4: Running `pytest` with the new doctests

3.1.4 Parsing matrix expressions

Parsing is quite an interesting problem and something I didn't feel able to tackle head-on, so I wrote the unit tests first. I had a basic idea of what I wanted the parser to return, but no real idea of how to implement that. My unit tests looked like this:

```python
# e9f7a81892278fe70684562052f330fb3a02bf9b
# tests/_parse/test_parse_and_validate_expression.py

expressions_and_parsed_expressions: list[tuple[str, MatrixParseList]] = [
    # Simple expressions
    ('A', [[('', 'A', '')]]),
    ('A^2', [[('', 'A', '2')]]),
    ('A^{2}', [[('', 'A', '2')]]),
    ('3A', [[('3', 'A', '')]]),
    ('1.4A^3', [[('1.4', 'A', '3')]]),

    # Multiplications
    ('4A^{3} 6B^2', [[('4', 'A', '3'), ('6', 'B', '2')]]),
    ('4.2A^{T} 6.1B^-1', [[('4.2', 'A', 'T'), ('6.1', 'B', '-1')]]),
    ('-1.2A^2 rot(45)^2', [[('-1.2', 'A', '2'), ('', 'rot(45)', '2')]]),
    ('3.2A^T 4.5B^{5} 9.6rot(121.3)', [[('3.2', 'A', 'T'), ('4.5', 'B', '5'), ('9.6', 'rot(121.3)', '')]]),
    ('-1.18A^{-2} 0.1B^{2} 9rot(34.6)^-1', [[('-1.18', 'A', '-2'), ('0.1', 'B', '2'), ('9', 'rot(34.6)', '-1')]]),

    # Additions
    ('A + B', [[('', 'A', '')], [('', 'B', '')]]),
    ('A + B - C', [[('', 'A', '')], [('', 'B', '')], [('-1', 'C', '')]]),
    ('2A^3 + 8B^T - 3C^-1', [[('2', 'A', '3')], [('8', 'B', 'T')], [('-3', 'C', '-1')]]),

    # Additions with multiplication
    ('2.14A^{3} 4.5rot(14.5)^-1 + 8B^T - 3C^-1', [[('2.14', 'A', '3'), ('4.5', 'rot(14.5)', '-1')],
                                                  [('8', 'B', 'T')], [('-3', 'C', '-1')]]),
    ('2.14A^{3} 4.5rot(14.5)^-1 + 8.5B^T 5.97C^4 - 3.14D^{-1} 6.7E^T',
     [[('2.14', 'A', '3'), ('4.5', 'rot(14.5)', '-1')], [('8.5', 'B', 'T'), ('5.97', 'C', '4')],
      [('-3.14', 'D', '-1'), ('6.7', 'E', 'T')]]),
]


@pytest.mark.skip(reason='parse_matrix_expression() not implemented')
def test_parse_matrix_expression() -> None:
    """Test the parse_matrix_expression() function."""
    for expression, parsed_expression in expressions_and_parsed_expressions:
        # Test it with and without whitespace
        assert parse_matrix_expression(expression) == parsed_expression
        assert parse_matrix_expression(expression.replace(' ', '')) == parsed_expression
```

```
(lintrans) dyson@Harold-Ubuntu:~/repos/lintrans [main *]
$ pytest -v
============================================================ test session starts =============================================================
platform linux -- Python 3.11.0, pytest-7.2.1, pluggy-1.0.0 -- /home/dyson/temp/lintrans/venv/bin/python
cachedir: .pytest_cache
rootdir: /home/dyson/temp/lintrans, configfile: pyproject.toml, testpaths: tests
collected 19 items

tests/_parse/test_parse_and_validate_expression.py::test_validate_matrix_expression[inputs0-True] PASSED                                [  5%]
tests/_parse/test_parse_and_validate_expression.py::test_validate_matrix_expression[inputs1-False] PASSED                               [ 10%]
tests/_parse/test_parse_and_validate_expression.py::test_parse_matrix_expression SKIPPED (parse_matrix_expression() not implemented)    [ 15%]
tests/matrices/test_rotation_matrices.py::test_create_rotation_matrix PASSED                                                          [ 21%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_simple_matrix_addition PASSED                                         [ 26%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_simple_two_matrix_multiplication PASSED                               [ 31%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_identity_multiplication PASSED                                        [ 36%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_simple_three_matrix_multiplication PASSED                             [ 42%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_matrix_inverses PASSED                                                [ 47%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_matrix_powers PASSED                                                  [ 52%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_matrix_transpose PASSED                                               [ 57%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_rotation_matrices PASSED                                              [ 63%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_value_errors PASSED                                                   [ 68%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_get_matrix PASSED                                                     [ 73%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_get_name_error PASSED                                                 [ 78%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_set_matrix PASSED                                                     [ 84%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_set_identity_error PASSED                                             [ 89%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_set_name_error PASSED                                                 [ 94%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_set_type_error PASSED                                                 [100%]

========================================================== 18 passed, 1 skipped in 0.33s ==========================================================
```

Figure 3.1.5: Running `pytest` with the new tests

I just had example inputs and what I expected as output. I also wanted the parser to ignore whitespace.

The decorator on line 69 just skips the test because the parser wasn't implemented yet.

When implementing the parser, I first had to tighten up validation to remove anomalies like `'A--1B'` being valid. I did this by factoring out the optional minus signs from being part of a number, to being optionally in front of a number. This eliminated this kind of repetition and made `'A--1B'` invalid, as it should be.

```
# fd80d8d3b0e975e92dcc7c10f1f0f1276879f408
# src/lintrans/_parse/matrices.py

32  def compile_valid_expression_pattern() -> Pattern[str]:
33      """Compile the single regular expression that will match a valid matrix expression."""
34      digit_no_zero = '[123456789]'
35      digits = '\\d+'
36      integer_no_zero = digit_no_zero + '(' + digits + ')?'
37      real_number = f'({integer_no_zero}(\\.{digits})?|0?\\.{digits})'
38
39      index_content = f'(-?{integer_no_zero}|T)'
40      index = f'(\\^\\{{{index_content}\\}}|\\^{index_content}|t)'
41      matrix_identifier = f'([A-Z]|rot\\(-?{real_number}\\))'
42      matrix = '(' + real_number + '?' + matrix_identifier + index + '?)'
43      expression = f'-?{matrix}+((\\+|-){matrix}+)*'
44
45      return re.compile(expression)
```

The code can be a bit hard to read with all the RegEx stuff, but the BNF illustrates these changes nicely.

Compare the old version:

```
# 39b918651f60bc72bc19d2018075b24a6fc3af17
# src/lintrans/_parse/matrices.py

29  def validate_matrix_expression(expression: str) -> bool:
...
36      Here is the schema for a valid expression given in a version of BNF:
...
38          expression        ::=  matrices { ( "+" | "-" ) matrices };
39          matrices          ::=  matrix { matrix };
40          matrix            ::=  [ real_number ] matrix_identifier [ index ];
41          matrix_identifier ::=  "A" .. "Z" | "rot(" real_number ")";
42          index             ::=  "^{" index_content "}" | "^" index_content | "t";
43          index_content     ::=  integer_not_zero | "T";
44
45          digit_no_zero     ::=  "1" | "2" | "3" | "4" | "5" | "6" | "7" | "8" | "9";
46          digit             ::=  "0" | digit_no_zero;
47          digits            ::=  digit | digits digit;
48          integer_not_zero  ::=  [ "-" ] digit_no_zero [ digits ];
49          real_number       ::=  ( integer_not_zero [ "." digits ] | [ "-" ] [ "0" ] "." digits );
```

to the new version:

```
# fd80d8d3b0e975e92dcc7c10f1f0f1276879f408
# src/lintrans/_parse/matrices.py

52  def validate_matrix_expression(expression: str) -> bool:
...
59      Here is the schema for a valid expression given in a version of BNF:
...
61          expression        ::=  [ "-" ] matrices { ( "+" | "-" ) matrices };
62          matrices          ::=  matrix { matrix };
63          matrix            ::=  [ real_number ] matrix_identifier [ index ];
64          matrix_identifier ::=  "A" .. "Z" | "rot(" [ "-" ] real_number ")";
65          index             ::=  "^{" index_content "}" | "^" index_content | "t";
66          index_content     ::=  [ "-" ] integer_not_zero | "T";
67
```

```
68          digit_no_zero     ::=  "1" | "2" | "3" | "4" | "5" | "6" | "7" | "8" | "9";
69          digit             ::=  "0" | digit_no_zero;
70          digits            ::=  digit | digits digit;
71          integer_not_zero  ::=  digit_no_zero [ digits ];
72          real_number       ::=  ( integer_not_zero [ "." digits ] | [ "0" ] "." digits );
```

Then once I'd fixed the validation, I could implement the parser itself.

```
# fd80d8d3b0e975e92dcc7c10f1f0f1276879f408
# src/lintrans/_parse/matrices.py

86  def parse_matrix_expression(expression: str) -> MatrixParseList:
87      """Parse the matrix expression and return a list of results.
88
89      The return value is a list of results. This results list contains lists of tuples.
90      The top list is the expressions that should be added together, and each sublist
91      is expressions that should be multiplied together. These expressions to be
92      multiplied are tuples, where each tuple is (multiplier, matrix identifier, index).
93      The multiplier can be any real number, the matrix identifier is either a named
94      matrix or a new rotation matrix declared with 'rot()', and the index is an
95      integer or 'T' for transpose.
96
97      :param str expression: The expression to be parsed
98      :returns MatrixParseTuple: A list of results
99      """
100     # Remove all whitespace
101     expression = re.sub(r'\s', '', expression)
102
103     # Check if it's valid
104     if not validate_matrix_expression(expression):
105         raise MatrixParseError('Invalid expression')
106
107     # Wrap all exponents and transposition powers with {}
108     expression = re.sub(r'(?<=\^)(-?\d+|T)(?=[^}]|$)', r'{\g<0>}', expression)
109
110     # Remove any standalone minuses
111     expression = re.sub(r'-(?=[A-Z])', '-1', expression)
112
113     # Replace subtractions with additions
114     expression = re.sub(r'-(?=\d+\.?\d*([A-Z]|rot))', '+-', expression)
115
116     # Get rid of a potential leading + introduced by the last step
117     expression = re.sub(r'^\+', '', expression)
118
119     return [
120         [
121             # The tuple returned by re.findall is (multiplier, matrix identifier, full index, stripped index),
122             # so we have to remove the full index, which contains the {}
123             (t[0], t[1], t[3])
124             for t in re.findall(r'(-?\d+\.?\d*)?([A-Z]|rot\(-?\d+\.?\d*\))(\^{(-?\d+|T)})?', group)
125         ]
126         # We just split the expression by '+' to have separate groups
127         for group in expression.split('+')
128     ]
```

It works similarly to the old `MatrixWrapper.parse_expression()` method in §3.1.2 but with a powerful list comprehension at the end. It splits the expression up into groups and then uses some RegEx magic to find all the matrices in these groups as a tuple.

This method passes all the unit tests, as expected.

My next step was then to rewrite the evaluation to use this new parser, like so:

```
# a453774bcdf824676461f9b9b441d7b94969ea55
# src/lintrans/matrices/wrapper.py

22  class MatrixWrapper:
```

```
...
147         def evaluate_expression(self, expression: str) -> MatrixType:
148             """Evaluate a given expression and return the matrix for that expression.
149 
150             Expressions are written with standard LaTeX notation for exponents. All whitespace is ignored.
151 
152             Here is documentation on syntax:
153                 A single matrix is written as a capital letter like 'A', or as 'rot(x)', where x is some angle in
                    ↪  degrees.
154                 Matrix A multiplied by matrix B is written as 'AB'
155                 Matrix A plus matrix B is written as 'A+B'
156                 Matrix A minus matrix B is written as 'A-B'
157                 Matrix A squared is written as 'A^2'
158                 Matrix A to the power of 10 is written as 'A^10' or 'A^{10}'
159                 The inverse of matrix A is written as 'A^-1' or 'A^{-1}'
160                 The transpose of matrix A is written as 'A^T' or 'At'
161                 Any matrix may be multiplied by a real constant, like '3A', or '1.2B'
162 
163             :param str expression: The expression to be parsed
164             :returns MatrixType: The matrix result of the expression
165 
166             :raises ValueError: If the expression is invalid
167             """
168             if not self.is_valid_expression(expression):
169                 raise ValueError('The expression is invalid')
170 
171             parsed_result = _parse.parse_matrix_expression(expression)
172             final_groups: list[list[MatrixType]] = []
173 
174             for group in parsed_result:
175                 f_group: list[MatrixType] = []
176 
177                 for matrix in group:
178                     if matrix[2] == 'T':
179                         m = self[matrix[1]]
180                         assert m is not None
181                         matrix_value = m.T
182                     else:
183                         matrix_value = np.linalg.matrix_power(self[matrix[1]],
184                                                               1 if (index := matrix[2]) == '' else int(index))
185 
186                     matrix_value *= 1 if (multiplier := matrix[0]) == '' else float(multiplier)
187                     f_group.append(matrix_value)
188 
189                 final_groups.append(f_group)
190 
191             return reduce(add, [reduce(matmul, group) for group in final_groups])
```

Here, we go through the list of tuples and evaluate the matrix represented by each tuple, putting this together in a list as we go. Then at the end, we simply reduce the sublists and then reduce these new matrices using a list comprehension in the `reduce()` call using `add` and `matmul` from the `operator` library. It's written in a functional programming style, and it passes all the previous tests.

3.2 Initial GUI

3.2.1 First basic GUI

The discrepancy in all the GUI code between `snake_case` and `camelCase` is because Qt5 was originally a C++ framework that was adapted into PyQt5 for Python. All the Qt API is in `camelCase`, but my Python code is in `snake_case`.

```
# 93ce763f7b993439fc0da89fad39456d8cc4b52c
# src/lintrans/gui/main_window.py

"""The module to provide the main window as a QMainWindow object."""

import sys

from PyQt5 import QtCore, QtGui, QtWidgets
from PyQt5.QtWidgets import QApplication, QHBoxLayout, QMainWindow, QVBoxLayout

from lintrans.matrices import MatrixWrapper


class LintransMainWindow(QMainWindow):
    """The class for the main window in the lintrans GUI."""

    def __init__(self):
        """Create the main window object, creating every widget in it."""
        super().__init__()

        self.matrix_wrapper = MatrixWrapper()

        self.setWindowTitle('Linear Transformations')
        self.setMinimumWidth(750)

        # === Create widgets

        # Left layout: the plot and input box

        # NOTE: This QGraphicsView is only temporary
        self.plot = QtWidgets.QGraphicsView(self)

        self.text_input_expression = QtWidgets.QLineEdit(self)
        self.text_input_expression.setPlaceholderText('Input matrix expression...')
        self.text_input_expression.textChanged.connect(self.update_render_buttons)

        # Right layout: all the buttons

        # Misc buttons

        self.button_create_polygon = QtWidgets.QPushButton(self)
        self.button_create_polygon.setText('Create polygon')
        # TODO: Implement create_polygon()
        # self.button_create_polygon.clicked.connect(self.create_polygon)
        self.button_create_polygon.setToolTip('Define a new polygon to view the transformation of')

        self.button_change_display_settings = QtWidgets.QPushButton(self)
        self.button_change_display_settings.setText('Change\ndisplay settings')
        # TODO: Implement change_display_settings()
        # self.button_change_display_settings.clicked.connect(self.change_display_settings)
        self.button_change_display_settings.setToolTip('Change which things are rendered on the plot')

        # Define new matrix buttons

        self.label_define_new_matrix = QtWidgets.QLabel(self)
        self.label_define_new_matrix.setText('Define a\nnew matrix')
        self.label_define_new_matrix.setAlignment(QtCore.Qt.AlignCenter)

        # TODO: Implement defining a new matrix visually, numerically, as a rotation, and as an expression

        self.button_define_visually = QtWidgets.QPushButton(self)
        self.button_define_visually.setText('Visually')
```

```
60              self.button_define_visually.setToolTip('Drag the basis vectors')
61
62              self.button_define_numerically = QtWidgets.QPushButton(self)
63              self.button_define_numerically.setText('Numerically')
64              self.button_define_numerically.setToolTip('Define a matrix just with numbers')
65
66              self.button_define_as_rotation = QtWidgets.QPushButton(self)
67              self.button_define_as_rotation.setText('As a rotation')
68              self.button_define_as_rotation.setToolTip('Define an angle to rotate by')
69
70              self.button_define_as_expression = QtWidgets.QPushButton(self)
71              self.button_define_as_expression.setText('As an expression')
72              self.button_define_as_expression.setToolTip('Define a matrix in terms of other matrices')
73
74              # Render buttons
75
76              self.button_render = QtWidgets.QPushButton(self)
77              self.button_render.setText('Render')
78              self.button_render.setEnabled(False)
79              self.button_render.clicked.connect(self.render_expression)
80              self.button_render.setToolTip('Render the expression<br><b>(Ctrl + Enter)</b>')
81
82              self.button_render_shortcut = QtWidgets.QShortcut(QtGui.QKeySequence('Ctrl+Return'), self)
83              self.button_render_shortcut.activated.connect(self.button_render.click)
84
85              self.button_animate = QtWidgets.QPushButton(self)
86              self.button_animate.setText('Animate')
87              self.button_animate.setEnabled(False)
88              self.button_animate.clicked.connect(self.animate_expression)
89              self.button_animate.setToolTip('Animate the expression<br><b>(Ctrl + Shift + Enter)</b>')
90
91              self.button_animate_shortcut = QtWidgets.QShortcut(QtGui.QKeySequence('Ctrl+Shift+Return'), self)
92              self.button_animate_shortcut.activated.connect(self.button_animate.click)
93
94              # === Arrange widgets
95
96              self.setContentsMargins(10, 10, 10, 10)
97
98              self.vlay_left = QVBoxLayout()
99              self.vlay_left.addWidget(self.plot)
100             self.vlay_left.addWidget(self.text_input_expression)
101
102             self.vlay_misc_buttons = QVBoxLayout()
103             self.vlay_misc_buttons.setSpacing(20)
104             self.vlay_misc_buttons.addWidget(self.button_create_polygon)
105             self.vlay_misc_buttons.addWidget(self.button_change_display_settings)
106
107             self.vlay_define_new_matrix = QVBoxLayout()
108             self.vlay_define_new_matrix.setSpacing(20)
109             self.vlay_define_new_matrix.addWidget(self.label_define_new_matrix)
110             self.vlay_define_new_matrix.addWidget(self.button_define_visually)
111             self.vlay_define_new_matrix.addWidget(self.button_define_numerically)
112             self.vlay_define_new_matrix.addWidget(self.button_define_as_rotation)
113             self.vlay_define_new_matrix.addWidget(self.button_define_as_expression)
114
115             self.vlay_render = QVBoxLayout()
116             self.vlay_render.setSpacing(20)
117             self.vlay_render.addWidget(self.button_animate)
118             self.vlay_render.addWidget(self.button_render)
119
120             self.vlay_right = QVBoxLayout()
121             self.vlay_right.setSpacing(50)
122             self.vlay_right.addLayout(self.vlay_misc_buttons)
123             self.vlay_right.addLayout(self.vlay_define_new_matrix)
124             self.vlay_right.addLayout(self.vlay_render)
125
126             self.hlay_all = QHBoxLayout()
127             self.hlay_all.setSpacing(15)
128             self.hlay_all.addLayout(self.vlay_left)
129             self.hlay_all.addLayout(self.vlay_right)
130
131             self.central_widget = QtWidgets.QWidget()
132             self.central_widget.setLayout(self.hlay_all)
```

```
133             self.setCentralWidget(self.central_widget)
134
135         def update_render_buttons(self) -> None:
136             """Enable or disable the render and animate buttons according to the validity of the matrix expression."""
137             valid = self.matrix_wrapper.is_valid_expression(self.text_input_expression.text())
138             self.button_render.setEnabled(valid)
139             self.button_animate.setEnabled(valid)
140
141         def render_expression(self) -> None:
142             """Render the expression in the input box, and then clear the box."""
143             # TODO: Render the expression
144             self.text_input_expression.setText('')
145
146         def animate_expression(self) -> None:
147             """Animate the expression in the input box, and then clear the box."""
148             # TODO: Animate the expression
149             self.text_input_expression.setText('')
150
151
152     def main() -> None:
153         """Run the GUI."""
154         app = QApplication(sys.argv)
155         window = LintransMainWindow()
156         window.show()
157         sys.exit(app.exec_())
158
159
160     if __name__ == '__main__':
161         main()
```

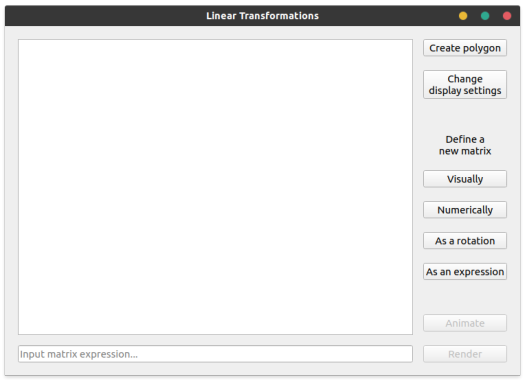


Figure 3.2.1: The first version of the GUI

A lot of the methods here don't have implementations yet, but they will. This version is just a very early prototype to get a rough draft of the GUI.

I create the widgets and layouts in the constructor as well as configuring all of them. The most important non-constructor method is `update_render_buttons()`. It gets called whenever the text in `text_input_expression` is changed. This happens because we connect it to the `textChanged` signal on line 32.

The big white box here will eventually be replaced with an actual viewport. This is just a prototype.

3.2.2 Numerical definition dialog

My next major addition was a dialog that would allow the user to define a matrix numerically.

```
# cedbd3ed126a1183f197c27adf6dabb4e5d301c7
# src/lintrans/gui/dialogs/define_new_matrix.py

1   """The module to provide dialogs for defining new matrices."""
2
3   from numpy import array
4   from PyQt5 import QtGui, QtWidgets
5   from PyQt5.QtWidgets import QDialog, QGridLayout, QHBoxLayout, QVBoxLayout
6
7   from lintrans.matrices import MatrixWrapper
8
9   ALPHABET_NO_I = 'ABCDEFGHJKLMNOPQRSTUVWXYZ'
10
11
12  def is_float(string: str) -> bool:
13      """Check if a string is a float."""
```

```
14          try:
15              float(string)
16              return True
17          except ValueError:
18              return False
19
20
21      class DefineNumericallyDialog(QDialog):
22          """The dialog class that allows the user to define a new matrix numerically."""
23
24          def __init__(self, matrix_wrapper: MatrixWrapper, *args, **kwargs):
25              """Create the dialog, but don't run it yet.
26
27              :param matrix_wrapper: The MatrixWrapper that this dialog will mutate
28              :type matrix_wrapper: MatrixWrapper
29              """
30              super().__init__(*args, **kwargs)
31
32              self.matrix_wrapper = matrix_wrapper
33              self.setWindowTitle('Define a matrix')
34
35              # === Create the widgets
36
37              self.button_confirm = QtWidgets.QPushButton(self)
38              self.button_confirm.setText('Confirm')
39              self.button_confirm.setEnabled(False)
40              self.button_confirm.clicked.connect(self.confirm_matrix)
41              self.button_confirm.setToolTip('Confirm this as the new matrix<br><b>(Ctrl + Enter)</b>')
42
43              QtWidgets.QShortcut(QtGui.QKeySequence('Ctrl+Return'), self).activated.connect(self.button_confirm.click)
44
45              self.button_cancel = QtWidgets.QPushButton(self)
46              self.button_cancel.setText('Cancel')
47              self.button_cancel.clicked.connect(self.close)
48              self.button_cancel.setToolTip('Cancel this definition<br><b>(Ctrl + Q)</b>')
49
50              QtWidgets.QShortcut(QtGui.QKeySequence('Ctrl+Q'), self).activated.connect(self.button_cancel.click)
51
52              self.element_tl = QtWidgets.QLineEdit(self)
53              self.element_tl.textChanged.connect(self.update_confirm_button)
54
55              self.element_tr = QtWidgets.QLineEdit(self)
56              self.element_tr.textChanged.connect(self.update_confirm_button)
57
58              self.element_bl = QtWidgets.QLineEdit(self)
59              self.element_bl.textChanged.connect(self.update_confirm_button)
60
61              self.element_br = QtWidgets.QLineEdit(self)
62              self.element_br.textChanged.connect(self.update_confirm_button)
63
64              self.matrix_elements = (self.element_tl, self.element_tr, self.element_bl, self.element_br)
65
66              self.letter_combo_box = QtWidgets.QComboBox(self)
67
68              # Everything except I, because that's the identity
69              for letter in ALPHABET_NO_I:
70                  self.letter_combo_box.addItem(letter)
71
72              self.letter_combo_box.activated.connect(self.load_matrix)
73
74              # === Arrange the widgets
75
76              self.setContentsMargins(10, 10, 10, 10)
77
78              self.grid_matrix = QGridLayout()
79              self.grid_matrix.setSpacing(20)
80              self.grid_matrix.addWidget(self.element_tl, 0, 0)
81              self.grid_matrix.addWidget(self.element_tr, 0, 1)
82              self.grid_matrix.addWidget(self.element_bl, 1, 0)
83              self.grid_matrix.addWidget(self.element_br, 1, 1)
84
85              self.hlay_buttons = QHBoxLayout()
86              self.hlay_buttons.setSpacing(20)
```

```
87              self.hlay_buttons.addWidget(self.button_cancel)
88              self.hlay_buttons.addWidget(self.button_confirm)
89
90              self.vlay_right = QVBoxLayout()
91              self.vlay_right.setSpacing(20)
92              self.vlay_right.addLayout(self.grid_matrix)
93              self.vlay_right.addLayout(self.hlay_buttons)
94
95              self.hlay_all = QHBoxLayout()
96              self.hlay_all.setSpacing(20)
97              self.hlay_all.addWidget(self.letter_combo_box)
98              self.hlay_all.addLayout(self.vlay_right)
99
100             self.setLayout(self.hlay_all)
101
102             # Finally, we load the default matrix A into the boxes
103             self.load_matrix(0)
104
105         def update_confirm_button(self) -> None:
106             """Enable the confirm button if there are numbers in every box."""
107             for elem in self.matrix_elements:
108                 if elem.text() == '' or not is_float(elem.text()):
109                     # If they're not all numbers, then we can't confirm it
110                     self.button_confirm.setEnabled(False)
111                     return
112
113             # If we didn't find anything invalid
114             self.button_confirm.setEnabled(True)
115
116         def load_matrix(self, index: int) -> None:
117             """If the selected matrix is defined, load it into the boxes."""
118             matrix = self.matrix_wrapper[ALPHABET_NO_I[index]]
119
120             if matrix is None:
121                 for elem in self.matrix_elements:
122                     elem.setText('')
123
124             else:
125                 self.element_tl.setText(str(matrix[0][0]))
126                 self.element_tr.setText(str(matrix[0][1]))
127                 self.element_bl.setText(str(matrix[1][0]))
128                 self.element_br.setText(str(matrix[1][1]))
129
130             self.update_confirm_button()
131
132         def confirm_matrix(self) -> None:
133             """Confirm the inputted matrix and assign it to the name."""
134             letter = self.letter_combo_box.currentText()
135             matrix = array([
136                 [float(self.element_tl.text()), float(self.element_tr.text())],
137                 [float(self.element_bl.text()), float(self.element_br.text())]
138             ])
139
140             self.matrix_wrapper[letter] = matrix
141             self.close()
```

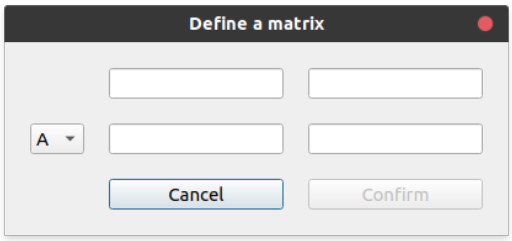


Figure 3.2.2: The first version of the numerical definition dialog

When I add more definition dialogs, I will factor out a superclass, but this is just a prototype to make sure it all works as intended.

Hopefully the methods are relatively self explanatory, but they're just utility methods to update the GUI when things are changed. We connect the `QLineEdit` widgets to the `update_confirm_button()` slot to make sure the confirm button is always up to date.

The `confirm_matrix()` method just updates the instance's matrix wrapper with the new matrix. We

pass a reference to the `LintransMainWindow` instance's matrix wrapper when we open the dialog, so we're just updating the referenced object directly.

In the `LintransMainWindow` class, we're just connecting a lambda slot to the button so that it opens the dialog, as seen here:

```
# cedbd3ed126a1183f197c27adf6dabb4e5d301c7
# src/lintrans/gui/main_window.py

12  class LintransMainWindow(QMainWindow):
...
15      def __init__(self):
...
66          self.button_define_numerically.clicked.connect(
67              lambda: DefineNumericallyDialog(self.matrix_wrapper, self).exec()
68          )
```

3.2.3 More definition dialogs

I then factored out the constructor into a `DefineDialog` superclass so that I could easily create other definition dialogs.

```
# 5d04fb7233a03d0cd8fa0768f6387c6678da9df3
# src/lintrans/gui/dialogs/define_new_matrix.py

22  class DefineDialog(QDialog):
23      """A superclass for definitions dialogs."""
24
25      def __init__(self, matrix_wrapper: MatrixWrapper, *args, **kwargs):
26          """Create the dialog, but don't run it yet.
27
28          :param matrix_wrapper: The MatrixWrapper that this dialog will mutate
29          :type matrix_wrapper: MatrixWrapper
30          """
31          super().__init__(*args, **kwargs)
32
33          self.matrix_wrapper = matrix_wrapper
34          self.setWindowTitle('Define a matrix')
35
36          # === Create the widgets
37
38          self.button_confirm = QtWidgets.QPushButton(self)
39          self.button_confirm.setText('Confirm')
40          self.button_confirm.setEnabled(False)
41          self.button_confirm.clicked.connect(self.confirm_matrix)
42          self.button_confirm.setToolTip('Confirm this as the new matrix<br><b>(Ctrl + Enter)</b>')
43          QShortcut(QKeySequence('Ctrl+Return'), self).activated.connect(self.button_confirm.click)
44
45          self.button_cancel = QtWidgets.QPushButton(self)
46          self.button_cancel.setText('Cancel')
47          self.button_cancel.clicked.connect(self.close)
48          self.button_cancel.setToolTip('Cancel this definition<br><b>(Ctrl + Q)</b>')
49          QShortcut(QKeySequence('Ctrl+Q'), self).activated.connect(self.button_cancel.click)
50
51          self.label_equals = QtWidgets.QLabel()
52          self.label_equals.setText('=')
53
54          self.letter_combo_box = QtWidgets.QComboBox(self)
55
56          # Everything except I, because that's the identity
57          for letter in ALPHABET_NO_I:
58              self.letter_combo_box.addItem(letter)
59
60          self.letter_combo_box.activated.connect(self.load_matrix)
```

This superclass just has a constructor that subclasses can use. When I added the `DefineAsARotationDialog`

class, I also moved the cancel and confirm buttons into the constructor and added abstract methods that all dialog subclasses must implement.

```python
# 0d534c35c6a4451e317d41a0d2b3ecb17827b45f
# src/lintrans/gui/dialogs/define_new_matrix.py

class DefineDialog(QDialog):
...
    def __init__(self, matrix_wrapper: MatrixWrapper, *args, **kwargs):
...
        # === Arrange the widgets

        self.setContentsMargins(10, 10, 10, 10)

        self.horizontal_spacer = QSpacerItem(50, 5, hPolicy=QSizePolicy.Expanding, vPolicy=QSizePolicy.Minimum)

        self.hlay_buttons = QHBoxLayout()
        self.hlay_buttons.setSpacing(20)
        self.hlay_buttons.addItem(self.horizontal_spacer)
        self.hlay_buttons.addWidget(self.button_cancel)
        self.hlay_buttons.addWidget(self.button_confirm)

    @property
    def selected_letter(self) -> str:
        """The letter currently selected in the combo box."""
        return self.letter_combo_box.currentText()

    @abc.abstractmethod
    def update_confirm_button(self) -> None:
        """Enable the confirm button if it should be enabled."""
        ...

    @abc.abstractmethod
    def confirm_matrix(self) -> None:
        """Confirm the inputted matrix and assign it.

        This should mutate self.matrix_wrapper and then call self.accept().
        """
        ...
```

I then added the class for the rotation definition dialog.

```python
# 0d534c35c6a4451e317d41a0d2b3ecb17827b45f
# src/lintrans/gui/dialogs/define_new_matrix.py

class DefineAsARotationDialog(DefineDialog):
    """The dialog that allows the user to define a new matrix as a rotation."""

    def __init__(self, matrix_wrapper: MatrixWrapper, *args, **kwargs):
        """Create the dialog, but don't run it yet."""
        super().__init__(matrix_wrapper, *args, **kwargs)

        # === Create the widgets

        self.label_equals.setText('= rot(')

        self.text_angle = QtWidgets.QLineEdit(self)
        self.text_angle.setPlaceholderText('angle')
        self.text_angle.textChanged.connect(self.update_confirm_button)

        self.label_close_paren = QtWidgets.QLabel(self)
        self.label_close_paren.setText(')')

        self.checkbox_radians = QtWidgets.QCheckBox(self)
        self.checkbox_radians.setText('Radians')

        # === Arrange the widgets

        self.hlay_checkbox_and_buttons = QHBoxLayout()
        self.hlay_checkbox_and_buttons.setSpacing(20)
```

```
207             self.hlay_checkbox_and_buttons.addWidget(self.checkbox_radians)
208             self.hlay_checkbox_and_buttons.addItem(self.horizontal_spacer)
209             self.hlay_checkbox_and_buttons.addLayout(self.hlay_buttons)
210
211             self.hlay_definition = QHBoxLayout()
212             self.hlay_definition.addWidget(self.letter_combo_box)
213             self.hlay_definition.addWidget(self.label_equals)
214             self.hlay_definition.addWidget(self.text_angle)
215             self.hlay_definition.addWidget(self.label_close_paren)
216
217             self.vlay_all = QVBoxLayout()
218             self.vlay_all.setSpacing(20)
219             self.vlay_all.addLayout(self.hlay_definition)
220             self.vlay_all.addLayout(self.hlay_checkbox_and_buttons)
221
222             self.setLayout(self.vlay_all)
223
224         def update_confirm_button(self) -> None:
225             """Enable the confirm button if there is a valid float in the angle box."""
226             self.button_confirm.setEnabled(is_float(self.text_angle.text()))
227
228         def confirm_matrix(self) -> None:
229             """Confirm the inputted matrix and assign it."""
230             self.matrix_wrapper[self.selected_letter] = create_rotation_matrix(
231                 float(self.text_angle.text()),
232                 degrees=not self.checkbox_radians.isChecked()
233             )
234             self.accept()
```

This dialog class just overrides the abstract methods of the superclass with its own implementations. This will be the pattern that all of the definition dialogs will follow.

It has a checkbox for radians, since this is supported in `create_rotation_matrix()`, but the textbox only supports numbers, so the user would have to calculate some multiple of π and paste in several decimal places. I expect people to only use degrees, because these are easier to use.

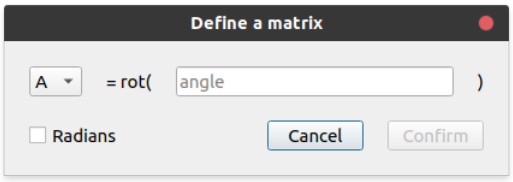


Figure 3.2.3: The first version of the rotation definition dialog

Additionally, I created a helper method in `LintransMainWindow`. Rather than connecting the `clicked` signal of the buttons to lambdas that instantiate an instance of the `DefineDialog` subclass and call `.exec()` on it, I now connect the `clicked` signal of the buttons to lambdas that call `self.dialog_define_matrix()` with the specific subclass.

```
# 6269e04d453df7be2d2f9c7ee176e83406ccc139
# src/lintrans/gui/main_window.py

17  class LintransMainWindow(QMainWindow):
...
170     def dialog_define_matrix(self, dialog_class: Type[DefineDialog]) -> None:
171         """Open a generic definition dialog to define a new matrix.
172
173         The class for the desired dialog is passed as an argument. We create an
174         instance of this class and the dialog is opened asynchronously and modally
175         (meaning it blocks interaction with the main window) with the proper method
176         connected to the ``dialog.finished`` slot.
177
178         .. note::
179            ``dialog_class`` must subclass :class:`lintrans.gui.dialogs.define_new_matrix.DefineDialog`.
180
181         :param dialog_class: The dialog class to instantiate
182         :type dialog_class: Type[lintrans.gui.dialogs.define_new_matrix.DefineDialog]
183         """
184         # We create a dialog with a deepcopy of the current matrix_wrapper
185         # This avoids the dialog mutating this one
```

```
186             dialog = dialog_class(deepcopy(self.matrix_wrapper), self)
187
188             # .open() is asynchronous and doesn't spawn a new event loop, but the dialog is still modal (blocking)
189             dialog.open()
190
191             # So we have to use the finished slot to call a method when the user accepts the dialog
192             # If the user rejects the dialog, this matrix_wrapper will be the same as the current one, because we copied
                ↪  it
193             # So we don't care, we just assign the wrapper anyway
194             dialog.finished.connect(lambda: self._assign_matrix_wrapper(dialog.matrix_wrapper))
195
196         def _assign_matrix_wrapper(self, matrix_wrapper: MatrixWrapper) -> None:
197             """Assign a new value to self.matrix_wrapper.
198
199             This is a little utility function that only exists because a lambda
200             callback can't directly assign a value to a class attribute.
201
202             :param matrix_wrapper: The new value of the matrix wrapper to assign
203             :type matrix_wrapper: MatrixWrapper
204             """
205             self.matrix_wrapper = matrix_wrapper
```

I also then implemented a simple `DefineAsAnExpressionDialog`, which evaluates a given expression in the current `MatrixWrapper` context and assigns the result to the given matrix name.

```
# d5f930e15c3c8798d4990486532da46e926a6cb9
# src/lintrans/gui/dialogs/define_new_matrix.py

241 class DefineAsAnExpressionDialog(DefineDialog):
242     """The dialog that allows the user to define a matrix as an expression."""
243
244     def __init__(self, matrix_wrapper: MatrixWrapper, *args, **kwargs):
245         """Create the dialog, but don't run it yet."""
246         super().__init__(matrix_wrapper, *args, **kwargs)
247
248         self.setMinimumWidth(450)
249
250         # === Create the widgets
251
252         self.text_box_expression = QtWidgets.QLineEdit(self)
253         self.text_box_expression.setPlaceholderText('Enter matrix expression...')
254         self.text_box_expression.textChanged.connect(self.update_confirm_button)
255
256         # === Arrange the widgets
257
258         self.hlay_definition.addWidget(self.text_box_expression)
259
260         self.vlay_all = QVBoxLayout()
261         self.vlay_all.setSpacing(20)
262         self.vlay_all.addLayout(self.hlay_definition)
263         self.vlay_all.addLayout(self.hlay_buttons)
264
265         self.setLayout(self.vlay_all)
266
267     def update_confirm_button(self) -> None:
268         """Enable the confirm button if the expression is valid."""
269         self.button_confirm.setEnabled(
270             self.matrix_wrapper.is_valid_expression(self.text_box_expression.text())
271         )
272
273     def confirm_matrix(self) -> None:
274         """Evaluate the matrix expression and assign its value to the chosen matrix."""
275         self.matrix_wrapper[self.selected_letter] = \
276             self.matrix_wrapper.evaluate_expression(self.text_box_expression.text())
277         self.accept()
```

My next dialog that I wanted to implement was a visual definition dialog, which would allow the user to drag around the basis vectors to define a transformation. However, I would first need to create the `lintrans.gui.plots` package to allow for actually visualizing matrices and transformations.

3.3 Visualizing matrices

3.3.1 Asking strangers on the internet for help

After creating most of the GUI skeleton, I wanted to build the viewport. Unfortunately, I had no idea what I was doing.

While looking through the PyQt5 docs, I found a pretty comprehensive explanation of the Qt5 'Graphics View Framework'[37], which seemed pretty good, but not really what I was looking for. I wanted a way to easily draw lots of straight, parallel lines. This framework seemed more focussed on manipulating objects on a canvas, almost like sprites. I knew of a different Python library called `matplotlib`, which has various backends available. I learned that it could be embedded in a standard PyQt5 GUI, so I started doing some research.

I didn't get very far with `matplotlib`. I hadn't used it much before and it's designed for visualizing data. It can draw manually defined straight lines on a canvas, but that's not what it's designed for and it's not very good at it. Thankfully, my horrific `matplotlib` code has been lost to time. I used the `Qt5Agg` backend from `matplotlib` to create a custom PyQt5 widget for the GUI and I could graph randomly generated data with it after following a tutorial[33].

I realised that I wasn't going to get very far with `matplotlib`, but I didn't know what else to do. I couldn't find any relevant examples on the internet, so I decided to post a question on a forum myself. I'd had experience with StackOverflow and its unfriendly community before, so I decided to ask the `r/learnpython` subreddit[4].

I only got one response, but it was incredibly helpful. The person told me that if I couldn't find an easy way to do what I wanted, I could write a custom PyQt5 widget. I knew this was possible with a class that just inherited from `QWidget`, but had no idea how to actually make something useful. Thankfully, this person provided a link to a GitLab repository of theirs, where they had multiple examples of custom widgets with PyQt5[5].

When looking through this repo, I found out how to draw on a widget like a simple canvas. All I have to do is override the `paintEvent()` method and use a `QPainter` object to draw on the widget. I used this knowledge to start creating the actual viewport for the GUI, starting with the background axes.

3.3.2 Creating the plots package

Initially, the `lintrans.gui.plots` package just has some classes for widgets. `TransformationPlotWidget` acts as a base class and then `ViewTransformationWidget` acts as a wrapper. I will expand this class in the future.

```
# 4af63072b383dc9cef9adbb8900323aa007e7f26
# src/lintrans/gui/plots/plot_widget.py

"""This module provides the basic classes for plotting transformations."""

from __future__ import annotations

from PyQt5.QtCore import Qt
from PyQt5.QtGui import QColor, QPainter, QPaintEvent, QPen
from PyQt5.QtWidgets import QWidget


class TransformationPlotWidget(QWidget):
    """An abstract superclass for plot widgets.

    This class provides a background (untransformed) plane, and all the backend
    details for a Qt application, but does not provide useful functionality. To
    be useful, this class must be subclassed and behaviour must be implemented
    by the subclass.
```

```
17
18          .. warning:: This class should never be directly instantiated, only subclassed.
19
20          .. note::
21             I would make this class have ``metaclass=abc.ABCMeta``, but I can't because it subclasses ``QWidget``,
22             and a every superclass of a class must have the same metaclass, and ``QWidget`` is not an abstract class.
23          """
24
25          def __init__(self, *args, **kwargs):
26              """Create the widget, passing ``*args`` and ``**kwargs`` to the superclass constructor (``QWidget``)."""
27              super().__init__(*args, **kwargs)
28
29              self.setAutoFillBackground(True)
30
31              # Set the background to white
32              palette = self.palette()
33              palette.setColor(self.backgroundRole(), Qt.white)
34              self.setPalette(palette)
35
36              # Set the gird colour to grey and the axes colour to black
37              self.grid_colour = QColor(128, 128, 128)
38              self.axes_colour = QColor(0, 0, 0)
39
40              self.grid_spacing: int = 50
41              self.line_width: float = 0.4
42
43          @property
44          def w(self) -> int:
45              """Return the width of the widget."""
46              return self.size().width()
47
48          @property
49          def h(self) -> int:
50              """Return the height of the widget."""
51              return self.size().height()
52
53          def paintEvent(self, e: QPaintEvent):
54              """Handle a ``QPaintEvent`` by drawing the widget."""
55              qp = QPainter()
56              qp.begin(self)
57              self.draw_widget(qp)
58              qp.end()
59
60          def draw_widget(self, qp: QPainter):
61              """Draw the grid and axes in the widget."""
62              qp.setRenderHint(QPainter.Antialiasing)
63              qp.setBrush(Qt.NoBrush)
64
65              # Draw the grid
66              qp.setPen(QPen(self.grid_colour, self.line_width))
67
68              # We draw the background grid, centered in the middle
69              # We deliberately exclude the axes - these are drawn separately
70              for x in range(self.w // 2 + self.grid_spacing, self.w, self.grid_spacing):
71                  qp.drawLine(x, 0, x, self.h)
72                  qp.drawLine(self.w - x, 0, self.w - x, self.h)
73
74              for y in range(self.h // 2 + self.grid_spacing, self.h, self.grid_spacing):
75                  qp.drawLine(0, y, self.w, y)
76                  qp.drawLine(0, self.h - y, self.w, self.h - y)
77
78              # Now draw the axes
79              qp.setPen(QPen(self.axes_colour, self.line_width))
80              qp.drawLine(self.w // 2, 0, self.w // 2, self.h)
81              qp.drawLine(0, self.h // 2, self.w, self.h // 2)
82
83
84      class ViewTransformationWidget(TransformationPlotWidget):
85          """This class is used to visualise matrices as transformations."""
86
87          def __init__(self, *args, **kwargs):
88              """Create the widget, passing ``*args`` and ``**kwargs`` to the superclass constructor."""
89              super().__init__(*args, **kwargs)
```

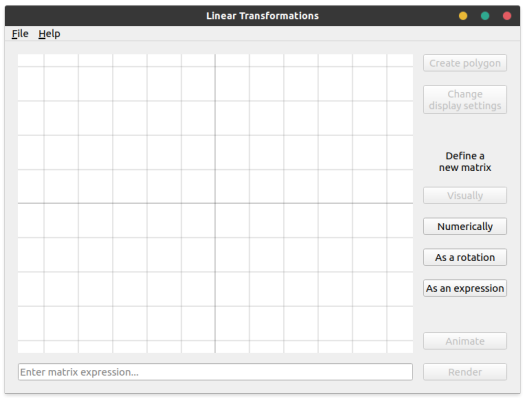


Figure 3.3.1: The GUI with background axes

The meat of this class is the `draw_widget()` method. Right now, this method only draws the background axes. My next step is to implement basis vector attributes and draw them in `draw_widget()`. After changing the the `plot` attribute in `LintransMainWindow` to an instance of `ViewTransformationWidget`, the plot was visible in the GUI.

I then refactored the code slightly to rename `draw_widget()` to `draw_background()` and then call it from the `paintEvent()` method in `ViewTransformationWidget`.

3.3.3 Implementing basis vectors

My first step in implementing basis vectors was to add some utility methods to convert between coordinate systems. The matrices are using Cartesian coordinates with $(0, 0)$ in the middle, positive x going to the right, and positive y going up. However, Qt5 is using standard computer graphics coordinates, with $(0, 0)$ in the top left, positive x going to the right, and positive y going down. I needed a way to convert Cartesian 'grid' coordinates to Qt5 'canvas' coordinates, so I wrote some little utility methods.

```
# 1fa7e1c61d61cb6aeff773b9698541f82fee39ea
# src/lintrans/gui/plots/plot_widget.py

class TransformationPlotWidget(QWidget):
...
    @property
    def origin(self) -> tuple[int, int]:
        """Return the canvas coords of the origin."""
        return self.width() // 2, self.height() // 2

    def trans_x(self, x: float) -> int:
        """Transform an x coordinate from grid coords to canvas coords."""
        return int(self.origin[0] + x * self.grid_spacing)

    def trans_y(self, y: float) -> int:
        """Transform a y coordinate from grid coords to canvas coords."""
        return int(self.origin[1] - y * self.grid_spacing)

    def trans_coords(self, x: float, y: float) -> tuple[int, int]:
        """Transform a coordinate in grid coords to canvas coords."""
        return self.trans_x(x), self.trans_y(y)
```

Once I had a way to convert coordinates, I could add the basis vectors themselves. I did this by creating attributes for the points in the constructor and creating a `transform_by_matrix()` method to change these point attributes accordingly.

```
# 37e7c208a33d7cbbc8e0bb6c94cd889e2918c605
# src/lintrans/gui/plots/plot_widget.py

class ViewTransformationWidget(TransformationPlotWidget):
    """This class is used to visualise matrices as transformations."""

    def __init__(self, *args, **kwargs):
        """Create the widget, passing ``*args`` and ``**kwargs`` to the superclass constructor."""
        super().__init__(*args, **kwargs)

        self.point_i: tuple[float, float] = (1., 0.)
        self.point_j: tuple[float, float] = (0., 1.)
```

```
101
102             self.colour_i = QColor(37, 244, 15)
103             self.colour_j = QColor(8, 8, 216)
104
105             self.width_vector_line = 1
106             self.width_transformed_grid = 0.6
107
108         def transform_by_matrix(self, matrix: MatrixType) -> None:
109             """Transform the plane by the given matrix."""
110             self.point_i = (matrix[0][0], matrix[1][0])
111             self.point_j = (matrix[0][1], matrix[1][1])
112             self.update()
```

I also created a `draw_transformed_grid()` method which gets called in `paintEvent()`.

```
# 37e7c208a33d7cbbc8e0bb6c94cd889e2918c605
# src/lintrans/gui/plots/plot_widget.py

92  class ViewTransformationWidget(TransformationPlotWidget):
...
122         def draw_transformed_grid(self, painter: QPainter) -> None:
123             """Draw the transformed version of the grid, given by the unit vectors."""
124             # Draw the unit vectors
125             painter.setPen(QPen(self.colour_i, self.width_vector_line))
126             painter.drawLine(*self.origin, *self.trans_coords(*self.point_i))
127             painter.setPen(QPen(self.colour_j, self.width_vector_line))
128             painter.drawLine(*self.origin, *self.trans_coords(*self.point_j))
```

I then changed the `render_expression()` method in `LintransMainWindow` to call this new `transform_by_matrix()` method.

```
# 37e7c208a33d7cbbc8e0bb6c94cd889e2918c605
# src/lintrans/gui/main_window.py

19  class LintransMainWindow(QMainWindow):
...
229         def render_expression(self) -> None:
230             """Render the expression in the input box, and then clear the box."""
231             self.plot.transform_by_matrix(
232                 self.matrix_wrapper.evaluate_expression(
233                     self.lineedit_expression_box.text()
234                 )
235             )
```

Testing this new code shows that it works well.

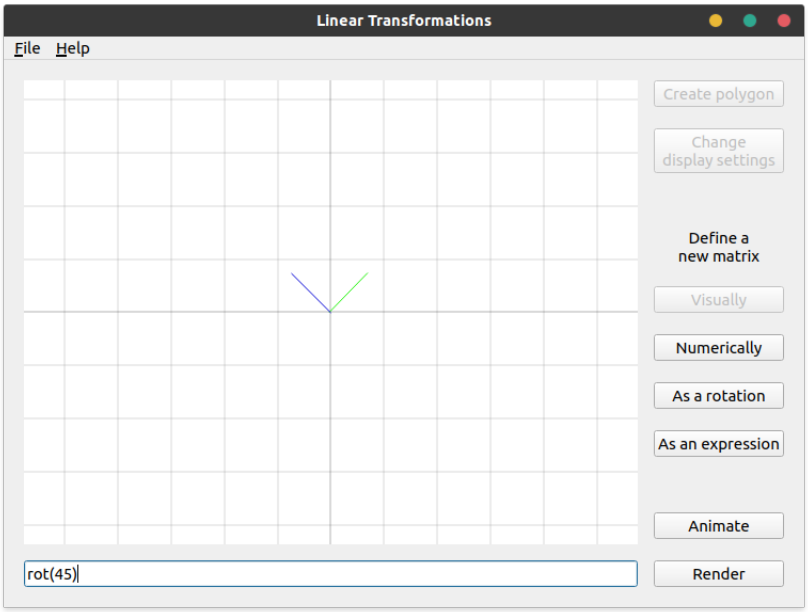


Figure 3.3.2: Basis vectors drawn for a 45° rotation

3.3.4 Drawing the transformed grid

After drawing the basis vectors, I wanted to draw the transformed version of the grid. I first created a `grid_corner()` utility method to return the grid coordinates of the top right corner of the canvas. This allows me to find the bounding box in which to draw the grid lines.

```
# 2ade98ac28d1c3f6691e4afa819142a3ab8e9fd9
# src/lintrans/gui/plots/plot_widget.py

14  class TransformationPlotWidget(QWidget):
...
64      def grid_corner(self) -> tuple[float, float]:
65          """Return the grid coords of the top right corner."""
66          return self.width() / (2 * self.grid_spacing), self.height() / (2 * self.grid_spacing)
```

I then created a `draw_parallel_lines()` method that would fill the bounding box with a set of lines parallel to a given vector with spacing defined by the intersection with a given point.

```
# 2ade98ac28d1c3f6691e4afa819142a3ab8e9fd9
# src/lintrans/gui/plots/plot_widget.py

96  class ViewTransformationWidget(TransformationPlotWidget):
...
126     def draw_parallel_lines(self, painter: QPainter, vector: tuple[float, float], point: tuple[float, float]) ->
        ↪ None:
127         """Draw a set of grid lines parallel to ``vector`` intersecting ``point``."""
128         max_x, max_y = self.grid_corner()
129         vector_x, vector_y = vector
130         point_x, point_y = point
131
132         if vector_x == 0:
133             painter.drawLine(self.trans_x(0), 0, self.trans_x(0), self.height())
134
135             for i in range(int(max_x / point_x)):
136                 painter.drawLine(
137                     self.trans_x((i + 1) * point_x),
138                     0,
139                     self.trans_x((i + 1) * point_x),
```

```
140                     self.height()
141                 )
142                 painter.drawLine(
143                     self.trans_x(-1 * (i + 1) * point_x),
144                     0,
145                     self.trans_x(-1 * (i + 1) * point_x),
146                     self.height()
147                 )
148 
149         elif vector_y == 0:
150             painter.drawLine(0, self.trans_y(0), self.width(), self.trans_y(0))
151 
152             for i in range(int(max_y / point_y)):
153                 painter.drawLine(
154                     0,
155                     self.trans_y((i + 1) * point_y),
156                     self.width(),
157                     self.trans_y((i + 1) * point_y)
158                 )
159                 painter.drawLine(
160                     0,
161                     self.trans_y(-1 * (i + 1) * point_y),
162                     self.width(),
163                     self.trans_y(-1 * (i + 1) * point_y)
164                 )
```

I then called this method from `draw_transformed_grid()`.

```
# 2ade98ac28d1c3f6691e4afa819142a3ab8e9fd9
# src/lintrans/gui/plots/plot_widget.py

96  class ViewTransformationWidget(TransformationPlotWidget):
...
166     def draw_transformed_grid(self, painter: QPainter) -> None:
167         """Draw the transformed version of the grid, given by the unit vectors."""
168         # Draw the unit vectors
169         painter.setPen(QPen(self.colour_i, self.width_vector_line))
170         painter.drawLine(*self.origin, *self.trans_coords(*self.point_i))
171         painter.setPen(QPen(self.colour_j, self.width_vector_line))
172         painter.drawLine(*self.origin, *self.trans_coords(*self.point_j))
173 
174         # Draw all the parallel lines
175         painter.setPen(QPen(self.colour_i, self.width_transformed_grid))
176         self.draw_parallel_lines(painter, self.point_i, self.point_j)
177         painter.setPen(QPen(self.colour_j, self.width_transformed_grid))
178         self.draw_parallel_lines(painter, self.point_j, self.point_i)
```

This worked quite well when the matrix involved no rotation, as seen on the right, but this didn't work with rotation. When trying `'rot(45)'` for example, it looked the same as in Figure 3.3.2.

Also, the vectors aren't particularly clear. They'd be much better with arrowheads on their tips, but this is just a prototype. The arrowheads will come later.

My next step was to make the transformed grid lines work with rotations.

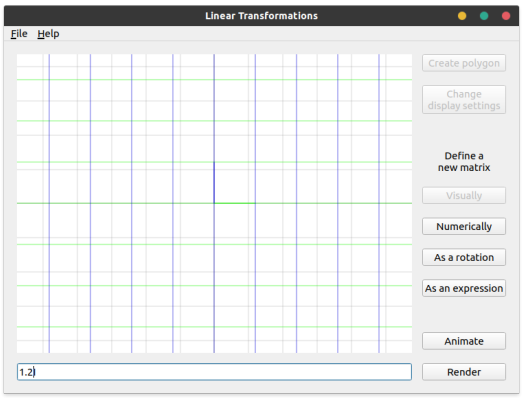


Figure 3.3.3: Parallel lines being drawn for matrix 1.2**I**

```
# 7dfe1e24729562501e2fd88a839dca6b653a3375
# src/lintrans/gui/plots/plot_widget.py
```

```
96  class ViewTransformationWidget(TransformationPlotWidget):
...
126     def draw_parallel_lines(self, painter: QPainter, vector: tuple[float, float], point: tuple[float, float]) ->
        ↪ None:
127         """Draw a set of grid lines parallel to ``vector`` intersecting ``point``."""
128         max_x, max_y = self.grid_corner()
129         vector_x, vector_y = vector
130         point_x, point_y = point
131
132         print(max_x, max_y, vector_x, vector_y, point_x, point_y)
133
134         # We want to use y = mx + c but m = y / x and if either of those are 0, then this
135         # equation is harder to work with, so we deal with these edge cases first
136         if abs(vector_x) < 1e-12 and abs(vector_y) < 1e-12:
137             # If both components of the vector are practically 0, then we can't render any grid lines
138             return
139
140         elif abs(vector_x) < 1e-12:
141             painter.drawLine(self.trans_x(0), 0, self.trans_x(0), self.height())
142
143             for i in range(abs(int(max_x / point_x))):
144                 painter.drawLine(
145                     self.trans_x((i + 1) * point_x),
146                     0,
147                     self.trans_x((i + 1) * point_x),
148                     self.height()
149                 )
150                 painter.drawLine(
151                     self.trans_x(-1 * (i + 1) * point_x),
152                     0,
153                     self.trans_x(-1 * (i + 1) * point_x),
154                     self.height()
155                 )
156
157         elif abs(vector_y) < 1e-12:
158             painter.drawLine(0, self.trans_y(0), self.width(), self.trans_y(0))
159
160             for i in range(abs(int(max_y / point_y))):
161                 painter.drawLine(
162                     0,
163                     self.trans_y((i + 1) * point_y),
164                     self.width(),
165                     self.trans_y((i + 1) * point_y)
166                 )
167                 painter.drawLine(
168                     0,
169                     self.trans_y(-1 * (i + 1) * point_y),
170                     self.width(),
171                     self.trans_y(-1 * (i + 1) * point_y)
172                 )
173
174         else:  # If the line is not horizontal or vertical, then we can use y = mx + c
175             m = vector_y / vector_x
176             c = point_y - m * point_x
177
178             # For c = 0
179             painter.drawLine(
180                 *self.trans_coords(
181                     -1 * max_x,
182                     m * -1 * max_x
183                 ),
184                 *self.trans_coords(
185                     max_x,
186                     m * max_x
187                 )
188             )
189
190             # Count up how many multiples of c we can have without wasting time rendering lines off screen
191             multiples_of_c: int = 0
192             ii: int = 1
193             while True:
194                 y1 = m * max_x + ii * c
```

```
                y2 = -1 * m * max_x + ii * c

                if y1 < max_y or y2 < max_y:
                    multiples_of_c += 1
                    ii += 1

                else:
                    break

            # Once we know how many lines we can draw, we just draw them all
            for i in range(1, multiples_of_c + 1):
                painter.drawLine(
                    *self.trans_coords(
                        -1 * max_x,
                        m * -1 * max_x + i * c
                    ),
                    *self.trans_coords(
                        max_x,
                        m * max_x + i * c
                    )
                )
                painter.drawLine(
                    *self.trans_coords(
                        -1 * max_x,
                        m * -1 * max_x - i * c
                    ),
                    *self.trans_coords(
                        max_x,
                        m * max_x - i * c
                    )
                )
```

This code checks if x or y is zero[10] and if they're not, then we have to use the standard straight line equation $y = mx + c$ to create parallel lines. We find our value of m and then iterate through all the values of c that keep the line within the bounding box.

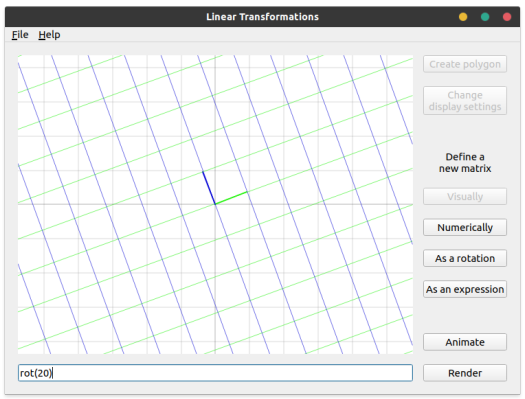


Figure 3.3.4: An example of a 20° rotation

There are some serious logical errors in this code. It works fine for things like `'3rot(45)'` or `'0.5rot(20)'`, but something like `'rot(115)'` will leave the program hanging indefinitely.

In fact, this code only works for rotations between 0° and 90°, and will hang forever when given a matrix like $\left(\begin{smallmatrix}12 & 4\\ -2 & 3\end{smallmatrix}\right)$, because it's just not very good.

I will fix these issues in the future, but it works somewhat decently, so I decided to do animation next, because that sounded more fun.

3.3.5 Implementing animation

Now that I had a very crude renderer, I could create a method to animate a matrix. Eventually I want to be able to apply a given matrix to the currently rendered scene and animate between them. However, I wanted to start simple by animating from the identity to the given matrix.

```
# 829a130af5aee9819bf0269c03ecfb20bec1a108
# src/lintrans/gui/main_window.py

class LintransMainWindow(QMainWindow):
```

[10] We actually check if they're less than 10^{-12} to allow for floating point errors

```
...
238         def animate_expression(self) -> None:
239             """Animate the expression in the input box, and then clear the box."""
240             self.button_render.setEnabled(False)
241             self.button_animate.setEnabled(False)
242 
243             matrix = self.matrix_wrapper.evaluate_expression(self.lineedit_expression_box.text())
244             matrix_move = matrix - self.matrix_wrapper['I']
245             steps: int = 100
246 
247             for i in range(0, steps + 1):
248                 self.plot.visualize_matrix_transformation(
249                     self.matrix_wrapper['I'] + (i / steps) * matrix_move
250                 )
251 
252                 self.update()
253                 self.repaint()
254 
255                 time.sleep(0.01)
256 
257             self.button_render.setEnabled(False)
258             self.button_animate.setEnabled(False)
```

This code creates the `matrix_move` variable and adds scaled versions of it to the identity matrix and renders that each frame. It's simple, but it works well for this simple use case. Unfortunately, it's very hard to show off an animation in a PDF, since all these images are static. The git commit hashes are included in the code snippets if you want to clone the repo[3], checkout this commit, and run it yourself if you want.

3.3.6 Preserving determinants

Ignoring the obvious flaw with not being able to render transformations with a more than 90° rotation, the animations don't respect determinants. When rotating 90°, the determinant changes during the animation, even though we're going from a determinant 1 matrix (the identity) to another determinant 1 matrix. This is because we're just moving each vector to its new position in a straight line. I want to animate in a way that smoothly transitions the determinant.

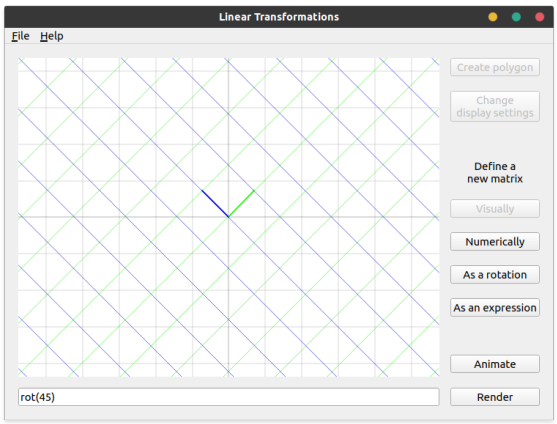


Figure 3.3.5: What we would expect halfway through a 90° rotation

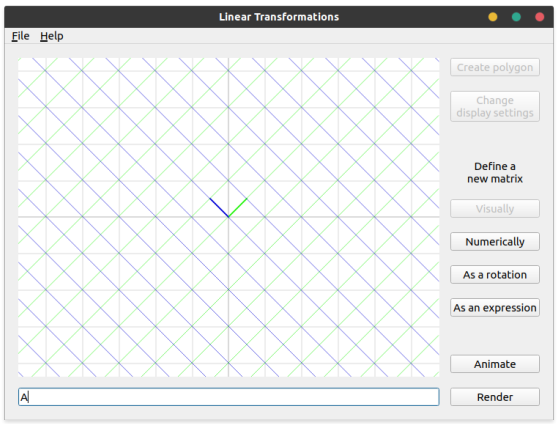


Figure 3.3.6: What we actually get halfway through a 90° rotation

In order to smoothly animate the determinant, I had to do some maths. I first defined the matrix $\mathbf{A}$ to be equivalent to the `matrix_move` variable from before - the target matrix minus the identity, scaled by the proportion. I then wanted to normalize $\mathbf{A}$ so that it had a determinant of 1 so that I could scale it up with the `proportion` variable through the animation.

I think I first tried just multiplying $\mathbf{A}$ by $\frac{1}{\det(\mathbf{A})}$ but that didn't work, so I googled it. I found a

post[29] on ResearchGate about the topic, and thanks to a very helpful comment from Jeffrey L Stuart, I learned that for a 2×2 matrix $\mathbf{A}$ and a scalar c, $\det(c\mathbf{A}) = c^2 \det(\mathbf{A})$.

I wanted a c such that $\det(c\mathbf{A}) = 1$. Therefore $c = \dfrac{1}{\sqrt{|\det(\mathbf{A})|}}$. I then defined matrix $\mathbf{B}$ to be $c\mathbf{A}$.

Then I wanted to scale this normalized matrix $\mathbf{B}$ to have the same determinant as the target matrix $\mathbf{T}$ using some scalar d. We know that $\det(d\mathbf{B}) = d^2 \det(\mathbf{B}) = \det(\mathbf{T})$. We can just rearrange to find d and get $d = \sqrt{\left|\dfrac{\det(\mathbf{T})}{\det(\mathbf{B})}\right|}$. But $\mathbf{B}$ is defined so that $\det(\mathbf{B}) = 1$, so we can get $d = \sqrt{|\det(\mathbf{T})|}$.

However, we want to scale this over time with our `proportion` variable p, so our final scalar $s = 1 + p\left(\sqrt{|\det(\mathbf{T})|} - 1\right)$. We define a matrix $\mathbf{C} = s\mathbf{B}$ and render $\mathbf{C}$ each frame. When in code form, this is the following:

```
# 6ff49450d8438ea2b2e7d2a97125dc518e648bc5
# src/lintrans/gui/main_window.py

22  class LintransMainWindow(QMainWindow):
...
240     def animate_expression(self) -> None:
...
245         # Get the target matrix and it's determinant
246         matrix_target = self.matrix_wrapper.evaluate_expression(self.lineedit_expression_box.text())
247         det_target = linalg.det(matrix_target)
248
249         identity = self.matrix_wrapper['I']
250         steps: int = 100
251
252         for i in range(0, steps + 1):
253             # This proportion is how far we are through the loop
254             proportion = i / steps
255
256             # matrix_a is the identity plus some part of the target, scaled by the proportion
257             # If we just used matrix_a, then things would animate, but the determinants would be weird
258             matrix_a = identity + proportion * (matrix_target - identity)
259
260             # So to fix the determinant problem, we get the determinant of matrix_a and use it to normalise
261             det_a = linalg.det(matrix_a)
262
263             # For a 2x2 matrix A and a scalar c, we know that det(cA) = c^2 det(A)
264             # We want B = cA such that det(B) = 1, so then we can scale it with the animation
265             # So we get c^2 det(A) = 1 => c = sqrt(1 / abs(det(A)))
266             # Then we scale A down to get a determinant of 1, and call that matrix_b
267             if det_a == 0:
268                 c = 0
269             else:
270                 c = np.sqrt(1 / abs(det_a))
271
272             matrix_b = c * matrix_a
273
274             # matrix_c is the final matrix that we transform by
275             # It's B, but we scale it up over time to have the target determinant
276
277             # We want some C = dB such that det(C) is some target determinant T
278             # det(dB) = d^2 det(B) = T => d = sqrt(abs(T / det(B))
279             # But we defined B to have det 1, so we can ignore it there
280
281             # We're also subtracting 1 and multiplying by the proportion and then adding one
282             # This just scales the determinant along with the animation
283             scalar = 1 + proportion * (np.sqrt(abs(det_target)) - 1)
284
285             matrix_c = scalar * matrix_b
286
287             self.plot.visualize_matrix_transformation(matrix_c)
288
289             self.repaint()
290             time.sleep(0.01)
```

Unfortunately, the system I use to render matrices is still quite bad at its job. This makes it hard to test properly. But, transformations like `'2rot(90)'` work exactly as expected, which is very good.

3.4 Improving the GUI

3.4.1 Fixing rendering

Now that I had the basics of matrix visualization sorted, I wanted to make the GUI and UX better. My first step was overhauling the rendering code to make it actually work with rotations of more than 90°.

I narrowed down the issue with PyCharm's debugger and found that the loop in `VectorGridPlot.draw_parallel_lines()` was looping forever if it tried to doing anything outside of the top right quadrant. To fix this, I decided to instead delegate this task of drawing a set of oblique lines to a separate method, and work on that instead.

```
# cf05e09e5ebb6ea7a96db8660d0d8de6b946490a
# src/lintrans/gui/plots/classes.py

118 class VectorGridPlot(BackgroundPlot):
...
150     def draw_parallel_lines(self, painter: QPainter, vector: tuple[float, float], point: tuple[float, float]) ->
        ↪ None:
...
203         else:  # If the line is not horizontal or vertical, then we can use y = mx + c
204             m = vector_y / vector_x
205             c = point_y - m * point_x
206
207             # For c = 0
208             painter.drawLine(
209                 *self.trans_coords(
210                     -1 * max_x,
211                     m * -1 * max_x
212                 ),
213                 *self.trans_coords(
214                     max_x,
215                     m * max_x
216                 )
217             )
218
219             # We keep looping and increasing the multiple of c until we stop drawing lines on the canvas
220             multiple_of_c = 1
221             while self.draw_pair_of_oblique_lines(painter, m, multiple_of_c * c):
222                 multiple_of_c += 1
```

This separation of functionality made designing and debugging this part of the solution much easier. The `draw_pair_of_oblique_lines()` method looked like this:

```
# cf05e09e5ebb6ea7a96db8660d0d8de6b946490a
# src/lintrans/gui/plots/classes.py

118 class VectorGridPlot(BackgroundPlot):
...
224     def draw_pair_of_oblique_lines(self, painter: QPainter, m: float, c: float) -> bool:
225         """Draw a pair of oblique lines, using the equation y = mx + c.
226
227         This method just calls :meth:`draw_oblique_line` with ``c`` and ``-c``,
228         and returns True if either call returned True.
229
230         :param QPainter painter: The ``QPainter`` object to use for drawing the vectors and grid lines
231         :param float m: The gradient of the lines to draw
232         :param float c: The y-intercept of the lines to draw. We use the positive and negative versions
233         :returns bool: Whether we were able to draw any lines on the canvas
234         """
235         return any([
236             self.draw_oblique_line(painter, m, c),
237             self.draw_oblique_line(painter, m, -c)
238         ])
239
```

```
240         def draw_oblique_line(self, painter: QPainter, m: float, c: float) -> bool:
241             """Draw an oblique line, using the equation y = mx + c.
242 
243             We only draw the part of the line that fits within the canvas, returning True if
244             we were able to draw a line within the boundaries, and False if we couldn't draw a line
245 
246             :param QPainter painter: The ``QPainter`` object to use for drawing the vectors and grid lines
247             :param float m: The gradient of the line to draw
248             :param float c: The y-intercept of the line to draw
249             :returns bool: Whether we were able to draw a line on the canvas
250             """
251             max_x, max_y = self.grid_corner()
252 
253             # These variable names are shortened for convenience
254             # myi is max_y_intersection, mmyi is minus_max_y_intersection, etc.
255             myi = (max_y - c) / m
256             mmyi = (-max_y - c) / m
257             mxi = max_x * m + c
258             mmxi = -max_x * m + c
259 
260             # The inner list here is a list of coords, or None
261             # If an intersection fits within the bounds, then we keep its coord,
262             # else it is None, and then gets discarded from the points list
263             # By the end, points is a list of two coords, or an empty list
264             points: list[tuple[float, float]] = [
265                 x for x in [
266                     (myi, max_y) if -max_x < myi < max_x else None,
267                     (mmyi, -max_y) if -max_x < mmyi < max_x else None,
268                     (max_x, mxi) if -max_y < mxi < max_y else None,
269                     (-max_x, mmxi) if -max_y < mmxi < max_y else None
270                 ] if x is not None
271             ]
272 
273             # If no intersections fit on the canvas
274             if len(points) < 2:
275                 return False
276 
277             # If we can, then draw the line
278             else:
279                 painter.drawLine(
280                     *self.trans_coords(*points[0]),
281                     *self.trans_coords(*points[1])
282                 )
283                 return True
```

To illustrate what this code is doing, I'll use a diagram.

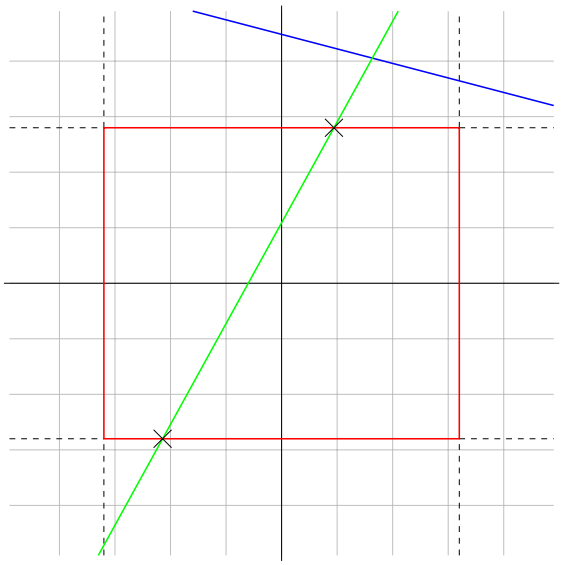


Figure 3.4.1: Two example lines and the viewport box

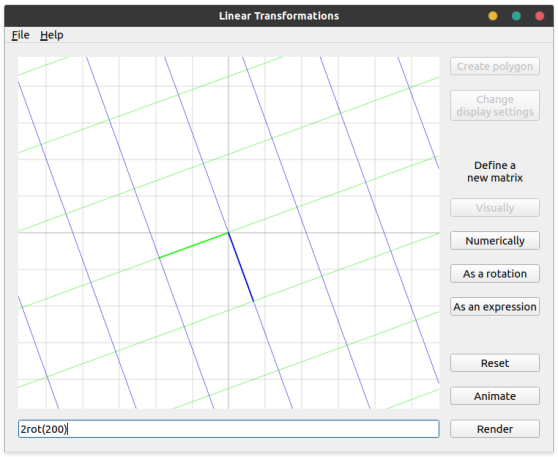


Figure 3.4.2: A demonstration of the new oblique lines system.

The red box represents the viewport of the GUI. The dashed lines represent the extensions of the red box. For a given line we want to draw, we first want to find where it intersects these orthogonal lines. Any oblique line will intersect each of these lines exactly once. This is what the `myi`, `mmyi`, `mxi`, and `mmxi` variables represent. The value of `myi` is the x value where the line intersects the maximum y line, for example.

In the case of the blue line, all 4 intersection points are outside the bounds of the box, whereas the green line intersects with the box, as shown with the crosses. We use a list comprehension over a list of ternaries to get the `points` list. This list contains 0 or 2 coordinates, and we may or may not draw a line accordingly.

That's how the `draw_oblique_line()` method works, and the `draw_pair_of_oblique_lines()` method just calls it with positive and negative values of c.

3.4.2 Adding vector arrowheads

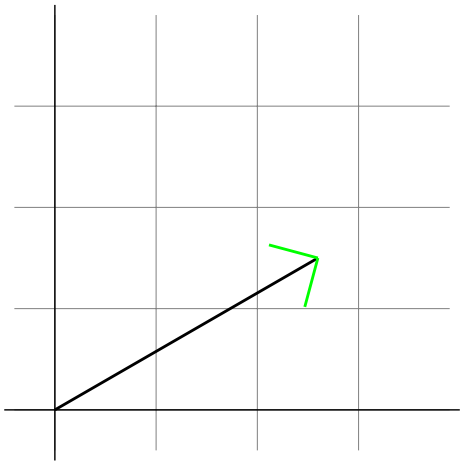


Figure 3.4.3: An example of a vector with the arrowheads highlighted in green

Now that I had a good renderer, I wanted to add arrowheads to the vectors to make them easier to see. They were already thicker than the gridlines, but adding arrowheads like in the 3blue1brown series would make them much easier to see. Unfortunately, I couldn't work out how to do this.

I wanted a function that would take a coordinate, treat it as a unit vector, and draw lines at 45° angles at the tip. This wasn't how I was conceptualising the problem at the time and because of that, I couldn't work out how to solve this problem. I could create this 45° lines in the top right quadrant, but none of my possible solutions worked for any arbitrary point.

So I started googling and found a very nice algorithm on `csharphelper.com`[56], which I adapted for Python.

```
# 5373b1ad8040f6726147cccea523c0570251cf67
# src/lintrans/gui/plots/widgets.py

class VisualizeTransformationWidget(VectorGridPlot):
...
    def draw_arrowhead_away_from_origin(self, painter: QPainter, point: tuple[float, float]) -> None:
        """Draw an arrowhead at ``point``, pointing away from the origin.

        :param QPainter painter: The ``QPainter`` object to use to draw the arrowheads with
        :param point: The point to draw the arrowhead at, given in grid coords
        :type point: tuple[float, float]
        """
        # This algorithm was adapted from a C# algorithm found at
        # http://csharphelper.com/blog/2014/12/draw-lines-with-arrowheads-in-c/

        # Get the x and y coords of the point, and then normalize them
        # We have to normalize them, or else the size of the arrowhead will
        # scale with the distance of the point from the origin
        x, y = point
        nx = x / np.sqrt(x * x + y * y)
        ny = y / np.sqrt(x * x + y * y)

        # We choose a length and do some magic to find the steps in the x and y directions
        length = 0.15
        dx = length * (-nx - ny)
        dy = length * (nx - ny)

        # Then we just plot those lines
        painter.drawLine(*self.trans_coords(x, y), *self.trans_coords(x + dx, y + dy))
        painter.drawLine(*self.trans_coords(x, y), *self.trans_coords(x - dy, y + dx))

    def draw_vector_arrowheads(self, painter: QPainter) -> None:
        """Draw arrowheads at the tips of the basis vectors.

        :param QPainter painter: The ``QPainter`` object to use to draw the arrowheads with
        """
        painter.setPen(QPen(self.colour_i, self.width_vector_line))
        self.draw_arrowhead_away_from_origin(painter, self.point_i)
        painter.setPen(QPen(self.colour_j, self.width_vector_line))
        self.draw_arrowhead_away_from_origin(painter, self.point_j)
```

As the comments suggest, we get the x and y components of the normalised vector, and then do some magic with a chosen length and get some distance values, and then draw those lines. I don't really understand how this code works, but I'm happy that it does. All we have to do is call `draw_vector_arrowheads()` from `paintEvent()`.

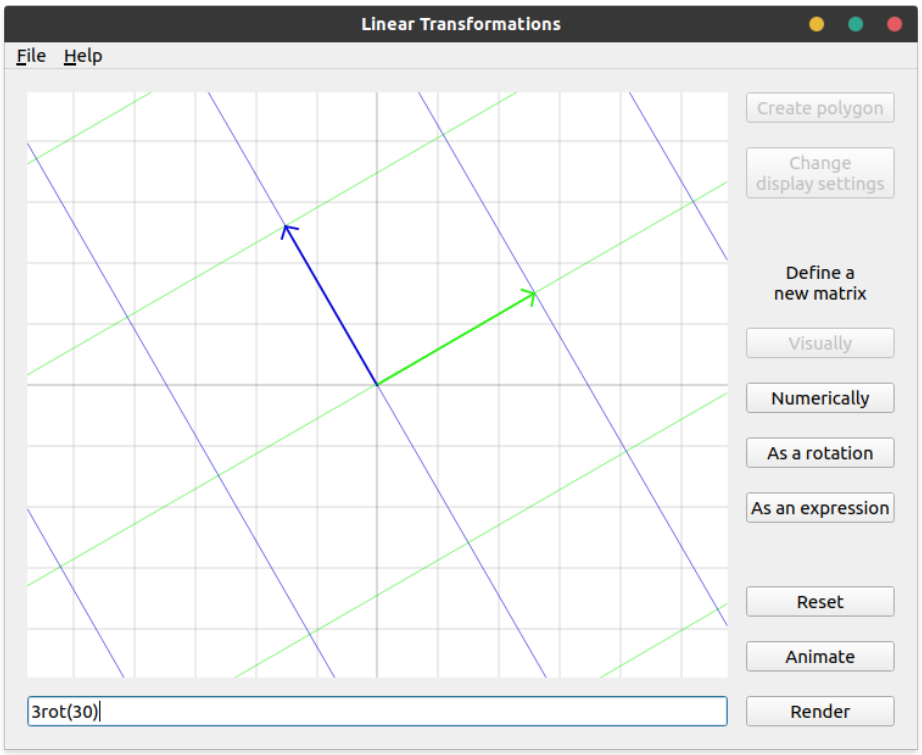


Figure 3.4.4: An example of the i and j vectors with arrowheads

3.4.3 Implementing zoom

The next thing I wanted to do was add the ability to zoom in and out of the viewport, and I wanted a button to reset the zoom level as well. I added a `default_grid_spacing` class attribute in `BackgroundPlot` and used that as the `grid_spacing` instance attribute in `__init__()`.

```
# d944e86e1d0fdc2c4be4d63479bc6bc3a31568ef
# src/lintrans/gui/plots/classes.py

12  class BackgroundPlot(QWidget):
...
27      default_grid_spacing: int = 50
28
29      def __init__(self, *args, **kwargs):
30          """Create the widget and setup backend stuff for rendering.
31
32          .. note:: ``*args`` and ``**kwargs`` are passed the superclass constructor (``QWidget``).
33          """
34          super().__init__(*args, **kwargs)
35
36          self.setAutoFillBackground(True)
37
38          # Set the background to white
39          palette = self.palette()
40          palette.setColor(self.backgroundRole(), Qt.white)
41          self.setPalette(palette)
42
43          # Set the gird colour to grey and the axes colour to black
44          self.colour_background_grid = QColor(128, 128, 128)
45          self.colour_background_axes = QColor(0, 0, 0)
46
47          self.grid_spacing = BackgroundPlot.default_grid_spacing
```

The reset button in `LintransMainWindow` simply sets `plot.grid_spacing` to the default.

To actually allow for zooming, I had to implement the `wheelEvent()` method in `BackgroundPlot` to listen for mouse wheel events. After reading through the docs for the `QWheelEvent` class[45], I learned how to handle this event.

```
# d944e86e1d0fdc2c4be4d63479bc6bc3a31568ef
# src/lintrans/gui/plots/classes.py

12  class BackgroundPlot(QWidget):
...
119     def wheelEvent(self, event: QWheelEvent) -> None:
120         """Handle a ``QWheelEvent`` by zooming in or our of the grid."""
121         # angleDelta() returns a number of units equal to 8 times the number of degrees rotated
122         degrees = event.angleDelta() / 8
123
124         if degrees is not None:
125             self.grid_spacing = max(1, self.grid_spacing + degrees.y())
126
127         event.accept()
128         self.update()
```

All we do is get the amount that the user scrolled and add that to the current spacing, taking the max with 1, which acts as a minimum grid spacing. We need to use `degrees.y()` on line 125 because Qt5 allows for mice that can scroll in the x and y directions, and we only want the y component. Line 127 marks the event as accepted so that the parent widget doesn't try to act on it.

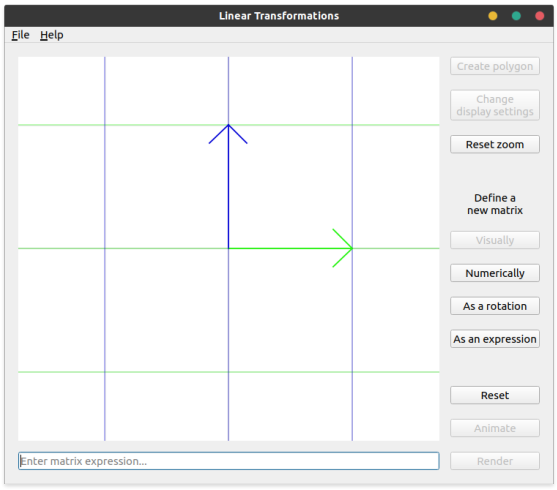


Figure 3.4.5: The GUI zoomed in a bit

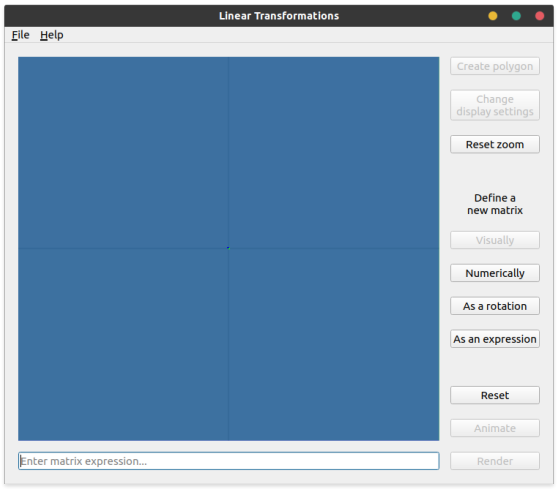


Figure 3.4.6: The GUI zoomed out as far as possible

There are two things I don't like here. Firstly, the minimum grid spacing is too small. The user can zoom out too far. Secondly, the arrowheads are too big in figure 3.4.5.

The first problem is minor and won't be fixed for quite a while, but I fixed the second problem quite quickly.

We want the arrowhead length to not just be 0.15, but to scale with the zoom level (the ratio between default grid spacing and current spacing).

This creates a slight issue when zoomed out all the way, because the arrowheads are then far larger than the vectors themselves, so we take the minimum of the scaled length and the vector length.

I factored out the default arrowhead length into the `arrowhead_length` instance attribute and initialize it in `__init__()`.

```
# 3d19a003368ae992ebb60049685bb04fde0836b5
# src/lintrans/gui/plots/widgets.py
```

```
12  class VisualizeTransformationWidget(VectorGridPlot):
...
54      def draw_arrowhead_away_from_origin(self, painter: QPainter, point: tuple[float, float]) -> None:
...
68          vector_length = np.sqrt(x * x + y * y)
69          nx = x / vector_length
70          ny = y / vector_length
71
72          # We choose a length and find the steps in the x and y directions
73          length = min(
74              self.arrowhead_length * self.default_grid_spacing / self.grid_spacing,
75              vector_length
76          )
```

This code results in arrowheads that stay the same length unless the user is zoomed out basically as far as possible.

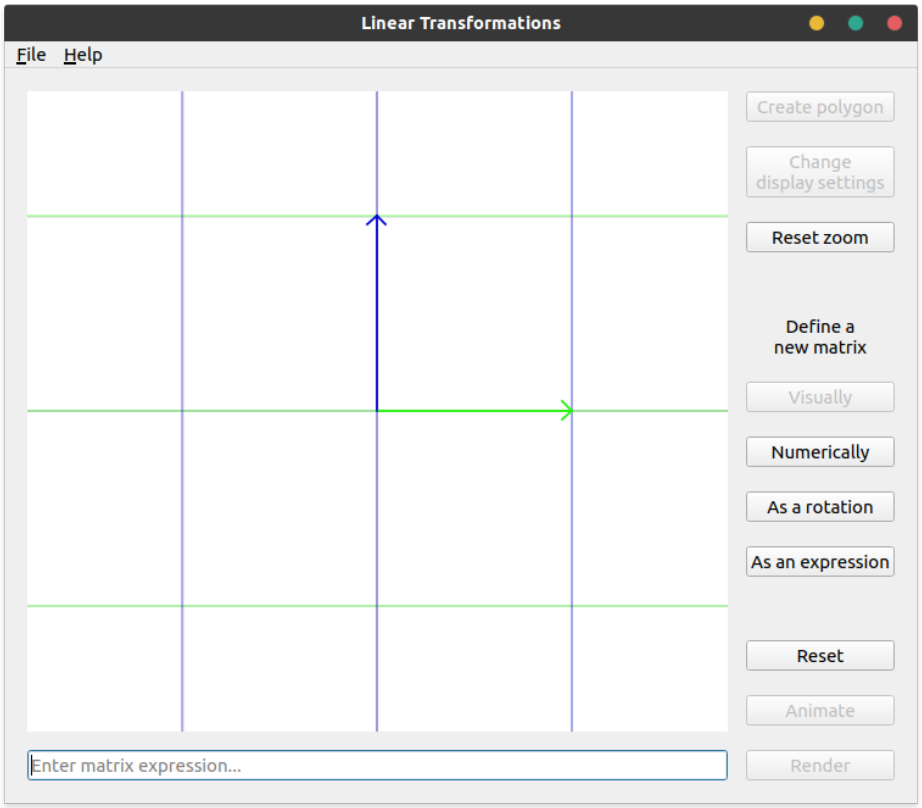


Figure 3.4.7: The arrowheads adjusted for zoom level

3.4.4 Animation blocks zooming

The biggest problem with this new zoom feature is that when animating between matrices, the user is unable to zoom. This is because when `LintransMainWindow.animate_expression()` is called, it uses Python's standard library `time.sleep()` function to delay each frame, which prevents Qt from handling user interaction while we're animating. This was a problem.

I did some googling and found a helpful post on StackOverflow[23] that gave me a nice solution. The user `ekhumoro` used the functions `QApplication.processEvents()` and `QThread.msleep()` to solve the problem, and I used these functions in my own app, with much success.

After reading 'The Event System' in the Qt5 documentation[57], I learned that Qt5 uses an event loop,

a lot like JavaScript. This means that events are scheduled to be executed on the next pass of the event loop. I also read the documentation for the `repaint()` and `update()` methods on the `QWidget` class[48, 50] and decided that it would be better to just queue a repaint by calling `update()` on the plot rather than immediately repaint with `repaint()`, and then call `QApplication.processEvents()` to process the pending events on the main thread. This is a nicer way of repainting, which reduces potential flickering issues, and using `QThread.msleep()` allows for asynchronous processing and therefore non-blocking animation.

3.4.5 Rank 1 transformations

The rank of a matrix is the dimension of its column space. This is the dimension of the span of its columns, which is to say the dimension of the output space. The rank of a matrix must be less than or equal to the dimension of the matrix, so we only need to worry about ranks 0, 1, and 2. There is only one rank 0 matrix, which is the **0** matrix itself. I've already covered this case by just not drawing any transformed grid lines.

Rank 2 matrices encompass most 2D matrices, and I've already covered this case in §3.3.4 and §3.4.1. A rank 1 matrix collapses all of 2D space onto a single line, so for this type of matrix, we should just draw this line.

This code is in `VectorGridPlot.draw_parallel_lines()`. We assemble the matrix $\begin{pmatrix}\texttt{vector\_x} & \texttt{point\_x} \\ \texttt{vector\_y} & \texttt{point\_y}\end{pmatrix}$ (which is actually the matrix used to create the transformation we're trying to render lines for) and use this matrix to check determinant and rank.

```
# 677b38c87bb6722b16aaf35058cf3cef66e43c21
# src/lintrans/gui/plots/classes.py

132 class VectorGridPlot(BackgroundPlot):
...
164     def draw_parallel_lines(self, painter: QPainter, vector: tuple[float, float], point: tuple[float, float]) ->
        ↪ None:
...
177         # If the determinant is 0
178         if abs(vector_x * point_y - vector_y * point_x) < 1e-12:
179             rank = np.linalg.matrix_rank(
180                 np.array([
181                     [vector_x, point_x],
182                     [vector_y, point_y]
183                 ])
184             )
185
186             # If the matrix is rank 1, then we can draw the column space line
187             if rank == 1:
188                 self.draw_oblique_line(painter, vector_y / vector_x, 0)
189
190             # If the rank is 0, then we don't draw any lines
191             else:
192                 return
```

Additionally, there was a bug with animating these determinant 0 matrices, since we try to scale the determinant through the animation, as documented in §3.3.6, but when the determinant is 0, this causes issues. To fix this, we just check the `det_target` variable in `LintransMainWindow.animate_expression` and if it's 0, we use the non-scaled version of the matrix.

```
# b889b686d997c2b64124bee786bccba3fc4f6b08
# src/lintrans/gui/main_window.py

22 class LintransMainWindow(QMainWindow):
...
262     def animate_expression(self) -> None:
...
```

```
274             for i in range(0, steps + 1):
...
307                 # If we're animating towards a det 0 matrix, then we don't want to scale the
308                 # determinant with the animation, because this makes the process not work
309                 # I'm doing this here rather than wrapping the whole animation logic in an
310                 # if block mainly because this looks nicer than an extra level of indentation
311                 # The extra processing cost is negligible thanks to NumPy's optimizations
312                 if det_target == 0:
313                     matrix_c = matrix_a
314                 else:
315                     matrix_c = scalar * matrix_b
```

3.4.6 Matrices that are too big

One of my friends was playing around with the prototype and she discovered a bug. When trying to render really big matrices, we can get errors like '`OverflowError: argument 3 overflowed: value must be in the range -2147483648 to 2147483647`' because PyQt5 is a wrapper over Qt5, which is a C++ library that uses the C++ `int` type for the `painter.drawLine()` call. This type is a 32-bit integer. Python can store integers of arbitrary precision, but when PyQt5 calls the underlying C++ library code, this gets cast to a C++ `int` and we can get an `OverflowError`.

This isn't a problem with the gridlines, because we only draw them inside the viewport, as discussed in §3.4.1, and these calculations all happen in Python, so integer precision is not a concern. However, when drawing the basis vectors, we just draw them directly, so we'll have to check that they're within the limit.

I'd previously created a `LintransMainWindow.show_error_message()` method for telling the user when they try to take the inverse of a singular matrix[11].

```
# 0f699dd95b6431e95b2311dcb03e7af49c19613f
# src/lintrans/gui/main_window.py

23  class LintransMainWindow(QMainWindow):
...
378     def show_error_message(self, title: str, text: str, info: str | None = None) -> None:
379         """Show an error message in a dialog box.
380
381         :param str title: The window title of the dialog box
382         :param str text: The simple error message
383         :param info: The more informative error message
384         :type info: Optional[str]
385         """
386         dialog = QMessageBox(self)
387         dialog.setIcon(QMessageBox.Critical)
388         dialog.setWindowTitle(title)
389         dialog.setText(text)
390
391         if info is not None:
392             dialog.setInformativeText(info)
393
394         dialog.open()
395
396         dialog.finished.connect(self.update_render_buttons)
```

I then created the `is_matrix_too_big()` method to just check that the elements of the matrix are within the desired bounds. If it returns `True` when we try to render or animate, then we call `show_error_message()`.

```
# 4682a7b225747cfd77aca0fe3abcdd1397b7c5dd
# src/lintrans/gui/main_window.py
```

[11] This commit didn't get a standalone section in this write-up because it was so small

```
24  class LintransMainWindow(QMainWindow):
...
407     def is_matrix_too_big(self, matrix: MatrixType) -> bool:
408         """Check if the given matrix will actually fit onto the canvas.
409
410         Convert the elements of the matrix to canvas coords and make sure they fit within Qt's 32-bit integer limit.
411
412         :param MatrixType matrix: The matrix to check
413         :returns bool: Whether the matrix fits on the canvas
414         """
415         coords: list[tuple[int, int]] = [self.plot.trans_coords(*vector) for vector in matrix.T]
416
417         for x, y in coords:
418             if not (-2147483648 <= x <= 2147483647 and -2147483648 <= y <= 2147483647):
419                 return True
420
421         return False
```

3.4.7 Creating the `DefineVisuallyDialog`

Next, I wanted to allow the user to define a matrix visually by dragging the basis vectors. To do this, I obviously needed a new `DefineDialog` subclass for it.

```
# 16ca0229aab73b3f4a8fe752dee3608f3ed6ead5
# src/lintrans/gui/dialogs/define_new_matrix.py

135 class DefineVisuallyDialog(DefineDialog):
136     """The dialog class that allows the user to define a matrix visually."""
137
138     def __init__(self, matrix_wrapper: MatrixWrapper, *args, **kwargs):
139         """Create the widgets and layout of the dialog.
140
141         :param MatrixWrapper matrix_wrapper: The MatrixWrapper that this dialog will mutate
142         """
143         super().__init__(matrix_wrapper, *args, **kwargs)
144
145         self.setMinimumSize(500, 450)
146
147         # === Create the widgets
148
149         self.combobox_letter.activated.connect(self.show_matrix)
150
151         self.plot = DefineVisuallyWidget(self)
152
153         # === Arrange the widgets
154
155         self.hlay_definition.addWidget(self.plot)
156         self.hlay_definition.setStretchFactor(self.plot, 1)
157
158         self.vlay_all = QVBoxLayout()
159         self.vlay_all.setSpacing(20)
160         self.vlay_all.addLayout(self.hlay_definition)
161         self.vlay_all.addLayout(self.hlay_buttons)
162
163         self.setLayout(self.vlay_all)
164
165         # We load the default matrix A into the plot
166         self.show_matrix(0)
167
168         # We also enable the confirm button, because any visually defined matrix is valid
169         self.button_confirm.setEnabled(True)
170
171     def update_confirm_button(self) -> None:
172         """Enable the confirm button.
173
174         .. note::
175            The confirm button is always enabled in this dialog and this method is never actually used,
176            so it's got an empty body. It's only here because we need to implement the abstract method.
177         """
```

```
178
179         def show_matrix(self, index: int) -> None:
180             """Show the selected matrix on the plot. If the matrix is None, show the identity."""
181             matrix = self.matrix_wrapper[ALPHABET_NO_I[index]]
182
183             if matrix is None:
184                 matrix = self.matrix_wrapper['I']
185
186             self.plot.visualize_matrix_transformation(matrix)
187             self.plot.update()
188
189         def confirm_matrix(self) -> None:
```

This `DefineVisuallyDialog` class just implements the normal methods needed for a `DefineDialog` and has a `plot` attribute to handle drawing graphics and handling mouse movement. After creating the `DefineVisuallyWidget` as a skeleton and doing some more research in the Qt5 docs[47], I renamed the `trans_coords()` methods to `canvas_coords()` to make the intent more clear, and created a `grid_coords()` method.

```
# 417aea6555029b049c470faff18df29f064f6101
# src/lintrans/gui/plots/classes.py

13  class BackgroundPlot(QWidget):
...
85          def grid_coords(self, x: int, y: int) -> tuple[float, float]:
86              """Convert a coordinate from canvas coords to grid coords.
87
88              :param int x: The x component of the canvas coordinate
89              :param int y: The y component of the canvas coordinate
90              :returns: The resultant grid coordinates
91              :rtype: tuple[float, float]
92              """
93              # We get the maximum grid coords and convert them into canvas coords
94              return (x - self.canvas_origin[0]) / self.grid_spacing, (-y + self.canvas_origin[1]) / self.grid_spacing
```

I then needed to implement the methods to handle mouse movement in the `DefineVisuallyWidget` class. Thankfully, Ross Wilson, the person who helped me learn about the `QWidget.paintEvent()` method in §3.3.1, also wrote an example of draggable points[6]. In my post, I had explained that I needed draggable points on my canvas, and Ross was helpful enough to create an example in their own time. I probably could've worked it out myself eventually, but this example allowed me to learn a lot quicker.

```
# 417aea6555029b049c470faff18df29f064f6101
# src/lintrans/gui/plots/widgets.py

56  class DefineVisuallyWidget(VisualizeTransformationWidget):
57      """This class is the widget that allows the user to visually define a matrix.
58
59      This is just the widget itself. If you want the dialog, use
60      :class:`lintrans.gui.dialogs.define_new_matrix.DefineVisuallyDialog`.
61      """
62
63      def __init__(self, *args, **kwargs):
64          """Create the widget and enable mouse tracking. ``*args`` and ``**kwargs`` are passed to ``super()``."""
65          super().__init__(*args, **kwargs)
66
67          # self.setMouseTracking(True)
68          self.dragged_point: tuple[float, float] | None = None
69
70          # This is the distance that the cursor needs to be from the point to drag it
71          self.epsilon: int = 5
72
73      def mousePressEvent(self, event: QMouseEvent) -> None:
74          """Handle a QMouseEvent when the user pressed a button."""
75          mx = event.x()
76          my = event.y()
```

```
77          button = event.button()
78
79          if button != Qt.LeftButton:
80              event.ignore()
81              return
82
83          for point in (self.point_i, self.point_j):
84              px, py = self.canvas_coords(*point)
85              if abs(px - mx) <= self.epsilon and abs(py - my) <= self.epsilon:
86                  self.dragged_point = point[0], point[1]
87
88          event.accept()
89
90      def mouseReleaseEvent(self, event: QMouseEvent) -> None:
91          """Handle a QMouseEvent when the user release a button."""
92          if event.button() == Qt.LeftButton:
93              self.dragged_point = None
94              event.accept()
95          else:
96              event.ignore()
97
98      def mouseMoveEvent(self, event: QMouseEvent) -> None:
99          """Handle the mouse moving on the canvas."""
100         mx = event.x()
101         my = event.y()
102
103         if self.dragged_point is not None:
104             x, y = self.grid_coords(mx, my)
105
106             if self.dragged_point == self.point_i:
107                 self.point_i = x, y
108
109             elif self.dragged_point == self.point_j:
110                 self.point_j = x, y
111
112             self.dragged_point = x, y
113
114             self.update()
115
116             print(self.dragged_point)
117             print(self.point_i, self.point_j)
118
119             event.accept()
120
121         event.ignore()
```

This snippet has the line '`self.setMouseTracking(True)`' commented out. This line was in the example, but it turns out that I don't want it. Mouse tracking means that a widget will receive a `QMouseEvent` every time the mouse moves. But if it's disabled (the default), then the widget will only receive a `QMouseEvent` for mouse movement when a button is held down at the same time.

I've also left in some print statements on lines 116 and 117. These small oversights are there because I just forgot to remove them before I committed these changes. They were removed 3 commits later.

3.4.8 Fixing a division by zero bug

When drawing the rank line for a determinant 0, rank 1 matrix, we can encounter a division by zero error. I'm sure this originally manifested in a crash with a `ZeroDivisionError` at runtime, but now I can only get a `RuntimeWarning` when running the old code from commit `16ca0229aab73b3f4a8fe752dee3608f3ed6ead5`. Whether it crashes or just warns the user, there is a division by zero bug when trying to render $\begin{pmatrix} k & 0 \\ 0 & 0 \end{pmatrix}$ or $\begin{pmatrix} 0 & 0 \\ 0 & k \end{pmatrix}$. To fix this, I just handled those cases separately in `VectorGridPlot.draw_parallel_lines(⌟)`.

```python
# 40bee6461d477a5c767ed132359cd511c0051e3b
# src/lintrans/gui/plots/classes.py

class VectorGridPlot(BackgroundPlot):
...
    def draw_parallel_lines(self, painter: QPainter, vector: tuple[float, float], point: tuple[float, float]) ->
    ↪ None:
...
        if abs(vector_x * point_y - vector_y * point_x) < 1e-12:
...
            # If the matrix is rank 1, then we can draw the column space line
            if rank == 1:
                if abs(vector_x) < 1e-12:
                    painter.drawLine(self.width() // 2, 0, self.width() // 2, self.height())
                elif abs(vector_y) < 1e-12:
                    painter.drawLine(0, self.height() // 2, self.width(), self.height() // 2)
                else:
                    self.draw_oblique_line(painter, vector_y / vector_x, 0)

            # If the rank is 0, then we don't draw any lines
            else:
                return
```

3.4.9 Implementing transitional animation

Currently, all animation animates from $\mathbf{I}$ to the target matrix $\mathbf{T}$. This means it resets the plot at the start. I eventually want an applicative animation system, where the matrix in the box is applied to the current scene. But I also want an option for a transitional animation, where the program animates from the start matrix $\mathbf{S}$ to the target matrix $\mathbf{T}$, and this seems easier to implement, so I'll do it first.

In `LintransMainWindow`, I created a new method called `animate_between_matrices()` and I call it from `animate_expression()`. The maths for smoothening determinants in §3.3.6 assumed the starting matrix had a determinant of 1, but when using transitional animation, this may not always be true.

If we let $\mathbf{S}$ be the starting matrix, and $\mathbf{A}$ be the matrix from the first stage of calculation as specified in §3.3.6, then we want a c such that $\det(c\mathbf{A}) = \det(\mathbf{S})$, so we get $c = \sqrt{\left|\frac{\det(\mathbf{S})}{\det(\mathbf{A})}\right|}$ by the identity $\det(c\mathbf{A}) = c^2 \det(\mathbf{A})$.

Following the same logic as in §3.3.6, we can let $\mathbf{B} = c\mathbf{A}$ and then scale it by d to get the same determinant as the target matrix $\mathbf{T}$ and find that $d = \sqrt{\left|\frac{\det(\mathbf{T})}{\det(\mathbf{B})}\right|}$. Unlike previously, $\det(\mathbf{B})$ could be any scalar, so we can't simplify our expression for d.

We then scale this with our `proportion` variable p to get a scalar $s = 1 + p\left(\sqrt{\left|\frac{\det(\mathbf{T})}{\det(\mathbf{B})}\right|} - 1\right)$ and render $\mathbf{C} = s\mathbf{B}$ on each frame.

In code, that looks like this:

```python
# 4017b84fbce67d8e041bc9ce84cefcb0b6e65e1f
# src/lintrans/gui/main_window.py

class LintransMainWindow(QMainWindow):
...
    def animate_expression(self) -> None:
        """Animate from the current matrix to the matrix in the expression box."""
        self.button_render.setEnabled(False)
        self.button_animate.setEnabled(False)

        # Get the target matrix and it's determinant
        try:
```

```
282             matrix_target = self.matrix_wrapper.evaluate_expression(self.lineedit_expression_box.text())
283
284         except linalg.LinAlgError:
285             self.show_error_message('Singular matrix', 'Cannot take inverse of singular matrix')
286             return
287
288         matrix_start: MatrixType = np.array([
289             [self.plot.point_i[0], self.plot.point_j[0]],
290             [self.plot.point_i[1], self.plot.point_j[1]]
291         ])
292
293         self.animate_between_matrices(matrix_start, matrix_target)
294
295         self.button_render.setEnabled(True)
296         self.button_animate.setEnabled(True)
297
298     def animate_between_matrices(self, matrix_start: MatrixType, matrix_target: MatrixType, steps: int = 100) ->
    ↪ None:
299         """Animate from the start matrix to the target matrix."""
300         det_target = linalg.det(matrix_target)
301         det_start = linalg.det(matrix_start)
302
303         for i in range(0, steps + 1):
304             # This proportion is how far we are through the loop
305             proportion = i / steps
306
307             # matrix_a is the start matrix plus some part of the target, scaled by the proportion
308             # If we just used matrix_a, then things would animate, but the determinants would be weird
309             matrix_a = matrix_start + proportion * (matrix_target - matrix_start)
310
311             # So to fix the determinant problem, we get the determinant of matrix_a and use it to normalise
312             det_a = linalg.det(matrix_a)
313
314             # For a 2x2 matrix A and a scalar c, we know that det(cA) = c^2 det(A)
315             # We want B = cA such that det(B) = det(S), where S is the start matrix,
316             # so then we can scale it with the animation, so we get
317             # det(cA) = c^2 det(A) = det(S) => c = sqrt(abs(det(S) / det(A)))
318             # Then we scale A to get the determinant we want, and call that matrix_b
319             if det_a == 0:
320                 c = 0
321             else:
322                 c = np.sqrt(abs(det_start / det_a))
323
324             matrix_b = c * matrix_a
325             det_b = linalg.det(matrix_b)
326
327             # matrix_c is the final matrix that we then render for this frame
328             # It's B, but we scale it over time to have the target determinant
329
330             # We want some C = dB such that det(C) is some target determinant T
331             # det(dB) = d^2 det(B) = T => d = sqrt(abs(T / det(B))
332
333             # We're also subtracting 1 and multiplying by the proportion and then adding one
334             # This just scales the determinant along with the animation
335             scalar = 1 + proportion * (np.sqrt(abs(det_target / det_b)) - 1)
336
337             # If we're animating towards a det 0 matrix, then we don't want to scale the
338             # determinant with the animation, because this makes the process not work
339             # I'm doing this here rather than wrapping the whole animation logic in an
340             # if block mainly because this looks nicer than an extra level of indentation
341             # The extra processing cost is negligible thanks to NumPy's optimizations
342             if det_target == 0:
343                 matrix_c = matrix_a
344             else:
345                 matrix_c = scalar * matrix_b
346
347             if self.is_matrix_too_big(matrix_c):
348                 self.show_error_message('Matrix too big', "This matrix doesn't fit on the canvas")
349                 return
350
351             self.plot.visualize_matrix_transformation(matrix_c)
352
353             # We schedule the plot to be updated, tell the event loop to
```

```
354                 # process events, and asynchronously sleep for 10ms
355                 # This allows for other events to be processed while animating, like zooming in and out
356                 self.plot.update()
```

This change results in an animation system that will transition from the current matrix to whatever the user types into the input box.

3.4.10 Allowing for sequential animation with commas

Applicative animation has two main forms. There's the version where a standard matrix expression gets applied to the current scene, and the kind where the user defines a sequence of matrices and we animate through the sequence, applying one at a time. Both of these are referenced in success criterion 6.

I want the user to be able to decide if they want applicative animation or transitional animation, so I'll need to create some form of display settings. However, transitional animation doesn't make much sense for sequential animation[12], so I can implement this now.

Applicative animation is just animating from the matrix **C** representing the current scene to the composition **TC** with the target matrix **T**.

We use **TC** instead of **CT** because matrix multiplication can be thought of as applying successive transformations from right to left. **TC** is the same as starting with the identity **I**, applying **C** (to get to the current scene), and then applying **T**.

Doing this in code is very simple. We just split the expression on commas, and then apply each sub-expression to the current scene one by one, pausing on each comma.

```
# 60584d2559cacbf23479a1bebbb986a800a32331
# src/lintrans/gui/main_window.py

25  class LintransMainWindow(QMainWindow):
...
284     def animate_expression(self) -> None:
285         """Animate from the current matrix to the matrix in the expression box."""
286         self.button_render.setEnabled(False)
287         self.button_animate.setEnabled(False)
288
289         matrix_start: MatrixType = np.array([
290             [self.plot.point_i[0], self.plot.point_j[0]],
291             [self.plot.point_i[1], self.plot.point_j[1]]
292         ])
293
294         text = self.lineedit_expression_box.text()
295
296         # If there's commas in the expression, then we want to animate each part at a time
297         if ',' in text:
298             current_matrix = matrix_start
299
300             # For each expression in the list, right multiply it by the current matrix,
301             # and animate from the current matrix to that new matrix
302             for expr in text.split(',')[::-1]:
303                 new_matrix = self.matrix_wrapper.evaluate_expression(expr) @ current_matrix
304
305                 self.animate_between_matrices(current_matrix, new_matrix)
306                 current_matrix = new_matrix
307
308                 # Here we just redraw and allow for other events to be handled while we pause
309                 self.plot.update()
310                 QApplication.processEvents()
311                 QThread.msleep(500)
```

[12] I have since changed my thoughts on this, and I allowed sequential transitional animation much later, in commit `41907b81661f3878e435b794d9d719491ef14237`

```
312
313             # If there's no commas, then just animate directly from the start to the target
314             else:
315                 # Get the target matrix and it's determinant
316                 try:
317                     matrix_target = self.matrix_wrapper.evaluate_expression(text)
318
319                 except linalg.LinAlgError:
320                     self.show_error_message('Singular matrix', 'Cannot take inverse of singular matrix')
321                     return
322
323                 self.animate_between_matrices(matrix_start, matrix_target)
324
325             self.update_render_buttons()
```

We're deliberately not checking if the sub-expressions are valid here. We would normally validate the expression in `LintransMainWindow.update_render_buttons()` and only allow the user to render or animate an expression if it's valid. Now we have to check all the sub-expressions if the expression contains commas. Additionally, we can only animate these expressions with commas in them, so rendering should be disabled when the expression contains commas.

Compare the old code to the new code:

```
# 4017b84fbce67d8e041bc9ce84cefcb0b6e65e1f
# src/lintrans/gui/main_window.py

25  class LintransMainWindow(QMainWindow):
...
243     def update_render_buttons(self) -> None:
244         """Enable or disable the render and animate buttons according to whether the matrix expression is valid."""
245         valid = self.matrix_wrapper.is_valid_expression(self.lineedit_expression_box.text())
246         self.button_render.setEnabled(valid)
247         self.button_animate.setEnabled(valid)


# 60584d2559cacbf23479a1bebbb986a800a32331
# src/lintrans/gui/main_window.py

25  class LintransMainWindow(QMainWindow):
...
243     def update_render_buttons(self) -> None:
244         """Enable or disable the render and animate buttons according to whether the matrix expression is valid."""
245         text = self.lineedit_expression_box.text()
246
247         if ',' in text:
248             self.button_render.setEnabled(False)
249
250             valid = all(self.matrix_wrapper.is_valid_expression(x) for x in text.split(','))
251             self.button_animate.setEnabled(valid)
252
253         else:
254             valid = self.matrix_wrapper.is_valid_expression(text)
255             self.button_render.setEnabled(valid)
256             self.button_animate.setEnabled(valid)
```

3.5 Adding display settings

3.5.1 Creating the dataclass (and implementing applicative animation)

The first step of adding display settings is creating a dataclass to hold all of the settings. This dataclass will hold attributes to manage how a matrix transformation is displayed. Things like whether to show eigenlines or the determinant parallelogram. It will also hold information for animation. We can factor out the code used to smoothen the determinant, as written in §3.3.6, and make it dependant on a `bool` attribute of the `DisplaySettings` dataclass.

This is a standard class rather than some form of singleton to allow different plots to have different display settings. For example, the user might want different settings for the main view and the visual definition dialog. Allowing each instance of a subclass of `VectorGridPlot` to have its own `DisplaySettings` attribute allows for separate settings for separate plots.

However, this class initially just contained attributes relevant to animation, so it was only an attribute on `LintransMainWindow`.

```
# 2041c7a24d963d8d142d6f0f20ec3828ba8257c6
# src/lintrans/gui/settings.py

"""This module contains the :class:`DisplaySettings` class, which holds configuration for display."""

from dataclasses import dataclass


@dataclass
class DisplaySettings:
    """This class simply holds some attributes to configure display."""

    animate_determinant: bool = True
    """This controls whether we want the determinant to change smoothly during the animation."""

    applicative_animation: bool = True
    """There are two types of simple animation, transitional and applicative.

    Let ``C`` be the matrix representing the currently displayed transformation, and let ``T`` be the target matrix.
    Transitional animation means that we animate directly from ``C`` from ``T``,
    and applicative animation means that we animate from ``C`` to ``TC``, so we apply ``T`` to ``C``.
    """

    animation_pause_length: int = 400
    """This is the number of milliseconds that we wait between animations when using comma syntax."""
```

Once I had the dataclass, I just had to add '`from .settings import DisplaySettings`' to the top of the file, and '`self.display_settings = DisplaySettings()`' to the constructor of `LintransMainWindow`. I could then use the attributes of this dataclass in `animate_expression()`.

```
# 2041c7a24d963d8d142d6f0f20ec3828ba8257c6
# src/lintrans/gui/main_window.py

class LintransMainWindow(QMainWindow):
...
    def animate_expression(self) -> None:
        """Animate from the current matrix to the matrix in the expression box."""
        self.button_render.setEnabled(False)
        self.button_animate.setEnabled(False)

        matrix_start: MatrixType = np.array([
            [self.plot.point_i[0], self.plot.point_j[0]],
            [self.plot.point_i[1], self.plot.point_j[1]]
        ])

        text = self.lineedit_expression_box.text()

```

```
298             # If there's commas in the expression, then we want to animate each part at a time
299             if ',' in text:
300                 current_matrix = matrix_start
301 
302                 # For each expression in the list, right multiply it by the current matrix,
303                 # and animate from the current matrix to that new matrix
304                 for expr in text.split(',')[::-1]:
305                     new_matrix = self.matrix_wrapper.evaluate_expression(expr) @ current_matrix
306 
307                     self.animate_between_matrices(current_matrix, new_matrix)
308                     current_matrix = new_matrix
309 
310                     # Here we just redraw and allow for other events to be handled while we pause
311                     self.plot.update()
312                     QApplication.processEvents()
313                     QThread.msleep(self.display_settings.animation_pause_length)
314 
315             # If there's no commas, then just animate directly from the start to the target
316             else:
317                 # Get the target matrix and it's determinant
318                 try:
319                     matrix_target = self.matrix_wrapper.evaluate_expression(text)
320 
321                 except linalg.LinAlgError:
322                     self.show_error_message('Singular matrix', 'Cannot take inverse of singular matrix')
323                     return
324 
325                 # The concept of applicative animation is explained in /gui/settings.py
326                 if self.display_settings.applicative_animation:
327                     matrix_target = matrix_target @ matrix_start
328 
329                 self.animate_between_matrices(matrix_start, matrix_target)
330 
331             self.update_render_buttons()
```

Lines 327 are very important here. I included applicative animation as an option in the display settings because once I'd implemented animating from one matrix to another, it was very easy to implement applicative animation.

The user will input whatever matrix they wanted to apply to the current scene. Let's call that target matrix $\mathbf{T}$. The matrix representing the starting state of the viewport is $\mathbf{S}$. Animating from $\mathbf{S}$ to $\mathbf{T}$ is a transitional animation, but an applicative animation is simply animating from $\mathbf{S}$ to $\mathbf{TS}$, so we can just say `matrix_target = matrix_target @ matrix_start` on line 327 (where `@` is the matrix multiplication operator), and continue as normal.

I also wrapped the main logic of `animate_between_matrices()` in an `if` block to check if the user wants the determinant to be smoothed.

```
# 03e154e1326dc256ffc1a539e97d8ef5ec89f6fd
# src/lintrans/gui/main_window.py

26  class LintransMainWindow(QMainWindow):
...
333     def animate_between_matrices(self, matrix_start: MatrixType, matrix_target: MatrixType, steps: int = 100) ->
        ↪ None:
334         """Animate from the start matrix to the target matrix."""
335         det_target = linalg.det(matrix_target)
336         det_start = linalg.det(matrix_start)
337 
338         for i in range(0, steps + 1):
339             # This proportion is how far we are through the loop
340             proportion = i / steps
341 
342             # matrix_a is the start matrix plus some part of the target, scaled by the proportion
343             # If we just used matrix_a, then things would animate, but the determinants would be weird
344             matrix_a = matrix_start + proportion * (matrix_target - matrix_start)
345 
346             if self.display_settings.animate_determinant and det_target != 0:
347                 # To fix the determinant problem, we get the determinant of matrix_a and use it to normalise
```

```
348                 det_a = linalg.det(matrix_a)
349
350                 # For a 2x2 matrix A and a scalar c, we know that det(cA) = c^2 det(A)
351                 # We want B = cA such that det(B) = det(S), where S is the start matrix,
352                 # so then we can scale it with the animation, so we get
353                 # det(cA) = c^2 det(A) = det(S) => c = sqrt(abs(det(S) / det(A)))
354                 # Then we scale A to get the determinant we want, and call that matrix_b
355                 if det_a == 0:
356                     c = 0
357                 else:
358                     c = np.sqrt(abs(det_start / det_a))
359
360                 matrix_b = c * matrix_a
361                 det_b = linalg.det(matrix_b)
362
363                 # matrix_to_render is the final matrix that we then render for this frame
364                 # It's B, but we scale it over time to have the target determinant
365
366                 # We want some C = dB such that det(C) is some target determinant T
367                 # det(dB) = d^2 det(B) = T => d = sqrt(abs(T / det(B))
368
369                 # We're also subtracting 1 and multiplying by the proportion and then adding one
370                 # This just scales the determinant along with the animation
371                 scalar = 1 + proportion * (np.sqrt(abs(det_target / det_b)) - 1)
372                 matrix_to_render = scalar * matrix_b
373
374             else:
375                 matrix_to_render = matrix_a
376
377             if self.is_matrix_too_big(matrix_to_render):
378                 self.show_error_message('Matrix too big', "This matrix doesn't fit on the canvas")
379                 return
380
381             self.plot.visualize_matrix_transformation(matrix_to_render)
382
383             # We schedule the plot to be updated, tell the event loop to
384             # process events, and asynchronously sleep for 10ms
385             # This allows for other events to be processed while animating, like zooming in and out
386             self.plot.update()
387             QApplication.processEvents()
388             QThread.msleep(1000 // steps)
```

3.5.2 Creating the settings dialog

Display settings are good, but useless on their own. My next step was to add a settings dialog that would allow the user to edit these settings.

I first had to create the dialog class itself, so I created the `SettingsDialog` superclass first, so that I could use it for global settings in the future, as well as the specific `DisplaySettingsDialog` subclass now.

As far as I know, a dialog in Qt can't really return a value when it's closed[13], so the dialog keeps a public instance attribute for the `DisplaySettings` class itself, and then the main window can copy that instance attribute when the dialog is closed.

```
# b1ba4adc3c7723c95b490e831e651a7781af7d99
# src/lintrans/gui/dialogs/settings.py

1   """This module provides dialogs to edit settings within the app."""
2
3   from __future__ import annotations
4
5   import abc
```

[13]This is because Qt uses a system of event loops, so the main window continues executing its main loop while the dialog is doing the same. That means that the main window can't wait around for the dialog to close, so nothing can be returned from it.

```python
import copy

from PyQt5 import QtWidgets
from PyQt5.QtCore import Qt
from PyQt5.QtGui import QIntValidator, QKeySequence
from PyQt5.QtWidgets import QCheckBox, QDialog, QHBoxLayout, QShortcut, QSizePolicy, QSpacerItem, QVBoxLayout

from lintrans.gui.settings import DisplaySettings


class SettingsDialog(QDialog):
    """An abstract superclass for other simple dialogs."""

    def __init__(self, *args, **kwargs):
        """Create the widgets and layout of the dialog, passing ``*args`` and ``**kwargs`` to super."""
        super().__init__(*args, **kwargs)

        # === Create the widgets

        self.button_confirm = QtWidgets.QPushButton(self)
        self.button_confirm.setText('Confirm')
        self.button_confirm.clicked.connect(self.confirm_settings)
        self.button_confirm.setToolTip('Confirm these new settings<br><b>(Ctrl + Enter)</b>')
        QShortcut(QKeySequence('Ctrl+Return'), self).activated.connect(self.button_confirm.click)

        self.button_cancel = QtWidgets.QPushButton(self)
        self.button_cancel.setText('Cancel')
        self.button_cancel.clicked.connect(self.reject)
        self.button_cancel.setToolTip('Revert these settings<br><b>(Escape)</b>')

        # === Arrange the widgets

        self.setContentsMargins(10, 10, 10, 10)

        self.hlay_buttons = QHBoxLayout()
        self.hlay_buttons.setSpacing(20)
        self.hlay_buttons.addItem(QSpacerItem(50, 5, hPolicy=QSizePolicy.Expanding, vPolicy=QSizePolicy.Minimum))
        self.hlay_buttons.addWidget(self.button_cancel)
        self.hlay_buttons.addWidget(self.button_confirm)

        self.vlay_options = QVBoxLayout()
        self.vlay_options.setSpacing(20)

        self.vlay_all = QVBoxLayout()
        self.vlay_all.setSpacing(20)
        self.vlay_all.addLayout(self.vlay_options)
        self.vlay_all.addLayout(self.hlay_buttons)

        self.setLayout(self.vlay_all)

    @abc.abstractmethod
    def load_settings(self) -> None:
        """Load the current settings into the widgets."""

    @abc.abstractmethod
    def confirm_settings(self) -> None:
        """Confirm the settings chosen in the dialog."""


class DisplaySettingsDialog(SettingsDialog):
    """The dialog to allow the user to edit the display settings."""

    def __init__(self, display_settings: DisplaySettings, *args, **kwargs):
        """Create the widgets and layout of the dialog.

        :param DisplaySettings display_settings: The :class:`lintrans.gui.settings.DisplaySettings` object to mutate
        """
        super().__init__(*args, **kwargs)

        self.display_settings = display_settings
        self.setWindowTitle('Change display settings')

        # === Create the widgets
```

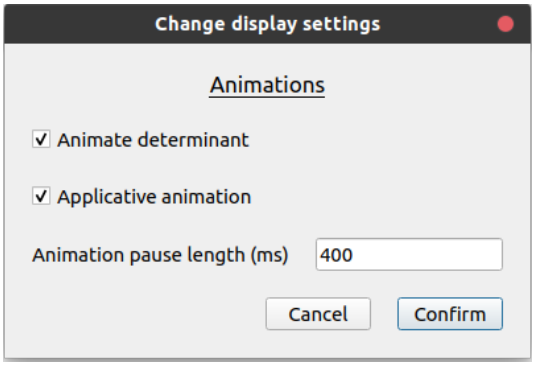
```
79
80              font_label = self.font()
81              font_label.setUnderline(True)
82              font_label.setPointSize(int(font_label.pointSize() * 1.2))
83
84              self.label_animations = QtWidgets.QLabel(self)
85              self.label_animations.setText('Animations')
86              self.label_animations.setAlignment(Qt.AlignCenter)
87              self.label_animations.setFont(font_label)
88
89              self.checkbox_animate_determinant = QCheckBox(self)
90              self.checkbox_animate_determinant.setText('Animate determinant')
91              self.checkbox_animate_determinant.setToolTip('Smoothly animate the determinant during animation')
92
93              self.checkbox_applicative_animation = QCheckBox(self)
94              self.checkbox_applicative_animation.setText('Applicative animation')
95              self.checkbox_applicative_animation.setToolTip(
96                  'Animate the new transformation applied to the current one,\n'
97                  'rather than just that transformation on its own'
98              )
99
100             self.label_animation_pause_length = QtWidgets.QLabel(self)
101             self.label_animation_pause_length.setText('Animation pause length (ms)')
102             self.label_animation_pause_length.setToolTip(
103                 'How many milliseconds to pause for in comma-separated animations'
104             )
105
106             self.lineedit_animation_pause_length = QtWidgets.QLineEdit(self)
107             self.lineedit_animation_pause_length.setValidator(QIntValidator(1, 999, self))
108
109             # === Arrange the widgets
110
111             self.hlay_animation_pause_length = QHBoxLayout()
112             self.hlay_animation_pause_length.addWidget(self.label_animation_pause_length)
113             self.hlay_animation_pause_length.addWidget(self.lineedit_animation_pause_length)
114
115             self.vlay_options.addWidget(self.label_animations)
116             self.vlay_options.addWidget(self.checkbox_animate_determinant)
117             self.vlay_options.addWidget(self.checkbox_applicative_animation)
118             self.vlay_options.addLayout(self.hlay_animation_pause_length)
119
120             # Finally, we load the current settings
121             self.load_settings()
122
123         def load_settings(self) -> None:
124             """Load the current display settings into the widgets."""
125             self.checkbox_animate_determinant.setChecked(self.display_settings.animate_determinant)
126             self.checkbox_applicative_animation.setChecked(self.display_settings.applicative_animation)
127             self.lineedit_animation_pause_length.setText(str(self.display_settings.animation_pause_length))
128
129         def confirm_settings(self) -> None:
130             """Build a :class:`lintrans.gui.settings.DisplaySettings` object and assign it."""
131             self.display_settings.animate_determinant = self.checkbox_animate_determinant.isChecked()
132             self.display_settings.applicative_animation = self.checkbox_applicative_animation.isChecked()
133             self.display_settings.animation_pause_length = int(self.lineedit_animation_pause_length.text())
134
135             self.accept()
```

I then just had to enable the button in the main GUI and implement the method to open the new dialog. I have to use a lambda to capture the local `dialog` variable, but a separate method to actually assign its display settings, since Python doesn't allow assignments in lambda expressions.

```
# b1ba4adc3c7723c95b490e831e651a7781af7d99
# src/lintrans/gui/main_window.py

27  class LintransMainWindow(QMainWindow):
...
436         def dialog_change_display_settings(self) -> None:
437             """Open the dialog to change the display settings."""
438             dialog = DisplaySettingsDialog(self.display_settings, self)
```

```
439             dialog.open()
440             dialog.finished.connect(lambda: self._assign_display_settings(dialog.display_settings))
441
442         def _assign_display_settings(self, display_settings: DisplaySettings) -> None:
443             """Assign a new value to ``self.display_settings``."""
444             self.display_settings = display_settings
```



The `dialog.finished` signal on line 440 should really be `dialog.accepted`. Currently, we re-assign the display settings whenever the dialog is closed in any way. Really, we should only re-assign them when the user hits the confirm button, but trying to cancel the changes will currently save them. This was a silly mistake and I fixed it along with some similar signal-related bugs a few weeks later. See §3.9.1.

Figure 3.5.1: The display settings dialog

3.5.3 Fixing a bug with transitional animation

While playing around with these new display settings, I encountered a bug with transitional animation. When you animate an expression with transitional animation and then animate the same thing again, nothing happens. This is because the app tries to transition from the starting position to the target position, but they are the same position, so nothing moves.

To fix this, I had to check if the start and target matrices were the same (within floating point error), and then reset the viewport to the identity first, before animating to the target as requested.

```
# fa4a65540749e84b750ddea8abfd36a86c224b47
# src/lintrans/gui/main_window.py

27  class LintransMainWindow(QMainWindow):
...
285     def animate_expression(self) -> None:
...
315         else:
...
328             # If we want a transitional animation and we're animating the same matrix, then restart the animation
329             # We use this check rather than equality because of small floating point errors
330             elif (matrix_start - matrix_target < 1e-12).all():
331                 matrix_start = self.matrix_wrapper['I']
332
333                 # We pause here for 200 ms to make the animation look a bit nicer
334                 self.plot.visualize_matrix_transformation(matrix_start)
335                 self.plot.update()
336                 QApplication.processEvents()
337                 QThread.msleep(200)
```

I later found a bug on line 330. If we subtract the start and target matrices and get a matrix of all negative numbers (rather than all zeroes, which is what I wanted to check for), then the if condition will still be true. That means that some completely different matrices can be considered the same, and the viewport will reset before animating them. To fix this, I can simply take the absolute value.

```
# 3c490c48a0f4017ab8ee9cf471a65c251817b00e
# src/lintrans/gui/main_window.py

333             elif (abs(matrix_start - matrix_target) < 1e-12).all():
```

3.5.4 Adding the determinant parallelogram

The determinant can be represented as the area of the parallelogram formed by the basis vectors. This would be good to visualize in the app.

To do that, I had to add a setting to the display settings, create a function to actually draw it in `VectorGridPlot`, and call that function from `paintEvent()`.

```
# e9e76c1d4f28452efc6ae18afb936616006fd04a
# src/lintrans/gui/settings.py

 9  class DisplaySettings:
...
26      draw_determinant_parallelogram: bool = False
27      """This controls whether or not we should shade the parallelogram representing the determinant of the matrix."""
```

```
# e9e76c1d4f28452efc6ae18afb936616006fd04a
# src/lintrans/gui/plots/classes.py

140 class VectorGridPlot(BackgroundPlot):
...
385     def draw_determinant_parallelogram(self, painter: QPainter) -> None:
386         """Draw the parallelogram of the determinant of the matrix."""
387         path = QPainterPath()
388         path.moveTo(*self.canvas_origin)
389         path.lineTo(*self.canvas_coords(*self.point_i))
390         path.lineTo(*self.canvas_coords(self.point_i[0] + self.point_j[0], self.point_i[1] + self.point_j[1]))
391         path.lineTo(*self.canvas_coords(*self.point_j))
392
393         brush = QBrush(QColor(16, 235, 253, alpha=128), Qt.SolidPattern)
394         painter.fillPath(path, brush)
```

```
# e9e76c1d4f28452efc6ae18afb936616006fd04a
# src/lintrans/gui/plots/widgets.py

13  class VisualizeTransformationWidget(VectorGridPlot):
...
42      def paintEvent(self, event: QPaintEvent) -> None:
43          """Handle a ``QPaintEvent`` by drawing the background grid and the transformed grid.
44
45          The transformed grid is defined by the basis vectors i and j, which can
46          be controlled with the :meth:`visualize_matrix_transformation` method.
47          """
48          painter = QPainter()
49          painter.begin(self)
50
51          painter.setRenderHint(QPainter.Antialiasing)
52          painter.setBrush(Qt.NoBrush)
53
54          self.draw_background(painter)
55          self.draw_transformed_grid(painter)
56          self.draw_vector_arrowheads(painter)
57
58          if self.display_settings.draw_determinant_parallelogram:
59              self.draw_determinant_parallelogram(painter)
60
61          painter.end()
62          event.accept()
```

I then wanted to change the determinant parallelogram to be blue when it's positive and red when it's negative. I did this by just checking the sign of the determinant and changing the colour accordingly.

```
# cc75c7dc85e941540f7e98fe027d0657ad5462b8
# src/lintrans/gui/plots/classes.py

140 class VectorGridPlot(BackgroundPlot):
```

```
...
385         def draw_determinant_parallelogram(self, painter: QPainter) -> None:
386             """Draw the parallelogram of the determinant of the matrix."""
387             det = np.linalg.det(np.array([
388                 [self.point_i[0], self.point_j[0]],
389                 [self.point_i[1], self.point_j[1]]
390             ]))
391
392             if det == 0:
393                 return
394
395             path = QPainterPath()
396             path.moveTo(*self.canvas_origin)
397             path.lineTo(*self.canvas_coords(*self.point_i))
398             path.lineTo(*self.canvas_coords(self.point_i[0] + self.point_j[0], self.point_i[1] + self.point_j[1]))
399             path.lineTo(*self.canvas_coords(*self.point_j))
400
401             color = (16, 235, 253) if det > 0 else (253, 34, 16)
402             brush = QBrush(QColor(*color, alpha=128), Qt.SolidPattern)
403
404             painter.fillPath(path, brush)
```

I then had the determinant parallelogram for positive and negative determinants.

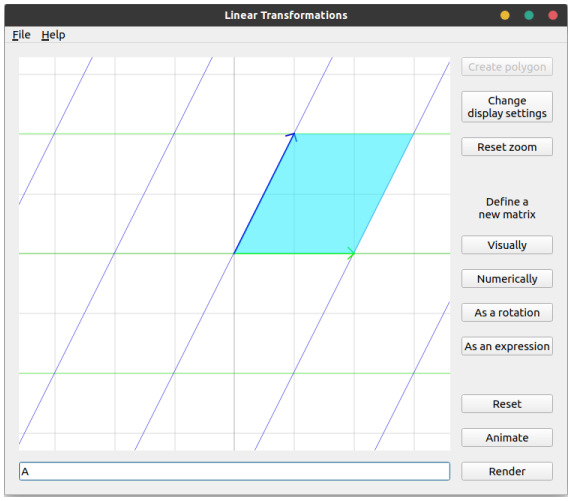


Figure 3.5.2: The blue parallelogram

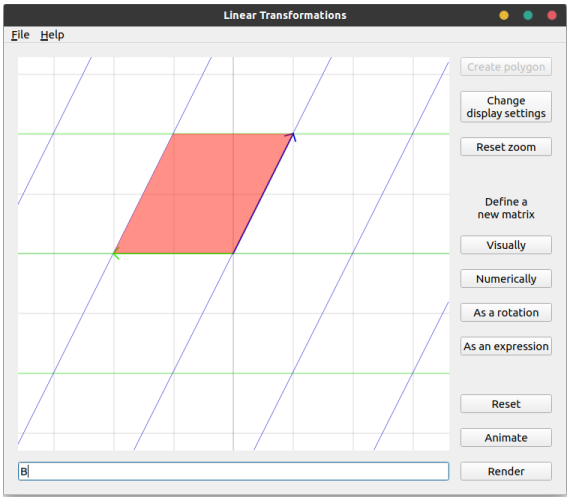


Figure 3.5.3: The red parallelogram

3.5.5 Adding the determinant text

Seeing the determinant as a shape is one thing, but knowing its exact value is also often very useful. To do this, I had to add a variable in the `DisplaySettings` for it, add a checkbox in the `DisplaySettingsDialog`, and create a method to actually draw the text in the right place, which I can call from `paintEvent()`.

```
# e344e50eccfd87c0834cfbdf459f0dd1d555fcd6
# src/lintrans/gui/settings.py

9   class DisplaySettings:
...
35      draw_determinant_text: bool = True
36      """This controls whether we should write the text value of the determinant inside the parallelogram.
37
38      The text only gets draw if :attr:`draw_determinant_parallelogram` is also True.
39      """


# e344e50eccfd87c0834cfbdf459f0dd1d555fcd6
# src/lintrans/gui/dialogs/settings.py
```

```
63      class DisplaySettingsDialog(SettingsDialog):
...
66          def __init__(self, display_settings: DisplaySettings, *args, **kwargs):
...
108             self.checkbox_draw_determinant_text = QCheckBox(self)
109             self.checkbox_draw_determinant_text.setText('Draw determinant text')
110             self.checkbox_draw_determinant_text.setToolTip(
111                 'Write the text value of the determinant inside the parallelogram'
112             )
```

```
# e344e50eccfd87c0834cfbdf459f0dd1d555fcd6
# src/lintrans/gui/plots/classes.py

142     class VectorGridPlot(BackgroundPlot):
...
416         def draw_determinant_text(self, painter: QPainter) -> None:
417             """Write the string value of the determinant in the middle of the parallelogram."""
418             painter.setPen(QPen(QColor(0, 0, 0), self.width_vector_line))
419             painter.drawText(
420                 *self.canvas_coords(
421                     (self.point_i[0] + self.point_j[0]) / 2,
422                     (self.point_i[1] + self.point_j[1]) / 2
423                 ),
424                 f'{self.det:.2f}'
425             )
```

It doesn't make much sense to show the text without also showing the parallelogram, so we should only show the text when the parallelogram is also being show, and the checkbox for the text should only be clickable when the parallelogram is enabled.

To do this, I created an `update_gui()` method which gets called when the parallelogram checkbox is clicked. This method will enable or disable the text checkbox appropriately.

```
# e344e50eccfd87c0834cfbdf459f0dd1d555fcd6
# src/lintrans/gui/plots/widgets.py

13      class VisualizeTransformationWidget(VectorGridPlot):
...
42          def paintEvent(self, event: QPaintEvent) -> None:
...
58              if self.display_settings.draw_determinant_parallelogram:
59                  self.draw_determinant_parallelogram(painter)
60
61              if self.display_settings.draw_determinant_text:
62                  self.draw_determinant_text(painter)
```

```
# 517773e1ace0dc4485c425134cd36ba482ba65df
# src/lintrans/gui/dialogs/settings.py

63      class DisplaySettingsDialog(SettingsDialog):
...
66          def __init__(self, display_settings: DisplaySettings, *args, **kwargs):
...
107             self.checkbox_draw_determinant_parallelogram.clicked.connect(self.update_gui)
...
173         def update_gui(self) -> None:
174             """Update the GUI according to other widgets in the GUI.
175
176             For example, this method updates which checkboxes are enabled based on the values of other checkboxes.
177             """
178             self.checkbox_draw_determinant_text.setEnabled(self.checkbox_draw_determinant_parallelogram.isChecked())
```

3.6 Fixing bugs and adding polish

3.6.1 Fixing an animation crash

The scaling logic in 3.3.6 creates a matrix **A** which is the start matrix plus some proportion of the difference between the target and start matrices. It then defines matrix **B** to be the matrix A normalised to have a determinant of 1. We then divide by det(**B**) to get matrix **C**, which we then render.

This works very well for most matrices, but if we're animating from **I** to $-\mathbf{I}$ for example, then we can get the following problem:

When we're halfway through the animation, $p = \frac{1}{2}$.

$$\begin{aligned}\mathbf{A} &= \mathbf{S} + p(\mathbf{T} - \mathbf{S}) \\ &= \mathbf{I} + \frac{1}{2}(-\mathbf{I} - \mathbf{I}) \\ &= \mathbf{I} + \frac{-1}{\cancel{2}}\cancel{2}\mathbf{I} \\ &= \mathbf{I} - \mathbf{I} = \mathbf{0}\end{aligned}$$

I'm using **I** as an example here, but this can happen with the right p for many matrix pairs. Since $\mathbf{A} = \mathbf{0}$, $\det(\mathbf{A}) = 0$. We check for this case already when we find c:

```
# f7a91cdc35695f8fb9269b17bc103e42578072bd
# src/lintrans/gui/main_window.py
```

```
367                 if det_a == 0:
368                     c = 0
369                 else:
370                     c = np.sqrt(abs(det_start / det_a))
```

But if $\det(\mathbf{A}) = 0$, then $c = 0$ and $\det(\mathbf{B}) = 0$, so we also need to check that before we divide by it.

Old:

```
# f7a91cdc35695f8fb9269b17bc103e42578072bd
# src/lintrans/gui/main_window.py
```

```
383                 scalar = 1 + proportion * (np.sqrt(abs(det_target / det_b)) - 1)
384                 matrix_to_render = scalar * matrix_b
```

New:

```
# 4383808a4cc29d192c55aca56161d8affda8c9a7
# src/lintrans/gui/main_window.py
```

```
384                 # That is all of course, if we can do that
385                 # We'll crash if we try to do this with det(B) == 0
386                 if det_b != 0:
387                     scalar = 1 + proportion * (np.sqrt(abs(det_target / det_b)) - 1)
388                     matrix_to_render = scalar * matrix_b
389
390                 else:
391                     matrix_to_render = matrix_a
```

This change fixes a division by zero bug, which eliminates a possible crash here.

3.6.2 Limiting parallel lines

If you try to render a matrix like `0.01Irot(45)`, then the app ends up drawing as many parallel lines as it can physically fit in the viewport. This leads to a lot of lag, especially when zoomed out far. To fix this, I just introduced a maximum number of parallel lines. I chose 150 as a number that was big enough to have enough parallel lines for matrices that need a lot, while also causing virtually no lag.

```
# bd9aaa2e3037214f65d0fc1d12d67db35af0e5ec
# src/lintrans/gui/plots/classes.py

142 class VectorGridPlot(BackgroundPlot):
...
151     def __init__(self, *args, **kwargs):
...
169         self.max_parallel_lines = 150
```

```
# bd9aaa2e3037214f65d0fc1d12d67db35af0e5ec
# src/lintrans/gui/plots/classes.py

142 class VectorGridPlot(BackgroundPlot):
...
191     def draw_parallel_lines(self, painter: QPainter, vector: tuple[float, float], point: tuple[float, float]) ->
        ↪ None:
...
230         # Draw vertical lines
231         elif abs(vector_x) < 1e-12:
232             painter.drawLine(self.canvas_x(0), 0, self.canvas_x(0), self.height())
233
234             for i in range(max(abs(int(max_x / point_x)), self.max_parallel_lines)):
235                 painter.drawLine(
236                     self.canvas_x((i + 1) * point_x),
237                     0,
238                     self.canvas_x((i + 1) * point_x),
239                     self.height()
240                 )
241                 painter.drawLine(
242                     self.canvas_x(-1 * (i + 1) * point_x),
243                     0,
244                     self.canvas_x(-1 * (i + 1) * point_x),
245                     self.height()
246                 )
247
248         # Draw horizontal lines
249         elif abs(vector_y) < 1e-12:
250             painter.drawLine(0, self.canvas_y(0), self.width(), self.canvas_y(0))
251
252             for i in range(max(abs(int(max_y / point_y)), self.max_parallel_lines)):
253                 painter.drawLine(
254                     0,
255                     self.canvas_y((i + 1) * point_y),
256                     self.width(),
257                     self.canvas_y((i + 1) * point_y)
258                 )
259                 painter.drawLine(
260                     0,
261                     self.canvas_y(-1 * (i + 1) * point_y),
262                     self.width(),
263                     self.canvas_y(-1 * (i + 1) * point_y)
264                 )
265
266         # If the line is oblique, then we can use y = mx + c
267         else:
268             m = vector_y / vector_x
269             c = point_y - m * point_x
270
271             self.draw_oblique_line(painter, m, 0)
272
273             # We don't want to overshoot the max number of parallel lines,
274             # but we should also stop looping as soon as we can't draw any more lines
```

```
275                 for i in range(1, self.max_parallel_lines + 1):
276                     if not self.draw_pair_of_oblique_lines(painter, m, i * c):
277                         break
```

The idea behind this code is just to limit the maximum number of parallel lines that get drawn. It works perfectly for oblique lines, but there's a small bug for orthogonal lines that I never noticed. I just forgot to test it.

On lines 234 and 252, I call the built-in `max()` function with the maximum number of parallel lines and the total number of lines that could fit in the viewport. This should be a call to `min()` instead. I fixed this before releasing it for my end users, but it took an embarrassingly long time to notice something this simple.

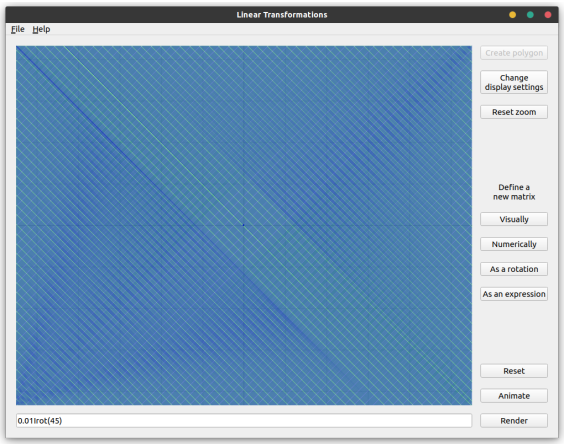


Figure 3.6.1: The old version with too many parallel lines.

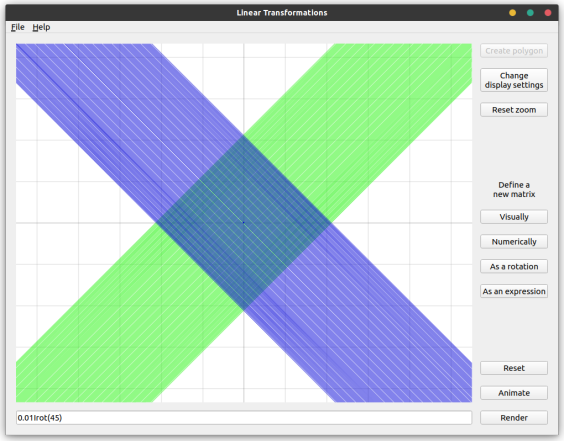


Figure 3.6.2: The fixed version with a maximum number of parallel lines.

3.6.3 Giving focus to the expression box

It would be quite nice to be able to just start typing an expression after defining a matrix or changing display settings. To do this, we can simply set the app's focus on the expression box after either of these actions.

Additionally, it would be nice to update the render buttons at the same time. That would allow the user to use a matrix in an expression, then define it, and be able to render the expression as soon as they close the dialog (assuming the expression is valid).

```
# bd7f8ba18266a8a095549d815dcfe6f24de514b6
# src/lintrans/gui/main_window.py

27  class LintransMainWindow(QMainWindow):
...
438     def assign_matrix_wrapper(self, matrix_wrapper: MatrixWrapper) -> None:
439         """Assign a new value to ``self.matrix_wrapper`` and give the expression box focus.
440
441         :param matrix_wrapper: The new value of the matrix wrapper to assign
442         :type matrix_wrapper: MatrixWrapper
443         """
444         self.matrix_wrapper = matrix_wrapper
445         self.lineedit_expression_box.setFocus()
446         self.update_render_buttons()
...
454     def assign_display_settings(self, display_settings: DisplaySettings) -> None:
455         """Assign a new value to ``self.plot.display_settings`` and give the expression box focus."""
456         self.plot.display_settings = display_settings
457         self.plot.update()
```

```
458             self.lineedit_expression_box.setFocus()
459             self.update_render_buttons()
```

3.6.4 Fixing a crash when animating singular matrices in sequence

If we have a matrix **A** defined as $\begin{pmatrix} 1 & 2 \\ 1 & 2 \end{pmatrix}$, then when we try to render `A^-1`, we get a pop-up dialog box saying that we can't take the inverse of a singular matrix. This is good, since if NumPy just took the inverse blindly, it would crash. When we try to animate `A^-1`, we get the same pop-up box. When we try to use it in an animation sequence, however, like `rot(45),A^-1`, we don't check if each element of the sequence for singularity, so NumPy takes the inverse blindly and the whole app crashes. This is bad.

To fix this, we can simply catch the error when trying to evaluate the element in the sequence.

```
# 8db0df1d9d6a1be1f15a6f705e779d982db9ee29
# src/lintrans/gui/main_window.py

27  class LintransMainWindow(QMainWindow):
...
287     def animate_expression(self) -> None:
...
300         if ',' in text:
301             current_matrix = matrix_start
302
303             # For each expression in the list, right multiply it by the current matrix,
304             # and animate from the current matrix to that new matrix
305             for expr in text.split(',')[::-1]:
306                 try:
307                     new_matrix = self.matrix_wrapper.evaluate_expression(expr) @ current_matrix
308                 except linalg.LinAlgError:
309                     self.show_error_message('Singular matrix', 'Cannot take inverse of singular matrix')
310                     return
```

3.6.5 Allowing animations to be cancelled

Currently, if you try to reset the viewport partway through an animation, it just resets the basis vectors for a tick, but then they start moving again, because the animation loop is still running. To fix this, we can track whether we should be animating using an instance variable, set it to false when the user hits reset, and break out of the animation loop when it's false.

```
# b665bc59ec99664ed7b2c17f94e76ae49c6eb331
# src/lintrans/gui/main_window.py

27  class LintransMainWindow(QMainWindow):
...
33      def __init__(self):
...
45          self.animating: bool = False
46          self.animating_sequence: bool = False
...
269     def reset_transformation(self) -> None:
270         """Reset the visualized transformation back to the identity."""
271         self.plot.visualize_matrix_transformation(self.matrix_wrapper['I'])
272         self.animating = False
273         self.animating_sequence = False
274         self.plot.update()
...
292     def animate_expression(self) -> None:
...
304         # If there's commas in the expression, then we want to animate each part at a time
305         if ',' in text:
306             current_matrix = matrix_start
```

```
307                 self.animating_sequence = True
308
309                 # For each expression in the list, right multiply it by the current matrix,
310                 # and animate from the current matrix to that new matrix
311                 for expr in text.split(',')[::-1]:
312                     try:
313                         new_matrix = self.matrix_wrapper.evaluate_expression(expr) @ current_matrix
314                     except linalg.LinAlgError:
315                         self.show_error_message('Singular matrix', 'Cannot take inverse of singular matrix')
316                         return
317
318                     if not self.animating_sequence:
319                         break
320
321                     self.animate_between_matrices(current_matrix, new_matrix)
322                     current_matrix = new_matrix
323
324                     # Here we just redraw and allow for other events to be handled while we pause
325                     self.plot.update()
326                     QApplication.processEvents()
327                     QThread.msleep(self.plot.display_settings.animation_pause_length)
328
329                 self.animating_sequence = False
...
360         def animate_between_matrices(self, matrix_start: MatrixType, matrix_target: MatrixType, steps: int = 100) ->
            ↪ None:
...
365             self.animating = True
366
367             for i in range(0, steps + 1):
368                 if not self.animating:
369                     break
370
...
429             self.animating = False
```

Here, `self.animating_sequence` is whether a sequence is being animated, and `self.animating` is whether an individual matrix is currently being animated. An individual matrix means a matrix on its own, or a single element in a sequence. That means that `self.animating` can be set and unset multiple times in a single sequence.

3.6.6 Validating expression input

The user can only render or animate an expression if it's actually valid, as discussed in §3.1.3, and the render and animate buttons will be greyed out if the expression is invalid. But they can still type anything into the box.

It was at this point that I learned about the `QValidator` class[44]. This class allows me to control what the user can actually type. Using the implementation below, they can only enter characters that are allowed in valid matrix expressions.

```
# f73575c017548d754e4171449344a52cb44b7ef4
# src/lintrans/gui/main_window.py

28  class LintransMainWindow(QMainWindow):
...
34      def __init__(self):
...
125         self.lineedit_expression_box.setValidator(MatrixExpressionValidator(self))
```

```
# f73575c017548d754e4171449344a52cb44b7ef4
# src/lintrans/gui/validate.py

1   """This simple module provides a :class:`MatrixExpressionValidator` class to validate matrix expression input."""
2
```

```
3   from __future__ import annotations
4
5   import re
6
7   from PyQt5.QtGui import QValidator
8
9   from lintrans.matrices import parse
10
11
12  class MatrixExpressionValidator(QValidator):
13      """This class validates matrix expressions in an Qt input box."""
14
15      def validate(self, text: str, pos: int) -> tuple[QValidator.State, str, int]:
16          """Validate the given text according to the rules defined in the :mod:`lintrans.matrices` module."""
17          clean_text = re.sub(r'[\sA-Z\d.rot()^{},+-]', '', text)
18
19          if clean_text == '':
20              if parse.validate_matrix_expression(clean_text):
21                  return QValidator.Acceptable, text, pos
22              else:
23                  return QValidator.Intermediate, text, pos
24
25          return QValidator.Invalid, text, pos
26
```

I also then added validators to the definition dialogs, to make sure that users can only enter valid input. Qt5 provides some basic validators already, for things like integers and floating point numbers (called **double** in C++, equivalent to `float` in Python).

```
# a2fd14b99fa752a18b42352a01142ffbc2600570
# src/lintrans/gui/dialogs/define_new_matrix.py

213 class DefineNumericallyDialog(DefineDialog):
...
225         # tl = top left, br = bottom right, etc.
226         self.element_tl = QtWidgets.QLineEdit(self)
227         self.element_tl.textChanged.connect(self.update_confirm_button)
228         self.element_tl.setValidator(QDoubleValidator())
229
230         self.element_tr = QtWidgets.QLineEdit(self)
231         self.element_tr.textChanged.connect(self.update_confirm_button)
232         self.element_tr.setValidator(QDoubleValidator())
233
234         self.element_bl = QtWidgets.QLineEdit(self)
235         self.element_bl.textChanged.connect(self.update_confirm_button)
236         self.element_bl.setValidator(QDoubleValidator())
237
238         self.element_br = QtWidgets.QLineEdit(self)
239         self.element_br.textChanged.connect(self.update_confirm_button)
240         self.element_br.setValidator(QDoubleValidator())
...
299 class DefineAsARotationDialog(DefineDialog):
...
314         self.lineedit_angle = QtWidgets.QLineEdit(self)
315         self.lineedit_angle.setPlaceholderText('angle')
316         self.lineedit_angle.textChanged.connect(self.update_confirm_button)
317         self.lineedit_angle.setValidator(QDoubleValidator())
...
358 class DefineAsAnExpressionDialog(DefineDialog):
...
372         self.lineedit_expression_box = QtWidgets.QLineEdit(self)
373         self.lineedit_expression_box.setPlaceholderText('Enter matrix expression...')
374         self.lineedit_expression_box.textChanged.connect(self.update_confirm_button)
375         self.lineedit_expression_box.setValidator(MatrixExpressionValidator())
```

3.6.7 Adding keyboard shortcuts

Keyboard shortcuts are often very useful and can make the process of using software much more efficient if you get good at using the shortcuts. On this note, I decided to add keyboard shortcuts to the display settings dialog.

Qt5 lets you use a `&` character in the text of a widget to act on the letter following it. This letter becomes underlined in the text, and the user can hold `Alt` and press this letter to activate the widget. I also want to be able to toggle the checkboxes by just pressing the letter without holding `Alt`, so I had to implement this myself with a dictionary and custom override of `keyPressEvent()`.

```
# 67d43a364ee2605b95b8caca9f1e4eb714cbb7c6
# src/lintrans/gui/dialogs/settings.py

63  class DisplaySettingsDialog(SettingsDialog):
64      """The dialog to allow the user to edit the display settings."""
65
66      def __init__(self, display_settings: DisplaySettings, *args, **kwargs):
67          """Create the widgets and layout of the dialog.
68
69          :param DisplaySettings display_settings: The :class:`lintrans.gui.settings.DisplaySettings` object to mutate
70          """
71          super().__init__(*args, **kwargs)
72
73          self.display_settings = display_settings
74          self.setWindowTitle('Change display settings')
75
76          self.dict_checkboxes: dict[str, QCheckBox] = dict()
77
78          # === Create the widgets
79
80          # Animations
81
82          self.checkbox_smoothen_determinant = QCheckBox(self)
83          self.checkbox_smoothen_determinant.setText('&Smoothen determinant')
84          self.checkbox_smoothen_determinant.setToolTip(
85              'Smoothly animate the determinant transition during animation (if possible)'
86          )
87          self.dict_checkboxes['s'] = self.checkbox_smoothen_determinant
88
89          self.checkbox_applicative_animation = QCheckBox(self)
90          self.checkbox_applicative_animation.setText('&Applicative animation')
91          self.checkbox_applicative_animation.setToolTip(
92              'Animate the new transformation applied to the current one,\n'
93              'rather than just that transformation on its own'
94          )
95          self.dict_checkboxes['a'] = self.checkbox_applicative_animation
96
97          self.label_animation_pause_length = QtWidgets.QLabel(self)
98          self.label_animation_pause_length.setText('Animation pause length (ms)')
99          self.label_animation_pause_length.setToolTip(
100             'How many milliseconds to pause for in comma-separated animations'
101         )
102
103         self.lineedit_animation_pause_length = QtWidgets.QLineEdit(self)
104         self.lineedit_animation_pause_length.setValidator(QIntValidator(1, 999, self))
105
106         # Matrix info
107
108         self.checkbox_draw_determinant_parallelogram = QCheckBox(self)
109         self.checkbox_draw_determinant_parallelogram.setText('Draw &determinant parallelogram')
110         self.checkbox_draw_determinant_parallelogram.setToolTip(
111             'Shade the parallelogram representing the determinant of the matrix'
112         )
113         self.checkbox_draw_determinant_parallelogram.clicked.connect(self.update_gui)
114         self.dict_checkboxes['d'] = self.checkbox_draw_determinant_parallelogram
115
116         self.checkbox_draw_determinant_text = QCheckBox(self)
117         self.checkbox_draw_determinant_text.setText('Draw determinant &text')
118         self.checkbox_draw_determinant_text.setToolTip(
```

```
119                 'Write the text value of the determinant inside the parallelogram'
120             )
121             self.dict_checkboxes['t'] = self.checkbox_draw_determinant_text
122 
123             # === Arrange the widgets in QGroupBoxes
124 
125             # Animations
126 
127             self.hlay_animation_pause_length = QHBoxLayout()
128             self.hlay_animation_pause_length.addWidget(self.label_animation_pause_length)
129             self.hlay_animation_pause_length.addWidget(self.lineedit_animation_pause_length)
130 
131             self.vlay_groupbox_animations = QVBoxLayout()
132             self.vlay_groupbox_animations.setSpacing(20)
133             self.vlay_groupbox_animations.addWidget(self.checkbox_smoothen_determinant)
134             self.vlay_groupbox_animations.addWidget(self.checkbox_applicative_animation)
135             self.vlay_groupbox_animations.addLayout(self.hlay_animation_pause_length)
136 
137             self.groupbox_animations = QGroupBox('Animations', self)
138             self.groupbox_animations.setLayout(self.vlay_groupbox_animations)
139 
140             # Matrix info
141 
142             self.vlay_groupbox_matrix_info = QVBoxLayout()
143             self.vlay_groupbox_matrix_info.setSpacing(20)
144             self.vlay_groupbox_matrix_info.addWidget(self.checkbox_draw_determinant_parallelogram)
145             self.vlay_groupbox_matrix_info.addWidget(self.checkbox_draw_determinant_text)
146 
147             self.groupbox_matrix_info = QGroupBox('Matrix info', self)
148             self.groupbox_matrix_info.setLayout(self.vlay_groupbox_matrix_info)
149 
150             self.vlay_options.addWidget(self.groupbox_animations)
151             self.vlay_options.addWidget(self.groupbox_matrix_info)
152 
153             # Finally, we load the current settings and update the GUI
154             self.load_settings()
155             self.update_gui()
...
188         def keyPressEvent(self, event: QKeyEvent) -> None:
189             """Handle a ``QKeyEvent`` by manually activating toggling checkboxes.
190 
191             Qt handles these shortcuts automatically and allows the user to do ``Alt + Key``
192             to activate a simple shortcut defined with ``&``. However, I like to be able to
193             just hit ``Key`` and have the shortcut activate.
194             """
195             letter = event.text().lower()
196             key = event.key()
197 
198             if letter in self.dict_checkboxes:
199                 self.dict_checkboxes[letter].animateClick()
200 
201             # Return or keypad enter
202             elif key == 0x01000004 or key == 0x01000005:
203                 self.button_confirm.click()
204 
205             # Escape
206             elif key == 0x01000000:
207                 self.button_cancel.click()
208 
209             else:
210                 event.ignore()
```

3.6.8 Centering text in the determinant parallelogram

The text in the determinant parallelogram is the numerical value of the determinant. Currently, it's not centered. It's drawn by just writing the text at a point, chosen to be the centre of the parallelogram. The `QPainter` class uses this point as the start of the baseline of the text, so it's effectively the bottom left corner.

```
# 67d43a364ee2605b95b8caca9f1e4eb714cbb7c6
# src/lintrans/gui/plots/classes.py

142 class VectorGridPlot(BackgroundPlot):
...
419     def draw_determinant_text(self, painter: QPainter) -> None:
420         """Write the string value of the determinant in the middle of the parallelogram."""
421         painter.setPen(QPen(QColor(0, 0, 0), self.width_vector_line))
422         painter.drawText(
423             *self.canvas_coords(
424                 (self.point_i[0] + self.point_j[0]) / 2,
425                 (self.point_i[1] + self.point_j[1]) / 2
426             ),
427             f'{self.det:.2f}'
428         )
```

Obviously, this text will look better if it's centered. To do this, we can create a bounding rectangle around the parallelogram and get the painter to draw the text in the centre of that rectangle.

We build the rectangle by getting the coordinates of each vertex of the parallelogram. Then the top left corner is the minimum x coordinate with the maximum y coordinate, and the bottom right corner is the maximum x with the minimum y.

```
# 9550416c0b273b16c90eb8d6319f5e17493ef9a8
# src/lintrans/gui/plots/classes.py

142 class VectorGridPlot(BackgroundPlot):
...
419     def draw_determinant_text(self, painter: QPainter) -> None:
420         """Write the string value of the determinant in the middle of the parallelogram."""
421         painter.setPen(QPen(QColor(0, 0, 0), self.width_vector_line))
422
423         # We're building a QRect that encloses the determinant parallelogram
424         # Then we can center the text in this QRect
425         coords: list[tuple[float, float]] = [
426             (0, 0),
427             self.point_i,
428             self.point_j,
429             (
430                 self.point_i[0] + self.point_j[0],
431                 self.point_i[1] + self.point_j[1]
432             )
433         ]
434
435         xs = [t[0] for t in coords]
436         ys = [t[1] for t in coords]
437
438         top_left = QPoint(*self.canvas_coords(min(xs), max(ys)))
439         bottom_right = QPoint(*self.canvas_coords(max(xs), min(ys)))
440
441         rect = QRectF(top_left, bottom_right)
442
443         painter.drawText(
444             rect,
445             Qt.AlignHCenter | Qt.AlignVCenter,
446             f'{self.det:.2f}'
447         )
```

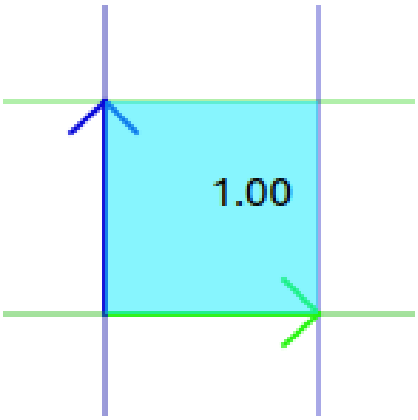


Figure 3.6.3: Text not centered.

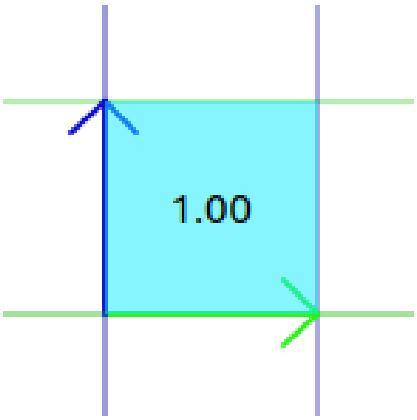


Figure 3.6.4: Text centered.

3.6.9 Defining matrices as expressions

Currently, you can "define" a matrix in terms of an expression, but it doesn't really define the matrix like that. Instead, it evaluates the expression immediately, and assigns that numerical result to the name you specified. It would be much better if the matrix could be actually defined as the expression, and then evaluated only when it needs to be used. Then, the user could have a matrix **M** defined as something like `0.5A^-1rot(45)B`, and it would always have that value, even if the user has changed the definition of **A** or **B** since defining **M**.

To do this, I'll have to completely change how matrices are stored and retrieved. The `MatrixWrapper` class contains a dictionary `self._matrices`, which currently maps `str` to `Optional[MatrixType]`, meaning that a matrix could be a 2×2 NumPy array, or nothing. I'm going to change this type to `Optional[Union[MatrixType, str]]`. This means that if a matrix exists, then it's either a 2×2 NumPy array or a string. We then check which one it is when we retrieve the matrix, and act accordingly. If it's an expression, then we evaluate and return the numerical result.

Here's the relevant parts of the old `MatrixWrapper` class:

```
# 9550416c0b273b16c90eb8d6319f5e17493ef9a8
# src/lintrans/matrices/wrapper.py

17  class MatrixWrapper:
...
35      def __init__(self):
36          """Initialise a :class:`MatrixWrapper` object with a dictionary of matrices which can be accessed."""
37          self._matrices: dict[str, Optional[MatrixType]] = {
38              'A': None, 'B': None, 'C': None, 'D': None,
39              'E': None, 'F': None, 'G': None, 'H': None,
40              'I': np.eye(2),  # I is always defined as the identity matrix
41              'J': None, 'K': None, 'L': None, 'M': None,
42              'N': None, 'O': None, 'P': None, 'Q': None,
43              'R': None, 'S': None, 'T': None, 'U': None,
44              'V': None, 'W': None, 'X': None, 'Y': None,
45              'Z': None
46          }
...
91      def __getitem__(self, name: str) -> Optional[MatrixType]:
92          """Get the matrix with the given name.
93
94          If it is a simple name, it will just be fetched from the dictionary. If the name is ``rot(x)``, with
95          a given angle in degrees, then we return a new matrix representing a rotation by that angle.
96
97          :param str name: The name of the matrix to get
98          :returns: The value of the matrix (may be None)
99          :rtype: Optional[MatrixType]
100
```

```
101             :raises NameError: If there is no matrix with the given name
102             """
103             # Return a new rotation matrix
104             if (match := re.match(r'rot\((-?\d*\.?\d*)\)', name)) is not None:
105                 return create_rotation_matrix(float(match.group(1)))
106 
107             if name not in self._matrices:
108                 raise NameError(f'Unrecognised matrix name "{name}"')
109 
110             # We copy the matrix before we return it so the user can't accidentally mutate the matrix
111             return copy(self._matrices[name])
112 
113         def __setitem__(self, name: str, new_matrix: Optional[MatrixType]) -> None:
114             """Set the value of matrix ``name`` with the new_matrix.
115 
116             :param str name: The name of the matrix to set the value of
117             :param Optional[MatrixType] new_matrix: The value of the new matrix (may be None)
118 
119             :raises NameError: If the name isn't a valid matrix name or is 'I'
120             :raises TypeError: If the matrix isn't a valid 2x2 NumPy array
121             """
122             if name not in self._matrices:
123                 raise NameError('Matrix name must be a single capital letter')
124 
125             if name == 'I':
126                 raise NameError('Matrix name cannot be "I"')
127 
128             if new_matrix is None:
129                 self._matrices[name] = None
130                 return
131 
132             if not is_matrix_type(new_matrix):
133                 raise TypeError('Matrix must be a 2x2 NumPy array')
134 
135             # All matrices must have float entries
136             a = float(new_matrix[0][0])
137             b = float(new_matrix[0][1])
138             c = float(new_matrix[1][0])
139             d = float(new_matrix[1][1])
140 
141             self._matrices[name] = np.array([[a, b], [c, d]])
142 
143         def is_valid_expression(self, expression: str) -> bool:
144             """Check if the given expression is valid, using the context of the wrapper.
145 
146             This method calls :func:`lintrans.matrices.parse.validate_matrix_expression`, but also
147             ensures that all the matrices in the expression are defined in the wrapper.
148 
149             :param str expression: The expression to validate
150             :returns: Whether the expression is valid in this wrapper
151             :rtype: bool
152             """
153             # Get rid of the transposes to check all capital letters
154             new_expression = expression.replace('^T', '').replace('^{T}', '')
155 
156             # Make sure all the referenced matrices are defined
157             for matrix in {x for x in new_expression if re.match('[A-Z]', x)}:
158                 if self[matrix] is None:
159                     return False
160 
161             return validate_matrix_expression(expression)
```

And here's the new version, which supports matrices defined as expressions:

```
# 01e866a74cf0f02ecba6438763d43e6eb90fe218
# src/lintrans/matrices/wrapper.py

17  class MatrixWrapper:
...
38      def __init__(self):
39          """Initialise a :class:`MatrixWrapper` object with a dictionary of matrices which can be accessed."""
```

```
40              self._matrices: dict[str, Optional[Union[MatrixType, str]]] = {
41                  'A': None, 'B': None, 'C': None, 'D': None,
42                  'E': None, 'F': None, 'G': None, 'H': None,
43                  'I': np.eye(2),  # I is always defined as the identity matrix
44                  'J': None, 'K': None, 'L': None, 'M': None,
45                  'N': None, 'O': None, 'P': None, 'Q': None,
46                  'R': None, 'S': None, 'T': None, 'U': None,
47                  'V': None, 'W': None, 'X': None, 'Y': None,
48                  'Z': None
49              }
...
94          def __getitem__(self, name: str) -> Optional[MatrixType]:
95              """Get the matrix with the given name.
96
97              If it is a simple name, it will just be fetched from the dictionary. If the name is ``rot(x)``, with
98              a given angle in degrees, then we return a new matrix representing a rotation by that angle.
99
100             :param str name: The name of the matrix to get
101             :returns: The value of the matrix (may be None)
102             :rtype: Optional[MatrixType]
103
104             :raises NameError: If there is no matrix with the given name
105             """
106             # Return a new rotation matrix
107             if (match := re.match(r'rot\((-?\d*\.?\d*)\)', name)) is not None:
108                 return create_rotation_matrix(float(match.group(1)))
109
110             if name not in self._matrices:
111                 raise NameError(f'Unrecognised matrix name "{name}"')
112
113             # We copy the matrix before we return it so the user can't accidentally mutate the matrix
114             matrix = copy(self._matrices[name])
115
116             if isinstance(matrix, str):
117                 return self.evaluate_expression(matrix)
118
119             return matrix
120
121         def __setitem__(self, name: str, new_matrix: Optional[Union[MatrixType, str]]) -> None:
122             """Set the value of matrix ``name`` with the new_matrix.
123
124             :param str name: The name of the matrix to set the value of
125             :param Optional[Union[MatrixType, str]] new_matrix: The value of the new matrix (may be None)
126
127             :raises NameError: If the name isn't a legal matrix name
128             :raises TypeError: If the matrix isn't a valid 2x2 NumPy array
129             """
130             if not (name in self._matrices and name != 'I'):
131                 raise NameError('Matrix name is illegal')
132
133             if new_matrix is None:
134                 self._matrices[name] = None
135                 return
136
137             if isinstance(new_matrix, str):
138                 if self.is_valid_expression(new_matrix):
139                     self._matrices[name] = new_matrix
140                     return
141
142             if not is_matrix_type(new_matrix):
143                 raise TypeError('Matrix must be a 2x2 NumPy array')
144
145             # All matrices must have float entries
146             a = float(new_matrix[0][0])
147             b = float(new_matrix[0][1])
148             c = float(new_matrix[1][0])
149             d = float(new_matrix[1][1])
150
151             self._matrices[name] = np.array([[a, b], [c, d]])
152
153         def get_expression(self, name: str) -> Optional[str]:
154             """If the named matrix is defined as an expression, return that expression, else return None.
155
```

```
156             :param str name: The name of the matrix
157             :returns: The expression that the matrix is defined as, or None
158             :rtype: Optional[str]
159
160             :raises NameError: If the name is invalid
161             """
162             if name not in self._matrices:
163                 raise NameError('Matrix must have a legal name')
164
165             matrix = self._matrices[name]
166             if isinstance(matrix, str):
167                 return matrix
168
169             return None
170
171         def is_valid_expression(self, expression: str) -> bool:
172             """Check if the given expression is valid, using the context of the wrapper.
173
174             This method calls :func:`lintrans.matrices.parse.validate_matrix_expression`, but also
175             ensures that all the matrices in the expression are defined in the wrapper.
176
177             :param str expression: The expression to validate
178             :returns: Whether the expression is valid in this wrapper
179             :rtype: bool
180             """
181             # Get rid of the transposes to check all capital letters
182             new_expression = expression.replace('^T', '').replace('^{T}', '')
183
184             # Make sure all the referenced matrices are defined
185             for matrix in {x for x in new_expression if re.match('[A-Z]', x)}:
186                 if self[matrix] is None:
187                     return False
188
189                 if (expr := self.get_expression(matrix)) is not None:
190                     if not self.is_valid_expression(expr):
191                         return False
192
193             return validate_matrix_expression(expression)
```

One of the more subtle things added here is on lines 189-191. When checking if an expression is valid in the context of the wrapper, we have to make sure all the referenced matrices are actually defined, but if any of those matrices are defined as an expression, then obviously that expression has to be valid as well. This recursion means that all references to matrices must be valid, even traversing down through matrices that are defined as expressions.

I also added some unit tests to automatically test this new feature.

```
# 239bcbfd1dde3f7623318d03e8544dd67dc02e3d
# tests/matrices/matrix_wrapper/test_setitem_and_getitem.py

42  def test_set_expression(test_wrapper: MatrixWrapper) -> None:
43      """Test that MatrixWrapper.__setitem__() can accept a valid expression."""
44      test_wrapper['N'] = 'A^2'
45      test_wrapper['O'] = 'BA+2C'
46      test_wrapper['P'] = 'E^T'
47      test_wrapper['Q'] = 'C^-1B'
48      test_wrapper['R'] = 'A^{2}3B'
49      test_wrapper['S'] = 'N^-1'
50      test_wrapper['T'] = 'PQP^-1'
51
52      with pytest.raises(TypeError):
53          test_wrapper['U'] = 'A+1'
54          test_wrapper['V'] = 'K'
55          test_wrapper['W'] = 'L^2'
56          test_wrapper['X'] = 'M^-1'
57
58
59  def test_simple_dynamic_evaluation(test_wrapper: MatrixWrapper) -> None:
60      """Test that expression-defined matrices are evaluated dynamically."""
61      test_wrapper['N'] = 'A^2'
```

```
        test_wrapper['O'] = '4B'
        test_wrapper['P'] = 'A+C'

        assert (test_wrapper['N'] == test_wrapper.evaluate_expression('A^2')).all()
        assert (test_wrapper['O'] == test_wrapper.evaluate_expression('4B')).all()
        assert (test_wrapper['P'] == test_wrapper.evaluate_expression('A+C')).all()

        assert (test_wrapper.evaluate_expression('N^2 + 3O') ==
                la.matrix_power(test_wrapper.evaluate_expression('A^2'), 2) +
                3 * test_wrapper.evaluate_expression('4B')
                ).all()
        assert (test_wrapper.evaluate_expression('P^-1 - 3NO^2') ==
                la.inv(test_wrapper.evaluate_expression('A+C')) -
                (3 * test_wrapper.evaluate_expression('A^2')) @
                la.matrix_power(test_wrapper.evaluate_expression('4B'), 2)
                ).all()

        test_wrapper['A'] = np.array([
            [19, -21.5],
            [84, 96.572]
        ])
        test_wrapper['B'] = np.array([
            [-0.993, 2.52],
            [1e10, 0]
        ])
        test_wrapper['C'] = np.array([
            [0, 19512],
            [1.414, 19]
        ])

        assert (test_wrapper['N'] == test_wrapper.evaluate_expression('A^2')).all()
        assert (test_wrapper['O'] == test_wrapper.evaluate_expression('4B')).all()
        assert (test_wrapper['P'] == test_wrapper.evaluate_expression('A+C')).all()

        assert (test_wrapper.evaluate_expression('N^2 + 3O') ==
                la.matrix_power(test_wrapper.evaluate_expression('A^2'), 2) +
                3 * test_wrapper.evaluate_expression('4B')
                ).all()
        assert (test_wrapper.evaluate_expression('P^-1 - 3NO^2') ==
                la.inv(test_wrapper.evaluate_expression('A+C')) -
                (3 * test_wrapper.evaluate_expression('A^2')) @
                la.matrix_power(test_wrapper.evaluate_expression('4B'), 2)
                ).all()


    def test_recursive_dynamic_evaluation(test_wrapper: MatrixWrapper) -> None:
        """Test that dynamic evaluation works recursively."""
        test_wrapper['N'] = 'A^2'
        test_wrapper['O'] = '4B'
        test_wrapper['P'] = 'A+C'

        test_wrapper['Q'] = 'N^-1'
        test_wrapper['R'] = 'P-4O'
        test_wrapper['S'] = 'NOP'

        assert test_wrapper['Q'] == pytest.approx(test_wrapper.evaluate_expression('A^-2'))
        assert test_wrapper['R'] == pytest.approx(test_wrapper.evaluate_expression('A + C - 16B'))
        assert test_wrapper['S'] == pytest.approx(test_wrapper.evaluate_expression('A^{2}4BA + A^{2}4BC'))


    def test_set_identity_error(new_wrapper: MatrixWrapper) -> None:
        """Test that MatrixWrapper().__setitem__() raises a NameError when trying to assign to I."""
        with pytest.raises(NameError):
            new_wrapper['I'] = test_matrix


    def test_set_name_error(new_wrapper: MatrixWrapper) -> None:
        """Test that MatrixWrapper().__setitem__() raises a NameError when trying to assign to an invalid name."""
        with pytest.raises(NameError):
            new_wrapper['bad name'] = test_matrix
            new_wrapper['123456'] = test_matrix
            new_wrapper['Th15 Is an 1nV@l1D n@m3'] = test_matrix
            new_wrapper['abc'] = test_matrix
```

```
        new_wrapper['a'] = test_matrix


def test_set_type_error(new_wrapper: MatrixWrapper) -> None:
    """Test that MatrixWrapper().__setitem__() raises a TypeError when trying to set a non-matrix."""
    with pytest.raises(TypeError):
        new_wrapper['M'] = 12
        new_wrapper['M'] = [1, 2, 3, 4, 5]
        new_wrapper['M'] = [[1, 2], [3, 4]]
        new_wrapper['M'] = True
        new_wrapper['M'] = 24.3222
        new_wrapper['M'] = 'This is totally a matrix, I swear'
        new_wrapper['M'] = MatrixWrapper
        new_wrapper['M'] = MatrixWrapper()
        new_wrapper['M'] = np.array([[1, 2, 3], [4, 5, 6], [7, 8, 9]])
        new_wrapper['M'] = np.eye(100)


# ea00703f19c13af86c39ae30170569819937fa31
# tests/matrices/matrix_wrapper/test_misc.py

"""Test the miscellaneous methods of the MatrixWrapper class."""

from lintrans.matrices import MatrixWrapper


def test_get_expression(test_wrapper: MatrixWrapper) -> None:
    """Test the get_expression method of the MatrixWrapper class."""
    test_wrapper['N'] = 'A^2'
    test_wrapper['O'] = '4B'
    test_wrapper['P'] = 'A+C'

    test_wrapper['Q'] = 'N^-1'
    test_wrapper['R'] = 'P-4O'
    test_wrapper['S'] = 'NOP'

    assert test_wrapper.get_expression('A') is None
    assert test_wrapper.get_expression('B') is None
    assert test_wrapper.get_expression('C') is None
    assert test_wrapper.get_expression('D') is None
    assert test_wrapper.get_expression('E') is None
    assert test_wrapper.get_expression('F') is None
    assert test_wrapper.get_expression('G') is None

    assert test_wrapper.get_expression('N') == 'A^2'
    assert test_wrapper.get_expression('O') == '4B'
    assert test_wrapper.get_expression('P') == 'A+C'

    assert test_wrapper.get_expression('Q') == 'N^-1'
    assert test_wrapper.get_expression('R') == 'P-4O'
    assert test_wrapper.get_expression('S') == 'NOP'
```

```
(lintrans) dyson@Harold-Ubuntu:~/repos/lintrans [main *]
$ pytest -v
============================================================ test session starts =============================================================
platform linux -- Python 3.11.0, pytest-7.2.1, pluggy-1.0.0 -- /home/dyson/temp/lintrans/venv/bin/python
cachedir: .pytest_cache
rootdir: /home/dyson/temp/lintrans, configfile: pyproject.toml, testpaths: tests
collected 29 items

tests/gui/test_dialog_utility_functions.py::test_is_valid_float[inputs0-True] PASSED                                                  [  3%]
tests/gui/test_dialog_utility_functions.py::test_is_valid_float[inputs1-False] PASSED                                                 [  6%]
tests/gui/test_dialog_utility_functions.py::test_round_float PASSED                                                                   [ 10%]
tests/matrices/test_parse_and_validate_expression.py::test_validate_matrix_expression[inputs0-True] PASSED                            [ 13%]
tests/matrices/test_parse_and_validate_expression.py::test_validate_matrix_expression[inputs1-False] PASSED                           [ 17%]
tests/matrices/test_parse_and_validate_expression.py::test_parse_matrix_expression PASSED                                             [ 20%]
tests/matrices/test_rotation_matrices.py::test_create_rotation_matrix PASSED                                                          [ 24%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_simple_matrix_addition PASSED                                         [ 27%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_simple_two_matrix_multiplication PASSED                               [ 31%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_identity_multiplication PASSED                                       [ 34%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_simple_three_matrix_multiplication PASSED                             [ 37%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_matrix_inverses PASSED                                                [ 41%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_matrix_powers PASSED                                                  [ 44%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_matrix_transpose PASSED                                               [ 48%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_rotation_matrices PASSED                                              [ 51%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_multiplication_and_addition PASSED                                    [ 55%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_complicated_expressions PASSED                                        [ 58%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_value_errors PASSED                                                   [ 62%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_linalgerror PASSED                                                    [ 65%]
tests/matrices/matrix_wrapper/test_misc.py::test_get_expression PASSED                                                                [ 68%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_basic_get_matrix PASSED                                               [ 72%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_get_name_error PASSED                                                 [ 75%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_basic_set_matrix PASSED                                               [ 79%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_set_expression PASSED                                                 [ 82%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_simple_dynamic_evaluation PASSED                                      [ 86%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_recursive_dynamic_evaluation PASSED                                   [ 89%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_set_identity_error PASSED                                             [ 93%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_set_name_error PASSED                                                 [ 96%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_set_type_error PASSED                                                 [100%]

============================================================ 29 passed in 0.36s ==============================================================
```

Figure 3.6.5: Running `pytest` with the new tests

I then had to fix a small bug where the `DefineAsAnExpressionDialog` would evaluate the expression before assigning it, so I had to change that to just assign the test instead.

```
# 54e10dbfd3a1f3a962955c7fa3908848f5bd95b0
# src/lintrans/gui/dialogs/define_new_matrix.py

343 class DefineAsAnExpressionDialog(DefineDialog):
...
388     def confirm_matrix(self) -> None:
389         """Evaluate the matrix expression and assign its value to the name in the combo box."""
390         self.matrix_wrapper[self.selected_letter] = self.lineedit_expression_box.text()
391         self.accept()
```

I also created a virtual method in the `DefineDialog` superclass, which standardised how dialogs load a matrix when it's selected in the drop-down. The numerical and visual definition dialogs already did this, but it was inconsistent, so I made it the same across all subclasses, and added it to the expression dialog.

```
# d1b60b20666ab9297cdbf675b6226587fd2e417f
# src/lintrans/gui/dialogs/define_new_matrix.py

 59 class DefineDialog(QDialog):
...
 69     def __init__(self, matrix_wrapper: MatrixWrapper, *args, **kwargs):
...
 98         self.combobox_letter = QtWidgets.QComboBox(self)
 99
100         for letter in ALPHABET_NO_I:
101             self.combobox_letter.addItem(letter)
102
103         self.combobox_letter.activated.connect(self.load_matrix)
...
134     def load_matrix(self, index: int) -> None:
135         """Load the selected matrix into the dialog.
136
137         This method is optionally able to be overridden. If it is not overridden,
138         then no matrix is loaded when selecting a name.
139
140         We have this method in the superclass so that we can define it as the slot
141         for the combobox.changed signal in this constructor, rather than having to
```

```
142             define that in the constructor of every subclass.
143             """
...
352     class DefineAsAnExpressionDialog(DefineDialog):
...
386         def load_matrix(self, index: int) -> None:
387             """If the selected matrix is defined an expression, load that expression into the box."""
388             name = ALPHABET_NO_I[index]
389 
390             if (expr := self.matrix_wrapper.get_expression(name)) is not None:
391                 self.lineedit_expression_box.setText(expr)
392             else:
393                 self.lineedit_expression_box.setText('')
```

Unfortunately, my initial implementation of this had a few bugs, and I noticed a few hours later that if you first define **A** as anything concrete, then you can define **A** to be the expression `A`. Then, when you put it in the expression box, the app just crashes. This is because it recurs forever, since it doesn't realise that the definition of **A** is self-referential[14].

To fix this, I can check that the expression is valid and that it doesn't contain itself before assigning the expression to the matrix name.

```
# 742e0955e344deab2c9302ba9a6c7298ec4583d4
# src/lintrans/gui/dialogs/define_new_matrix.py

362     class DefineAsAnExpressionDialog(DefineDialog):
...
393         def update_confirm_button(self) -> None:
...
395             text = self.lineedit_expression_box.text()
396             valid_expression = self.matrix_wrapper.is_valid_expression(text)
397 
398             self.button_confirm.setEnabled(valid_expression and self.selected_letter not in text)
```

I also added this logic directly to the wrapper, so that there was no risk of me creating this kind of bug elsewhere.

```
# e56a5a90034f8335b046dd1bf76321eb48892050
# src/lintrans/matrices/wrapper.py

 17     class MatrixWrapper:
...
125         def __setitem__(self, name: str, new_matrix: Optional[Union[MatrixType, str]]) -> None:
...
145             if isinstance(new_matrix, str):
146                 if self.is_valid_expression(new_matrix):
147                     if name not in new_matrix:
148                         self._matrices[name] = new_matrix
149                         return
150                     else:
151                         raise ValueError('Cannot define a matrix recursively')
```

While I was working with expressions so much, I realised that defining a matrix as a rotation was a bit redundant when you can just use an expression like `rot(45)`. I spoke to the teacher that's going to use `lintrans` when it's finished, and she said that radians aren't really needed. The radians checkbox was the only unique part of the `DefineAsARotationDialog` class. Since it's not important, I decided to remove the whole dialog.

[14] Obviously it doesn't actually recur forever, but Python stops recursion after 1000 levels and crashes the program.

3.7 Implementing eigenstuffs

It's not universal, but the word 'eigenstuffs' is common enough in mathematics that I'm comfortable using it here to mean eigenvalues, eigenvectors, and eigenlines, where an eigenline is the span of an eigenvector.

3.7.1 Drawing eigenvectors

An eigenvector $\mathbf{v}$ of a matrix $\mathbf{M}$ is a vector that satisfies the equation $\mathbf{Mv} = \lambda\mathbf{v}$ for some scalar λ. Thankfully, I don't have to worry about actually computing $\mathbf{v}$ or λ, since NumPy has the `numpy.linalg.eig()` function[30].

This function takes a square matrix and returns an array of eigenvalues (λ), and a matrix of their associated eigenvectors ($\mathbf{v}$). Some matrices don't have any real eigenvalues, but all 2×2 matrices will have 2 (possibly complex) eigenvalues, as a direct consequence of the Fundamental Theorem of Algebra[15]. We don't want to try to render an eigenvector if its eigenvalue is complex, so we have to check and only render the real ones. Python doesn't distinguish really between `float` and `complex` types, so we can just check the `.imag` property no matter what. If it's 0, then we keep the eigenvalue. NumPy normalizes the eigenvectors to have a length of 1, but I'd much prefer them to have a length equal to their associated eigenvalue. To do that, we can just multiply the eigenvectors by their eigenvalues.

We then just draw a vector, consisting of a line and an arrowhead, from the origin to the extended eigenvector.

```
# b8614334de5cba4b1a6d92508b08fa8bd2fe77c0
# src/lintrans/gui/plots/classes.py

142 class VectorGridPlot(BackgroundPlot):
...
151     def __init__(self, *args, **kwargs):
...
163         self.colour_eigen = QColor('#fff900')
...
450     def draw_eigenvectors(self, painter: QPainter) -> None:
451         """Draw the eigenvectors of the displayed matrix transformation."""
452         painter.setPen(QPen(self.colour_eigen, self.width_vector_line))
453
454         values, vectors = np.linalg.eig(self.matrix)
455         vectors = vectors.T
456
457         for value, vector in zip(values, vectors):
458             x = value * vector[0]
459             y = value * vector[1]
460
461             if x.imag != 0 or y.imag != 0:
462                 continue
463
464             painter.drawLine(*self.canvas_origin, *self.canvas_coords(x, y))
465             self.draw_arrowhead_away_from_origin(painter, (x, y))


# b8614334de5cba4b1a6d92508b08fa8bd2fe77c0
# src/lintrans/gui/plots/widgets.py

 13 class VisualizeTransformationWidget(VectorGridPlot):
...
 42     def paintEvent(self, event: QPaintEvent) -> None:
...
 58         self.draw_eigenvectors(painter)
```

[15] $\mathbf{Mv} = \lambda\mathbf{v} \implies \mathbf{Mv} = \lambda\mathbf{Iv} \implies (\mathbf{M} - \lambda\mathbf{I})\mathbf{v} = \mathbf{0} \implies \det(\mathbf{M} - \lambda\mathbf{I}) = 0$ (since we only want non-zero vectors)
$\implies \begin{vmatrix} a-\lambda & b \\ c & d-\lambda \end{vmatrix} = 0 \implies (a-\lambda)(d-\lambda) - bc = 0 \implies \lambda^2 - (a+d)\lambda + (ad-bc) = 0$
$\implies \lambda$ has 2 solutions in $\mathbb{C}$ by the Fundamental Theorem of Algebra[15]

At this point in development, I didn't particularly care about the colours of various elements. It was more important to get things working first, so I ended up choosing this horrible yellow for the eigenvectors. It's clearly an awful choice for text, and it's not very good for the eigenvectors either, since it makes them hard to see against the white background. I wasn't really considering the usability features discussed in §2.4, but since I was the only user, and changing a few colours later on wouldn't be much work, I wasn't worried about it.

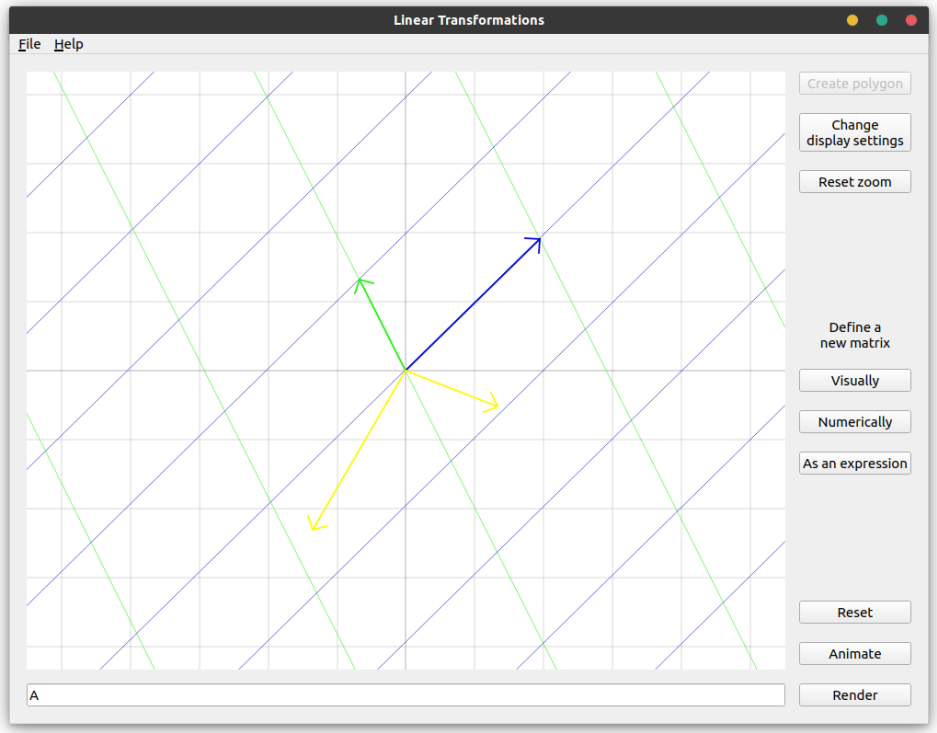


Figure 3.7.1: The eigenvectors being displayed for an arbitrary matrix

3.7.2 Adding display settings for eigenvectors

Once I'd got the eigenvectors working and being drawn, I wanted to be able to turn them on and off from the display settings. This was a simple case of just adding it to the `DisplaySettings` dataclass, adding the checkbox to the dialog, and only drawing the eigenvectors if this display setting is true.

```
# 3ebb5997a7a887e751b5f4f717aa5161ed013e62
# src/lintrans/gui/settings.py

 9  class DisplaySettings:
...
41      draw_eigenvectors: bool = False
42      """This controls whether we should draw the eigenvectors of the transformation."""


# 3ebb5997a7a887e751b5f4f717aa5161ed013e62
# src/lintrans/gui/dialogs/settings.py

63  class DisplaySettingsDialog(SettingsDialog):
...
66      def __init__(self, display_settings: DisplaySettings, *args, **kwargs):
...
123         self.checkbox_draw_eigenvectors = QCheckBox(self)
124         self.checkbox_draw_eigenvectors.setText('Draw &eigenvectors')
125         self.checkbox_draw_eigenvectors.setToolTip('Draw the eigenvectors of the transformations')
126         self.dict_checkboxes['e'] = self.checkbox_draw_eigenvectors
```

```
# 3ebb5997a7a887e751b5f4f717aa5161ed013e62
# src/lintrans/gui/plots/widgets.py

13  class VisualizeTransformationWidget(VectorGridPlot):
...
42      def paintEvent(self, event: QPaintEvent) -> None:
...
58          if self.display_settings.draw_eigenvectors:
59              self.draw_eigenvectors(painter)
```

3.7.3 Refactoring drawing vectors

Since I've now got several drawing methods that involve drawing vectors, I thought I should factor out this functionality into a separate utility method which I could call from all these places.

```
# 754eba0318a682b068a8a5d5ca451decbaa204ce
# src/lintrans/gui/plots/classes.py

142 class VectorGridPlot(BackgroundPlot):
...
388     def draw_position_vector(self, painter: QPainter, point: tuple[float, float], colour: QColor) -> None:
389         """Draw a vector from the origin to the given point.
390
391         :param QPainter painter: The ``QPainter`` object to use to draw the arrowheads with
392         :param point: The tip of the position vector in grid coords
393         :type point: tuple[float, float]
394         :param QColor colour: The colour to draw the position vector in
395         """
396         painter.setPen(QPen(colour, self.width_vector_line))
397         painter.drawLine(*self.canvas_origin, *self.canvas_coords(*point))
398         self.draw_arrowhead_away_from_origin(painter, point)
399
400     def draw_basis_vectors(self, painter: QPainter) -> None:
401         """Draw arrowheads at the tips of the basis vectors.
402
403         :param QPainter painter: The ``QPainter`` object to use to draw the arrowheads with
404         """
405         self.draw_position_vector(painter, self.point_i, self.colour_i)
406         self.draw_position_vector(painter, self.point_j, self.colour_j)
...
454     def draw_eigenvectors(self, painter: QPainter) -> None:
455         """Draw the eigenvectors of the displayed matrix transformation."""
456         values, vectors = np.linalg.eig(self.matrix)
457         vectors = vectors.T
458
459         for value, vector in zip(values, vectors):
460             x = value * vector[0]
461             y = value * vector[1]
462
463             if x.imag != 0 or y.imag != 0:
464                 continue
465
466             self.draw_position_vector(painter, (x, y), self.colour_eigen)
```

When I was testing this refactor, I realised that the `draw_transformed_grid()` method originally drew the bodies of the basis vectors and the caller had to draw the arrowheads separately. This is silly and was never planned that way; it was an unfortunate consequence of implementing the lines and arrowheads at different times. But now after this refactor, the caller has to call `draw_basis_vectors()` to draw the whole basis vectors. So I had to add this call to `VisualizeTransformationWidget.paintEvent()` and `DefineVisuallyWidget.paintEvent()` in `src/lintrans/gui/plots/widgets.py` and remove the calls to `draw_vector_arrowheads()`.

3.7.4 Adding eigenlines

Drawing some eigenvectors that point in a general direction is fine, but drawing the whole span of the vector would be much more useful. These spans are called eigenlines, and are just lines in the direction of the vector. To implement these, I knew I would have to get the eigenvalues and eigenvectors, zip them, and iterate over them like I did in §3.7.1. To make this simpler, I decided to factor out this zipping into a separate `self.eigs` property[16].

```
# e1606f1e45ba93102dddb74b45ab22649a63fa53
# src/lintrans/gui/plots/classes.py

144 class VectorGridPlot(BackgroundPlot):
...
187     @property
188     def eigs(self) -> Iterable[tuple[float, NDArray[(1, 2), Float]]]:
189         """Return the eigenvalues and eigenvectors zipped together to be iterated over.
190
191         :rtype: Iterable[tuple[float, NDArray[(1, 2), Float]]]
192         """
193         values, vectors = np.linalg.eig(self.matrix)
194         return zip(values, vectors.T)
...
465     def draw_eigenvectors(self, painter: QPainter) -> None:
466         """Draw the eigenvectors of the displayed matrix transformation."""
467         for value, vector in self.eigs:
468             x = value * vector[0]
469             y = value * vector[1]
470
471             if x.imag != 0 or y.imag != 0:
472                 continue
473
474             self.draw_position_vector(painter, (x, y), self.colour_eigen)
```

I could then create a new method to find the gradient of the vector line and draw an orthogonal or oblique line respectively. Like before, we only want to render the eigenlines for real-valued eigenvectors, so we have to check their imaginary part.

```
# 8d4d41fc4780cc037be39a0e574158e6cd34e997
# src/lintrans/gui/plots/classes.py

144 class VectorGridPlot(BackgroundPlot):
...
476     def draw_eigenlines(self, painter: QPainter) -> None:
477         """Draw the eigenlines (invariant lines).
478
479         :param QPainter painter: The painter to draw the lines with
480         """
481         painter.setPen(QPen(self.colour_eigen, self.width_transformed_grid))
482
483         for value, vector in self.eigs:
484             if value.imag != 0:
485                 continue
486
487             x, y = vector
488
489             if x == 0:
490                 x_mid = int(self.width() / 2)
491                 painter.drawLine(x_mid, 0, x_mid, self.height())
492
493             elif y == 0:
494                 y_mid = int(self.height() / 2)
495                 painter.drawLine(0, y_mid, self.width(), y_mid)
496
497             else:
498                 self.draw_oblique_line(painter, y / x, 0)
```

[16] A `@property` in Python is a value on a class which is dynamically evaluated only when it's needed. It functions just like a method with no arguments, but has more concise syntax for the caller.

I then just had to put these new eigenlines behind a display setting.

```
# 12cfabde606ebd3d48b2c3efaad0412f6100c3c5
# src/lintrans/gui/settings.py

 9  class DisplaySettings:
...
44      draw_eigenlines: bool = False
45      """This controls whether we should draw the eigenlines of the transformation."""


# 12cfabde606ebd3d48b2c3efaad0412f6100c3c5
# src/lintrans/gui/dialogs/settings.py

63  class DisplaySettingsDialog(SettingsDialog):
...
66      def __init__(self, display_settings: DisplaySettings, *args, **kwargs):
...
128         self.checkbox_draw_eigenlines = QCheckBox(self)
129         self.checkbox_draw_eigenlines.setText('Draw eigen&lines')
130         self.checkbox_draw_eigenlines.setToolTip('Draw the eigenlines (invariant lines) of the transformations')
131         self.dict_checkboxes['l'] = self.checkbox_draw_eigenlines


# 12cfabde606ebd3d48b2c3efaad0412f6100c3c5
# src/lintrans/gui/plots/widgets.py

13  class VisualizeTransformationWidget(VectorGridPlot):
...
42      def paintEvent(self, event: QPaintEvent) -> None:
...
58          if self.display_settings.draw_eigenlines:
59              self.draw_eigenlines(painter)
```

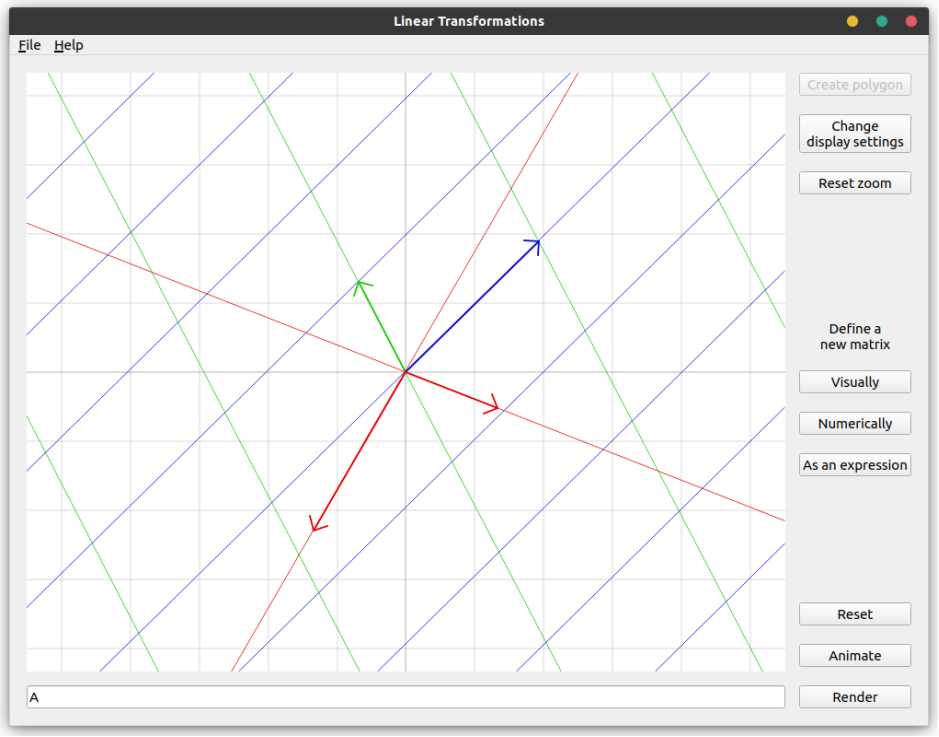


Figure 3.7.2: The eigenvectors being displayed for a similar matrix as in Figure 3.7.1

3.7.5 Adding eigenvalues as text

The next thing I wanted to do was tell the user what the actual eigenvalue numbers were. I decided the best way to do this would be to have the eigenvectors labelled with their associated eigenvalues.

To align the text properly, I decided to do something similar to what I did for determinants in §3.6.8. There, I enclosed the parallelogram in a rectangle and drew the text in the centre of it. Here, I decided to create a rectangle based on which quadrant the eigenvector was in. The rectangle would have corners of the tip of the eigenvector, and the appropriate corner of the viewport. I also had to choose a suitable alignment for each quadrant, so that the text would appear in the correct corner of the rectangle, next to the tip of the eigenvector.

```
# a7e9a17ecdb2a585e9f766b13029116d7ba29bdc
# src/lintrans/gui/plots/classes.py
```

```
144 class VectorGridPlot(BackgroundPlot):
...
466     def draw_eigenvectors(self, painter: QPainter) -> None:
467         """Draw the eigenvectors of the displayed matrix transformation."""
468         for value, vector in self.eigs:
469             x = value * vector[0]
470             y = value * vector[1]
471
472             if x.imag != 0 or y.imag != 0:
473                 continue
474
475             self.draw_position_vector(painter, (x, y), self.colour_eigen)
476
477             # Now we need to draw the eigenvalue at the tip of the eigenvector
478
479             offset = 3
480             top_left: QPoint
481             bottom_right: QPoint
482             alignment_flags: int
483
484             if x >= 0 and y >= 0:  # Q1
485                 top_left = QPoint(self.canvas_x(x) + offset, 0)
486                 bottom_right = QPoint(self.width(), self.canvas_y(y) - offset)
487                 alignment_flags = Qt.AlignLeft | Qt.AlignBottom
488
489             elif x < 0 and y >= 0:  # Q2
490                 top_left = QPoint(0, 0)
491                 bottom_right = QPoint(self.canvas_x(x) - offset, self.canvas_y(y) - offset)
492                 alignment_flags = Qt.AlignRight | Qt.AlignBottom
493
494             elif x < 0 and y < 0:  # Q3
495                 top_left = QPoint(0, self.canvas_y(y) + offset)
496                 bottom_right = QPoint(self.canvas_x(x) - offset, self.height())
497                 alignment_flags = Qt.AlignRight | Qt.AlignTop
498
499             else:  # Q4
500                 top_left = QPoint(self.canvas_x(x) + offset, self.canvas_y(y) + offset)
501                 bottom_right = QPoint(self.width(), self.height())
502                 alignment_flags = Qt.AlignLeft | Qt.AlignTop
503
504             painter.setPen(QPen(self.colour_text, self.width_vector_line))
505             painter.drawText(QRectF(top_left, bottom_right), alignment_flags, f'{value:.2f}')
```

3.7.6 A tiny UI change

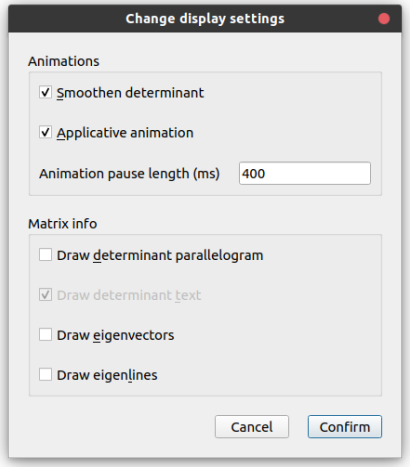


Figure 3.7.3: The display settings

This bit isn't really related to eigenvectors, but it's a tiny change that doesn't really have a good place anywhere else, and it fits roughly here chronologically.

I really liked the groupboxes used in the display settings (left) and I'd quite like to enclose the matrix definition buttons in their own groupbox to separate them from the rest of the UI and better associate them with the label above them. This was a trivial addition.

```
# 90425137edd4596219ab564ccbeccd65b5754008
# src/lintrans/gui/main_window.py

27  class LintransMainWindow(QMainWindow):
...
33      def __init__(self):
...
173         self.vlay_define_new_matrix = QVBoxLayout()
174         self.vlay_define_new_matrix.setSpacing(20)
175         self.vlay_define_new_matrix.addWidget(self.button_define_visually)
176         self.vlay_define_new_matrix.addWidget(self.button_define_numerically)
177         self.vlay_define_new_matrix.addWidget(self.button_define_as_expression)
178
179         self.groupbox_define_new_matrix = QtWidgets.QGroupBox('Define a new matrix', self)
180         self.groupbox_define_new_matrix.setLayout(self.vlay_define_new_matrix)
...
226         self.vlay_right.addWidget(self.groupbox_define_new_matrix)
```

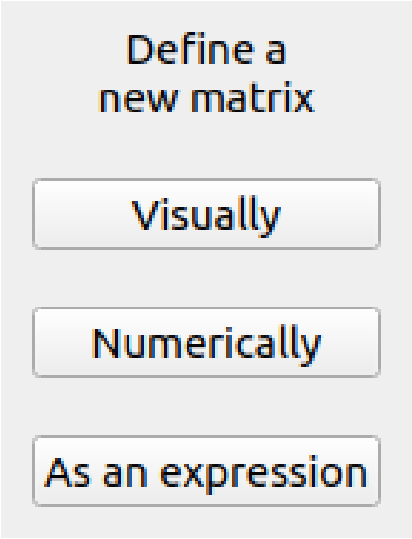


Figure 3.7.4: The old matrix definition buttons

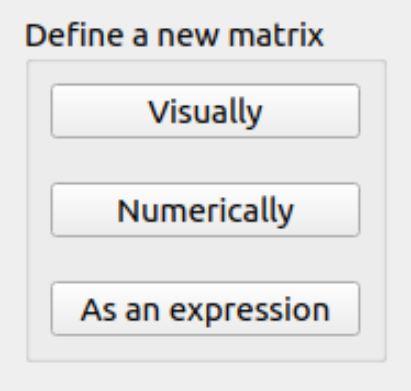


Figure 3.7.5: The new matrix definition buttons

3.8 Fumbling with SemVer

3.8.1 The first version numbers

At this point, I've been developing lintrans for quite a while, but I don't have any kind of version numbers yet. I wanted to fix this, to keep track of versions through history. SemVer[52] is a system of numbering versions of software that ensures compatibility across versions and gives semantic meaning to the version numbers.

My first foray into using SemVer was to declare `lintrans` at this point to be `0.1.0-alpha`. In retrospect, these early versions don't make much sense. I didn't release anything for anyone else to use until version `0.3.0`, so everything before then doesn't make much sense and should probably just be ignored.

I then made a few adjustments to syntax and documentation before declaring version `0.1.1-alpha` just over 24 hours later. This one was completely unnecessary in hindsight and I think I was just excited about being able to tag git commits. Additionally, there is a `__version__` variable in the root of the package, and the value of this variable is still `"0.1.0-alpha"` at the `v0.1.1-alpha` tag because I forgot to update it before I tagged the commit, and I didn't know how to fix it at the time.

3.8.2 Licensing

Using version numbers reminded me of licensing. I was already using the GNU GPLv3[19] for `lintrans` and most of my other projects, so I just wanted to add the copyright notice to all the source files of the project, as per the license. I already had the `COPYING` file in the project root with the full license, as required.

The notice looks like this[17]:

```
1  # lintrans - The linear transformation visualizer
2  # Copyright (C) 2021-2022 D. Dyson (DoctorDalek1963)
3
4  # This program is licensed under GNU GPLv3, available here:
5  # <https://www.gnu.org/licenses/gpl-3.0.html>
```

3.8.3 Making the package executable

So far, I'd been running the program by running a separate script called `run_gui.py`, but Python lets you make a package executable by creating a file called `__main__.py` in the project root. You can then run it by using the command `python -m package_name`. This will make the whole program more cohesive by integrating the execution into the same directory as the source library code. I just moved the script here and changed its docstring a little bit.

```
   # 847cdf61f64b30e81edf0821b7a8d2eb060fb825
   # src/lintrans/__main__.py

9  """This module very simply runs the app by calling :func:`lintrans.gui.main_window.main`.
10
11 This allows the user to run the app like ``python -m lintrans`` from the command line.
12 """
13
14 import sys
15
16 from lintrans.gui import main_window
```

[17] I'm calling myself D. Dyson here because my name is Dyson, and I was in the process of getting it legally changed to Dyson Dyson when I made this change. I can't attribute this copyright to Dyson, since that's already a registered trademark of Dyson Limited. Calling myself Dyson Dyson felt strange, especially since it wasn't even my legal name at the time. So I chose to use D. Dyson instead.

```

if __name__ == '__main__':
    main_window.main(sys.argv)
```

Somehow this caused a conflict between my `lintrans.typing` package, which contained custom types like `MatrixType`, and the standard library `typing` package, so I had to rename mine to `lintrans.typing_`.

3.8.4 Adding a graph of internal imports

Throughout the whole project, I've been using GitHub Actions[17] to automatically do things like test and lint my code, as well as compile the documentation whenever I push my changes to GitHub. I recently learned about `pylint`'s ability to generate a graph of all the internal imports in a package[36]. This graph shows how modules in the project depend on each other internally. It doesn't include external imports like `numpy`. I decided to generate this graph automatically and add it to my documentation.

```
# 39a3727fca69ea65571a15c55741578abce1e763
# .github/workflows/compile-docs.yaml

name: Compile docs for gh-pages

on:
  push:
    branches: [ main ]

jobs:
  compile-docs:
    runs-on: ubuntu-latest

    concurrency:
      group: ${{ github.workflow }}-${{ github.ref }}

    steps:
    - uses: actions/checkout@v2

    - name: Set up Python 3.10
      uses: actions/setup-python@v2
      with:
        python-version: '3.10'

    - name: Install dependencies
      run: |
        pip install --upgrade pip
        pip install -r requirements.txt -r docs/docs_requirements.txt
        pip install -e .
        pip install pylint
        sudo apt-get install -y graphviz

    - name: Create pylint import graphs
      run: |
        shopt -s globstar
        pylint --rcfile=/dev/null --exit-zero --reports=y --disable=all --enable=imports,RP0402
        ↪  --int-import-graph=docs/source/int-imports.png src/lintrans/**/*.py

    - name: Build docs
      run: cd docs/ && make html && cd ..

    - name: Deploy
      uses: peaceiris/actions-gh-pages@v3.8.0
      if: ${{ github.ref == 'refs/heads/main' }}
      with:
        github_token: ${{ secrets.GITHUB_TOKEN }}
        publish_dir: ./docs/build/html/
        keep_files: true
        destination_dir: docs
        user_name: 'github-actions[bot]'
```

```
47          user_email: 'github-actions[bot]@users.noreply.github.com'
48          commit_message: 'compile docs:'
```

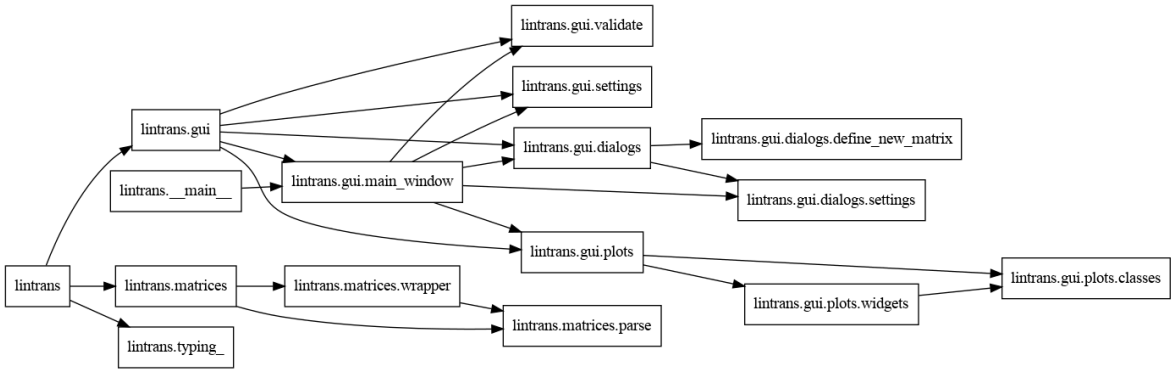


Figure 3.8.1: The internal imports graph

3.8.5 Fixing the colours

Now that I was using version numbers, I thought it was finally time to fix the colours in accordance with §2.4. I decided to use red and blue for the basis vectors, since these are the most easily distinguished colours for colour blind users. I decided to keep the green colour and use it for the eigenvectors and eigenlines. These are very visually distinct from the basis vectors, so I don't think I need to further distinguish them with colours. Red-green colour blind users should be able to tell them apart with ease.

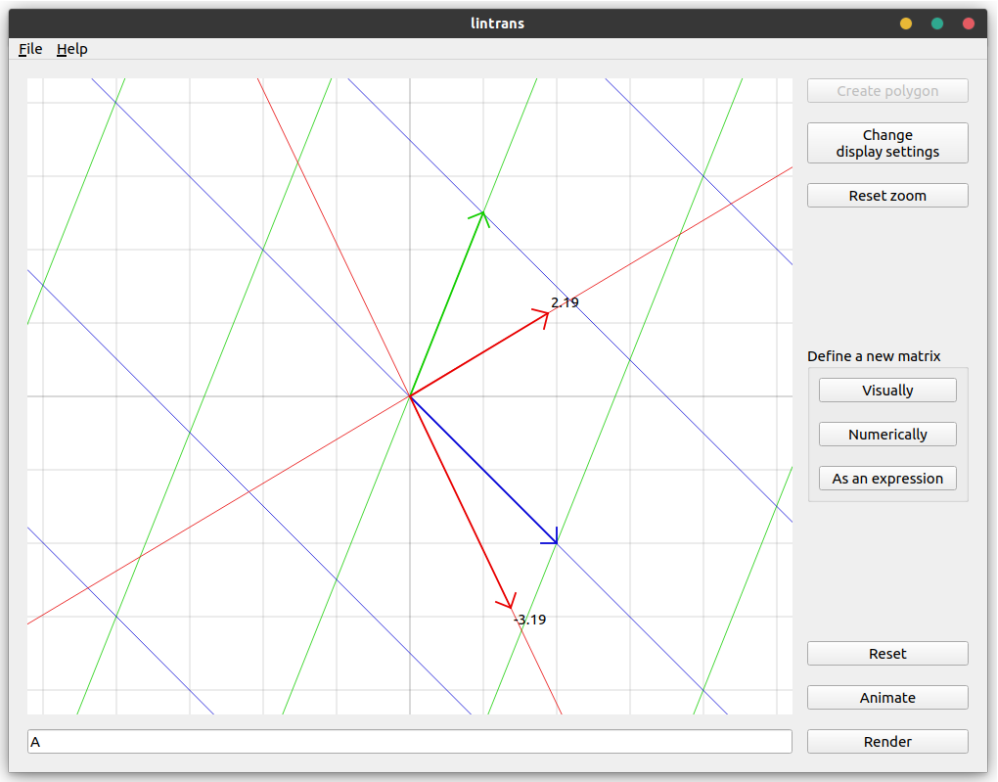


Figure 3.8.2: The old colours

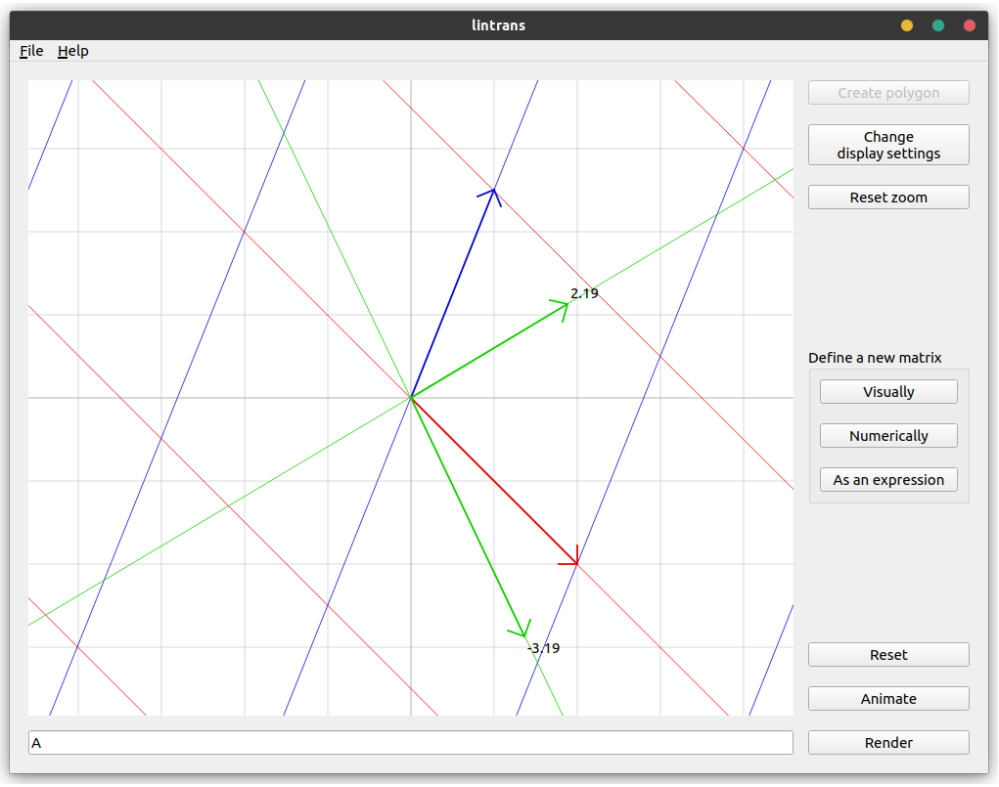


Figure 3.8.3: The new colours

3.8.6 Compiling for release

At this point, I felt ready to show `lintrans` to some teachers. Obviously I didn't expect them to have a modern version of Python to run the program, especially not on a school laptop, so I had to compile the program. I had a look at things like Nuitka[31], but I had a few issues with it and it took ages to compile. Eventually I chose PyInstaller[34], which I've used to compile Python programs before. It's fast and effective and works very well.

I use Ubuntu as my daily driver, so I don't really want to spin up a Windows virtual machine and following some exact steps every time I want to compile `lintrans` for release, so I automated the process with GitHub Actions.

```yaml
# 9d0cbe69c596c04a07809a288d72b5e624f485d7
# .github/workflows/compile-release.yaml

name: Compile and release

on:
  push:
    tags:
      - 'v*.*.*'

jobs:
  check:
    runs-on: ubuntu-latest
    steps:
      - uses: actions/checkout@v2

      - name: Set up Python ${{ matrix.python-version }}
        uses: actions/setup-python@v2
        with:
          python-version: '3.10'

```

```yaml
      - name: Install dependencies
        run: |
          pip install --upgrade pip
          pip install -r requirements.txt -r dev_requirements.txt
          pip install -e .

      - name: Check
        run: |
          mypy src/ tests/
          flake8 src/ tests/
          pycodestyle src/ tests/
          pydocstyle src/ tests/

  test:
    needs: check
    runs-on: ${{ matrix.os }}

    strategy:
      matrix:
        os: [ubuntu-latest, macos-latest, windows-latest]

    steps:
      - uses: actions/checkout@v2

      - name: Set up Python 3.10
        uses: actions/setup-python@v2
        with:
          python-version: '3.10'

      - name: Install dependencies
        run: |
          pip install --upgrade pip
          pip install -r requirements.txt -r dev_requirements.txt
          pip install -e .

      - name: Test
        run: |
          pytest
          pytest --doctest-modules src/

  compile:
    needs: test
    runs-on: ${{ matrix.os }}

    strategy:
      matrix:
        os: [ubuntu-latest, macos-latest, windows-latest]

    steps:
      - uses: actions/checkout@v2

      - name: Set up Python 3.10
        uses: actions/setup-python@v2
        with:
          python-version: '3.10'

      - name: Install dependencies
        run: |
          pip install --upgrade pip
          pip install -r requirements.txt -r dev_requirements.txt
          pip install -e .
          pip install pyinstaller

      - name: Compile
        run: pyinstaller --onefile --windowed --distpath=./dist --name lintrans-${{ runner.os }}
        ↪  src/lintrans/__main__.py

      - name: Upload artifact
        uses: actions/upload-artifact@v3
        with:
          name: ${{ matrix.os }}-binary
          path: dist/lintrans*

```

```yaml
  publish:
    needs: compile
    runs-on: ubuntu-latest

    steps:
      - uses: actions/checkout@v2

      - name: Download Windows binary
        uses: actions/download-artifact@v3
        with:
          name: windows-latest-binary
          path: dist/

      - name: Download macOS binary
        uses: actions/download-artifact@v3
        with:
          name: macos-latest-binary
          path: dist/

      - name: Download Linux binary
        uses: actions/download-artifact@v3
        with:
          name: ubuntu-latest-binary
          path: dist/

      - name: Check for alpha
        id: checkalpha
        run: |
          isalpha=$(if [ -n "$(echo $GITHUB_REF | grep -o -- 'alpha')" ]; then echo 1; else echo 0; fi)
          echo "::set-output name=isalpha::$isalpha"

      - name: Upload binaries (normal release)
        if: steps.checkalpha.outputs.isalpha == 0
        uses: softprops/action-gh-release@v1
        with:
          fail_on_unmatched_files: true
          prerelease: false
          draft: true  # I'll manually add the title and description when the draft is online
          files: |
            dist/lintrans-Windows.exe
            dist/lintrans-macOS
            dist/lintrans-Linux

      - name: Upload binaries (pre-release)
        if: steps.checkalpha.outputs.isalpha == 1
        uses: softprops/action-gh-release@v1
        with:
          fail_on_unmatched_files: true
          prerelease: true
          draft: true  # I'll manually add the title and description when the draft is online
          files: |
            dist/lintrans-Windows.exe
            dist/lintrans-macOS
            dist/lintrans-Linux
```

This workflow only runs when I push a tag containing a version number. It firstly installs Python[18] and then lints and tests everything. If that all passes, then it compiles `lintrans` on Ubuntu, macOS, and Windows. Then it publishes the compiled binaries to a GitHub draft release. I then go in when it's finished to add a description to the release and publish it.

Now that I had this in place, I released version `v0.2.0-alpha`.

After some minor adjustments, such as including the tag name in the binary name, and installing UPX[60] for the Linux compilation[19], I released `v0.2.0` just 6 hours later.

[18] There's a mistake on line 14. There is no strategy matrix, so '`${{ matrix.python-version }}`' is treated as plain text rather than an actual version number. This was caused by copying a previous workflow. The actual version that it installs is fine, though. It's only the name of the step that doesn't look right.

[19] UPX is designed to compress executable files, but I later learned that PyInstaller doesn't even use UPX on Linux; it only uses it on Windows.

I made a few minor adjustments to the workflows, but soon moved on from this version number fiasco and started doing more actual work.

3.9 Preparing for `v0.2.1`

3.9.1 Fixing slots and signals

I was perusing the Qt5 documentation when I learned about the difference between the `dialog.finished` signal and the `dialog.accepted` signal. I decided to rework some old code to make better use these signals.

When defining a new matrix or dialog settings, we only want to save the new data if the user actually accepted the dialog by clicking the confirm button. We don't want to save it if they clicked cancel. However, in the case of the error message dialog, we always want to update the render buttons when it's closed, no matter how the user closed the dialog.

```
# 66242465222a153a5f37c4a1a3c2bd50bfd90933
# src/lintrans/gui/main_window.py

35  class LintransMainWindow(QMainWindow):
...
447         @pyqtSlot(DefineDialog)
448         def dialog_define_matrix(self, dialog_class: Type[DefineDialog]) -> None:
...
461             # We create a dialog with a deepcopy of the current matrix_wrapper
462             # This avoids the dialog mutating this one
463             dialog = dialog_class(deepcopy(self.matrix_wrapper), self)
464
465             # .open() is asynchronous and doesn't spawn a new event loop, but the dialog is still modal (blocking)
466             dialog.open()
467
468             # So we have to use the accepted signal to call a method when the user accepts the dialog
469             dialog.accepted.connect(self.assign_matrix_wrapper)
...
478         @pyqtSlot()
479         def dialog_change_display_settings(self) -> None:
480             """Open the dialog to change the display settings."""
481             dialog = DisplaySettingsDialog(self.plot.display_settings, self)
482             dialog.open()
483             dialog.accepted.connect(lambda: self.assign_display_settings(dialog.display_settings))
...
493         def show_error_message(self, title: str, text: str, info: str | None = None) -> None:
...
511             # This is `finished` rather than `accepted` because we want to update the buttons no matter what
512             dialog.finished.connect(self.update_render_buttons)
```

I also added the `@pyqtSlot()` decorator to all the relevant methods in the matrix definition dialogs. The types in the brackets indicate the signature of the method.

A slot in Qt5 is just a method that is expected to be connected to a signal, so it gets called from the event loop. Using the decorator makes it clear that a method is a slot, and also allows slightly better performance.

```
# 9beff9cf25d3af655e134205572a5668279f42cc
# src/lintrans/gui/dialogs/define_new_matrix.py

67  class DefineDialog(QDialog):
...
138         @abc.abstractmethod
139         @pyqtSlot()
140         def update_confirm_button(self) -> None:
...
143         @pyqtSlot(int)
144         def load_matrix(self, index: int) -> None:
...
155         @abc.abstractmethod
156         @pyqtSlot()
157         def confirm_matrix(self) -> None:
```

```
...
164     class DefineVisuallyDialog(DefineDialog):
...
194         @pyqtSlot()
195         def update_confirm_button(self) -> None:
...
203         @pyqtSlot(int)
204         def load_matrix(self, index: int) -> None:
...
214         @pyqtSlot()
215         def confirm_matrix(self) -> None:
...
226     class DefineNumericallyDialog(DefineDialog):
...
276         @pyqtSlot()
277         def update_confirm_button(self) -> None:
...
288         @pyqtSlot(int)
289         def load_matrix(self, index: int) -> None:
...
305         @pyqtSlot()
306         def confirm_matrix(self) -> None:
...
317     class DefineAsAnExpressionDialog(DefineDialog):
...
348         @pyqtSlot()
349         def update_confirm_button(self) -> None:
...
356         @pyqtSlot(int)
357         def load_matrix(self, index: int) -> None:
...
364         @pyqtSlot()
365         def confirm_matrix(self) -> None:
```

3.9.2 Linking in documentation

I've been using Sphinx[55] for my documentation this whole time, and I've been using the Sphinx extension `intersphinx` to link to the Python standard library documentation. It uses a system of binary inventory files which define a reference map between names to use in the documentation, and where to link those names to. I recently learned of the `sphobjinv` Python package, which allows you to easily create your own local inventory files to reference some external source of documentation, such as the Qt5 documentation. I read through the `sphobjinv` documentation[54] and designed a small script to read a custom text file, and create the binary inventory file needed by Sphinx.

```
# 5455265a51666e29ab976152c1a758a422e1004a
# docs/create_objects_inv.py

 9  """A simple script to convert my manually curated text file to an invetory file that intersphinx can use.
10
11  .. note:: The URIs in the text file must not have .html suffices
12  """
13
14  import re
15  from glob import glob
16
17  import sphobjinv as soi
18
19
20  pattern = re.compile(r'^(\S+)\s+([^:\s]+):([^:\s]+)\s+(\d+)\s+(\S+)\s+(\S+)$')
21
22
23  def generate_objects_inv(prefix: str) -> None:
24      """Generate the ``objects.inv`` file for PyQt5.
25
26      We read from ``prefix-objects.txt`` and write to ``prefix-objects.inv``,
27      so if you want to use ``pyqt5-objects.txt``, then the prefix should be ``pyqt5``.
28
29      :param str prefix: The prefix for the object files
```

```
30          """
31          inv = soi.Inventory()
32          inv.project = 'PyQt5'
33          inv.version = '5.15'
34
35          with open(prefix + '-objects.txt', 'r', encoding='utf-8') as f:
36              text = f.read().splitlines()
37
38          for line in text:
39              if line == '' or line.lstrip().startswith('#'):
40                  continue
41
42              if (match := re.match(pattern, line)) is None:
43                  raise ValueError(f'Every line in {prefix}-objects.txt must match the pattern')
44
45              name, domain, role, priority, uri, disp_name = match.groups()
46
47              inv.objects.append(soi.DataObjStr(
48                  name=name, domain=domain, role=role, priority=priority, uri=uri, dispname=disp_name
49              ))
50
51          compressed_text = soi.compress(inv.data_file(contract=True))
52          soi.writebytes(f'source/{prefix}-objects.inv', compressed_text)
53
54
55      def main() -> None:
56          """Call :func:`generate_objects_inv` for every file matching the glob pattern '*-objects.txt'."""
57          for filename in glob('*-objects.txt'):
58              prefix = filename[:-12]
59              print(f'Generating {prefix}-objects.inv')
60              generate_objects_inv(prefix)
61
62
63      if __name__ == '__main__':
64          main()
```

Line 11 should say ‘must have .html suffices’.

```
# aab8e88b0e2cdae8038c9935031c74bcdae0ad5c
# docs/pyqt5-objects.txt

1   # This format is:
2   # <reference name> <domain>:<role> <priority> <URI> <display name>
3   # Sphinx handles the prefix for the URI
4   # If the display name is '-', then it's the same as the reference name
5
6   # === Classes
7
8   QApplication py:class 1 qapplication.html -
9   QDialog      py:class 1 qdialog.html      -
10  QKeyEvent    py:class 1 qkeyevent.html    -
11  QPainter     py:class 1 qpainter.html     -
12  QPaintEvent  py:class 1 qpaintevent.html  -
13  QWheelEvent  py:class 1 qwheelevent.html  -
14  QWidget      py:class 1 qwidget.html      -
15
16  # === Methods
17
18  QPainter.drawLine:iiii py:method 1 qpainter.html#drawLine-2 QPainter.drawLine()
19
20  # === Signals
21
22  QComboBox.activated py:method 1 qcombobox.html#activated -
23  QDialog.accepted    py:method 1 qdialog.html#accepted    -
24
25  # These are in full form so that autodoc can reference base classes and param types
26
27  PyQt5.QtGui.QKeyEvent   py:class 1 qkeyevent.html   -
28  PyQt5.QtGui.QPainter    py:class 1 qpainter.html    -
29  PyQt5.QtGui.QPaintEvent py:class 1 qpaintevent.html -
30  PyQt5.QtGui.QWheelEvent py:class 1 qwheelevent.html -
```

```
31      PyQt5.QtWidgets.QDialog py:class 1 qdialog.html     -
32      PyQt5.QtWidgets.QWidget py:class 1 qwidget.html     -
```

I then just had to change all the references to Qt5 things in the documentation and then Sphinx would automatically link all the Qt5 references to their appropriate links, as defined in this file.

3.9.3 Improving tests

I made some small improvements to the unit tests by making sure they handled greedy index parsing, which means that something like `A^2 3B` will get parsed as `A^{23}B` because whitespace is ignored, as well asserting that all invalid expressions raise `MatrixParseError`. I also added the copyright comment to the test files.

This was a tiny change, but worth noting.

```
        # c07d97024e1fe00ab110f43e5c7e6737c955d680
        # tests/matrices/test_parse_and_validate_expression.py

41      expressions_and_parsed_expressions: list[tuple[str, MatrixParseList]] = [
...
50          ('A^12', [[('', 'A', '12')]]),
51          ('A^234', [[('', 'A', '234')]]),
...
55          ('A^2 3B', [[('', 'A', '23'), ('', 'B', '')]]),
...
72          ('2.14A^{3} 4.5rot(14.5)^-1 + 8.5B^T 5.97C^14 - 3.14D^{-1} 6.7E^T',
73           [[('2.14', 'A', '3'), ('4.5', 'rot(14.5)', '-1')], [('8.5', 'B', 'T'), ('5.97', 'C', '14')],
...
75      ]
...
78      def test_parse_matrix_expression() -> None:
79          """Test the parse_matrix_expression() function."""
80          for expression, parsed_expression in expressions_and_parsed_expressions:
81              # Test it with and without whitespace
82              assert parse_matrix_expression(expression) == parsed_expression
83              assert parse_matrix_expression(expression.replace(' ', '')) == parsed_expression


        # 70e1a7271a61f3009cc4d342f46743b248498a1c
        # tests/matrices/test_parse_and_validate_expression.py

26      invalid_inputs: list[str] = [
27          '', 'rot()', 'A^', 'A^1.2', 'A^{3.4}', '1,2A', 'ro(12)', '5', '12^2', '^T', '^{12}',
28          'A^{13', 'A^3}', 'A^A', '^2', 'A--B', '--A', '+A', '--1A', 'A--B', 'A--1B', '.A', '1.A'
29
30          'This is 100% a valid matrix expression, I swear'
31      ]
...
86      def test_parse_error() -> None:
87          """Test that parse_matrix_expression() raises a MatrixParseError."""
88          for expression in invalid_inputs:
89              with pytest.raises(MatrixParseError):
90                  parse_matrix_expression(expression)
```

```
(lintrans) dyson@Harold-Ubuntu:~/repos/lintrans [main *]
$ pytest -v
================================================= test session starts =================================================
platform linux -- Python 3.11.0, pytest-7.2.1, pluggy-1.0.0 -- /home/dyson/temp/lintrans/venv/bin/python
cachedir: .pytest_cache
rootdir: /home/dyson/temp/lintrans, configfile: pyproject.toml, testpaths: tests
collected 30 items

tests/gui/test_dialog_utility_functions.py::test_is_valid_float[inputs0-True] PASSED                                 [  3%]
tests/gui/test_dialog_utility_functions.py::test_is_valid_float[inputs1-False] PASSED                                [  6%]
tests/gui/test_dialog_utility_functions.py::test_round_float PASSED                                                  [ 10%]
tests/matrices/test_parse_and_validate_expression.py::test_validate_matrix_expression[inputs0-True] PASSED           [ 13%]
tests/matrices/test_parse_and_validate_expression.py::test_validate_matrix_expression[inputs1-False] PASSED          [ 16%]
tests/matrices/test_parse_and_validate_expression.py::test_parse_matrix_expression PASSED                            [ 20%]
tests/matrices/test_parse_and_validate_expression.py::test_parse_error PASSED                                        [ 23%]
tests/matrices/test_rotation_matrices.py::test_create_rotation_matrix PASSED                                         [ 26%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_simple_matrix_addition PASSED                        [ 30%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_simple_two_matrix_multiplication PASSED              [ 33%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_identity_multiplication PASSED                       [ 36%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_simple_three_matrix_multiplication PASSED            [ 40%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_matrix_inverses PASSED                               [ 43%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_matrix_powers PASSED                                 [ 46%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_matrix_transpose PASSED                              [ 50%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_rotation_matrices PASSED                             [ 53%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_multiplication_and_addition PASSED                   [ 56%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_complicated_expressions PASSED                       [ 60%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_value_errors PASSED                                  [ 63%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_linalgerror PASSED                                   [ 66%]
tests/matrices/matrix_wrapper/test_misc.py::test_get_expression PASSED                                               [ 70%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_basic_get_matrix PASSED                              [ 73%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_get_name_error PASSED                                [ 76%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_basic_set_matrix PASSED                              [ 80%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_set_expression PASSED                                [ 83%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_simple_dynamic_evaluation PASSED                     [ 86%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_recursive_dynamic_evaluation PASSED                  [ 90%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_set_identity_error PASSED                            [ 93%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_set_name_error PASSED                                [ 96%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_set_type_error PASSED                                [100%]

================================================== 30 passed in 0.36s ==================================================
```

Figure 3.9.1: Running `pytest` with the new tests

3.9.4 The Windows version file

Windows stores metadata for `.exe` files inside the `.exe` files themselves[61][62]. PyInstaller lets you embed that metadata when compiling on Windows, using a version file[35]. Obviously, I wanted to include this metadata in my compiled `.exe` in the release.

I created a simple `precompile.py` script that would create different pre-compilation artefacts. I could then use these in the compilation workflow for GitHub Actions. I started with just Windows, but obviously I'm going to expand into Linux and macOS as well later.

```python
# 2126959cb6f836b1bc6c92dad859b43cbd86e1ab
# precompile.py

"""A simple pre-compile script for the automated GitHub page compilation action."""

import re
import sys


def precompile_macos() -> None:
    """Run the pre-compile steps for macOS."""
    print('Pre-compile for macOS not implemented yet')


def precompile_windows(args: list[str]) -> None:
    """Run the pre-compile steps for Windows."""
    print('Pre-compiling for Windows')

    if len(args) < 1:
        raise ValueError('Windows pre-compile needs tag name argument')

    tag_name = args[0]

    if (m := re.match(r'v(\d+)\.(\d+)\.(\d+)(-alpha)?', tag_name)) is not None:
        major, minor, patch, alpha = m.groups()

```

```
        else:
            raise ValueError('Tag name must match format')

        if alpha is not None:
            flags = '0x2'
        else:
            flags = '0x0'

        version_tuple = f'{major}, {minor}, {patch}, 0'

        version_info = f'''VSVersionInfo(
      ffi=FixedFileInfo(
        filevers=({version_tuple}),
        prodvers=({version_tuple}),
        mask=0x3f,
        flags={flags},
        OS=0x40004,
        fileType=0x1,
        subtype=0x0,
        date=(0, 0)
      ),
      kids=[
        StringFileInfo(
          [
            StringTable(
              '040904B0',
              kids=[
                StringStruct('CompanyName', 'D. Dyson (DoctorDalek1963)'),
                StringStruct('FileDescription', 'Linear transformation visualizer'),
                StringStruct('FileVersion', '{tag_name}'),
                StringStruct('InternalName', 'lintrans'),
                StringStruct('LegalCopyright', '(C) D. Dyson (DoctorDalek1963) under GPLv3'),
                StringStruct('OriginalFilename', 'lintrans-Windows-{tag_name}.exe'),
                StringStruct('ProductName', 'lintrans'),
                StringStruct('ProductVersion', '{tag_name}')
              ]
            )
          ]
        ),
        VarFileInfo([VarStruct('Translation', [2057, 1200])])
      ]
    )
    '''

        with open('version_info.txt', 'w', encoding='utf-8') as f:
            f.write(version_info)

        print('Version file written to version_info.txt')


    def main(args: list[str]) -> None:
        """Evaluate the arguments and pre-compile accordingly."""
        if len(args) < 1:
            raise ValueError('Script must be supplied with the name of an operating system.')

        os_name = args[0].lower()

        if os_name == 'linux':
            print("Linux doesn't need any pre-compilation")

        elif os_name == 'macos':
            precompile_macos()

        elif os_name == 'windows':
            precompile_windows(args[1:])

        else:
            raise ValueError(f'Unsupported operating system "{os_name}"')


    if __name__ == '__main__':
        main(sys.argv[1:])
```

```yaml
# 2126959cb6f836b1bc6c92dad859b43cbd86e1ab
# .github/workflows/compile-release.yaml

jobs:
...
  compile:
...
    steps:
...
      - name: Pre-compile
        run: python precompile.py ${{ runner.os }} $GITHUB_REF_NAME
        shell: bash

      - name: Compile (Linux)
        if: runner.os == 'Linux'
        run: pyinstaller --onefile --windowed --distpath=./dist --name lintrans-${{ runner.os }}-$GITHUB_REF_NAME
        ↪  src/lintrans/__main__.py
        shell: bash

      - name: Compile (macOS)
        if: runner.os == 'macOS'
        run: pyinstaller --onefile --windowed --distpath=./dist --name lintrans-${{ runner.os }}-$GITHUB_REF_NAME
        ↪  src/lintrans/__main__.py
        shell: bash

      - name: Compile (Windows)
        if: runner.os == 'Windows'
        run: pyinstaller --onefile --windowed --distpath=./dist --version-file version_info.txt --name
        ↪  lintrans-${{ runner.os }}-$GITHUB_REF_NAME src/lintrans/__main__.py
        shell: bash
```

I quickly realised that this design would make the compilation process more complicated, since the process would be in separate parts. Instead, I decided to create a unified compilation script, which runs a pre-compile step dependent on the operating system, and then compiles the program with the `PyInstaller.__main__.run()` function.

```python
# ca674c7f7d61e8eed3410d456787cfe5b2bc28e5
# compile.py

"""A simple pre-compile script for the automated GitHub page compilation action."""

import argparse
import os
import re
import shutil
import sys
from textwrap import dedent

from PyInstaller.__main__ import run as run_pyi

import lintrans


class Compiler:
    """A simple class to encapsulate compilation logic."""

    def __init__(
            self, *,
            platform: str | None = None,
            version_name: str | None = None,
            filename: str | None = None
    ):
        """Create a Compiler object."""
        self.platform = platform if platform else sys.platform
        self.version_name = version_name if version_name else lintrans.__version__
        self.filename = filename if filename else 'lintrans'

    def _precompile_windows(self) -> None:
        """Pre-compile for Windows."""
        if (m := re.match(r'v?(\d+)\.(\d+)\.(\d+)(-alpha)?', self.version_name)) is not None:
```

```
            major, minor, patch, alpha = m.groups()

        else:
            raise ValueError('Tag name must match format')

        if alpha is not None:
            flags = '0x2'
        else:
            flags = '0x0'

        version_tuple = f'{major}, {minor}, {patch}, 0'

        version_info = dedent(f'''
        VSVersionInfo(
          ffi=FixedFileInfo(
            filevers=({version_tuple}),
            prodvers=({version_tuple}),
            mask=0x3f,
            flags={flags},
            OS=0x40004,
            fileType=0x1,
            subtype=0x0,
            date=(0, 0)
          ),
          kids=[
            StringFileInfo(
              [
                StringTable(
                  '040904B0',
                  kids=[
                    StringStruct('CompanyName', 'D. Dyson (DoctorDalek1963)'),
                    StringStruct('FileDescription', 'Linear transformation visualizer'),
                    StringStruct('FileVersion', '{self.version_name}'),
                    StringStruct('InternalName', 'lintrans'),
                    StringStruct('LegalCopyright', '(C) D. Dyson (DoctorDalek1963) under GPLv3'),
                    StringStruct('OriginalFilename', '{self.filename}.exe'),
                    StringStruct('ProductName', 'lintrans'),
                    StringStruct('ProductVersion', '{self.version_name}')
                  ]
                )
              ]
            ),
            VarFileInfo([VarStruct('Translation', [2057, 1200])])
          ]
        )
        ''')

        with open('version_info.txt', 'w', encoding='utf-8') as f:
            f.write(version_info)

        print('Version file written to version_info.txt')

    def precompile(self) -> None:
        """Pre-compile for the appropriate operating system."""
        if self.platform == 'linux':
            print("Linux doesn't need any pre-compilation")

        elif self.platform == 'darwin':
            print("macOS doesn't need any pre-compilation")

        elif self.platform == 'win32':
            print('Pre-compiling for Windows')
            self._precompile_windows()

        else:
            raise ValueError(f'Unsupported operating system "{self.platform}"')

    def _get_pyi_args(self) -> list[str]:
        """Return the common args for PyInstaller."""
        return [
            'src/lintrans/__main__.py',
            '--onefile',
            '--windowed',
```

```
            '--distpath=./dist',
            '--workpath=./build',
            '--noconfirm',
            '--clean',
            f'--name={self.filename}'
        ]

    def _compile_macos(self) -> None:
        """Compile for macOS."""
        run_pyi(self._get_pyi_args())

        os.rename(os.path.join('dist', self.filename + '.app'), self.filename + '.app')

    def _compile_linux(self) -> None:
        """Compile for Linux."""
        run_pyi(self._get_pyi_args())

        os.rename(os.path.join('dist', self.filename), self.filename)

    def _compile_windows(self) -> None:
        """Compile for Windows."""
        if not os.path.isfile('version_info.txt'):
            raise ValueError('Windows compilation requires version_info.txt from pre-compilation')

        run_pyi([
            *self._get_pyi_args(),
            '--version-file',
            'version_info.txt'
        ])

        os.remove('version_info.txt')

        os.rename(os.path.join('dist', self.filename + '.exe'), self.filename + '.exe')

    def compile(self) -> None:
        """Compile for the appropriate operating system."""
        if self.platform == 'darwin':
            self._compile_macos()

        elif self.platform == 'linux':
            self._compile_linux()

        elif self.platform == 'win32':
            self._compile_windows()

        else:
            raise ValueError(f'Unsupported operating system "{self.platform}"')

        shutil.rmtree('dist')
        shutil.rmtree('build')
        os.remove(self.filename + '.spec')


def main() -> None:
    """Run any pre-compilation, and then compile."""
    parser = argparse.ArgumentParser(description='Compile this version of lintrans for your operating system',
    ↪  add_help=True)
    parser.add_argument('-f', '--filename', type=str, required=False, default=None, help='the filename (without
    ↪  extension)')
    parser.add_argument('-v', '--version', type=str, required=False, default=None, help='the version name in the
    ↪  format v1.2.3')

    args = parser.parse_args()

    compiler = Compiler(filename=args.filename, version_name=args.version)
    compiler.precompile()
    compiler.compile()


if __name__ == '__main__':
    main()
```

This new compilation script captures the whole process. On Linux or macOS, it just compiles the program with PyInstaller. On Windows, it has to generate the version file, then compile the program with an additional argument to include the version file. I then updated the GitHub Actions workflow to use this new compilation script.

```
# e47fe732954bf018128bdcb5ee9c354910517f36
# .github/workflows/compile-release.yaml

 8  jobs:
...
60    compile:
...
68      steps:
...
87        - name: Compile
88          run: python compile.py -f lintrans-${{ runner.os }}-${{ env.GITHUB_REF_NAME }} -v $GITHUB_REF_NAME
```

3.9.5 Compiling for macOS

Compiling for macOS is considerably more difficult. I run Ubuntu as my primary operating system. I used to use Windows and I have a Windows 10 virtual machine, so compiling for Windows was never an issue. But I've never used a Mac, and Apple don't like people installing macOS on non-Apple hardware. Getting a virtual machine set up running macOS Monterey was quite difficult, but I eventually managed to get it working somewhat properly.

Once I had `lintrans` compiling on macOS, I wanted to do something similar to what I did with Windows, where I added extra metadata to the executable. In macOS, executables are bundled as `.app` files, which are just directory structures, containing the necessary files and metadata[13]. All the metadata for an application bundle is contained in the `Info.plist` file in the bundle[10][9]. After reading the documentation for these files, I created one for `lintrans`.

```
# e716000521c92259ed4a1b33ab37e3860a7b7875
# compile.py

23  class Compiler:
...
92      def _macos_replace_info_plist(self) -> None:
93          """Replace the Info.plist file in the macOS app."""
94          short_version_name = self.version_name
95
96          if short_version_name.startswith('v'):
97              short_version_name = short_version_name[1:]
98
99          if short_version_name.endswith('-alpha'):
100             short_version_name = short_version_name[:-6]
101
102         new_info_plist = dedent(f'''
103         <?xml version="1.0" encoding="UTF-8"?>
104         <!DOCTYPE plist PUBLIC "-//Apple//DTD PLIST 1.0//EN" "http://www.apple.com/DTDs/PropertyList-1.0.dtd"
105         <plist version="1.0">
106         <dict>
107             <key>CFBundleDisplayName</key>
108             <string>lintrans</string>
109             <key>CFBundleExecutable</key>
110             <string>lintrans</string>
111             <key>CFBundleIconFile</key>
112             <string>icon-windowed.icns</string>
113             <key>CFBundleIdentifier</key>
114             <string>lintrans</string>
115             <key>CFBundleInfoDictionaryVersion</key>
116             <string>6.0</string>
117             <key>CFBundleName</key>
118             <string>lintrans</string>
119             <key>CFBundleType</key>
120             <string>APPL</string>
```

```
            <key>CFBundleVersion</key>
            <string>{self.version_name}</string>
            <key>CFBundleShortVersionString</key>
            <string>{short_version_name}</string>
            <key>NSHighResolutionCapable</key>
            <true/>
            <key>NSHumanReadableCopyright</key>
            <string>(C) D. Dyson (DoctorDalek1963) under GPLv3</string>
        </dict>
        </plist>
        '''[1:])

        with open(os.path.join(self.filename + '.app','Contents', 'Info.plist'), 'w', encoding='utf-8') as f:
            f.write(new_info_plist)
...
    def _compile_macos(self) -> None:
        """Compile for macOS."""
        run_pyi(self._get_pyi_args())

        os.rename(os.path.join('dist', self.filename + '.app'), self.filename + '.app')

        self._macos_replace_info_plist()
```

This could would automatically generate the `Info.plist` file and write it to the correct place. However, I couldn't distribute this bundled app, since Apple requires an app to be signed by a trusted author before other people can download and run that code on their own Apple devices[8]. And unfortunately, Apple charges $99 per year for membership to their 'Apple Developer Program', which is required to become a trusted developer[11][20].

Microsoft also wants its developers to sign their code for security and trust, and also charges for this privilege. But on Windows, you can run a foreign, unsigned app so long as you dismiss the potential virus warning. On macOS, it's completely forbidden.

I don't particularly want to pay $99 per year to compile `lintrans` for macOS, when my audience on that platform is realistically almost zero, so I just removed macOS from the GitHub Actions publish workflow. For anyone that wants to run `lintrans` on macOS, I will provide instructions to compile it from source, since I can't distribute a binary file that I built myself. I will however continue to run the unit tests and compile the program on macOS in GitHub Actions, to ensure that everything works fine on that platform.

3.9.6 Supporting flags

Most Linux apps support command line arguments and/or flags[21], and so I wanted to support these with `lintrans`. I wanted one flag to display help for the program, and one flag to display the version number of the program. Implementing this was very simple and I didn't bother using a library like `argparse`; I just used `sys.argv`.

```
# ffc603f1bf049811cb927f879ce7989456f6a537
# src/lintrans/__main__.py

"""This module provides a :func:`main` function to interpret command line arguments and run the program."""

import sys
from textwrap import dedent

from lintrans import __version__
from lintrans.gui import main_window


def main(prog_name: str, args: list[str]) -> None:
    """Interpret program-specific command line arguments and run the main window in most cases.
```

[20] The price is listed in the small print at the bottom of the page.

[21] For explanation and examples, see `https://betterdev.blog/command-line-arguments-anatomy-explained/`

```
20
21          If the user supplies --help or --version, then we simply respond to that and then return.
22          If they don't supply either of these, then we run :func:`lintrans.gui.main_window.main`.
23
24          ``prog_name`` is ``sys.argv[0]`` when this script is run with ``python -m lintrans``.
25
26          :param str prog_name: The name of the program
27          :param list[str] args: The other arguments to the program
28          """
29          if '-h' in args or '--help' in args:
30              print(dedent(f'''
31              Usage: {prog_name} [option]
32
33              Options:
34                  -h, --help       Display this help text and exit
35                  -V, --version    Display the version information and exit
36
37              Any other options will get passed to the QApplication constructor.
38              If you don't know what that means, then don't provide any arguments and just the run the program.'''[1:]))
39
40          elif '-V' in args or '--version' in args:
41              print(dedent(f'''
42              lintrans (version {__version__})
43              The linear transformation visualizer
44
45              Copyright (C) 2021-2022 D. Dyson (DoctorDalek1963)
46
47              This program is licensed under GNU GPLv3, available here:
48              <https://www.gnu.org/licenses/gpl-3.0.html>'''[1:]))
49
50          else:
51              main_window.main(args)
52
53
54      if __name__ == '__main__':
55          main(sys.argv[0], sys.argv[1:])
```

Here is the expected output when using these flags at a shell prompt:

```
$ python -m lintrans --help
Usage: /home/dyson/repos/lintrans/src/lintrans/__main__.py [option]

Options:
    -h, --help       Display this help text and exit
    -V, --version    Display the version information and exit

Any other options will get passed to the QApplication constructor.
If you don't know what that means, then don't provide any arguments and just the run the program.
$ python -m lintrans --version
lintrans (version 0.2.0)
The linear transformation visualizer

Copyright (C) 2021-2022 D. Dyson (DoctorDalek1963)

This program is licensed under GNU GPLv3, available here:
<https://www.gnu.org/licenses/gpl-3.0.html>
```

3.9.7 Adding the about dialog

In addition to the help and version information available from the command line, most apps with a GUI provide a graphical way to access information about the app, typically in the form of an about box. I wanted to do this for `lintrans`. I had intended to have this from the start, but it now felt like the right time to implement it, since I was preparing to release version `0.2.1`.

To do this, I create a new file to house the new dialog class, and then added the functionality to the original button, so that it would now open the new dialog.

```python
# 7423fff72f09b5f5a3253c734d42c4e7c3182efe
# src/lintrans/gui/dialogs/misc.py

"""This module provides miscellaneous dialog classes like :class:`AboutDialog`."""

from __future__ import annotations

import platform

from PyQt5 import QtWidgets
from PyQt5.QtCore import Qt
from PyQt5.QtWidgets import QDialog, QVBoxLayout

import lintrans


class AboutDialog(QDialog):
    """A simple dialog class to display information about the app to the user.

    It only has an :meth:`__init__` method because it only has label widgets, so no other methods are necessary here.
    """

    def __init__(self, *args, **kwargs):
        """Create an :class:`AboutDialog` object with all the label widgets."""
        super().__init__(*args, **kwargs)

        self.setWindowTitle('About lintrans')

        # === Create the widgets

        label_title = QtWidgets.QLabel(self)
        label_title.setText(f'lintrans (version {lintrans.__version__})')
        label_title.setAlignment(Qt.AlignCenter)

        font_title = label_title.font()
        font_title.setPointSize(font_title.pointSize() * 2)
        label_title.setFont(font_title)

        label_version_info = QtWidgets.QLabel(self)
        label_version_info.setText(
            f'With Python version {platform.python_version()}\n'
            f'Running on {platform.platform()}'
        )
        label_version_info.setAlignment(Qt.AlignCenter)

        label_info = QtWidgets.QLabel(self)
        label_info.setText(
            'lintrans is a program designed to help visualise<br>'
            '2D linear transformations represented with matrices.<br><br>'
            "It's designed for teachers and students and any feedback<br>"
            'is greatly appreciated at <a href="https://github.com/DoctorDalek1963/lintrans" '
            'style="color: black;">my GitHub page</a><br>or via email '
            '(<a href="mailto:dyson.dyson@icloud.com" style="color: black;">dyson.dyson@icloud.com</a>).'
        )
        label_info.setAlignment(Qt.AlignCenter)
        label_info.setTextFormat(Qt.RichText)
        label_info.setOpenExternalLinks(True)

        label_copyright = QtWidgets.QLabel(self)
        label_copyright.setText(
            'This program is free software.<br>Copyright 2021-2022 D. Dyson (DoctorDalek1963).<br>'
            'This program is licensed under GPLv3, which can be found '
            '<a href="https://www.gnu.org/licenses/gpl-3.0.html" style="color: black;">here</a>.'
        )
        label_copyright.setAlignment(Qt.AlignCenter)
        label_copyright.setTextFormat(Qt.RichText)
        label_copyright.setOpenExternalLinks(True)

        # === Arrange the widgets

        self.setContentsMargins(10, 10, 10, 10)

```

```
76              vlay = QVBoxLayout()
77              vlay.setSpacing(20)
78              vlay.addWidget(label_title)
79              vlay.addWidget(label_version_info)
80              vlay.addWidget(label_info)
81              vlay.addWidget(label_copyright)
82
83              self.setLayout(vlay)
84
85              self.setFixedSize(self.baseSize())
```

```
# 7423fff72f09b5f5a3253c734d42c4e7c3182efe
# src/lintrans/gui/main_window.py

36  class LintransMainWindow(QMainWindow):
...
42      def __init__(self):
...
64              self.menu_help = QtWidgets.QMenu(self.menubar)
65              self.menu_help.setTitle('&Help')
...
97              self.action_about = QtWidgets.QAction(self)
98              self.action_about.setText('&About')
99              self.action_about.triggered.connect(lambda: dialogs.AboutDialog(self).open())
...
117             self.menu_help.addAction(self.action_about)
```

This feature works just as expected.

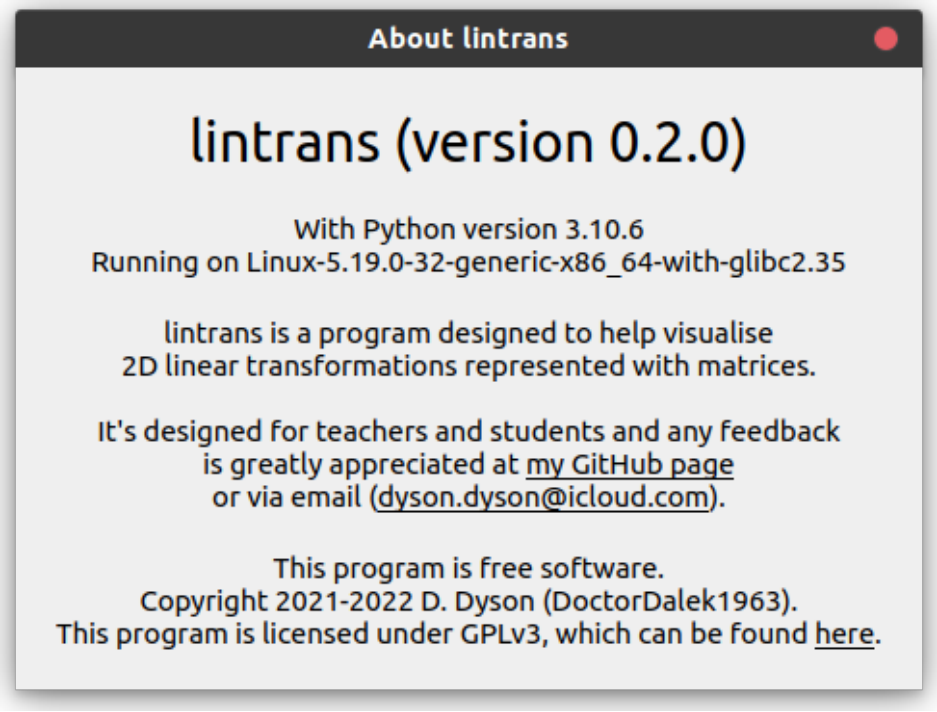


Figure 3.9.2: The about dialog

3.9.8 Creating the `FixedSizeDialog` class

Currently, several dialogs are a fixed size, meaning they can't be resized. Qt5 doesn't have the option to make a dialog non-resizeable - that's only available for whole windows - so to achieve this effect, I had to add the line `self.setFixedSize(self.baseSize())` to the end of the constructor for every fixed

size dialog[22]. This was easy to forget and it didn't make it immediately clear which dialogs were fixed size and which weren't.

To fix this, I decided to use a different technique, by overriding the `open()` method of the dialog. This method gets called when the dialog is first opened. If I called the superclass' implementation first to do all the actual opening logic, then I could use that same previous technique to set the fixed size to whatever Qt5 had calculated it to be. By overriding a method, I could put that override into a simple superclass called `FixedSizeDialog` and then make all fixed size dialogs inherit from this class instead of just `QDialog`.

```
# a59ea87fb37fc593cf0bae3066bdbd24be656798
# src/lintrans/gui/dialogs/misc.py

20  class FixedSizeDialog(QDialog):
21      """A simple superclass to create modal dialog boxes with fixed size.
22
23      We override the :meth:`open` method to set the fixed size as soon as the dialog is opened modally.
24      """
25
26      def open(self) -> None:
27          """Override :meth:`QDialog.open` to set the dialog to a fixed size."""
28          super().open()
29          self.setFixedSize(self.size())
...
32  class AboutDialog(FixedSizeDialog):


# a59ea87fb37fc593cf0bae3066bdbd24be656798
# src/lintrans/gui/dialogs/define_new_matrix.py

68  class DefineDialog(FixedSizeDialog):


# a59ea87fb37fc593cf0bae3066bdbd24be656798
# src/lintrans/gui/dialogs/settings.py

21  class SettingsDialog(FixedSizeDialog):
```

I used `self.size()` here instead of `self.baseSize()` like before. There doesn't seem to be much difference, but the docs seem to suggest that `self.size()` is more appropriate for this use case[46][49].

3.9.9 Increasing minimum grid spacing

When you zoom out, the grid lines get closer and closer together. I previously limited this to 1 pixel, since the program would hang or crash if it was any lower. However, having the grid lines that close together made it very hard to see what was happening. I could easily fix this by limiting the minimum grid spacing to say, 5 pixels.

[22] This works because Qt5 needs to arrange all the widgets and allocate space for all of them first, and then we can use that calculated size as the fixed size.

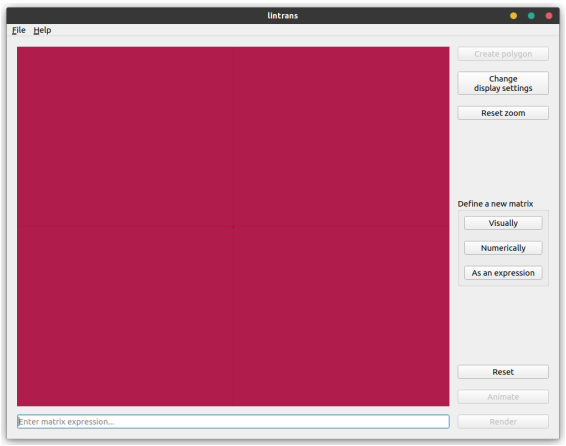


Figure 3.9.3: Fully zoomed out before

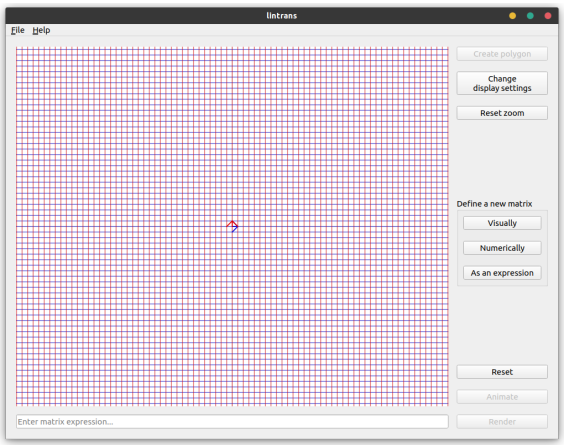


Figure 3.9.4: Fully zoomed out after

```
# 51d35018c81deaaf7e32646b1f99d6e46643bf24
# src/lintrans/gui/plots/classes.py

class BackgroundPlot(QWidget):
...
    minimum_grid_spacing: int = 5
...
    def wheelEvent(self, event: QWheelEvent) -> None:
        """Handle a :class:`QWheelEvent` by zooming in or our of the grid."""
        # angleDelta() returns a number of units equal to 8 times the number of degrees rotated
        degrees = event.angleDelta() / 8

        if degrees is not None:
            new_spacing = max(1, self.grid_spacing + degrees.y())

            if new_spacing >= self.minimum_grid_spacing:
                self.grid_spacing = new_spacing

        event.accept()
        self.update()
```

3.9.10 Creating a changelog

I've know about changelogs for a long time. They're used to keep track of changes to a project over time. I recently learned about the project 'keep a changelog', which tries to create a standard for changelog formats[27]. I want to have a proper changelog for lintrans, so I decided to implement one.

```
<!-- 47c68c7f4780d0e2c374cf12b9b54c031277af6d -->
<!-- CHANGELOG.md -->

# Changelog

All notable changes to this project will be documented in this file.

The format is based on [Keep a Changelog](https://keepachangelog.com/en/1.0.0/),
and this project adheres to [Semantic Versioning](https://semver.org/spec/v2.0.0.html).

## [Unreleased]

### Added

- Explicit `@pyqtSlot` decorators
- Link to Qt5 docs in project docs with intersphinx
- Copyright comment in tests and `setup.py`
- Create version file for Windows compilation
- Create full compile.py script
- Add `Info.plist` file for macOS compilation
```

```
- Support --help and --version flags in `__main__.py`
- Create about dialog in help menu
- Implement minimum grid spacing

### Fixed

- Fix problems with compile script
- Fix small bugs and docstrings

## [0.2.0] - 2022-03-11

There were alpha tags before this, but I wasn't properly adhering to semantic versioning, so I'll start the
↪  changelog here.

If I'd been using semantic versioning from the start, there would much more changelog here, but instead, I'll just
↪  summarise the features.

### Added

- Matrix context with the `MatrixWrapper` class
- Parsing and evaluating matrix expressions
- A simple GUI with a viewport to render linear transformations
- Simple dialogs to create matrices and assign them to names
- Ability to render and animate linear transformations parsed from defined matrices
- Ability to zoom in and out of the viewport
- Add dialog to change display settings

[Unreleased]: https://github.com/DoctorDalek1963/lintrans/compare/v0.2.0...HEAD
[0.2.0]: https://github.com/DoctorDalek1963/lintrans/compare/13600cc6ff6299dc4a8101a367bc52fe08607554...v0.2.0
```

3.9.11 Releasing `v0.2.1`

Now all I had to do for the release was update the version number in `__init__.py` and update the changelog to include the changes under the correct heading, and add a new, empty 'Unreleased' heading.

```
# d47f63eb0bcdc89cff5ed19afe2fc63899edf1d9
# src/lintrans/__init__.py

__version__ = '0.2.1'
```

```
<!-- d47f63eb0bcdc89cff5ed19afe2fc63899edf1d9 -->
<!-- CHANGELOG.md -->

# Changelog

All notable changes to this project will be documented in this file.

The format is based on [Keep a Changelog](https://keepachangelog.com/en/1.0.0/),
and this project adheres to [Semantic Versioning](https://semver.org/spec/v2.0.0.html).

## [Unreleased]

Nothing here yet...

## [0.2.1] - 2022-03-22

### Added

- Explicit `@pyqtSlot` decorators
- Link to Qt5 docs in project docs with intersphinx
- Copyright comment in tests and `setup.py`
- Create version file for Windows compilation
- Create full compile.py script
- Add `Info.plist` file for macOS compilation
- Support --help and --version flags in `__main__.py`
- Create about dialog in help menu
- Implement minimum grid spacing
```

```
25
26  ### Fixed
27
28  - Fix problems with compile script
29  - Fix small bugs and docstrings
30
31  ## [0.2.0] - 2022-03-11
32
33  There were alpha tags before this, but I wasn't properly adhering to semantic versioning, so I'll start the
    ↪  changelog here.
34
35  If I'd been using semantic versioning from the start, there would much more changelog here, but instead, I'll just
    ↪  summarise the features.
36
37  ### Added
38
39  - Matrix context with the `MatrixWrapper` class
40  - Parsing and evaluating matrix expressions
41  - A simple GUI with a viewport to render linear transformations
42  - Simple dialogs to create matrices and assign them to names
43  - Ability to render and animate linear transformations parsed from defined matrices
44  - Ability to zoom in and out of the viewport
45  - Add dialog to change display settings
46
47  [Unreleased]: https://github.com/DoctorDalek1963/lintrans/compare/v0.2.1...HEAD
48  [0.2.1]: https://github.com/DoctorDalek1963/lintrans/compare/v0.2.0...v0.2.1
49  [0.2.0]: https://github.com/DoctorDalek1963/lintrans/compare/13600cc6ff6299dc4a8101a367bc52fe08607554...v0.2.0
```

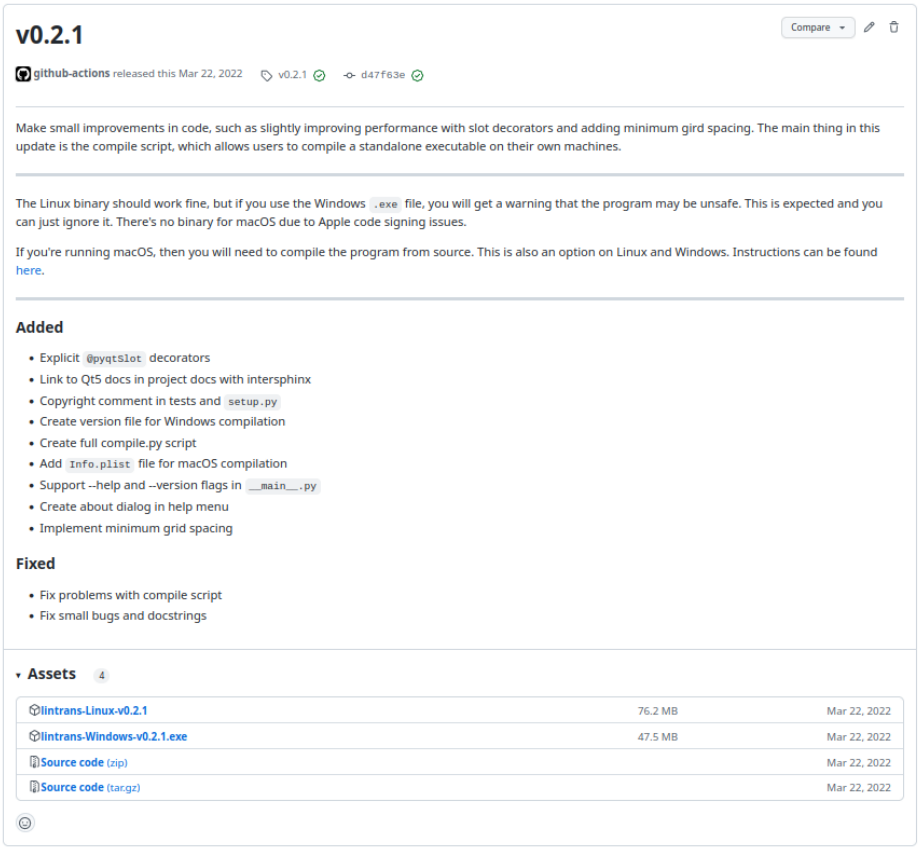


Figure 3.9.5: The release of `v0.2.1` on GitHub

3.9.12 Automating release note generation

I had to copy the changelog over and polish up the release notes myself for this release. It would be quite convenient to have a script that does this automatically, so I made one.

```
# 99a88575f9beb8fed2dcc41dacbb020b31bc8176
# generate_release_notes.py

"""A very simple script to generate release notes."""

import re
import sys

TEXT = '''DESCRIPTION

---

The Linux binary should work fine, but if you use the Windows `.exe` file, you will get a warning that the program may be unsafe. This is expected and you can just ignore it. There's no binary for macOS due to Apple code signing issues.

If you're running macOS, then you will need to compile the program from source. This is also an option on Linux and Windows. Instructions can be found [here](https://doctordalek1963.github.io/lintrans/tutorial/compile/).

---

CHANGELOG
'''

# This RegEx is complicated because of the newlines
# It requires the current tag to have a header like
# ## [0.2.1] - 2022-03-22
# And all other tags to have similar headers
# It also won't work on the first tag, but that's fine
RE_PATTERN = r'''(?<=## \[TAG_NAME\] - \d{4}-\d{2}-\d{2}

).*?(?=

## \[\d+\.\d+\.\d+(-[\S]+)?\] - \d{4}-\d{2}-\d{2})'''


def main(args: list[str]) -> None:
    """Generate the release notes for this release and write them to `release_notes.md`."""
    if len(args) < 1:
        raise ValueError('Tag name is required to generate release notes')

    tag_name = args[0]

    print(f'Generating release notes for tag {tag_name}')

    with open('CHANGELOG.md', 'r', encoding='utf-8') as f:
        changelog_text = f.read()

    if (m := re.search(
        RE_PATTERN.replace('TAG_NAME', re.escape(tag_name[1:])),
        changelog_text,
        flags=re.S
    )) is not None:
        text = TEXT.replace('CHANGELOG', m.group(0))

    else:
        raise ValueError('Error in searching for changelog notes. Bad format')

    with open('release_notes.md', 'w', encoding='utf-8') as f:
        f.write(text)


if __name__ == '__main__':
    main(sys.argv[1:])
```

This script just parses the changelog and generates a file called `release_notes.md`, which I can then automatically use as the body for the GitHub release by changing the workflow.

```yaml
# 99a88575f9beb8fed2dcc41dacbb020b31bc8176
# .github/workflows/compile-release.yaml

jobs:
...
  publish:
...
    steps:
...
      - name: Generate release notes
        run: python generate_release_notes.py $GITHUB_REF_NAME

      # This is practically the same step twice just to allow for pre-releases
      - name: Upload binaries (normal release)
        if: steps.checkprerelease.outputs.isprerelease == 0
        uses: softprops/action-gh-release@v1
        with:
          fail_on_unmatched_files: true
          prerelease: false
          draft: true
          body_path: release_notes.md
          files: dist/lintrans*

      - name: Upload binaries (pre-release)
        if: steps.checkprerelease.outputs.isprerelease == 1
        uses: softprops/action-gh-release@v1
        with:
          fail_on_unmatched_files: true
          prerelease: true
          draft: true
          body_path: release_notes.md
          files: dist/lintrans*
```

3.10 Making `v0.2.2`

3.10.1 Hiding the background and transformed grids

I spoke to my main stakeholder, who is the teacher that will be using `lintrans` when it's finished, and she said that the background grid and transformed grid can get a little bit in the way of the core action and make it harder to understand what's happening. Taking this feedback on board, I decided to add a display setting to toggle the background grid, and one to toggle the transformed grid.

I did the background grid first and then repeated everything for the transformed version of the grid as well. I am combining them here for brevity. The first step was of course to add a display setting for each of them. Then I had to add checkboxes for them in the display settings dialog, and then incorporate the settings into the actual drawing of the canvas.

```
# d045057d568ac133b621ee9ca9daed361d570d7a
# src/lintrans/gui/settings.py

@dataclass
class DisplaySettings:
    """This class simply holds some attributes to configure display."""

    # === Basic stuff

    draw_background_grid: bool = True
    """This controls whether we want to draw the background grid.

    The background axes will always be drawn. This makes it easy to identify the center of the space.
    """

    draw_transformed_grid: bool = True
    """This controls whether we want to draw the transformed grid. Vectors are handled separately."""
```

```
# d045057d568ac133b621ee9ca9daed361d570d7a
# src/lintrans/gui/dialogs/settings.py

class DisplaySettingsDialog(SettingsDialog):
...
    def __init__(self, display_settings: DisplaySettings, *args, **kwargs):
...
        self.checkbox_draw_background_grid = QCheckBox(self)
        self.checkbox_draw_background_grid.setText('Draw &background grid')
        self.checkbox_draw_background_grid.setToolTip(
            'Draw the background grid (axes are always drawn)'
        )
        self.dict_checkboxes['b'] = self.checkbox_draw_background_grid

        self.checkbox_draw_transformed_grid = QCheckBox(self)
        self.checkbox_draw_transformed_grid.setText('Draw t&ransformed grid')
        self.checkbox_draw_transformed_grid.setToolTip(
            'Draw the transformed grid (vectors are handled separately)'
        )
        self.dict_checkboxes['r'] = self.checkbox_draw_transformed_grid
...
    def load_settings(self) -> None:
...
        self.checkbox_draw_background_grid.setChecked(self.display_settings.draw_background_grid)
        self.checkbox_draw_transformed_grid.setChecked(self.display_settings.draw_transformed_grid)
...
    def confirm_settings(self) -> None:
...
        self.display_settings.draw_background_grid = self.checkbox_draw_background_grid.isChecked()
        self.display_settings.draw_transformed_grid = self.checkbox_draw_transformed_grid.isChecked()
```

```
# d045057d568ac133b621ee9ca9daed361d570d7a
# src/lintrans/gui/plots/widgets.py
```

```
19  class VisualizeTransformationWidget(VectorGridPlot):
...
48      def paintEvent(self, event: QPaintEvent) -> None:
...
60          self.draw_background(painter, self.display_settings.draw_background_grid)
61
62          if self.display_settings.draw_transformed_grid:
63              self.draw_transformed_grid(painter)
```

```
# d045057d568ac133b621ee9ca9daed361d570d7a
# src/lintrans/gui/plots/classes.py

23  class BackgroundPlot(QWidget):
...
129     def draw_background(self, painter: QPainter, draw_grid: bool) -> None:
130         """Draw the background grid.
131
132         .. note:: This method is just a utility method for subclasses to use to render the background grid.
133
134         :param QPainter painter: The painter to draw the background with
135         :param bool draw_grid: Whether to draw the grid lines
136         """
137         if draw_grid:
138             painter.setPen(QPen(self.colour_background_grid, self.width_background_grid))
139
140             # Draw equally spaced vertical lines, starting in the middle and going out
141             # We loop up to half of the width. This is because we draw a line on each side in each iteration
142             for x in range(self.width() // 2 + self.grid_spacing, self.width(), self.grid_spacing):
143                 painter.drawLine(x, 0, x, self.height())
144                 painter.drawLine(self.width() - x, 0, self.width() - x, self.height())
145
146             # Same with the horizontal lines
147             for y in range(self.height() // 2 + self.grid_spacing, self.height(), self.grid_spacing):
148                 painter.drawLine(0, y, self.width(), y)
149                 painter.drawLine(0, self.height() - y, self.width(), self.height() - y)
150
151         # Now draw the axes
152         painter.setPen(QPen(self.colour_background_axes, self.width_background_grid))
153         painter.drawLine(self.width() // 2, 0, self.width() // 2, self.height())
154         painter.drawLine(0, self.height() // 2, self.width(), self.height() // 2)
```

Then I added this change to the changelog.

```
<!-- d045057d568ac133b621ee9ca9daed361d570d7a -->
<!-- CHANGELOG.md -->

12  ### Added
13
14  - Add options to hide background grid and transformed grid
```

3.10.2 Hiding the basis vectors

While I was implementing new display settings, I decided to implement hiding basis vectors. This will give users the option of just seeing the grid get transformed. The process was exactly the same as before. Add the setting, add it to the dialog, use it when drawing.

```
# 11ffbaf71f9fe29e1832a62f2b127aa3939e520d
# src/lintrans/gui/settings.py

15  class DisplaySettings:
...
29      draw_basis_vectors: bool = True
30      """This controls whether we want to draw the transformed basis vectors."""
```

```
# 11ffbaf71f9fe29e1832a62f2b127aa3939e520d
# src/lintrans/gui/dialogs/settings.py
```

```
70  class DisplaySettingsDialog(SettingsDialog):
...
73      def __init__(self, display_settings: DisplaySettings, *args, **kwargs):
...
103         self.checkbox_draw_basis_vectors = QCheckBox(self)
104         self.checkbox_draw_basis_vectors.setText('Draw basis &vectors')
105         self.checkbox_draw_basis_vectors.setToolTip(
106             'Draw the transformed basis vectors'
107         )
108         self.dict_checkboxes['v'] = self.checkbox_draw_basis_vectors
...
212     def load_settings(self) -> None:
...
217         self.checkbox_draw_basis_vectors.setChecked(self.display_settings.draw_basis_vectors)
...
230     def confirm_settings(self) -> None:
...
235         self.display_settings.draw_basis_vectors = self.checkbox_draw_basis_vectors.isChecked()
```

```
# 11ffbaf71f9fe29e1832a62f2b127aa3939e520d
# src/lintrans/gui/plots/widgets.py

19  class VisualizeTransformationWidget(VectorGridPlot):
...
48      def paintEvent(self, event: QPaintEvent) -> None:
...
65          if self.display_settings.draw_basis_vectors:
66              self.draw_basis_vectors(painter)
```

And then of course add it to the changelog.

```
<!-- 11ffbaf71f9fe29e1832a62f2b127aa3939e520d -->
<!-- CHANGELOG.md -->

12  ### Added
13
14  - Add options to hide background grid, transformed grid, and basis vectors
```

3.10.3 Improving argument parsing

Qt5 accepts arguments to its main method. I don't really know what these arguments can do, but it would be nice to be able to use them. I also want to be able to save sessions as files in the future, and it would be quite useful to open a session file by passing it as a command line argument. To make both of these easier, I decided to refactor my argument parsing.

Python has a built-in library called `argparse`, which allows for more sophisticated argument parsing. One of the things `argparse` can do is parse only some of the command line arguments with a method called `parse_known_args()`[41]. I can then pass the unconsumed arguments on to Qt5. `__main__.py` now looks like this:

```
# a688a14839caba2ee14f8551764b771ae803d935
# src/lintrans/__main__.py

9   """This module provides a :func:`main` function to interpret command line arguments and run the program."""
10
11  from argparse import ArgumentParser
12  import sys
13  from textwrap import dedent
14
15  from lintrans import __version__
16  from lintrans.gui import main_window
17
18
```

```
19  def main(args: list[str]) -> None:
20      """Interpret program-specific command line arguments and run the main window in most cases.
21
22      If the user supplies --help or --version, then we simply respond to that and then return.
23      If they don't supply either of these, then we run :func:`lintrans.gui.main_window.main`.
24
25      :param list[str] args: The full argument list (including program name)
26      """
27      parser = ArgumentParser(add_help=False)
28
29      parser.add_argument(
30          '-h',
31          '--help',
32          default=False,
33          action='store_true'
34      )
35
36      parser.add_argument(
37          '-V',
38          '--version',
39          default=False,
40          action='store_true'
41      )
42
43      parsed_args, unparsed_args = parser.parse_known_args()
44
45      if parsed_args.help:
46          print(dedent('''
47          Usage: lintrans [option]
48
49          Options:
50              -h, --help       Display this help text and exit
51              -V, --version    Display the version information and exit
52
53          Any other options will get passed to the QApplication constructor.
54          If you don't know what that means, then don't provide any arguments and just the run the program.'''[1:]))
55          return
56
57      if parsed_args.version:
58          print(dedent(f'''
59          lintrans (version {__version__})
60          The linear transformation visualizer
61
62          Copyright (C) 2021-2022 D. Dyson (DoctorDalek1963)
63
64          This program is licensed under GNU GPLv3, available here:
65          <https://www.gnu.org/licenses/gpl-3.0.html>'''[1:]))
66          return
67
68      for arg in unparsed_args:
69          print(f'Passing "{arg}" to QApplication. See --help for recognised args')
70
71      main_window.main(args[:1] + unparsed_args)
72
73
74  if __name__ == '__main__':
75      main(sys.argv)
```

The ‘`args[:1] + unparsed_args`’ on line 71 means that we pass the name of the program first, and the rest of the unconsumed arguments after it.

And of course, I added it to the changelog, this time as a fix rather than an addition:

```
<!-- a688a14839caba2ee14f8551764b771ae803d935 -->
<!-- CHANGELOG.md -->

16  ### Fixed
17
18  - Improve command line argument handling
```

3.10.4 Respecting display settings in the visual definition dialog

`DefineVisuallyWidget` is a subclass of `VisualizeTransformationWidget`. If it had its own instance attribute of type `DisplaySettings`, then it could use its superclass's `paintEvent()` method, and that would respect the display settings in the visual definition dialog.

```
# 5850aa916b685992f31e58680267916927ed590d
# src/lintrans/gui/plots/widgets.py

84  class DefineVisuallyWidget(VisualizeTransformationWidget):
...
91      def __init__(self, *args, display_settings: DisplaySettings, **kwargs):
92          """Create the widget and enable mouse tracking. ``*args`` and ``**kwargs`` are passed to ``super()``."""
93          super().__init__(*args, display_settings=display_settings, **kwargs)


# 5850aa916b685992f31e58680267916927ed590d
# src/lintrans/gui/dialogs/define_new_matrix.py

166 class DefineVisuallyDialog(DefineDialog):
...
169     def __init__(self, *args, matrix_wrapper: MatrixWrapper, display_settings: DisplaySettings, **kwargs):
170         """Create the widgets and layout of the dialog.
171
172         :param MatrixWrapper matrix_wrapper: The MatrixWrapper that this dialog will mutate
173         """
174         super().__init__(*args, matrix_wrapper=matrix_wrapper, **kwargs)
175
176         self.setMinimumSize(700, 550)
177
178         # === Create the widgets
179
180         self.plot = DefineVisuallyWidget(self, display_settings=display_settings)
```

Since the `DefineVisuallyDialog` now accepts display settings but the other definition dialogs don't, we need change the `LintransMainWindow.dialog_define_matrix()` method to treat the visual definition dialog differently.

```
# 5850aa916b685992f31e58680267916927ed590d
# src/lintrans/gui/main_window.py

36  class LintransMainWindow(QMainWindow):
...
447     @pyqtSlot(DefineDialog)
448     def dialog_define_matrix(self, dialog_class: Type[DefineDialog]) -> None:
449         """Open a generic definition dialog to define a new matrix.
450
451         The class for the desired dialog is passed as an argument. We create an
452         instance of this class and the dialog is opened asynchronously and modally
453         (meaning it blocks interaction with the main window) with the proper method
454         connected to the :meth:`QDialog.accepted` signal.
455
456         .. note:: ``dialog_class`` must subclass :class:`lintrans.gui.dialogs.define_new_matrix.DefineDialog`.
457
458         :param dialog_class: The dialog class to instantiate
459         :type dialog_class: Type[lintrans.gui.dialogs.define_new_matrix.DefineDialog]
460         """
461         # We create a dialog with a deepcopy of the current matrix_wrapper
462         # This avoids the dialog mutating this one
463         if dialog_class == DefineVisuallyDialog:
464             dialog = DefineVisuallyDialog(
465                 self,
466                 matrix_wrapper=deepcopy(self.matrix_wrapper),
467                 display_settings=self.plot.display_settings
468             )
469         else:
470             dialog = dialog_class(self, matrix_wrapper=deepcopy(self.matrix_wrapper))
471
```

```
472             # .open() is asynchronous and doesn't spawn a new event loop, but the dialog is still modal (blocking)
473             dialog.open()
474
475             # So we have to use the accepted signal to call a method when the user accepts the dialog
476             dialog.accepted.connect(self.assign_matrix_wrapper)
```

And, of course, I updated the changelog:

```
<!-- 5850aa916b685992f31e58680267916927ed590d -->
<!-- CHANGELOG.md -->

12  ### Added
...
15  - Fully respect display settings in visual definition widget
```

3.10.5 Changing the order in which things are drawn

Currently, `VisualizeTransformationWidget` draws the background, then the transformed grid, then the basis vectors, then the eigenlines and eigenvectors, then the determinant parallelogram and text. This means that the determinant parallelogram gets drawn on top of the basis vectors, which doesn't look very good. To fix this, we can simply re-order the drawing of different things. If we instead draw the transformed grid and basis vectors last, then they will appear on top of everything else, which should look significantly better.

I also renamed the `draw_determinant_text` display setting attribute to `show_determinant_value`.

Before:

```
# e9da6737cbdb68e800c245bcc34e1c5c3824458a
# src/lintrans/gui/plots/widgets.py

19  class VisualizeTransformationWidget(VectorGridPlot):
...
48      def paintEvent(self, event: QPaintEvent) -> None:
...
60          self.draw_background(painter, self.display_settings.draw_background_grid)
61
62          if self.display_settings.draw_transformed_grid:
63              self.draw_transformed_grid(painter)
64
65          if self.display_settings.draw_basis_vectors:
66              self.draw_basis_vectors(painter)
67
68          if self.display_settings.draw_eigenlines:
69              self.draw_eigenlines(painter)
70
71          if self.display_settings.draw_eigenvectors:
72              self.draw_eigenvectors(painter)
73
74          if self.display_settings.draw_determinant_parallelogram:
75              self.draw_determinant_parallelogram(painter)
76
77              if self.display_settings.draw_determinant_text:
78                  self.draw_determinant_text(painter)
```

After:

```
# acdf206a69d346dce67f74f2c54ff4c512c96229
# src/lintrans/gui/plots/widgets.py

19  class VisualizeTransformationWidget(VectorGridPlot):
...
48      def paintEvent(self, event: QPaintEvent) -> None:
```

```
...
60          self.draw_background(painter, self.display_settings.draw_background_grid)
61
62          if self.display_settings.draw_eigenlines:
63              self.draw_eigenlines(painter)
64
65          if self.display_settings.draw_eigenvectors:
66              self.draw_eigenvectors(painter)
67
68          if self.display_settings.draw_determinant_parallelogram:
69              self.draw_determinant_parallelogram(painter)
70
71              if self.display_settings.show_determinant_value:
72                  self.draw_determinant_text(painter)
73
74          if self.display_settings.draw_transformed_grid:
75              self.draw_transformed_grid(painter)
76
77          if self.display_settings.draw_basis_vectors:
78              self.draw_basis_vectors(painter)
```

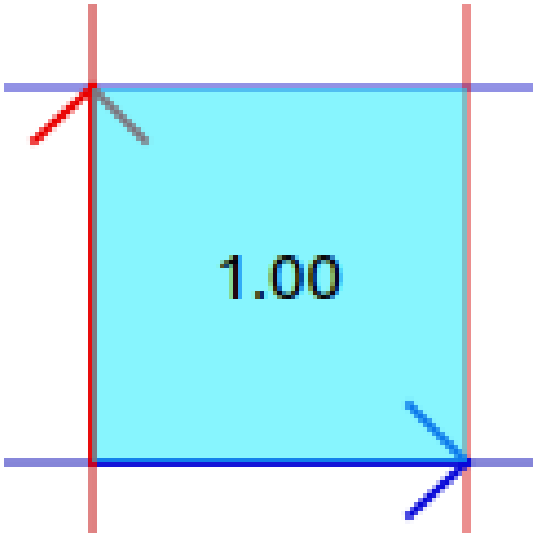


Figure 3.10.1: Before re-ordering drawing commands

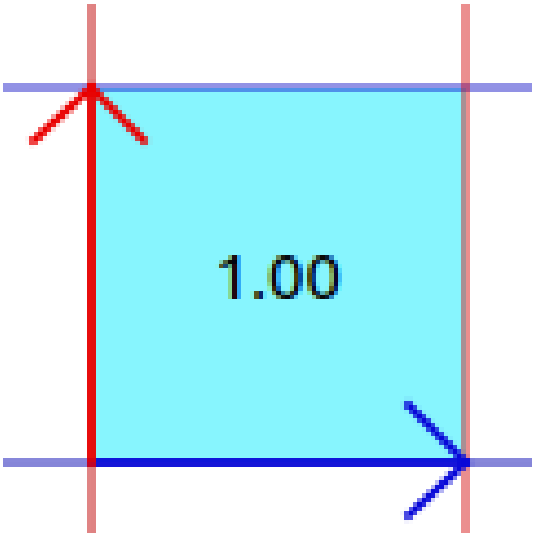


Figure 3.10.2: After re-ordering drawing commands

3.10.6 Improving online documentation with *Read the Docs*

So far, I've been building my documentation automatically using a tool called `Sphinx`[55]. I've been using it to scan through my source code, extract all the docstrings[20], and compile a HTML version of the source code documentation. I then publish this documentation to GitHub Pages[18], and all that happens automatically along with the unit tests whenever I push my changes to GitHub.

However, this system can't track changes in documentation over time. There's a popular website for hosting open source documentation, especially for Python packages, called *Read the Docs*[51]. It would be nice to host my documentation on there, since it would provide a standard build for the docs, and would allow me to keep track of documentation for different versions over time. I read through their tutorial and followed along with it, and then I could use Read the Docs for `lintrans`.

```
# a7a8aa09148f4acf8591547d6d8b9cd8b8d52905
# .readthedocs.yaml

version: 2

```

```yaml
build:
  os: ubuntu-20.04
  tools:
    python: "3.10"
  apt_packages:
    - graphviz

  jobs:
    pre_build:
      - cd docs/ && $(pwd | sed "s/checkouts\(\/[^/]\+\)\/docs\$/envs\1/")/bin/python create_objects_inv.py
      - $(pwd | sed "s/checkouts\(\/[^/]\+\)\$/envs\1/")/bin/python -m pylint --rcfile=/dev/null --exit-zero
      ↪  --reports=y --disable=all --enable=imports,RP0402 --int-import-graph=docs/source/int-imports.png $(find
      ↪  ./src/lintrans/ -name "*.py" | tr "\n" " ")
      - mkdir -p docs/source/_static
      - $(pwd | sed "s/checkouts\(\/[^/]\+\)\$/envs\1/")/bin/python -m pip install -e .
      - $(pwd | sed "s/checkouts\(\/[^/]\+\)\$/envs\1/")/bin/python -c "import lintrans" && echo success || echo
      ↪  fail

sphinx:
  builder: html
  configuration: docs/source/conf.py
  fail_on_warning: true

python:
  install:
    - requirements: requirements.txt
    - requirements: docs/docs_requirements.txt

  system_packages: false
```

This file governs the build pipeline for the documentation. It defines how the docs will be built on the remote machine. It basically just installs all the dependencies and `lintrans` itself in a virtual environment, generates the object inventory for `intersphinx` (see §3.9.2), builds the internal import graph (see §3.8.4), and makes sure that lintrans can be installed successfully in the virtual environment. The string '`$(pwd | sed "s/checkouts\(\/[^/]\+\)\/docs\$/envs\1/")/bin/python`' appears frequently. This string finds the version of Python that will be used for building the actual documentation at the end of the pipeline. `lintrans` has some issues with circular imports, which means that it can only be installed in editable mode[23]. This means that I have to bodge the build system to install `lintrans` properly.

Additionally, having a build system like this means that builds should be repeatable, which means I should pin the exact versions of all my dependencies, to avoid any breaking changes in the future.

```
# 152f9e59b5b4e22607cf2b687c85c70708054579
# requirements.txt

nptyping==1.4.4
numpy==1.21.0
pyqt5==5.15.6
```

```
# 152f9e59b5b4e22607cf2b687c85c70708054579
# dev_requirements.txt

flake8==4.0.1
mypy==0.942
pycodestyle==2.8.0
pydocstyle==6.1.1
pytest==6.2.5
pyqt5-stubs==5.15.2.0
toml==0.10.2
```

[23] Editable mode is an option that you can choose when installing a package with `pip`[32]. Instead of copying the source code to the installation directory like normal, it creates a link to the source code from the installation directory - basically a symlink in Linux. This means that if you change the source code, the installed version gets updated instantly, which is obviously very useful for fast, iterative development. It also has some strange effects with import order and resolution. Importing packages and modules is very complicated in Python[12], and I repeatedly failed to get `lintrans` to be installable without editable mode, so I had to resort to just using this bodge on Read the Docs instead.

```
# 152f9e59b5b4e22607cf2b687c85c70708054579
# docs/docs_requirements.txt

Sphinx==4.3.2
sphinx-rtd-theme==1.0.0
sphobjinv==2.2
```

Now that I was using Read the Docs, I could remove the old GitHub Actions workflow to compile the documentation.

3.10.7 Parsing parentheses

`git` has a feature called branches[16], which allow you to work on different things simultaneously. A branch is basically a sandbox where you can make changes and focus on a particular feature while not having to worry about the rest of the project. It's particularly good for teams where different people can work on different features at the same time, but it's also useful for individual developers. The first feature branch I merged for `lintrans` was called `dev/parse-parens`. I created it a week or two ago, and I used it to focus on improving the parser to understand parenthesised expressions like `"A(B+C)^2"`.

3.10.7.1 Extending validation

The first thing I needed to do was allow parenthesised expressions as valid. If the validator rejects them, then they can never be parsed. Any expression can be evaluated to a matrix, and a pair of balanced parentheses can contain any valid expression. As such, a parenthesised expression can be considered as a type of matrix.

```
# 1e49c1479939b8de04751ab1a798afb2145b1550
# docs/source/bnf.txt

expression        ::=  [ "-" ] matrices { ( "+" | "-" ) matrices };
matrices          ::=  matrix { matrix };
matrix            ::=  [ real_number ] matrix_identifier [ index ] | "(" expression ")";
matrix_identifier ::=  "A" .. "Z" | "rot(" [ "-" ] real_number ")";
index             ::=  "^{" index_content "}" | "^" index_content;
index_content     ::=  [ "-" ] integer_not_zero | "T";

digit_no_zero     ::=  "1" | "2" | "3" | "4" | "5" | "6" | "7" | "8" | "9";
digit             ::=  "0" | digit_no_zero;
digits            ::=  digit | digits digit;
integer_not_zero  ::=  digit_no_zero [ digits ];
real_number       ::=  ( integer_not_zero [ "." digits ] | [ "0" ] "." digits );
```

```
# 1e49c1479939b8de04751ab1a798afb2145b1550
# src/lintrans/matrices/parse.py

NAIVE_CHARACTER_CLASS = r'[-+\sA-Z0-9.rot()^{}]'
...
def compile_naive_expression_pattern() -> Pattern[str]:
    """Compile the single RegEx pattern that will match a valid matrix expression."""
    digit_no_zero = '[123456789]'
    digits = '\\d+'
    integer_no_zero = digit_no_zero + '(' + digits + ')?'
    real_number = f'({integer_no_zero}(\\.{digits})?|0?\\.{digits})'

    index_content = f'(-?{integer_no_zero}|T)'
    index = f'(\\^{{{index_content}}}|\\^{index_content})'
    matrix_identifier = f'([A-Z]|rot\\(-?{real_number}\\)|\\({NAIVE_CHARACTER_CLASS}+\\))'
    matrix = '(' + real_number + '?' + matrix_identifier + index + '?)'
    expression = f'^-?{matrix}+((\\+|-){matrix}+)*$'

    return re.compile(expression)
```

```python


# This is an expensive pattern to compile, so we compile it when this module is initialized
naive_expression_pattern = compile_naive_expression_pattern()


def find_sub_expressions(expression: str) -> list[str]:
    """Find all the sub-expressions in the given expression.

    This function only goes one level deep, so may return strings like ``'A(BC)D'``.

    :raises MatrixParseError: If there are unbalanced parentheses
    """
    sub_expressions: list[str] = []
    string = ''
    paren_depth = 0
    pointer = 0

    while True:
        char = expression[pointer]

        if char == '(' and expression[pointer - 3:pointer] != 'rot':
            paren_depth += 1

            # This is a bit of a manual bodge, but it eliminates extraneous parens
            if paren_depth == 1:
                pointer += 1
                continue

        elif char == ')' and re.match(f'{NAIVE_CHARACTER_CLASS}*?rot\\([-\\d.]+$', expression[:pointer]) is None:
            paren_depth -= 1

        if paren_depth > 0:
            string += char

        if paren_depth == 0 and string:
            sub_expressions.append(string)
            string = ''

        pointer += 1

        if pointer >= len(expression):
            break

    if paren_depth != 0:
        raise MatrixParseError('Unbalanced parentheses in expression')

    return sub_expressions


def validate_matrix_expression(expression: str) -> bool:
    """Validate the given matrix expression.

    This function simply checks the expression against the BNF schema documented in
    :ref:`expression-syntax-docs`. It is not aware of which matrices are actually defined
    in a wrapper. For an aware version of this function, use the
    :meth:`lintrans.matrices.wrapper.MatrixWrapper.is_valid_expression` method.

    :param str expression: The expression to be validated
    :returns bool: Whether the expression is valid according to the schema
    """
    # Remove all whitespace
    expression = re.sub(r'\s', '', expression)

    match = naive_expression_pattern.match(expression)

    if match is None:
        return False

    # Check that the whole expression was matched against
    if expression != match.group(0):
        return False


```

```
110         try:
111             sub_expressions = find_sub_expressions(expression)
112         except MatrixParseError:
113             return False
114 
115         if not sub_expressions:
116             return True
117 
118         return all(validate_matrix_expression(m) for m in sub_expressions)
```

We create a naïve character class that just contains all characters that could possibly be in a valid expression. Then when we compile the naïve expression pattern, we say that a matrix identifier can be one of three things: it can be a capital letter, the `rot()` command with a real number angle, or a balanced pair of parentheses around some characters. The characters in the parentheses are not validated at this stage (hence why this pattern is naïve), but we know that those characters are only allowed to be from the naïve character class.

Then we have a function that finds sub-expressions in a given expression. It simply scans through the given string with a pointer and keeps track of the current sub-expression. It uses the `paren_depth` variable to keep track of how deep into a sub-expression it currently is. This function deliberately avoids counting the parentheses from `rot()` commands towards the `paren_depth`. This is to avoid scanning an expression like `"3rot(45)^2"` and finding `"45"` as a sub-expression.

Then we have to actually use this function when validating. All we do is recursively check that each sub-expression is a valid expression on its own. The `find_sub_expressions()` function only goes one level deep, so in an expression like `"A(B+C(D^2-E))"`, it will only find `"B+C(D^2-E)"` as a sub-expression, so recursion is needed to make the validation work properly.

There's actually a small mistake in the BNF that I didn't notice until much much later. The validation code is correct - it treats a parenthesised expression as a matrix identifier, so it can accept a multiplier on the left and an index on the right - but the BNF treats a parenthesised expression as a full matrix, which means it can't accept a multiplier or index. This doesn't affect the code, but does make the documentation slightly confusing.

And of course, I then added to the automatic unit tests to make sure this new validation worked.

```
# 1e49c1479939b8de04751ab1a798afb2145b1550
# tests/matrices/test_parse_and_validate_expression.py

16  expected_sub_expressions: list[tuple[str, list[str]]] = [
17      ('2(AB)^-1', ['AB']),
18      ('-3(A+B)^2-C(B^TA)^-1', ['A+B', 'B^TA']),
19      ('rot(45)', []),
20      ('()', []),
21      ('(())', ['()']),
22      ('2.3A^-1(AB)^-1+(BC)^2', ['AB', 'BC']),
23      ('(2.3A^-1(AB)^-1+(BC)^2)', ['2.3A^-1(AB)^-1+(BC)^2']),
24  ]
25 
26 
27  def test_find_sub_expressions() -> None:
28      """Test the :func:`lintrans.matrices.parse.find_sub_expressions` function."""
29      for inp, output in expected_sub_expressions:
30          assert find_sub_expressions(inp) == output
...
33  valid_inputs: list[str] = [
...
50      '(A)', '(AB)^-1', '2.3(3B^TA)^2', '-3.4(9D^{2}3F^-1)^T+C', '(AB)(C)',
51      '3(rot(34)^-7A)^-1+B', '3A^2B+4A(B+C)^-1D^T-A(C(D+E)B)'
52  ]
...
54  invalid_inputs: list[str] = [
...
57      '2.3AB)^T', '(AB+)', '-4.6(9A', '-2(3.4A^{-1}-C^)^2', '9.2)', '3A^2B+4A(B+C)^-1D^T-A(C(D+EB)',
...
60  ]
```

```
...
 70     expressions_and_parsed_expressions: list[tuple[str, MatrixParseList]] = [
...
105         # Parenthesized expressions
106         ('(AB)^-1', [[('', 'AB', '-1')]]),
107         ('-3(A+B)^2-C(B^TA)^-1', [[('-3', 'A+B', '2')], [('-1', 'C', ''), ('', 'B^TA', '-1')]]),
108         ('2.3(3B^TA)^2', [[('2.3', '3B^TA', '2')]]),
109         ('-3.4(9D^{2}3F^-1)^T+C', [[('-3.4', '9D^{2}3F^-1', 'T')], [('', 'C', '')]]),
110         ('2.39(3.1A^{-1}2.3B(CD)^-1)^T + (AB^T)^-1', [[('2.39', '3.1A^{-1}2.3B(CD)^-1', 'T')], [('', 'AB^T', '-1')]])
111     ]
```

I also added `@pytest.mark.xfail` to `test_parse_matrix_expression()`, since parsing should fail with the parenthesised expressions because I haven't implemented it yet.

```
(lintrans) dyson@Harold-Ubuntu:~/repos/lintrans [main *]
$ pytest -v
============================================= test session starts ==============================================
platform linux -- Python 3.11.0, pytest-7.2.1, pluggy-1.0.0 -- /home/dyson/temp/lintrans/venv/bin/python
cachedir: .pytest_cache
rootdir: /home/dyson/temp/lintrans, configfile: pyproject.toml, testpaths: tests
collected 31 items

tests/gui/test_dialog_utility_functions.py::test_is_valid_float[inputs0-True] PASSED                          [  3%]
tests/gui/test_dialog_utility_functions.py::test_is_valid_float[inputs1-False] PASSED                         [  6%]
tests/gui/test_dialog_utility_functions.py::test_round_float PASSED                                           [  9%]
tests/matrices/test_parse_and_validate_expression.py::test_find_sub_expressions PASSED                        [ 12%]
tests/matrices/test_parse_and_validate_expression.py::test_validate_matrix_expression[inputs0-True] PASSED    [ 16%]
tests/matrices/test_parse_and_validate_expression.py::test_validate_matrix_expression[inputs1-False] PASSED   [ 19%]
tests/matrices/test_parse_and_validate_expression.py::test_parse_matrix_expression XFAIL                      [ 22%]
tests/matrices/test_parse_and_validate_expression.py::test_parse_error PASSED                                 [ 25%]
tests/matrices/test_rotation_matrices.py::test_create_rotation_matrix PASSED                                  [ 29%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_simple_matrix_addition PASSED                 [ 32%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_simple_two_matrix_multiplication PASSED       [ 35%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_identity_multiplication PASSED                [ 38%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_simple_three_matrix_multiplication PASSED     [ 41%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_matrix_inverses PASSED                        [ 45%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_matrix_powers PASSED                          [ 48%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_matrix_transpose PASSED                       [ 51%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_rotation_matrices PASSED                      [ 54%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_multiplication_and_addition PASSED            [ 58%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_complicated_expressions PASSED                [ 61%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_value_errors PASSED                           [ 64%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_linalgerror PASSED                            [ 67%]
tests/matrices/matrix_wrapper/test_misc.py::test_get_expression PASSED                                        [ 70%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_basic_get_matrix PASSED                       [ 74%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_get_name_error PASSED                         [ 77%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_basic_set_matrix PASSED                       [ 80%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_set_expression PASSED                         [ 83%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_simple_dynamic_evaluation PASSED              [ 87%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_recursive_dynamic_evaluation PASSED           [ 90%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_set_identity_error PASSED                     [ 93%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_set_name_error PASSED                         [ 96%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_set_type_error PASSED                         [100%]

========================================== 30 passed, 1 xfailed in 0.38s ===========================================
```

Figure 3.10.3: Running `pytest` with the new tests

3.10.7.2 Creating the parser class

I previously used regular expressions to parse matrix expressions. The algorithm would replace various parts of the expression to coerce it into the correct format, and then use a big RegEx at the end to find all the parts necessary for parsing. This was hard to understand and hard to maintain. It's now time to overhaul this parsing system and use a parser class to scan through the input and parse character-by-character, keeping track of the state as it goes.

```
# 736809714e0ad7579c419db03c4b5d8b8fd0c1a1
# src/lintrans/matrices/parse.py

122 @dataclass
123 class MatrixToken:
124     """A simple dataclass to hold information about a matrix token being parsed."""
125
126     multiplier: str = ''
127     identifier: str = ''
```

```
128         exponent: str = ''
129
130         @property
131         def tuple(self) -> tuple[str, str, str]:
132             """Create a tuple of the token for parsing."""
133             return self.multiplier, self.identifier, self.exponent
134
135
136     class ExpressionParser:
137         """A class to hold state during parsing."""
138
139         def __init__(self, expression: str):
140             """Create an instance of the parser with the given expression."""
141             # Remove all whitespace
142             expression = re.sub(r'\s', '', expression)
143
144             # Check if it's valid
145             if not validate_matrix_expression(expression):
146                 raise MatrixParseError('Invalid expression')
147
148             # Wrap all exponents and transposition powers with {}
149             expression = re.sub(r'(?<=\^)(-?\d+|T)(?=[^}]|$)', r'{\g<0>}', expression)
150
151             # Remove any standalone minuses
152             expression = re.sub(r'-(?=[A-Z])', '-1', expression)
153
154             # Replace subtractions with additions
155             expression = re.sub(r'-(?=\d+\.?\d*([A-Z]|rot))', '+-', expression)
156
157             # Get rid of a potential leading + introduced by the last step
158             expression = re.sub(r'^\+', '', expression)
159
160             self.expression = expression
161             self.pointer: int = 0
162
163             self.current_token: MatrixToken = MatrixToken()
164             self.current_group: list[tuple[str, str, str]] = []
165
166             self.final_list: MatrixParseList = []
167
168         def __repr__(self) -> str:
169             """Return a simple repr."""
170             return f'{self.__class__.__module__}.{self.__class__.__name__}("{self.expression}")'
171
172         @property
173         def char(self) -> str:
174             """Return the char pointed to by the pointer."""
175             return self.expression[self.pointer]
176
177         def parse(self) -> MatrixParseList:
178             """Parse the instance's matrix expression and return the MatrixParseList.
179
180             :returns MatrixParseList: The parsed expression
181             """
182             self._parse_multiplication_group()
183
184             while self.pointer < len(self.expression):
185                 if self.expression[self.pointer] != '+':
186                     raise MatrixParseError('Expected "+" between multiplication groups')
187
188                 self.pointer += 1
189                 self._parse_multiplication_group()
190
191             return self.final_list
192
193         def _parse_multiplication_group(self) -> None:
194             """Parse a group of matrices to be multiplied.
195
196             :returns bool: Success or failure
197             """
198             while self._parse_matrix():
199                 if self.pointer >= len(self.expression) or self.char == '+':
200                     self.final_list.append(self.current_group)
```

```
                self.current_group = []
                self.pointer += 1

    def _parse_matrix(self) -> bool:
        """Parse a full matrix using :meth:`_parse_matrix_part`.

        :returns bool: Success or failure
        """
        self.current_token = MatrixToken()

        while self._parse_matrix_part():
            pass  # The actual execution is taken care of in the loop condition

        if self.current_token.identifier == '':
            return False

        self.current_group.append(self.current_token.tuple)
        return True

    def _parse_matrix_part(self) -> bool:
        """Parse part of a matrix (multiplier, identifier, or exponent) from the expression and pointer.

        .. note:: This method mutates ``self.current_token``.

        :returns bool: Success or failure
        :raises MatrixParseError: If we fail to parse this part of the token
        """
        if self.pointer >= len(self.expression):
            return False

        if self.char.isdigit() or self.char == '-':
            if self.current_token.multiplier != '':
                return False

            self._parse_multiplier()

        elif self.char.isalpha() and self.char.isupper():
            if self.current_token.identifier != '':
                return False

            self.current_token.identifier = self.char
            self.pointer += 1

        elif self.char == 'r':
            if self.current_token.identifier != '':
                return False

            self._parse_rot_identifier()

        elif self.char == '(':
            if self.current_token.identifier != '':
                return False

            self._parse_sub_expression()

        elif self.char == '^':
            if self.current_token.exponent != '':
                return False

            self._parse_exponent()

        elif self.char == '+':
            return False

        else:
            raise MatrixParseError(f'Unrecognised character "{self.char}" in matrix expression')

        return True

    def _parse_multiplier(self) -> None:
        """Parse a multiplier from the expression and pointer.

        .. note:: This method mutates ``self.current_token.multiplier``.
```

```
274
275             :raises MatrixParseError: If we fail to parse this part of the token
276             """
277             multiplier = ''
278
279             while self.char.isdigit() or self.char in ('.', '-'):
280                 multiplier += self.char
281                 self.pointer += 1
282
283             # There can only be one dot in the multiplier
284             if len(multiplier.split('.')) > 2:
285                 raise MatrixParseError(f'Multiplier "{multiplier}" has more than one dot')
286
287             if '-' in multiplier and '-' in multiplier[1:]:
288                 raise MatrixParseError('Character "-" can only occur at the start of a multiplier')
289
290             self.current_token.multiplier = multiplier
291
292         def _parse_rot_identifier(self) -> None:
293             """Parse a ``rot()``-style identifier from the expression and pointer.
294
295             .. note:: this method mutates ``self.current_token.identifier``.
296
297             :raises MatrixParseError: If we fail to parse this part of the token
298             """
299             if match := re.match(r'rot\([^()]+\)', self.expression[self.pointer:]):
300                 self.current_token.identifier = match.group(0)
301                 self.pointer += len(match.group(0))
302             else:
303                 raise MatrixParseError(f'Invalid rot-identifier "{self.expression[self.pointer:self.pointer + 15]}..."')
304
305         def _parse_sub_expression(self) -> None:
306             """Parse a parenthesized sub-expression as the identifier, from the expression and pointer.
307
308             .. note:: this method mutates ``self.current_token.identifier``.
309
310             :raises MatrixParseError: If we fail to parse this part of the token
311             """
312             # TODO
313             raise MatrixParseError('Sub-expressions are currently not supported as identifiers')
314
315         def _parse_exponent(self) -> None:
316             """Parse a matrix exponent from the expression and pointer.
317
318             .. note:: this method mutates ``self.current_token.exponent``.
319
320             :raises MatrixParseError: If we fail to parse this part of the token
321             """
322             if match := re.match(r'\^\{(-?\d+|T)\}', self.expression[self.pointer:]):
323                 self.current_token.exponent = match.group(1)
324                 self.pointer += len(match.group(0))
325             else:
326                 raise MatrixParseError(f'Invalid exponent "{self.expression[self.pointer:self.pointer + 10]}..."')
327
328
329     def parse_matrix_expression(expression: str) -> MatrixParseList:
330         """Parse the matrix expression and return a :data:`lintrans.typing_.MatrixParseList`.
331
332         :Example:
333
334         >>> parse_matrix_expression('A')
335         [[('', 'A', '')]]
336         >>> parse_matrix_expression('-3M^2')
337         [[('-3', 'M', '2')]]
338         >>> parse_matrix_expression('1.2rot(12)^{3}2B^T')
339         [[('1.2', 'rot(12)', '3'), ('2', 'B', 'T')]]
340         >>> parse_matrix_expression('A^2 + 3B')
341         [[('', 'A', '2')], [('3', 'B', '')]]
342         >>> parse_matrix_expression('-3A^{-1}3B^T - 45M^2')
343         [[('-3', 'A', '-1'), ('3', 'B', 'T')], [('-45', 'M', '2')]]
344         >>> parse_matrix_expression('5.3A^{4} 2.6B^{-2} + 4.6D^T 8.9E^{-1}')
345         [[('5.3', 'A', '4'), ('2.6', 'B', '-2')], [('4.6', 'D', 'T'), ('8.9', 'E', '-1')]]
346
```

```
347         :param str expression: The expression to be parsed
348         :returns: A list of parsed components
349         :rtype: :data:`lintrans.typing_.MatrixParseList`
350         """
351         return ExpressionParser(expression).parse()
```

The `MatrixToken` class just holds data about a matrix multiplier, identifier, and exponent. It's just a simple way to package up this data into a single dataclass to keep track of which matrices we've parsed.

The `ExpressionParser` class works like so: when you create a new instance, you give it an expression to parse and it cleans up the expression by removing whitespace, making sure it's valid, wrapping exponents with `{}`, etc. Most of these replacement steps are taken from the previous RegEx-based parser. It then sets up some internal state to keep track of the expression, the pointer, the token that it's currently parsing, the group that it's currently parsing, and its progress so far.

When you've created a new instance, you should call the public `parse()` method, which will return the parsed expression at the end, in the same format that the old parser used. The `parse_matrix_expression()` function is a wrapper that just creates an `ExpressionParser` and calls `parse()`.

The `parse()` method itself just delegates to `_parse_multiplication_group()`. A multiplication group is a group of matrices that will be multiplied together in a particular order. An expression should start with a multiplication group, and may have extra ones separated with plus signs. When all the multiplication groups have been parsed, it returns the final parse list.

`_parse_multiplication_group()` tries to parse matrices until it reaches the end of the expression or it finds a plus sign, at which point it appends the current group to the final list and returns.

`_parse_matrix()` returns a boolean to indicate success. It just attempts to parse a 'matrix part' (multiplier, identifier, or exponent) until that fails, and then ensures that the resultant matrix token has a valid identifier. It then appends the matrix token to the current group.

`_parse_matrix_part()` is where most of the selection happens. This method has to determine if it's looking at a multiplier, which would start with a digit or a minus sign; a normal identifier, which would start with a capital letter; a rotation identifier, which would start with a lowercase letter r; a sub-expression, which would start with an open bracket; or an exponent, with will start with a caret. If it encounters a plus sign, then that's a soft error, so it can return `False`, but if it encounters something it doesn't recognise, then that's a hard error.

`_parse_multiplier()` just parses a real number into `self.current_token.multiplier`.

`_parse_rot_identifier()` parses a `rot()` command with a real number angle[24].

`_parse_sub_expression()` hasn't been implemented yet, but it will eventually parse sub-expressions, hence the name.

`_parse_exponent()` parses a caret, and then a balanced pair of braces, containing an integer or a capital letter T.

And of course, this new parser should still pass all the unit tests for the previous parser, which it does.

[24] It doesn't need to parse the real number itself to make sure it's valid, since the expression validator already ensured that it was a valid real number.

```
(lintrans) dyson@Harold-Ubuntu:~/repos/lintrans [main *]
$ pytest -v
============================================= test session starts ==============================================
platform linux -- Python 3.11.0, pytest-7.2.1, pluggy-1.0.0 -- /home/dyson/temp/lintrans/venv/bin/python
cachedir: .pytest_cache
rootdir: /home/dyson/temp/lintrans, configfile: pyproject.toml, testpaths: tests
collected 31 items

tests/gui/test_dialog_utility_functions.py::test_is_valid_float[inputs0-True] PASSED                          [  3%]
tests/gui/test_dialog_utility_functions.py::test_is_valid_float[inputs1-False] PASSED                         [  6%]
tests/gui/test_dialog_utility_functions.py::test_round_float PASSED                                           [  9%]
tests/matrices/test_parse_and_validate_expression.py::test_find_sub_expressions PASSED                        [ 12%]
tests/matrices/test_parse_and_validate_expression.py::test_validate_matrix_expression[inputs0-True] PASSED    [ 16%]
tests/matrices/test_parse_and_validate_expression.py::test_validate_matrix_expression[inputs1-False] PASSED   [ 19%]
tests/matrices/test_parse_and_validate_expression.py::test_parse_matrix_expression XFAIL                      [ 22%]
tests/matrices/test_parse_and_validate_expression.py::test_parse_error PASSED                                 [ 25%]
tests/matrices/test_rotation_matrices.py::test_create_rotation_matrix PASSED                                  [ 29%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_simple_matrix_addition PASSED                 [ 32%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_simple_two_matrix_multiplication PASSED       [ 35%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_identity_multiplication PASSED                [ 38%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_simple_three_matrix_multiplication PASSED     [ 41%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_matrix_inverses PASSED                        [ 45%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_matrix_powers PASSED                          [ 48%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_matrix_transpose PASSED                       [ 51%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_rotation_matrices PASSED                      [ 54%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_multiplication_and_addition PASSED            [ 58%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_complicated_expressions PASSED                [ 61%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_value_errors PASSED                           [ 64%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_linalgerror PASSED                            [ 67%]
tests/matrices/matrix_wrapper/test_misc.py::test_get_expression PASSED                                        [ 70%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_basic_get_matrix PASSED                       [ 74%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_get_name_error PASSED                         [ 77%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_basic_set_matrix PASSED                       [ 80%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_set_expression PASSED                         [ 83%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_simple_dynamic_evaluation PASSED              [ 87%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_recursive_dynamic_evaluation PASSED           [ 90%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_set_identity_error PASSED                     [ 93%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_set_name_error PASSED                         [ 96%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_set_type_error PASSED                         [100%]

============================================== 30 passed, 1 xfailed in 0.38s ===============================================
```

Figure 3.10.4: Running `pytest` with the new tests

3.10.7.3 Implementing sub-expression parsing

Of course, the next step was to actually implement sub-expression parsing. To do this, I used a very similar method to finding the sub-expressions, where I kept track of the depth of the parentheses. Except with this method, we only wanted the first sub-expression starting at the pointer. We can then assign this whole sub-expression to `self.current_token.identifier` at the end.

Much like when finding sub-expressions, this parser method only goes one level deep, but the `MatrixWrapper` will use recursion when evaluating the parsed expressions, so it will handle nested sub-expressions with.

```
# 493f8cf3fb658408466f099f978d276fc2262243
# src/lintrans/matrices/parse.py

136 class ExpressionParser:
...
305     def _parse_sub_expression(self) -> None:
306         """Parse a parenthesized sub-expression as the identifier, from the expression and pointer.
307
308         .. note:: this method mutates ``self.current_token.identifier``.
309
310         :raises MatrixParseError: If we fail to parse this part of the token
311         """
312         if self.char != '(':
313             raise MatrixParseError('Sub-expression must start with "("')
314
315         self.pointer += 1
316         paren_depth = 1
317         identifier = ''
318
319         while paren_depth > 0:
320             if self.char == '(':
321                 paren_depth += 1
322             elif self.char == ')':
```

```
323                 paren_depth -= 1
324
325             if paren_depth == 0:
326                 self.pointer += 1
327                 break
328
329             identifier += self.char
330             self.pointer += 1
331
332         self.current_token.identifier = identifier
```

3.10.7.4 Fixing little bugs

Since I've now implemented sub-expression parsing, I should be able to just remove the `@pytest.mark.xfail` line from before and all the tests should pass with no problem.

```
(lintrans) dyson@Harold-Ubuntu:~/repos/lintrans [main *=]
$ pytest -v
============================================================================= test session starts ==============================================================================
platform linux -- Python 3.11.0, pytest-7.2.1, pluggy-1.0.0 -- /home/dyson/temp/lintrans/venv/bin/python
cachedir: .pytest_cache
rootdir: /home/dyson/temp/lintrans, configfile: pyproject.toml, testpaths: tests
collected 31 items

tests/gui/test_dialog_utility_functions.py::test_is_valid_float[inputs0-True] PASSED                                                                                  [  3%]
tests/gui/test_dialog_utility_functions.py::test_is_valid_float[inputs1-False] PASSED                                                                                 [  6%]
tests/gui/test_dialog_utility_functions.py::test_round_float PASSED                                                                                                   [  9%]
tests/matrices/test_parse_and_validate_expression.py::test_find_sub_expressions PASSED                                                                                [ 12%]
tests/matrices/test_parse_and_validate_expression.py::test_validate_matrix_expression[inputs0-True] PASSED                                                           [ 16%]
tests/matrices/test_parse_and_validate_expression.py::test_validate_matrix_expression[inputs1-False] PASSED                                                          [ 19%]
tests/matrices/test_parse_and_validate_expression.py::test_parse_matrix_expression FAILED                                                                             [ 22%]
tests/matrices/test_parse_and_validate_expression.py::test_parse_error PASSED                                                                                         [ 25%]
tests/matrices/test_rotation_matrices.py::test_create_rotation_matrix PASSED                                                                                          [ 29%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_simple_matrix_addition PASSED                                                                         [ 32%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_simple_two_matrix_multiplication PASSED                                                               [ 35%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_identity_multiplication PASSED                                                                        [ 38%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_simple_three_matrix_multiplication PASSED                                                             [ 41%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_matrix_inverses PASSED                                                                                [ 45%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_matrix_powers PASSED                                                                                  [ 48%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_matrix_transpose PASSED                                                                               [ 51%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_rotation_matrices PASSED                                                                              [ 54%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_multiplication_and_addition PASSED                                                                    [ 58%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_complicated_expressions PASSED                                                                        [ 61%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_value_errors PASSED                                                                                   [ 64%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_linalgerror PASSED                                                                                    [ 67%]
tests/matrices/matrix_wrapper/test_misc.py::test_get_expression PASSED                                                                                                [ 70%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_basic_get_matrix PASSED                                                                               [ 74%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_get_name_error PASSED                                                                                 [ 77%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_basic_set_matrix PASSED                                                                               [ 80%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_set_expression PASSED                                                                                 [ 83%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_simple_dynamic_evaluation PASSED                                                                      [ 87%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_recursive_dynamic_evaluation PASSED                                                                   [ 90%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_set_identity_error PASSED                                                                             [ 93%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_set_name_error PASSED                                                                                 [ 96%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_set_type_error PASSED                                                                                 [100%]

================================================================================== FAILURES ==================================================================================
_____________________________________________________________________ test_parse_matrix_expression _____________________________________________________________________

    def test_parse_matrix_expression() -> None:
        """Test the parse_matrix_expression() function."""
        for expression, parsed_expression in expressions_and_parsed_expressions:
            # Test it with and without whitespace
>           assert parse_matrix_expression(expression) == parsed_expression

tests/matrices/test_parse_and_validate_expression.py:119:
_ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _
src/lintrans/matrices/parse.py:370: in parse_matrix_expression
    return ExpressionParser(expression).parse()
src/lintrans/matrices/parse.py:182: in parse
    self._parse_multiplication_group()
src/lintrans/matrices/parse.py:198: in _parse_multiplication_group
    while self._parse_matrix():
src/lintrans/matrices/parse.py:211: in _parse_matrix
    while self._parse_matrix_part():
- - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -

self = lintrans.matrices.parse.ExpressionParser(".1A")

    def _parse_matrix_part(self) -> bool:
        """Parse part of a matrix (multiplier, identifier, or exponent) from the expression and pointer.

        .. note:: This method mutates ``self.current_token``.

        :returns bool: Success or failure
        :raises MatrixParseError: If we fail to parse this part of the token
        """
        if self.pointer >= len(self.expression):
            return False

        if self.char.isdigit() or self.char == '-':
            if self.current_token.multiplier != '':
                return False

            self._parse_multiplier()

        elif self.char.isalpha() and self.char.isupper():
            if self.current_token.identifier != '':
                return False

            self.current_token.identifier = self.char
            self.pointer += 1

        elif self.char == 'r':
            if self.current_token.identifier != '':
                return False

            self._parse_rot_identifier()

        elif self.char == '(':
            if self.current_token.identifier != '':
                return False

            self._parse_sub_expression()

        elif self.char == '^':
            if self.current_token.exponent != '':
                return False

            self._parse_exponent()

        elif self.char == '+':
            return False

        else:
>           raise MatrixParseError(f'Unrecognised character "{self.char}" in matrix expression')
E           lintrans.matrices.parse.MatrixParseError: Unrecognised character "." in matrix expression

src/lintrans/matrices/parse.py:266: MatrixParseError
=========================================================================== short test summary info ============================================================================
FAILED tests/matrices/test_parse_and_validate_expression.py::test_parse_matrix_expression - lintrans.matrices.parse.MatrixParseError: Unrecognised character "." in matrix expression
========================================================================= 1 failed, 30 passed in 0.41s =========================================================================
```

Figure 3.10.5: One of the tests failing

Ah. That's not good. So what went wrong? Well, we can see from the output that `test_parse_matrix_expression()` is the one that failed. This test iterates over a whole list, so which element broke it? Well, we can see from the line '`self = lintrans.matrices.parse.ExpressionParser(".1A")`' that it was trying to parse the expression `".1A"`. This doesn't work, not because `ExpressionParser._parse_multiplier()` doesn't understand this type of multiplier, but because `ExpressionParser._parse_matrix_part()` doesn't recognise a dot as the start of a multiplier, so never calls `_parse_multiplier()`.

This would be a very easy fix, but this error got me thinking about these multipliers and I decided to just forbid them. They can create confusion; `"0.1A"` is easier to understand than `".1A"`. Implementing this change just meant removing this type of multiplier from the tests.

Once I'd done that, the parser should work fine, right?

```
(lintrans) dyson@Harold-Ubuntu:~/repos/lintrans [main *=]
$ pytest -v
============================================================================= test session starts ==============================================================================
platform linux -- Python 3.11.0, pytest-7.2.1, pluggy-1.0.0 -- /home/dyson/temp/lintrans/venv/bin/python
cachedir: .pytest_cache
rootdir: /home/dyson/temp/lintrans, configfile: pyproject.toml, testpaths: tests
collected 31 items

tests/gui/test_dialog_utility_functions.py::test_is_valid_float[inputs0-True] PASSED                                                                                  [  3%]
tests/gui/test_dialog_utility_functions.py::test_is_valid_float[inputs1-False] PASSED                                                                                 [  6%]
tests/gui/test_dialog_utility_functions.py::test_round_float PASSED                                                                                                   [  9%]
tests/matrices/test_parse_and_validate_expression.py::test_find_sub_expressions PASSED                                                                                [ 12%]
tests/matrices/test_parse_and_validate_expression.py::test_validate_matrix_expression[inputs0-True] PASSED                                                            [ 16%]
tests/matrices/test_parse_and_validate_expression.py::test_validate_matrix_expression[inputs1-False] PASSED                                                           [ 19%]
tests/matrices/test_parse_and_validate_expression.py::test_parse_matrix_expression FAILED                                                                             [ 22%]
tests/matrices/test_parse_and_validate_expression.py::test_parse_error PASSED                                                                                         [ 25%]
tests/matrices/test_rotation_matrices.py::test_create_rotation_matrix PASSED                                                                                          [ 29%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_simple_matrix_addition PASSED                                                                         [ 32%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_simple_two_matrix_multiplication PASSED                                                               [ 35%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_identity_multiplication PASSED                                                                        [ 38%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_simple_three_matrix_multiplication PASSED                                                             [ 41%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_matrix_inverses PASSED                                                                                [ 45%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_matrix_powers PASSED                                                                                  [ 48%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_matrix_transpose PASSED                                                                               [ 51%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_rotation_matrices PASSED                                                                              [ 54%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_multiplication_and_addition PASSED                                                                    [ 58%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_complicated_expressions PASSED                                                                        [ 61%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_value_errors PASSED                                                                                   [ 64%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_linalgerror PASSED                                                                                    [ 67%]
tests/matrices/matrix_wrapper/test_misc.py::test_get_expression PASSED                                                                                                [ 70%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_basic_get_matrix PASSED                                                                               [ 74%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_get_name_error PASSED                                                                                 [ 77%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_basic_set_matrix PASSED                                                                               [ 80%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_set_expression PASSED                                                                                 [ 83%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_simple_dynamic_evaluation PASSED                                                                      [ 87%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_recursive_dynamic_evaluation PASSED                                                                   [ 90%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_set_identity_error PASSED                                                                             [ 93%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_set_name_error PASSED                                                                                 [ 96%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_set_type_error PASSED                                                                                 [100%]

================================================================================== FAILURES ==================================================================================
_____________________________________________________________________ test_parse_matrix_expression _____________________________________________________________________

    def test_parse_matrix_expression() -> None:
        """Test the parse_matrix_expression() function."""
        for expression, parsed_expression in expressions_and_parsed_expressions:
            # Test it with and without whitespace
>           assert parse_matrix_expression(expression) == parsed_expression
E           AssertionError: assert [[('0.1', 'A'...'', 'B', '')]] == [[('', 'A', '...1', 'B', '')]]
E             At index 0 diff: [('0.1', 'A', ''), ('', 'B', '')] != [('', 'A', ''), ('0.1', 'B', '')]
E             Full diff:
E             - [[('', 'A', ''), ('0.1', 'B', '')]]
E             + [[('0.1', 'A', ''), ('', 'B', '')]]

tests/matrices/test_parse_and_validate_expression.py:119: AssertionError
=========================================================================== short test summary info ============================================================================
FAILED tests/matrices/test_parse_and_validate_expression.py::test_parse_matrix_expression - AssertionError: assert [[('0.1', 'A'...'', 'B', '')]] == [[('', 'A', '...1', 'B', '')]]
========================================================================= 1 failed, 30 passed in 0.39s =========================================================================
```

Figure 3.10.6: Another test failing

Well, that's strange. It was trying to parse the expression `"A 0.1B"` but it thought the `0.1` was part of the `A`. Why did that happen? Well, it's because of line 232 in this snippet:

```
# 9b1c69926c225574161d32dcbecd86055edb4065
# src/lintrans/matrices/parse.py

136 class ExpressionParser:
...
220     def _parse_matrix_part(self) -> bool:
...
231         if self.char.isdigit() or self.char == '-':
232             if self.current_token.multiplier != '':
233                 return False
234
235             self._parse_multiplier()
```

The parser parsed `"A"` as the matrix identifier and then encountered `"0"`. Since the current token didn't have a multiplier, it started parsing a multiplier for the matrix **A**. To fix this, we can just fail to parse a matrix part if we encounter the start of a multiplier when the current token already has an identifier. Failing to parse a matrix part here means that the parser will start parsing a new matrix.

```
# 8d7143fc33ea7bd4199e0f01b6a5308dfcf03ff9
# src/lintrans/matrices/parse.py

136 class ExpressionParser:
...
```

```
220         def _parse_matrix_part(self) -> bool:
...
231             if self.char.isdigit() or self.char == '-':
232                 if self.current_token.multiplier != '' \
233                         or (self.current_token.multiplier == '' and self.current_token.identifier != ''):
234                     return False
235 
236                 self._parse_multiplier()
```

That should fix the tests, right?

```
(lintrans) dyson@Harold-Ubuntu:~/repos/lintrans [main *=]
$ pytest -v
============================= test session starts ==============================
platform linux -- Python 3.11.0, pytest-7.2.1, pluggy-1.0.0 -- /home/dyson/temp/lintrans/venv/bin/python
cachedir: .pytest_cache
rootdir: /home/dyson/temp/lintrans, configfile: pyproject.toml, testpaths: tests
collected 31 items

tests/gui/test_dialog_utility_functions.py::test_is_valid_float[inputs0-True] PASSED [  3%]
tests/gui/test_dialog_utility_functions.py::test_is_valid_float[inputs1-False] PASSED [  6%]
tests/gui/test_dialog_utility_functions.py::test_round_float PASSED      [  9%]
tests/matrices/test_parse_and_validate_expression.py::test_find_sub_expressions PASSED [ 12%]
tests/matrices/test_parse_and_validate_expression.py::test_validate_matrix_expression[inputs0-True] PASSED [ 16%]
tests/matrices/test_parse_and_validate_expression.py::test_validate_matrix_expression[inputs1-False] PASSED [ 19%]
tests/matrices/test_parse_and_validate_expression.py::test_parse_matrix_expression FAILED [ 22%]
tests/matrices/test_parse_and_validate_expression.py::test_parse_error PASSED [ 25%]
tests/matrices/test_rotation_matrices.py::test_create_rotation_matrix PASSED [ 29%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_simple_matrix_addition PASSED [ 32%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_simple_two_matrix_multiplication PASSED [ 35%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_identity_multiplication PASSED [ 38%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_simple_three_matrix_multiplication PASSED [ 41%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_matrix_inverses PASSED [ 45%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_matrix_powers PASSED [ 48%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_matrix_transpose PASSED [ 51%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_rotation_matrices PASSED [ 54%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_multiplication_and_addition PASSED [ 58%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_complicated_expressions PASSED [ 61%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_value_errors PASSED [ 64%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_linalgerror PASSED [ 67%]
tests/matrices/matrix_wrapper/test_misc.py::test_get_expression PASSED   [ 70%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_basic_get_matrix PASSED [ 74%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_get_name_error PASSED [ 77%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_basic_set_matrix PASSED [ 80%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_set_expression PASSED [ 83%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_simple_dynamic_evaluation PASSED [ 87%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_recursive_dynamic_evaluation PASSED [ 90%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_set_identity_error PASSED [ 93%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_set_name_error PASSED [ 96%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_set_type_error PASSED [100%]

=================================== FAILURES ===================================
_____________________ test_parse_matrix_expression _____________________

    def test_parse_matrix_expression() -> None:
        """Test the parse_matrix_expression() function."""
        for expression, parsed_expression in expressions_and_parsed_expressions:
            # Test it with and without whitespace
>           assert parse_matrix_expression(expression) == parsed_expression
E           AssertionError: assert [[('-3', 'A+B...{T}A', '-1')]] == [[('-3', 'A+B...B^TA', '-1')]]
E             At index 1 diff: [('-1', 'C', ''), ('', 'B^{T}A', '-1')] != [('-1', 'C', ''), ('', 'B^TA', '-1')]
E             Full diff:
E             - [[('-3', 'A+B', '2')], [('-1', 'C', ''), ('', 'B^TA', '-1')]]
E             + [[('-3', 'A+B', '2')], [('-1', 'C', ''), ('', 'B^{T}A', '-1')]]
E             ?                                            + +

tests/matrices/test_parse_and_validate_expression.py:119: AssertionError
=========================== short test summary info ============================
FAILED tests/matrices/test_parse_and_validate_expression.py::test_parse_matrix_expression - AssertionError: assert [[('-3', 'A+B...{T}A', '-1')]] == [[('-3', 'A+B...B^TA', '-1')]]
========================= 1 failed, 30 passed in 0.39s =========================
```

Figure 3.10.7: *Another* test failing

I'm getting tired of this now. What's broken this time? Well, the parser processes its input to remove whitespace and add braces around exponents before any parsing takes place. This includes processing the contents of sub-expressions. That was never a problem before, since parsing wasn't affected by whitespace or braces, but now those changes propagate into the sub-expressions. I wrote the sub-expression parsing tests in §3.10.7.1 by using my literal expression input in the parsed sub-expressions. So to fix this error, I just had to account for the syntax transformations in the test input.

Now the tests should all pass, right?

```
(lintrans) dyson@Harold-Ubuntu:~/repos/lintrans [main *=]
$ pytest -v
============================================================ test session starts ============================================================
platform linux -- Python 3.11.0, pytest-7.2.1, pluggy-1.0.0 -- /home/dyson/temp/lintrans/venv/bin/python
cachedir: .pytest_cache
rootdir: /home/dyson/temp/lintrans, configfile: pyproject.toml, testpaths: tests
collected 31 items

tests/gui/test_dialog_utility_functions.py::test_is_valid_float[inputs0-True] PASSED                                                  [  3%]
tests/gui/test_dialog_utility_functions.py::test_is_valid_float[inputs1-False] PASSED                                                 [  6%]
tests/gui/test_dialog_utility_functions.py::test_round_float PASSED                                                                   [  9%]
tests/matrices/test_parse_and_validate_expression.py::test_find_sub_expressions PASSED                                                [ 12%]
tests/matrices/test_parse_and_validate_expression.py::test_validate_matrix_expression[inputs0-True] PASSED                           [ 16%]
tests/matrices/test_parse_and_validate_expression.py::test_validate_matrix_expression[inputs1-False] PASSED                          [ 19%]
tests/matrices/test_parse_and_validate_expression.py::test_parse_matrix_expression PASSED                                             [ 22%]
tests/matrices/test_parse_and_validate_expression.py::test_parse_error PASSED                                                         [ 25%]
tests/matrices/test_rotation_matrices.py::test_create_rotation_matrix PASSED                                                          [ 29%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_simple_matrix_addition PASSED                                         [ 32%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_simple_two_matrix_multiplication PASSED                               [ 35%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_identity_multiplication PASSED                                        [ 38%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_simple_three_matrix_multiplication PASSED                             [ 41%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_matrix_inverses PASSED                                                [ 45%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_matrix_powers PASSED                                                  [ 48%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_matrix_transpose PASSED                                               [ 51%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_rotation_matrices PASSED                                              [ 54%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_multiplication_and_addition PASSED                                    [ 58%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_complicated_expressions PASSED                                        [ 61%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_value_errors PASSED                                                   [ 64%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_linalgerror PASSED                                                    [ 67%]
tests/matrices/matrix_wrapper/test_misc.py::test_get_expression PASSED                                                                [ 70%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_basic_get_matrix PASSED                                               [ 74%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_get_name_error PASSED                                                 [ 77%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_basic_set_matrix PASSED                                               [ 80%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_set_expression PASSED                                                 [ 83%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_simple_dynamic_evaluation PASSED                                      [ 87%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_recursive_dynamic_evaluation PASSED                                   [ 90%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_set_identity_error PASSED                                             [ 93%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_set_name_error PASSED                                                 [ 96%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_set_type_error PASSED                                                 [100%]

============================================================ 31 passed in 0.34s =============================================================
```

Figure 3.10.8: All the tests finally passing

Thank god.

3.10.7.5 Making recursive evaluation work

When `MatrixWrapper.__getitem__()` tries to retrieve a matrix which is defined in terms of an expression, it has to call `MatrixWrapper.evaluate_expression()`. This method in turn calls `__getitem__()` again to evaluate the matrices used in the expression. Now that sub-expressions exist, `__getitem__()` might get called with a sub-expression identifier, so it needs to be able to evaluate these expressions. To do this, we can simply add another call to `evaluate_expression()`, as seen on lines 120-121.

```
# ba1ee72fcafd5129aed76992f743e5966f5c199d
# src/lintrans/matrices/wrapper.py

23  class MatrixWrapper:
...
100     def __getitem__(self, name: str) -> Optional[MatrixType]:
101         """Get the matrix with the given name.
102
103         If it is a simple name, it will just be fetched from the dictionary. If the name is ``rot(x)``, with
104         a given angle in degrees, then we return a new matrix representing a rotation by that angle.
105
106         .. note::
107            If the named matrix is defined as an expression, then this method will return its evaluation.
108            If you want the expression itself, use :meth:`get_expression`.
109
110         :param str name: The name of the matrix to get
111         :returns Optional[MatrixType]: The value of the matrix (could be None)
112
113         :raises NameError: If there is no matrix with the given name
114         """
115         # Return a new rotation matrix
116         if (match := re.match(r'rot\((-?\d*\.?\d*)\)', name)) is not None:
117             return create_rotation_matrix(float(match.group(1)))
118
119         if name not in self._matrices:
120             if validate_matrix_expression(name):
121                 return self.evaluate_expression(name)
122
123             raise NameError(f'Unrecognised matrix name "{name}"')
124
```

```
125             # We copy the matrix before we return it so the user can't accidentally mutate the matrix
126             matrix = copy(self._matrices[name])
127
128             if isinstance(matrix, str):
129                 return self.evaluate_expression(matrix)
130
131             return matrix
...
214         def evaluate_expression(self, expression: str) -> MatrixType:
215             """Evaluate a given expression and return the matrix evaluation.
216
217             :param str expression: The expression to be parsed
218             :returns MatrixType: The matrix result of the expression
219
220             :raises ValueError: If the expression is invalid
221             """
222             if not self.is_valid_expression(expression):
223                 raise ValueError('The expression is invalid')
224
225             parsed_result = parse_matrix_expression(expression)
226             final_groups: list[list[MatrixType]] = []
227
228             for group in parsed_result:
229                 f_group: list[MatrixType] = []
230
231                 for multiplier, identifier, index in group:
232                     if index == 'T':
233                         m = self[identifier]
234
235                         # This assertion is just so mypy doesn't complain
236                         # We know this won't be None, because we know that this matrix is defined in this wrapper
237                         assert m is not None
238                         matrix_value = m.T
239
240                     else:
241                         matrix_value = np.linalg.matrix_power(self[identifier], 1 if index == '' else int(index))
242
243                     matrix_value *= 1 if multiplier == '' else float(multiplier)
244                     f_group.append(matrix_value)
245
246                 final_groups.append(f_group)
247
248             return reduce(add, [reduce(matmul, group) for group in final_groups])
```

I then added a new unit test function to make sure parenthesised expressions get evaluated properly.

```
# ba1ee72fcafd5129aed76992f743e5966f5c199d
# tests/matrices/matrix_wrapper/test_evaluate_expression.py

229 def test_parenthesized_expressions(test_wrapper: MatrixWrapper) -> None:
230     """Test evaluation of parenthesized expressions."""
231     assert test_wrapper['A'] is not None and test_wrapper['B'] is not None and test_wrapper['C'] is not None and \
232            test_wrapper['D'] is not None and test_wrapper['E'] is not None and test_wrapper['F'] is not None and \
233            test_wrapper['G'] is not None
234
235     assert (test_wrapper.evaluate_expression('(A^T)^2') == la.matrix_power(test_wrapper['A'].T, 2)).all()
236     assert (test_wrapper.evaluate_expression('(B^T)^3') == la.matrix_power(test_wrapper['B'].T, 3)).all()
237     assert (test_wrapper.evaluate_expression('(C^T)^4') == la.matrix_power(test_wrapper['C'].T, 4)).all()
238     assert (test_wrapper.evaluate_expression('(D^T)^5') == la.matrix_power(test_wrapper['D'].T, 5)).all()
239     assert (test_wrapper.evaluate_expression('(E^T)^6') == la.matrix_power(test_wrapper['E'].T, 6)).all()
240     assert (test_wrapper.evaluate_expression('(F^T)^7') == la.matrix_power(test_wrapper['F'].T, 7)).all()
241     assert (test_wrapper.evaluate_expression('(G^T)^8') == la.matrix_power(test_wrapper['G'].T, 8)).all()
242
243     assert (test_wrapper.evaluate_expression('D^3(A+6.2F-0.397G^TE)^-2+A') ==
244             la.matrix_power(test_wrapper['D'], 3) @ la.matrix_power(
245                 test_wrapper['A'] + 6.2 * test_wrapper['F'] - 0.397 * test_wrapper['G'].T @ test_wrapper['E'],
246                 -2
247             ) + test_wrapper['A']).all()
248
249     assert (test_wrapper.evaluate_expression('-1.2F^{3}4.9D^T(A^2(B+3E^TF)^-1)^2') ==
250             -1.2 * la.matrix_power(test_wrapper['F'], 3) @ (4.9 * test_wrapper['D'].T) @
```

```
            la.matrix_power(
                la.matrix_power(test_wrapper['A'], 2) @ la.matrix_power(
                    test_wrapper['B'] + 3 * test_wrapper['E'].T @ test_wrapper['F'],
                    -1
                ),
                2
            )).all()
```

```
(lintrans) dyson@Harold-Ubuntu:~/repos/lintrans [main *=]
$ pytest -v
============================================================ test session starts ============================================================
platform linux -- Python 3.11.0, pytest-7.2.1, pluggy-1.0.0 -- /home/dyson/temp/lintrans/venv/bin/python
cachedir: .pytest_cache
rootdir: /home/dyson/temp/lintrans, configfile: pyproject.toml, testpaths: tests
collected 32 items

tests/gui/test_dialog_utility_functions.py::test_is_valid_float[inputs0-True] PASSED                                                   [  3%]
tests/gui/test_dialog_utility_functions.py::test_is_valid_float[inputs1-False] PASSED                                                  [  6%]
tests/gui/test_dialog_utility_functions.py::test_round_float PASSED                                                                    [  9%]
tests/matrices/test_parse_and_validate_expression.py::test_find_sub_expressions PASSED                                                 [ 12%]
tests/matrices/test_parse_and_validate_expression.py::test_validate_matrix_expression[inputs0-True] PASSED                            [ 15%]
tests/matrices/test_parse_and_validate_expression.py::test_validate_matrix_expression[inputs1-False] PASSED                           [ 18%]
tests/matrices/test_parse_and_validate_expression.py::test_parse_matrix_expression PASSED                                              [ 21%]
tests/matrices/test_parse_and_validate_expression.py::test_parse_error PASSED                                                          [ 25%]
tests/matrices/test_rotation_matrices.py::test_create_rotation_matrix PASSED                                                           [ 28%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_simple_matrix_addition PASSED                                          [ 31%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_simple_two_matrix_multiplication PASSED                                [ 34%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_identity_multiplication PASSED                                         [ 37%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_simple_three_matrix_multiplication PASSED                              [ 40%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_matrix_inverses PASSED                                                 [ 43%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_matrix_powers PASSED                                                   [ 46%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_matrix_transpose PASSED                                                [ 50%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_rotation_matrices PASSED                                               [ 53%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_multiplication_and_addition PASSED                                     [ 56%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_complicated_expressions PASSED                                         [ 59%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_parenthesized_expressions PASSED                                       [ 62%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_value_errors PASSED                                                    [ 65%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_linalgerror PASSED                                                     [ 68%]
tests/matrices/matrix_wrapper/test_misc.py::test_get_expression PASSED                                                                 [ 71%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_basic_get_matrix PASSED                                                [ 75%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_get_name_error PASSED                                                  [ 78%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_basic_set_matrix PASSED                                                [ 81%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_set_expression PASSED                                                  [ 84%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_simple_dynamic_evaluation PASSED                                       [ 87%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_recursive_dynamic_evaluation PASSED                                    [ 90%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_set_identity_error PASSED                                              [ 93%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_set_name_error PASSED                                                  [ 96%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_set_type_error PASSED                                                  [100%]

============================================================ 32 passed in 0.36s =============================================================
```

Figure 3.10.9: Running `pytest` with the new tests

I also improved the doctests for `parse_matrix_expression()` by adding a case for these new parenthesised expressions, and I added a doctest for the expression parser.

```
# e3d633133f293fc1308d6fc0c60a1febaf67dda0
# src/lintrans/matrices/parse.py

def parse_matrix_expression(expression: str) -> MatrixParseList:
    """Parse the matrix expression and return a :data:`lintrans.typing_.MatrixParseList`.

    :Example:

    >>> parse_matrix_expression('A')
    [[('', 'A', '')]]
    >>> parse_matrix_expression('-3M^2')
    [[('-3', 'M', '2')]]
    >>> parse_matrix_expression('1.2rot(12)^{3}2B^T')
    [[('1.2', 'rot(12)', '3'), ('2', 'B', 'T')]]
    >>> parse_matrix_expression('A^2 + 3B')
    [[('', 'A', '2')], [('3', 'B', '')]]
    >>> parse_matrix_expression('-3A^{-1}3B^T - 45M^2')
    [[('-3', 'A', '-1'), ('3', 'B', 'T')], [('-45', 'M', '2')]]
    >>> parse_matrix_expression('5.3A^{4} 2.6B^{-2} + 4.6D^T 8.9E^{-1}')
    [[('5.3', 'A', '4'), ('2.6', 'B', '-2')], [('4.6', 'D', 'T'), ('8.9', 'E', '-1')]]
    >>> parse_matrix_expression('2(A+B^TC)^2D')
    [[('2', 'A+B^{T}C', '2'), ('', 'D', '')]]

    :param str expression: The expression to be parsed
    :returns: A list of parsed components
    :rtype: :data:`lintrans.typing_.MatrixParseList`
    """
    return ExpressionParser(expression).parse()


# bf1f5a1eaac60d23964a44c9a6b8235c5e0fcab2
# src/lintrans/matrices/parse.py
```

```python
class ExpressionParser:
    """A class to hold state during parsing.

    Most of the methods in this class are class-internal and should not be used from outside.

    This class should be used like this:

    >>> ExpressionParser('3A^-1B').parse()
    [[('3', 'A', '-1'), ('', 'B', '')]]
    >>> ExpressionParser('4(M^TA^2)^-2').parse()
    [[('4', 'M^{T}A^{2}', '-2')]]
    """
```

```
(lintrans) dyson@Harold-Ubuntu:~/repos/lintrans [main *=]
$ pytest --doctest-modules src/ -v
========================================= test session starts ==========================================
platform linux -- Python 3.11.0, pytest-7.2.1, pluggy-1.0.0 -- /home/dyson/temp/lintrans/venv/bin/py
thon
cachedir: .pytest_cache
rootdir: /home/dyson/temp/lintrans, configfile: pyproject.toml
collected 4 items

src/lintrans/matrices/parse.py::lintrans.matrices.parse.ExpressionParser PASSED              [ 25%]
src/lintrans/matrices/parse.py::lintrans.matrices.parse.parse_matrix_expression PASSED       [ 50%]
src/lintrans/matrices/wrapper.py::lintrans.matrices.wrapper.MatrixWrapper PASSED             [ 75%]
src/lintrans/matrices/wrapper.py::lintrans.matrices.wrapper.create_rotation_matrix PASSED    [100%]

========================================== 4 passed in 0.33s ===========================================
```

Figure 3.10.10: Running `pytest` with the new and improved doctests

And of course, I updated the changelog:

```
<!-- 9e26079475e33f3ab2e02e76ea59a66217d18f76 -->
<!-- CHANGELOG.md -->

### Added
...
- Support parenthesized sub-expressions as matrix identifiers
```

3.10.7.6 Ensuring numerical formats

The validation checks the format of the numbers in multipliers, exponents and `rot()` commands, but it would be quite good to also validate the format of these numbers when parsing, just to make absolutely sure that they will be able to be correctly evaluated. To do this, we can simply perform the conversion in a try/except block. It would also be good to validate the sub-expressions.

```
# 761c6ed255ed65c3396c6a551acfa60bb7485a17
# src/lintrans/matrices/parse.py

class ExpressionParser:
...
    def _parse_multiplier(self) -> None:
        """Parse a multiplier from the expression and pointer.

        .. note:: This method mutates ``self.current_token.multiplier``.

        :raises MatrixParseError: If we fail to parse this part of the token
        """
        multiplier = ''

        while self.char.isdigit() or self.char in ('.', '-'):
            multiplier += self.char
            self.pointer += 1
```

```
294
295         try:
296             float(multiplier)
297         except ValueError as e:
298             raise MatrixParseError(f'Invalid multiplier "{multiplier}"') from e
299
300         self.current_token.multiplier = multiplier
301
302     def _parse_rot_identifier(self) -> None:
303         """Parse a ``rot()``-style identifier from the expression and pointer.
304
305         .. note:: This method mutates ``self.current_token.identifier``.
306
307         :raises MatrixParseError: If we fail to parse this part of the token
308         """
309         if match := re.match(r'rot\(([\d.-]+)\)', self.expression[self.pointer:]):
310             # Ensure that the number in brackets is a valid float
311             try:
312                 float(match.group(1))
313             except ValueError as e:
314                 raise MatrixParseError(f'Invalid angle number "{match.group(1)}" in rot-identifier') from e
315
316             self.current_token.identifier = match.group(0)
317             self.pointer += len(match.group(0))
318         else:
319             raise MatrixParseError(f'Invalid rot-identifier "{self.expression[self.pointer:self.pointer + 15]}..."')
320
321     def _parse_sub_expression(self) -> None:
322         """Parse a parenthesized sub-expression as the identifier, from the expression and pointer.
323
324         .. note:: This method mutates ``self.current_token.identifier``.
325
326         :raises MatrixParseError: If we fail to parse this part of the token
327         """
328         if self.char != '(':
329             raise MatrixParseError('Sub-expression must start with "("')
330
331         self.pointer += 1
332         paren_depth = 1
333         identifier = ''
334
335         while paren_depth > 0:
336             if self.char == '(':
337                 paren_depth += 1
338             elif self.char == ')':
339                 paren_depth -= 1
340
341             if paren_depth == 0:
342                 self.pointer += 1
343                 break
344
345             identifier += self.char
346             self.pointer += 1
347
348         if not validate_matrix_expression(identifier):
349             raise MatrixParseError(f'Invalid sub-expression identifier "{identifier}"')
350
351         self.current_token.identifier = identifier
352
353     def _parse_exponent(self) -> None:
354         """Parse a matrix exponent from the expression and pointer.
355
356         .. note:: This method mutates ``self.current_token.exponent``.
357
358         :raises MatrixParseError: If we fail to parse this part of the token
359         """
360         if match := re.match(r'\^\{(-?\d+|T)\}', self.expression[self.pointer:]):
361             exponent = match.group(1)
362
363             try:
364                 if exponent != 'T':
365                     int(exponent)
366             except ValueError as e:
```

```
367                 raise MatrixParseError(f'Invalid exponent "{match.group(1)}"') from e
368
369             self.current_token.exponent = exponent
370             self.pointer += len(match.group(0))
371         else:
372             raise MatrixParseError(f'Invalid exponent "{self.expression[self.pointer:self.pointer + 10]}..."')
```

3.10.8 Fixing premature `rot()` evaluation

Now that parenthesised expressions are done, I can focus on other improvements.

When playing around with this new feature, I discovered a bug where an expression like `"rot(45)^2"` would be evaluated in the same way as `"rot(45)"`. After lots of confusion and debugging, I discovered that this bug was in `MatrixWrapper.__getitem__()` when it tries to evaluate `rot()` commands. It does this by eagerly searching for the `rot()` RegEx in the string. This was never an issue before, but now that this method might get called with a whole expression, this RegEx can trigger too early. If it's given an expression which contains a `rot()` command anywhere in it, then it will return a rotation matrix immediately. To fix this, we just have to ensure that the `rot()` command takes up the whole string before returning a rotation matrix. We can do this by anchoring the RegEx with `^` and `$`.

```
# c23d540aa3b8df91b9478fb113cb42df4c7d5e42
# src/lintrans/matrices/wrapper.py

23  class MatrixWrapper:
...
100     def __getitem__(self, name: str) -> Optional[MatrixType]:
...
115         # Return a new rotation matrix
116         if (match := re.match(r'^rot\((-?\d*\.?\d*)\)$', name)) is not None:
117             return create_rotation_matrix(float(match.group(1)))
118
119         if name not in self._matrices:
120             if validate_matrix_expression(name):
121                 return self.evaluate_expression(name)
122
123             raise NameError(f'Unrecognised matrix name "{name}"')
124
125         # We copy the matrix before we return it so the user can't accidentally mutate the matrix
126         matrix = copy(self._matrices[name])
127
128         if isinstance(matrix, str):
129             return self.evaluate_expression(matrix)
130
131         return matrix
```

I also added cases to the parenthesised expressions test to cover this change.

```
# c23d540aa3b8df91b9478fb113cb42df4c7d5e42
# tests/matrices/matrix_wrapper/test_evaluate_expression.py

229 def test_parenthesized_expressions(test_wrapper: MatrixWrapper) -> None:
...
243     assert (test_wrapper.evaluate_expression('(rot(45)^1)^T') == create_rotation_matrix(45).T).all()
244     assert (test_wrapper.evaluate_expression('(rot(45)^2)^T') == la.matrix_power(create_rotation_matrix(45),
        ↪  2).T).all()
245     assert (test_wrapper.evaluate_expression('(rot(45)^3)^T') == la.matrix_power(create_rotation_matrix(45),
        ↪  3).T).all()
246     assert (test_wrapper.evaluate_expression('(rot(45)^4)^T') == la.matrix_power(create_rotation_matrix(45),
        ↪  4).T).all()
247     assert (test_wrapper.evaluate_expression('(rot(45)^5)^T') == la.matrix_power(create_rotation_matrix(45),
        ↪  5).T).all()
```

And then added it to the changelog.

```
<!-- c23d540aa3b8df91b9478fb113cb42df4c7d5e42 -->
<!-- CHANGELOG.md -->

18  ### Fixed
...
21  - Fixed bug with premature rot evaluation in sub-expressions
```

3.10.9 Animating rotations

When animating a rotation like `"rot(170)"`, it animates a rotation of 170°, but it doesn't look very good. I fixed an old rotation issue in §3.3.6, but the speed is still a problem.

The speed of rotation is significantly higher during the middle of the rotation, which makes it look unnatural. I want to fix this to make rotations look more natural. Ideally, the program would detect a rotation and animate it in a different way, by moving the tips of the basis vectors along the edge of a circle with the radius equal to the length of the basis vectors. That shouldn't be too hard. However, I'd also like to animate scaled rotations like `"2rot(170)"`. Animating in a circle won't work for this type of transformation, so I'll need to use a spiral.

This is a big feature, so I split it into a `dev/anim-rot` branch.

3.10.9.1 Factoring out animation frames

The `LintransMainWindow.animate_expression()` method obviously handles animating expressions. It does this by calling a separate method called `LintransMainWindow.animate_between_matrices()` after parsing and evaluating the expression. The first step of improving my rotational animation code is to factor out the generation of individual frames when animating between matrices. This separate method will make it easier to work on the new feature.

Here's the old code, including the `animate_expression()` method, which wasn't changed:

```
# 751f185a2b64d31fe7ddd53aafab110008cff50b
# src/lintrans/gui/main_window.py

36  class LintransMainWindow(QMainWindow):
...
376     def animate_between_matrices(self, matrix_start: MatrixType, matrix_target: MatrixType, steps: int = 100) ->
        ↪ None:
377         """Animate from the start matrix to the target matrix."""
378         det_target = linalg.det(matrix_target)
379         det_start = linalg.det(matrix_start)
380
381         self.animating = True
382
383         for i in range(0, steps + 1):
384             if not self.animating:
385                 break
386
387             # This proportion is how far we are through the loop
388             proportion = i / steps
389
390             # matrix_a is the start matrix plus some part of the target, scaled by the proportion
391             # If we just used matrix_a, then things would animate, but the determinants would be weird
392             matrix_a = matrix_start + proportion * (matrix_target - matrix_start)
393
394             if self.plot.display_settings.smoothen_determinant and det_start * det_target > 0:
395                 # To fix the determinant problem, we get the determinant of matrix_a and use it to normalize
396                 det_a = linalg.det(matrix_a)
397
398                 # For a 2x2 matrix A and a scalar c, we know that det(cA) = c^2 det(A)
399                 # We want B = cA such that det(B) = det(S), where S is the start matrix,
400                 # so then we can scale it with the animation, so we get
401                 # det(cA) = c^2 det(A) = det(S) => c = sqrt(abs(det(S) / det(A)))
```

```
402                 # Then we scale A to get the determinant we want, and call that matrix_b
403                 if det_a == 0:
404                     c = 0
405                 else:
406                     c = np.sqrt(abs(det_start / det_a))
407
408                 matrix_b = c * matrix_a
409                 det_b = linalg.det(matrix_b)
410
411                 # matrix_to_render is the final matrix that we then render for this frame
412                 # It's B, but we scale it over time to have the target determinant
413
414                 # We want some C = dB such that det(C) is some target determinant T
415                 # det(dB) = d^2 det(B) = T => d = sqrt(abs(T / det(B))
416
417                 # We're also subtracting 1 and multiplying by the proportion and then adding one
418                 # This just scales the determinant along with the animation
419
420                 # That is all of course, if we can do that
421                 # We'll crash if we try to do this with det(B) == 0
422                 if det_b != 0:
423                     scalar = 1 + proportion * (np.sqrt(abs(det_target / det_b)) - 1)
424                     matrix_to_render = scalar * matrix_b
425
426                 else:
427                     matrix_to_render = matrix_a
428
429             else:
430                 matrix_to_render = matrix_a
431
432             if self.is_matrix_too_big(matrix_to_render):
433                 self.show_error_message('Matrix too big', "This matrix doesn't fit on the canvas")
434                 return
435
436             self.plot.visualize_matrix_transformation(matrix_to_render)
437
438             # We schedule the plot to be updated, tell the event loop to
439             # process events, and asynchronously sleep for 10ms
440             # This allows for other events to be processed while animating, like zooming in and out
441             self.plot.update()
442             QApplication.processEvents()
443             QThread.msleep(1000 // steps)
444
445         self.animating = False
```

And here's the new code, not including the unchanged `animate_expression()` method:

```
# d47bb0165304d496caf7bbe3e09e4bbd12e45453
# src/lintrans/gui/main_window.py

36  class LintransMainWindow(QMainWindow):
...
376     def _get_animation_frame(self, start: MatrixType, target: MatrixType, proportion: float) -> MatrixType:
377         """Get the matrix to render for this frame of the animation.
378
379         This method will smoothen the determinant if that setting in enabled and if the determinant is positive.
380         It also animates rotation-like matrices using a logarithmic spiral to rotate around and scale continuously.
381         Essentially, it just makes things look good when animating.
382
383         :param MatrixType start: The starting matrix
384         :param MatrixType start: The target matrix
385         :param float proportion: How far we are through the loop
386         """
387         det_target = linalg.det(target)
388         det_start = linalg.det(start)
389
390         # This is the matrix that we're applying to get from start to target
391         # We want to check if it's rotation-like
392         matrix_application = target @ linalg.inv(start)
393
394         if linalg.det(matrix_application) > 0 and abs(np.dot(matrix_application.T[0], matrix_application.T[1])) <
            ↪  0.1:
```

```
395             # TODO: Use logarithmic spiral here and return
396             pass
397
398         # matrix_a is the start matrix plus some part of the target, scaled by the proportion
399         # If we just used matrix_a, then things would animate, but the determinants would be weird
400         matrix_a = start + proportion * (target - start)
401
402         if not self.plot.display_settings.smoothen_determinant or det_start * det_target <= 0:
403             return matrix_a
404
405         # To fix the determinant problem, we get the determinant of matrix_a and use it to normalize
406         det_a = linalg.det(matrix_a)
407
408         # For a 2x2 matrix A and a scalar c, we know that det(cA) = c^2 det(A)
409         # We want B = cA such that det(B) = det(S), where S is the start matrix,
410         # so then we can scale it with the animation, so we get
411         # det(cA) = c^2 det(A) = det(S) => c = sqrt(abs(det(S) / det(A)))
412         # Then we scale A to get the determinant we want, and call that matrix_b
413         if det_a == 0:
414             c = 0
415         else:
416             c = np.sqrt(abs(det_start / det_a))
417
418         matrix_b = c * matrix_a
419         det_b = linalg.det(matrix_b)
420
421         # matrix_to_render is the final matrix that we then render for this frame
422         # It's B, but we scale it over time to have the target determinant
423
424         # We want some C = dB such that det(C) is some target determinant T
425         # det(dB) = d^2 det(B) = T => d = sqrt(abs(T / det(B))
426
427         # We're also subtracting 1 and multiplying by the proportion and then adding one
428         # This just scales the determinant along with the animation
429
430         # That is all of course, if we can do that
431         # We'll crash if we try to do this with det(B) == 0
432         if det_b == 0:
433             return matrix_a
434
435         scalar = 1 + proportion * (np.sqrt(abs(det_target / det_b)) - 1)
436         return scalar * matrix_b
437
438     def animate_between_matrices(self, matrix_start: MatrixType, matrix_target: MatrixType, steps: int = 100) ->
    ↪  None:
439         """Animate from the start matrix to the target matrix."""
440         self.animating = True
441
442         for i in range(0, steps + 1):
443             if not self.animating:
444                 break
445
446             matrix_to_render = self._get_animation_frame(matrix_start, matrix_target, i / steps)
447
448             if self.is_matrix_too_big(matrix_to_render):
449                 self.show_error_message('Matrix too big', "This matrix doesn't fit on the canvas")
450                 self.animating = False
451                 return
452
453             self.plot.visualize_matrix_transformation(matrix_to_render)
454
455             # We schedule the plot to be updated, tell the event loop to
456             # process events, and asynchronously sleep for 10ms
457             # This allows for other events to be processed while animating, like zooming in and out
458             self.plot.update()
459             QApplication.processEvents()
460             QThread.msleep(1000 // steps)
461
462         self.animating = False
```

Notice the `if` statement on line 394. This checks if the determinant is positive and the dot product of the basis vectors is close to 0. If these are both true, then the application matrix is a rotation

matrix[25].

3.10.9.2 Utility functions and logarithmic spirals

I moved the `create_rotation_matrix()` function from `lintrans.matrices.wrapper` to a new `lintrans.matrices.utility` module, which will contain utility functions to help with animating rotations. And for the sake of consistency, I decided to only care about positive angles, so I adapted the function to make all angles positive by taking them modulo 360° or 2π radians.

I also added some other utility functions - `polar_coords()` and `rect_coords()` - which will convert rectilinear (Cartesian) coordinates to polar coordinates and back again, respectively.

```python
# 183dd02b4194c93aad51a21b7ad4147418c387c5
# src/lintrans/matrices/utility.py

"""This module provides simple utility methods for matrix and vector manipulation."""

from __future__ import annotations

import math

import numpy as np

from lintrans.typing_ import MatrixType


def polar_coords(x: float, y: float, *, degrees: bool = False) -> tuple[float, float]:
    """Return the polar coordinates of a given (x, y) Cartesian coordinate.

    .. note:: We're returning the angle in the range [0, 2pi)
    """
    radius = math.hypot(x, y)

    # PyCharm complains about np.angle taking a complex argument even though that's what it's designed for
    # noinspection PyTypeChecker
    angle = float(np.angle(x + y * 1j, degrees))

    if angle < 0:
        angle += 2 * np.pi

    return radius, angle


def rect_coords(radius: float, angle: float, *, degrees: bool = False) -> tuple[float, float]:
    """Return the rectilinear coordinates of a given polar coordinate."""
    if degrees:
        angle = np.radians(angle)

    return radius * np.cos(angle), radius * np.sin(angle)


def create_rotation_matrix(angle: float, *, degrees: bool = True) -> MatrixType:
    """Create a matrix representing a rotation (anticlockwise) by the given angle.

    :Example:

    >>> create_rotation_matrix(30)
    array([[ 0.8660254, -0.5      ],
           [ 0.5      ,  0.8660254]])
    >>> create_rotation_matrix(45)
    array([[ 0.70710678, -0.70710678],
           [ 0.70710678,  0.70710678]])
    >>> create_rotation_matrix(np.pi / 3, degrees=False)
    array([[ 0.5      , -0.8660254],
           [ 0.8660254,  0.5      ]])
```

[25] This isn't actually true. An enlargement matrix would also satisfy these conditions, but I didn't realise that at the time.

```
57
58          :param float angle: The angle to rotate anticlockwise by
59          :param bool degrees: Whether to interpret the angle as degrees (True) or radians (False)
60          :returns MatrixType: The resultant matrix
61          """
62          rad = np.deg2rad(angle % 360) if degrees else angle % (2 * np.pi)
63          return np.array([
64              [np.cos(rad), -1 * np.sin(rad)],
65              [np.sin(rad), np.cos(rad)]
66          ])
```

I then added unit tests for these functions and to assert that `create_rotation_matrix()` always makes its angle positive.

```
# 7b0c374d586e487e547dad886cc24239f768b554
# tests/matrices/utility/test_coord_conversion.py

7   """Test conversion between polar and rectilinear coordinates in :mod:`lintrans.matrices.utility`."""
8
9   from numpy import pi, sqrt
10  from pytest import approx
11
12  from lintrans.matrices.utility import polar_coords, rect_coords
13
14  expected_coords: list[tuple[tuple[float, float], tuple[float, float]]] = [
15      ((0, 0), (0, 0)),
16      ((1, 1), (sqrt(2), pi / 4)),
17      ((0, 1), (1, pi / 2)),
18      ((1, 0), (1, 0)),
19      ((sqrt(2), sqrt(2)), (2, pi / 4)),
20      ((-3, 4), (5, 2.214297436)),
21      ((4, -3), (5, 5.639684198)),
22      ((5, -0.2), (sqrt(626) / 5, 6.24320662)),
23      ((-1.3, -10), (10.08414597, 4.583113976)),
24      ((23.4, 0), (23.4, 0)),
25      ((pi, -pi), (4.442882938, 1.75 * pi))
26  ]
27
28
29  def test_polar_coords() -> None:
30      """Test that :func:`lintrans.matrices.utility.polar_coords` works as expected."""
31      for rect, polar in expected_coords:
32          assert polar_coords(*rect) == approx(polar)
33
34
35  def test_rect_coords() -> None:
36      """Test that :func:`lintrans.matrices.utility.rect_coords` works as expected."""
37      for rect, polar in expected_coords:
38          assert rect_coords(*polar) == approx(rect)
39
40      assert rect_coords(1, 0) == approx((1, 0))
41      assert rect_coords(1, pi) == approx((-1, 0))
42      assert rect_coords(1, 2 * pi) == approx((1, 0))
43      assert rect_coords(1, 3 * pi) == approx((-1, 0))
44      assert rect_coords(1, 4 * pi) == approx((1, 0))
45      assert rect_coords(1, 5 * pi) == approx((-1, 0))
46      assert rect_coords(1, 6 * pi) == approx((1, 0))
47      assert rect_coords(20, 100) == approx(rect_coords(20, 100 % (2 * pi)))


# 7b0c374d586e487e547dad886cc24239f768b554
# tests/matrices/utility/test_rotation_matrices.py

74  def test_create_rotation_matrix() -> None:
75      """Test that create_rotation_matrix() works with given angles and expected matrices."""
76      for degrees, radians, matrix in angles_and_matrices:
77          assert create_rotation_matrix(degrees, degrees=True) == pytest.approx(matrix)
78          assert create_rotation_matrix(radians, degrees=False) == pytest.approx(matrix)
79
80          assert create_rotation_matrix(-1 * degrees, degrees=True) == pytest.approx(np.linalg.inv(matrix))
81          assert create_rotation_matrix(-1 * radians, degrees=False) == pytest.approx(np.linalg.inv(matrix))
```

```
82
83          assert (create_rotation_matrix(-90, degrees=True) ==
84                  create_rotation_matrix(270, degrees=True)).all()
85          assert (create_rotation_matrix(-0.5 * np.pi, degrees=False) ==
86                  create_rotation_matrix(1.5 * np.pi, degrees=False)).all()
```

```
(lintrans) dyson@Harold-Ubuntu:~/repos/lintrans [main *=]
$ pytest -v
============================================= test session starts ==============================================
platform linux -- Python 3.11.0, pytest-7.2.1, pluggy-1.0.0 -- /home/dyson/temp/lintrans/venv/bin/python
cachedir: .pytest_cache
rootdir: /home/dyson/temp/lintrans, configfile: pyproject.toml, testpaths: tests
collected 32 items

tests/gui/test_dialog_utility_functions.py::test_is_valid_float[inputs0-True] PASSED                    [  3%]
tests/gui/test_dialog_utility_functions.py::test_is_valid_float[inputs1-False] PASSED                   [  6%]
tests/gui/test_dialog_utility_functions.py::test_round_float PASSED                                     [  9%]
tests/matrices/test_parse_and_validate_expression.py::test_validate_matrix_expression[inputs0-True] PASSED [ 12%]
tests/matrices/test_parse_and_validate_expression.py::test_validate_matrix_expression[inputs1-False] PASSED [ 15%]
tests/matrices/test_parse_and_validate_expression.py::test_parse_matrix_expression PASSED               [ 18%]
tests/matrices/test_parse_and_validate_expression.py::test_parse_error PASSED                           [ 21%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_simple_matrix_addition PASSED           [ 25%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_simple_two_matrix_multiplication PASSED [ 28%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_identity_multiplication PASSED          [ 31%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_simple_three_matrix_multiplication PASSED [ 34%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_matrix_inverses PASSED                  [ 37%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_matrix_powers PASSED                    [ 40%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_matrix_transpose PASSED                 [ 43%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_rotation_matrices PASSED                [ 46%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_multiplication_and_addition PASSED      [ 50%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_complicated_expressions PASSED          [ 53%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_value_errors PASSED                     [ 56%]
tests/matrices/matrix_wrapper/test_evaluate_expression.py::test_linalgerror PASSED                      [ 59%]
tests/matrices/matrix_wrapper/test_misc.py::test_get_expression PASSED                                  [ 62%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_basic_get_matrix PASSED                 [ 65%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_get_name_error PASSED                   [ 68%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_basic_set_matrix PASSED                 [ 71%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_set_expression PASSED                   [ 75%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_simple_dynamic_evaluation PASSED        [ 78%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_recursive_dynamic_evaluation PASSED     [ 81%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_set_identity_error PASSED               [ 84%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_set_name_error PASSED                   [ 87%]
tests/matrices/matrix_wrapper/test_setitem_and_getitem.py::test_set_type_error PASSED                   [ 90%]
tests/matrices/utility/test_coord_conversion.py::test_polar_coords PASSED                               [ 93%]
tests/matrices/utility/test_coord_conversion.py::test_rect_coords PASSED                                [ 96%]
tests/matrices/utility/test_rotation_matrices.py::test_create_rotation_matrix PASSED                    [100%]

============================================== 32 passed in 0.36s ==============================================
```

Figure 3.10.11: Running `pytest` with the new tests

Then I had to actually implement the logarithmic spiral. I spent several hours playing around with Desmos and various formulae on paper, and eventually devised a way to connect two points with a logarithmic spiral. Sometimes.

The formula I came up with was designed to give a polar coordinate (r, θ) which was some proportion p between 0 and 1 along the logarithmic spiral connecting the polar coordinates (r_1, θ_1) and (r_2, θ_2). A generic logarithmic spiral has the form $r = b^\theta$, where b is called the base. I came up with the following equations to define my connecting curve:

$$r = r_1 \times b^{(\theta - \theta_1)} \qquad \text{where } b = \left(\frac{r_2}{r_1}\right)^{\frac{-1}{\theta_1 - \theta_2}}$$

To get an arbitrary point with a proportion p along the curve, you can find θ by $\theta = \theta_1 + p(\theta_2 - \theta_1)$ and then plug that back in to find r.

Then I just had to implement this formula in code to move each basis vector accordingly.

```
# 2c86b3a7f40deb760e852fe6d0213cba15afcf9e
# src/lintrans/gui/main_window.py

37  class LintransMainWindow(QMainWindow):
...
377     def _get_animation_frame(self, start: MatrixType, target: MatrixType, proportion: float) -> MatrixType:
```

```
...
        det_target = linalg.det(target)
        det_start = linalg.det(start)

        # This is the matrix that we're applying to get from start to target
        # We want to check if it's rotation-like
        matrix_application = target @ linalg.inv(start)

        if linalg.det(matrix_application) > 0 and abs(np.dot(matrix_application.T[0], matrix_application.T[1])) <
        ↪  0.1:
            # Get the columns of the matrices
            # We're going to move i and then move j
            i_vectors = (start.T[0], target.T[0])
            j_vectors = (start.T[1], target.T[1])

            matrix_list: list[tuple[float, float]] = []

            for start_vector, end_vector in [i_vectors, j_vectors]:
                # We want the points in polar coordinates
                s_length, s_angle = polar_coords(start_vector[0], start_vector[1])
                e_length, e_angle = polar_coords(end_vector[0], end_vector[1])

                # We're using the standard formula for a logarithmic spiral,
                # but we want to connect two specific points
                # This base is just the base that we raise the angle to in the formula
                base = (e_length / s_length) ** (-1 / (s_angle - e_angle))

                angle = s_angle + proportion * (e_angle - s_angle)

                # Logarithmic spiral equation
                radius = s_length * base ** (angle - s_angle)

                matrix_list.append(rect_coords(radius, angle))

            return np.array(
                [
                    [matrix_list[0][0], matrix_list[1][0]],
                    [matrix_list[0][1], matrix_list[1][1]]
                ]
            )
```

It worked really well for simple rotations like `"rot(170)"` and even worked for `"2rot(180)"`, which I was very happy with. However, if you start from **I**, which is the default starting position, and try to rotate any more than 270°, the i vector goes anticlockwise, and the j vector goes clockwise. If you start at **I** and try to animate `"rot(180)"` more than once, then any time after the first, the basis vectors will rotate in opposite directions and go through each other. Even though after applying `"rot(180)"` twice, you should be back to **I**, the floating point error adds up and that tiny deviation breaks it.

This approach was a good start, but I'm going to need something better.

3.10.9.3 Checking for enlargement matrices

I found a bug where any enlargement matrix would immediately crash the program when you tried to animate. Suffice it to say, that's not very good. Recall back to footnote 25, where I said that the check would count enlargement matrices as rotation matrices. The logarithmic spiral formula can't connect two points with the same angle, since it would end up dividing by zero to find the base. This, of course, results in a crash.

To fix this bug, I simply changed the check to ignore any matrix that looks like an enlargement. If you divide an enlargement matrix by its determinant, then it will look like **I**, so we can just check that. Additionally, I only want to animate rotations smoothly like this if the smoothen determinant setting is on.

```
# 31100f35e8d46fcddaad18ee801e28904dc3011d
# src/lintrans/gui/main_window.py
```

```
37  class LintransMainWindow(QMainWindow):
...
377     def _get_animation_frame(self, start: MatrixType, target: MatrixType, proportion: float) -> MatrixType:
...
395         if self.plot.display_settings.smoothen_determinant \
396                 and linalg.det(matrix_application) > 0 \
397                 and abs(np.dot(matrix_application.T[0], matrix_application.T[1])) < 0.1 \
398                 and not (matrix_application / linalg.det(matrix_application) - np.eye(2) < 1e-5).all():
```

3.10.9.4 Using incremental circles instead

The logarithmic spiral was a nice idea, but the instability made it unsuitable as a long term solution. Instead, I decided to use incremental circles instead. I would scale a radius according the start and end radii, as well as the proportion of the way through the animation. Then I would find an angle in the same way and combine them into one polar coordinate.

Also, if the starting matrix is singular, then NumPy can't invert it so it crashes. This is obviously also bad, so I just had to check for it.

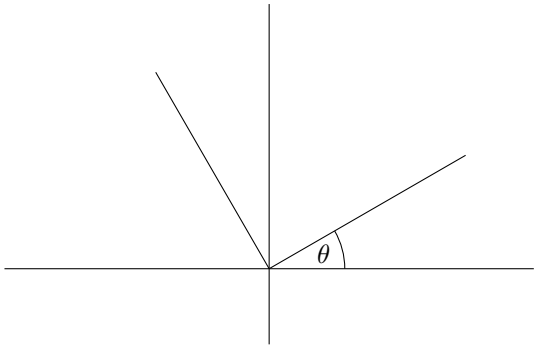
```
# f97f6542a051c05896711a01eb48a04dba693f64
# src/lintrans/gui/main_window.py

37  class LintransMainWindow(QMainWindow):
...
377     def _get_animation_frame(self, start: MatrixType, target: MatrixType, proportion: float) -> MatrixType:
...
388         det_target = linalg.det(target)
389         det_start = linalg.det(start)
390
391         # This is the matrix that we're applying to get from start to target
392         # We want to check if it's rotation-like
393         if linalg.det(start) == 0:
394             matrix_application = None
395         else:
396             matrix_application = target @ linalg.inv(start)
397
398         if matrix_application is not None \
399                 and self.plot.display_settings.smoothen_determinant \
400                 and linalg.det(matrix_application) > 0 \
401                 and abs(np.dot(matrix_application.T[0], matrix_application.T[1])) < 0.1:
402             # Get the columns of the matrices
403             # We're going to move i and then move j
404             i_vectors = (start.T[0], target.T[0])
405             j_vectors = (start.T[1], target.T[1])
406
407             matrix_list: list[tuple[float, float]] = []
408             TWO_PI = 2 * np.pi
409
410             for start_vector, end_vector in [i_vectors, j_vectors]:
411                 # We want the points in polar coordinates
412                 s_length, s_angle = polar_coords(start_vector[0], start_vector[1])
413                 e_length, e_angle = polar_coords(end_vector[0], end_vector[1])
414
415                 angle_difference = e_angle - s_angle % TWO_PI
416
417                 if angle_difference > np.pi + 0.01:  # Extra 0.01 accounts for floating point error
418                     angle = s_angle + proportion * (TWO_PI - angle_difference)
419                 else:
420                     angle = s_angle + proportion * angle_difference
421
422                 radius = s_length + proportion * (e_length - s_length)
423                 # angle = s_angle % TWO_PI + proportion * angle_difference
424
425                 matrix_list.append(rect_coords(radius, angle))
426
427             return np.array(
428                 [
```

```
                    [matrix_list[0][0], matrix_list[1][0]],
                    [matrix_list[0][1], matrix_list[1][1]]
                ]
            )
```

Does this solve the instability problem with the basis vectors rotating in opposite directions? No. Does it make this algorithm simpler and easier to improve? Yes.

3.10.9.5 Treating the rotation as one thing



After much thought and deliberation, I realised that my fatal error was rotating the basis vectors independently. This allowed small floating point errors to cause the basis vectors to be rotated in opposite directions. What I need to do instead was to find the angle from one basis vector, and use that to rotate both.

I can find the angle θ by using the first column of the application matrix, and then rotate both basis vectors by this same angle. By finding the angle just once and using a dedicated `rotate_coord()` utility function to avoid converting back and forth, it ensures that both the basis vectors get rotated by the same angle in the same direction.

I first added a type alias for a vector, mainly for convenience.

```
# c228904ab61cb33a6581fe28bbd6330b5c2ece97
# src/lintrans/typing_/__init__.py

VectorType = NDArray[(2,), Float]
"""This type represents a 2D vector as a NumPy array, for use with :attr:`MatrixType`."""
```

I then created a utility function to rotate a rectilinear coordinate by a given angle.

```
# 425f3d653770724a01fd5f94314c7d076dadfef2
# src/lintrans/matrices/utility.py

def rotate_coord(x: float, y: float, angle: float, *, degrees: bool = False) -> tuple[float, float]:
    """Rotate a rectilinear coordinate by the given angle."""
    if degrees:
        angle = np.radians(angle)

    r, theta = polar_coords(x, y, degrees=degrees)
    theta = (theta + angle) % (2 * np.pi)

    return rect_coords(r, theta, degrees=degrees)
```

Then when generating a frame, I normalise the angle θ to be $-\pi \leq \theta < \pi$ (radians) and then rotate the coordinates of each basis vector by a proportion of the angle for each frame in the animation.

```
# 425f3d653770724a01fd5f94314c7d076dadfef2
# src/lintrans/gui/main_window.py

class LintransMainWindow(QMainWindow):
...
    def _get_animation_frame(self, start: MatrixType, target: MatrixType, proportion: float) -> MatrixType:
```

```
        """Get the matrix to render for this frame of the animation.

        This method will smoothen the determinant if that setting in enabled and if the determinant is positive.
        It also animates rotation-like matrices using a logarithmic spiral to rotate around and scale continuously.
        Essentially, it just makes things look good when animating.

        :param MatrixType start: The starting matrix
        :param MatrixType start: The target matrix
        :param float proportion: How far we are through the loop
        """
        det_target = linalg.det(target)
        det_start = linalg.det(start)

        # This is the matrix that we're applying to get from start to target
        # We want to check if it's rotation-like
        if linalg.det(start) == 0:
            matrix_application = None
        else:
            matrix_application = target @ linalg.inv(start)

        if matrix_application is not None \
                and self.plot.display_settings.smoothen_determinant \
                and linalg.det(matrix_application) > 0 \
                and abs(np.dot(matrix_application.T[0], matrix_application.T[1])) < 0.1:
            rotation_vector: VectorType = matrix_application.T[0]  # Take the i column
            radius, angle = polar_coords(*rotation_vector)

            # We want the angle to be in [-pi, pi), so we have to subtract 2pi from it if it's too big
            if angle > np.pi:
                angle -= 2 * np.pi

            i: VectorType = start.T[0]
            j: VectorType = start.T[1]

            # Scale the coords with a list comprehension
            # It's a bit janky, but rotate_coords() will always return a 2-tuple,
            # so new_i and new_j will always be lists of length 2
            scale = (radius - 1) * proportion + 1
            new_i = [scale * c for c in rotate_coord(i[0], i[1], angle * proportion)]
            new_j = [scale * c for c in rotate_coord(j[0], j[1], angle * proportion)]

            return np.array(
                [
                    [new_i[0], new_j[0]],
                    [new_i[1], new_j[1]]
                ]
            )
```

And of course, I added this to the changelog.

```
<!-- 425f3d653770724a01fd5f94314c7d076dadfef2 -->
<!-- CHANGELOG.md -->

### Added
...
- Add proper rotation animation that rotates at constant speed
```

Now rotations finally work properly!

3.10.10 Adding a setting for animation time

Once I'd merged the `dev/anim-rot` branch, I was basically done with `v0.2.2`, but I still wanted to add one last thing. I already had a display setting to control the delay between animating consecutive matrices in a sequence, but I also wanted a display setting to control how long the actual animation lasts. This would allow a teacher to animate something slowly to more precisely show an animation. Implementing it was very simple.

I just had to add the setting to the `DisplaySettings` dataclass, add code to the display settings dialog to allow changing it, and then use it in animations.

```
# 86343c4b0dd4ed9052184fd4ed924062a1cd9264
# src/lintrans/gui/settings.py

15  class DisplaySettings:
...
51      animation_time: int = 1200
52      """This is the number of milliseconds that an animation takes."""


# 86343c4b0dd4ed9052184fd4ed924062a1cd9264
# src/lintrans/gui/dialogs/settings.py

21  class SettingsDialog(FixedSizeDialog):
...
24      def __init__(self, *args, **kwargs):
...
127         self.label_animation_time = QtWidgets.QLabel(self)
128         self.label_animation_time.setText('Total animation length (ms)')
129         self.label_animation_time.setToolTip(
130             'How long it takes for an animation to complete'
131         )
132
133         self.lineedit_animation_time = QtWidgets.QLineEdit(self)
134         self.lineedit_animation_time.setValidator(QIntValidator(1, 9999, self))
...
226     def load_settings(self) -> None:
...
236         self.lineedit_animation_time.setText(str(self.display_settings.animation_time))
...
245     def confirm_settings(self) -> None:
...
255         self.display_settings.animation_time = int(self.lineedit_animation_time.text())


# 86343c4b0dd4ed9052184fd4ed924062a1cd9264
# src/lintrans/gui/main_window.py

37  class LintransMainWindow(QMainWindow):
...
465     def animate_between_matrices(self, matrix_start: MatrixType, matrix_target: MatrixType) -> None:
466         """Animate from the start matrix to the target matrix."""
467         self.animating = True
468
469         # Making steps depend on animation_time ensures a smooth animation without
470         # massive overheads for small animation times
471         steps = self.plot.display_settings.animation_time // 10
472
473         for i in range(0, steps + 1):
474             if not self.animating:
475                 break
476
477             matrix_to_render = self._get_animation_frame(matrix_start, matrix_target, i / steps)
478
479             if self.is_matrix_too_big(matrix_to_render):
480                 self.show_error_message('Matrix too big', "This matrix doesn't fit on the canvas")
481                 self.animating = False
482                 return
483
484             self.plot.visualize_matrix_transformation(matrix_to_render)
485
486             # We schedule the plot to be updated, tell the event loop to
487             # process events, and asynchronously sleep for 10ms
488             # This allows for other events to be processed while animating, like zooming in and out
489             self.plot.update()
490             QApplication.processEvents()
491             QThread.msleep(self.plot.display_settings.animation_time // steps)
492
493         self.animating = False
```

And then finally, I added it to the changelog.

```
<!-- 86343c4b0dd4ed9052184fd4ed924062a1cd9264 -->
<!-- CHANGELOG.md -->

### Added
...
- Allow animation time to be varied
```

3.10.11 Releasing `v0.2.2`

Now I can just update the version number, tag the commit, and let GitHub Actions do the rest.

```
# 1139f94366be359aa5606c750c67b72c2777c961
# src/lintrans/__init__.py

__version__ = '0.2.2'
```

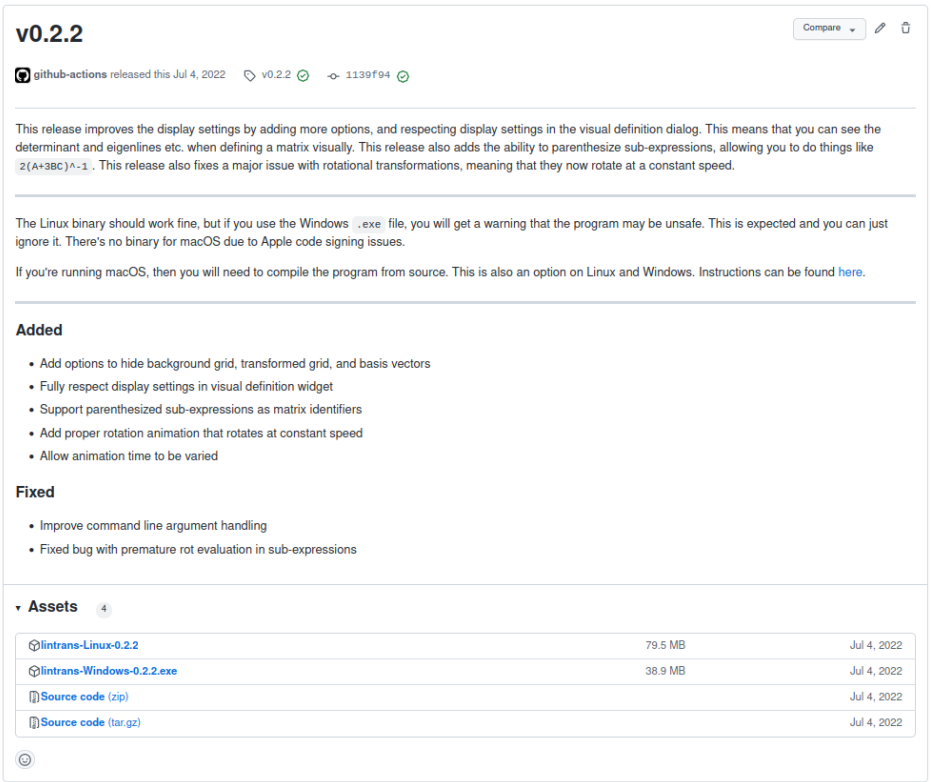


Figure 3.10.12: The release of `v0.2.2` on GitHub

3.11 Teacher suggestions

Now that I've got `v0.2.2` working and released, it's time to talk to some teachers. Ms Arnold is going to be the one that's actually using it, so obviously I needed to talk to her about it, but she wasn't available for a few days. I was talking to another maths teacher, Mr Dunkley, about my personal statement and took the opportunity to show him `lintrans` as well.

He was able to download and run it on a native Windows 10 installation, which was quite a relief. I'd been unable to test it on a real bare-metal Windows installation so far; I only had virtual machines.

He suggested two main improvements:

1. In the visual definition dialog, the basis vectors should snap to integer coordinates when they get close enough
2. There should be a dialog box which displays matrices that you've already defined

3.11.1 Fixing a bug with animating stretches

While Mr Dunkley was playing around with `lintrans`, I noticed a bug where animating uniform stretches, where every direction gets stretched equally work, just fine, but a matrix like $\begin{pmatrix} 3 & 0 \\ 0 & 1 \end{pmatrix}$ would be animated as if it was $\begin{pmatrix} 3 & 0 \\ 0 & 3 \end{pmatrix}$ and the plane would stretch equally in all directions.

After looking at the code later, I realised this was a problem with my new animation code detecting this type of matrix as a rotation. To fix this, I could just add a check to the `if` statement before the rotation animation code. This new check would make sure that the basis vectors of the application matrix were approximately the same length. By checking this as well, I fixed the bug.

```
# eb118f02db9fb9c76ce15a976f81a037415d2a4e
# src/lintrans/gui/main_window.py
```

```
39  class LintransMainWindow(QMainWindow):
...
389     def _get_animation_frame(self, start: MatrixType, target: MatrixType, proportion: float) -> MatrixType:
...
410         # For a matrix to represent a rotation, it must have a positive determinant,
411         # its vectors must be perpendicular, and its vectors must be the same length
412         # The checks for 'abs(value) < 1e-10' are to account for floating point error
413         if matrix_application is not None \
414                 and self.plot.display_settings.smoothen_determinant \
415                 and linalg.det(matrix_application) > 0 \
416                 and abs(np.dot(matrix_application.T[0], matrix_application.T[1])) < 1e-10 \
417                 and abs(np.hypot(*matrix_application.T[0]) - np.hypot(*matrix_application.T[1])) < 1e-10:
```

3.11.2 Fixing a hang after closing during an animation

This bug was tiny and only really affected me, but when I run `lintrans` from the terminal with `python -m lintrans` and close it during an animation, I have to wait a moment to get my shell prompt back. Clearly, the program is still running even after the main window is closed.

I'm not entirely sure what was happening here, but it was something to do with Qt5's event loop and threading model, and I could fix the bug by just overriding `LintransMainWindow.closeEvent()` to set `self.animating = False` and that would ensure that animations are stopped before the main window closes.

```
# d60c1878058799be544f5cf0847b478dccd3a021
# src/lintrans/gui/main_window.py
```

```
39  class LintransMainWindow(QMainWindow):
...
262     def closeEvent(self, event: QCloseEvent) -> None:
263         """Handle a :class:`QCloseEvent` by cancelling animation first."""
264         self.animating = False
265         event.accept()
```

3.11.3 Adding snapping in the visual definition dialog

I was now ready to implement snapping in the visual definition dialog.

The `DefineVisuallyWidget` class has a `self.dragged_point` attribute, which is the coordinates of the point being dragged. In `mouseMoveEvent()`, we get the coordinates of the current cursor position and set the dragged point accordingly. That's all that happens in the old code.

```
# d60c1878058799be544f5cf0847b478dccd3a021
# src/lintrans/gui/plots/widgets.py

86  class DefineVisuallyWidget(VisualizeTransformationWidget):
...
127     def mouseMoveEvent(self, event: QMouseEvent) -> None:
128         """Handle the mouse moving on the canvas."""
129         mx = event.x()
130         my = event.y()
131
132         if self.dragged_point is not None:
133             x, y = self.grid_coords(mx, my)
134
135             if self.dragged_point == self.point_i:
136                 self.point_i = x, y
137
138             elif self.dragged_point == self.point_j:
139                 self.point_j = x, y
140
141             self.dragged_point = x, y
142
143             self.update()
144
145             event.accept()
146
147         event.ignore()
```

To add snapping to this, we can just get the 4 integer coordinates around the dragged point, check each of their distances to the dragged point, and if it's sufficiently close to one of them, snap it to that point.

```
# f2de39fec299bb8ed155ee649d34c9063787e71a
# src/lintrans/gui/plots/widgets.py

87  class DefineVisuallyWidget(VisualizeTransformationWidget):
...
128     def mouseMoveEvent(self, event: QMouseEvent) -> None:
129         """Handle the mouse moving on the canvas."""
130         mx = event.x()
131         my = event.y()
132
133         if self.dragged_point is None:
134             event.ignore()
135             return
136
137         x, y = self.grid_coords(mx, my)
138
139         possible_snaps: List[Tuple[int, int]] = [
140             (floor(x), floor(y)),
141             (floor(x), ceil(y)),
```

```
142             (ceil(x), floor(y)),
143             (ceil(x), ceil(y))
144         ]
145
146         snap_distances: List[Tuple[float, Tuple[int, int]]] = [
147             (dist((x, y), coord), coord)
148             for coord in possible_snaps
149         ]
150
151         for snap_dist, coord in snap_distances:
152             if snap_dist < 0.1:
153                 x, y = coord
154
155         if self.dragged_point == self.point_i:
156             self.point_i = x, y
157
158         elif self.dragged_point == self.point_j:
159             self.point_j = x, y
160
161         self.dragged_point = x, y
162
163         self.update()
164
165         event.accept()
```

This all worked very well.

3.11.4 Respecting transitional animation in animation sequences

It's good to animate a sequence of matrices by applying them one after another, but it can also be beneficial to animate a sequence by just moving between them in a transitional animation style. This is already possible for individual animations by disabling the *Applicative animation* display setting, but it would be nice to respect this setting for animation sequences.

To do this, I just have to add a few lines to the part where we do animation sequences.

```
# 41907b81661f3878e435b794d9d719491ef14237
# src/lintrans/gui/main_window.py

39  class LintransMainWindow(QMainWindow):
...
327     def animate_expression(self) -> None:
...
339         # If there's commas in the expression, then we want to animate each part at a time
340         if ',' in text:
341             current_matrix = matrix_start
342             self.animating_sequence = True
343
344             # For each expression in the list, right multiply it by the current matrix,
345             # and animate from the current matrix to that new matrix
346             for expr in text.split(',')[::-1]:
347                 try:
348                     new_matrix = self.matrix_wrapper.evaluate_expression(expr)
349
350                     if self.plot.display_settings.applicative_animation:
351                         new_matrix = new_matrix @ current_matrix
352                 except LinAlgError:
353                     self.show_error_message('Singular matrix', 'Cannot take inverse of singular matrix')
354                     return
355
356                 if not self.animating_sequence:
357                     break
358
359                 self.animate_between_matrices(current_matrix, new_matrix)
360                 current_matrix = new_matrix
361
362                 # Here we just redraw and allow for other events to be handled while we pause
```

```
363                 self.plot.update()
364                 QApplication.processEvents()
365                 QThread.msleep(self.plot.display_settings.animation_pause_length)
366
367             self.animating_sequence = False
```

3.11.5 Adding the info panel

One of things that Mr Dunkley wanted to see was a panel or dialog box that would display all the matrices that you've already defined.

3.11.5.1 Creating the initial dialog

The first thing I did was create a new git branch, and then I created a new dialog class, added a button to display the new info panel, and created a simple utility method for a `MatrixWrapper` to return a list of all the matrices it's got defined.

```
# 6469f9f3678a89b3b7f388a6c5132335d9a6a947
# src/lintrans/matrices/wrapper.py

24  class MatrixWrapper:
...
251     def get_defined_matrices(self) -> List[Tuple[str, Union[MatrixType, str]]]:
252         """Return a list of tuples containing the name and value of all defined matrices in the wrapper.
253
254         :returns: A list of tuples where the first element is the name, and the second element is the value
255         :rtype: List[Tuple[str, Union[MatrixType, str]]]
256         """
257         matrices = []
258
259         for name, value in self._matrices.items():
260             if value is not None:
261                 matrices.append((name, value))
262
263         return matrices
```

```
# 6469f9f3678a89b3b7f388a6c5132335d9a6a947
# src/lintrans/gui/dialogs/misc.py

100 class InfoPanelDialog(FixedSizeDialog):
101     """A simple dialog class to display an info panel that shows all currently defined matrices."""
102
103     def __init__(self, matrix_wrapper: MatrixWrapper, *args, **kwargs):
104         super().__init__(*args, **kwargs)
105         self.wrapper = matrix_wrapper
106
107         self.setWindowTitle('Defined matrices')
108
109         for name, value in self.wrapper.get_defined_matrices():
110             print(name, value)
```

```
# 6469f9f3678a89b3b7f388a6c5132335d9a6a947
# src/lintrans/gui/main_window.py

39  class LintransMainWindow(QMainWindow):
...
45      def __init__(self):
...
203         # Info panel button
204
205         self.button_info_panel = QtWidgets.QPushButton(self)
206         self.button_info_panel.setText('Show defined matrices')
207         self.button_info_panel.setToolTip('Open an info panel with all matrices that have been defined in this
            ↪  session')
208         self.button_info_panel.clicked.connect(lambda: InfoPanelDialog(self.matrix_wrapper, self).open())
```

Trying to open the new info panel results in a tiny, useless dialog box appearing but the defined matrices get printed out in the terminal, which is exactly what I expected. It's a good proof of concept, but obviously needs a bit of visual polish.

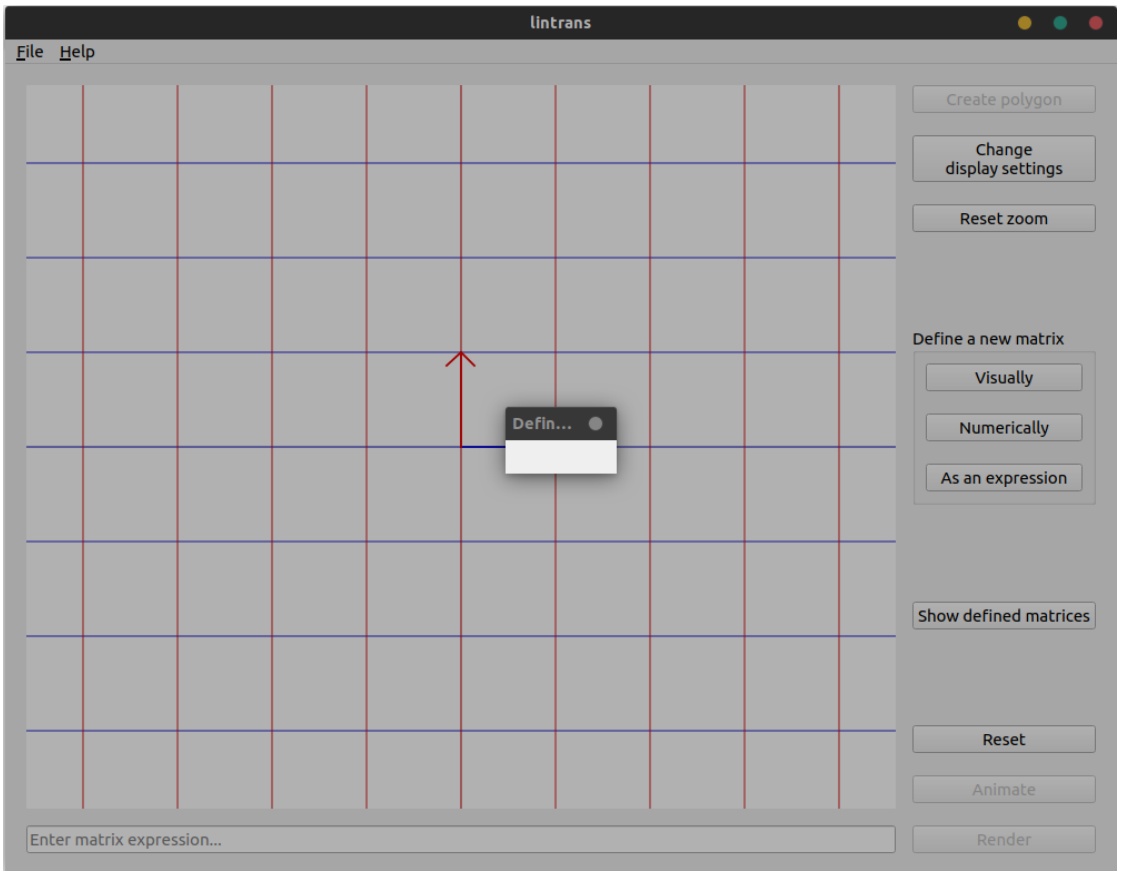


Figure 3.11.1: The GUI with the tiny dialog box and new button visible in the background

3.11.5.2 Adding the matrices to the panel

The next step was obviously to add the widgets that actually represent these matrices in the dialog box. To do this, I created a layout and iterated over the matrices in the wrapper to add some widgets for each. These widgets consist of a name label, a label for '=', and a container widget to display the content of the matrix. I created a separate method to generate a container widget for the matrix content.

```
# addc22a8984a9d8e1d100b5800836a2af3f42760
# src/lintrans/gui/dialogs/misc.py

class InfoPanelDialog(FixedSizeDialog):
    """A simple dialog class to display an info panel that shows all currently defined matrices."""

    def __init__(self, matrix_wrapper: MatrixWrapper, *args, **kwargs):
        """Create the dialog box with all the widgets needed to show the information."""
        super().__init__(*args, **kwargs)
        self.wrapper = matrix_wrapper

        self.setWindowTitle('Defined matrices')

        vlay_main = QVBoxLayout()
        vlay_main.setSpacing(20)

        for name, value in self.wrapper.get_defined_matrices():
```

```
            label_name = QLabel(self)
            label_name.setText(name)
            label_name.setAlignment(Qt.AlignLeft)

            label_equals = QLabel(self)
            label_equals.setText('=')
            label_equals.setAlignment(Qt.AlignLeft)

            widget_matrix = self._get_matrix_widget(value)

            hlay_matrix = QHBoxLayout()
            hlay_matrix.setSpacing(20)
            hlay_matrix.addWidget(label_name)
            hlay_matrix.addWidget(label_equals)
            hlay_matrix.addWidget(widget_matrix)

            vlay_main.addLayout(hlay_matrix)

        self.setContentsMargins(10, 10, 10, 10)
        self.setLayout(vlay_main)

    def _get_matrix_widget(self, matrix: Union[MatrixType, str]) -> QWidget:
        """Return a :class:`QWidget` containing the value of the matrix.

        If the matrix is defined as an expression, it will be a simple :class:`QLabel`.
        If the matrix is defined as a matrix, it will be a :class:`QWidget` container
        with multiple :class:`QLabel` objects in it.
        """
        if isinstance(matrix, str):
            label = QLabel(self)
            label.setText(matrix)
            return label

        elif is_matrix_type(matrix):
            container = QWidget(self)
            grid_layout = QGridLayout()

            # tl = top left, br = bottom right, etc.
            label_tl = QLabel(self)
            label_tl.setText(round_float(matrix[0][0]))

            label_tr = QLabel(self)
            label_tr.setText(round_float(matrix[0][1]))

            label_bl = QLabel(self)
            label_bl.setText(round_float(matrix[1][0]))

            label_br = QLabel(self)
            label_br.setText(round_float(matrix[1][1]))

            label_paren_left = QLabel(self)
            label_paren_left.setText('(')

            label_paren_right = QLabel(self)
            label_paren_right.setText(')')

            grid_layout.addWidget(label_paren_left, 0, 0, 2, 0)
            grid_layout.addWidget(label_tl, 0, 1)
            grid_layout.addWidget(label_tr, 0, 2)
            grid_layout.addWidget(label_bl, 1, 1)
            grid_layout.addWidget(label_br, 1, 2)
            grid_layout.addWidget(label_paren_right, 0, 3, 2, 0)

            container.setLayout(grid_layout)

            return container

        raise ValueError('Matrix was not MatrixType or str')
```

This container widget uses a grid layout to have the numbers arranged correctly, as well as stretching the parentheses either side to properly cover the numbers.

However, the parentheses don't stretch properly. I also get the message 'QGridLayout: Multi-cell fromCol greater than toCol' in the terminal whenever I open the info panel. One for each matrix defined numerically. Suffice to say, this is not what I was trying to do.

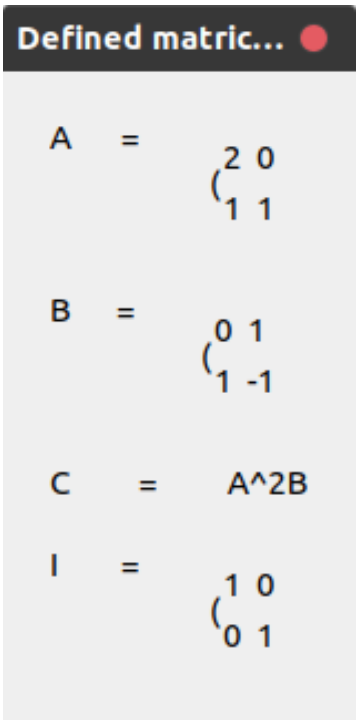


Figure 3.11.2: The info panel with some defined matrices, and the parentheses not working correctly

3.11.5.3 Fixing alignments and stretches

After checking the documentation for the `QGridLayout::addWidget()` function[42] and experimenting with some different numbers, I fixed the row and column numbers for the parentheses. I also created a temporary font for the parentheses to make them bigger. I had to make them thinner as well to avoid them looking weird. I also made the matrix names bold.

```
# 63279a27ac6fa86061c4ba10152244b2bb4ced87
# src/lintrans/gui/dialogs/misc.py

102 class InfoPanelDialog(FixedSizeDialog):
103     """A simple dialog class to display an info panel that shows all currently defined matrices."""
104
105     def __init__(self, matrix_wrapper: MatrixWrapper, *args, **kwargs):
106         """Create the dialog box with all the widgets needed to show the information."""
107         super().__init__(*args, **kwargs)
108         self.wrapper = matrix_wrapper
109
110         self.setWindowTitle('Defined matrices')
111
112         grid_layout = QGridLayout()
113         grid_layout.setSpacing(20)
114
115         bold_font = self.font()
116         bold_font.setBold(True)
117
118         name_value_pair: tuple[str, Union[MatrixType, str]]
119
120         for i, name_value_pair in enumerate(self.wrapper.get_defined_matrices()):
121             name, value = name_value_pair
122
123             label_name = QLabel(self)
124             label_name.setText(name)
125             label_name.setFont(bold_font)
```

```
126
127             label_equals = QLabel(self)
128             label_equals.setText('=')
129
130             widget_matrix = self._get_matrix_widget(value)
131
132             grid_layout.addWidget(label_name, i, 0, Qt.AlignCenter | Qt.AlignVCenter)
133             grid_layout.addWidget(label_equals, i, 1, Qt.AlignCenter | Qt.AlignVCenter)
134             grid_layout.addWidget(widget_matrix, i, 2, Qt.AlignCenter | Qt.AlignVCenter)
135
136         self.setContentsMargins(10, 10, 10, 10)
137         self.setLayout(grid_layout)
138
139     def _get_matrix_widget(self, matrix: Union[MatrixType, str]) -> QWidget:
140         """Return a :class:`QWidget` containing the value of the matrix.
141
142         If the matrix is defined as an expression, it will be a simple :class:`QLabel`.
143         If the matrix is defined as a matrix, it will be a :class:`QWidget` container
144         with multiple :class:`QLabel` objects in it.
145         """
146         if isinstance(matrix, str):
147             label = QLabel(self)
148             label.setText(matrix)
149             return label
150
151         elif is_matrix_type(matrix):
152             # tl = top left, br = bottom right, etc.
153             label_tl = QLabel(self)
154             label_tl.setText(round_float(matrix[0][0]))
155
156             label_tr = QLabel(self)
157             label_tr.setText(round_float(matrix[0][1]))
158
159             label_bl = QLabel(self)
160             label_bl.setText(round_float(matrix[1][0]))
161
162             label_br = QLabel(self)
163             label_br.setText(round_float(matrix[1][1]))
164
165             font_parens = self.font()
166             font_parens.setPointSize(int(font_parens.pointSize() * 2.5))
167             font_parens.setWeight(int(font_parens.weight() / 2.5))
168
169             label_paren_left = QLabel(self)
170             label_paren_left.setText('(')
171             label_paren_left.setFont(font_parens)
172
173             label_paren_right = QLabel(self)
174             label_paren_right.setText(')')
175             label_paren_right.setFont(font_parens)
176
177             container = QWidget(self)
178             grid_layout = QGridLayout()
179
180             grid_layout.addWidget(label_paren_left, 0, 0, -1, 1)
181             grid_layout.addWidget(label_tl, 0, 1)
182             grid_layout.addWidget(label_tr, 0, 2)
183             grid_layout.addWidget(label_bl, 1, 1)
184             grid_layout.addWidget(label_br, 1, 2)
185             grid_layout.addWidget(label_paren_right, 0, 3, -1, 1)
186
187             container.setLayout(grid_layout)
188
189             return container
190
191         raise ValueError('Matrix was not MatrixType or str')
```

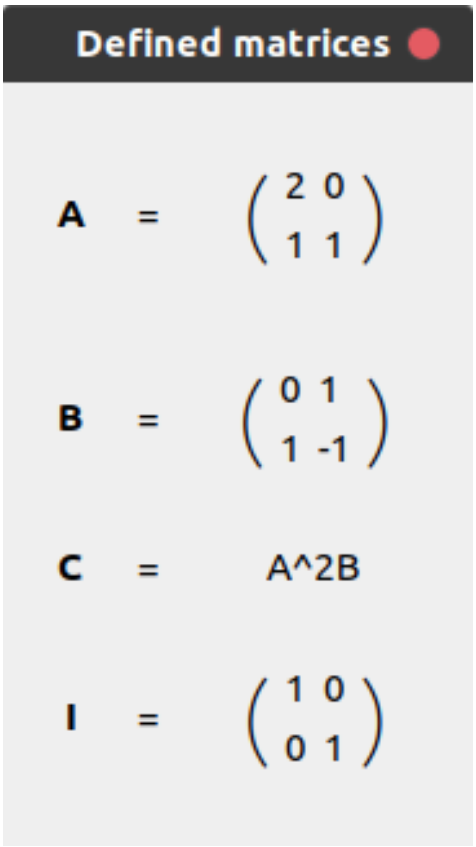


Figure 3.11.3: The new and improved info panel with correct alignment and stretching

3.11.5.4 Arranging matrices in multiple columns

The only remaining problem with the info panel is that it just extends into one long vertical column as more matrices are added. Obviously there are 26 letters in the alphabet, so 26 possible matrices that can be defined. However, 26 is a semiprime, which means if I want to arrange the matrices in a rectangle, I have to do 2×13 or 13×2. This is not particularly useful. Instead, I think it would be better to have an arrangement closer to a square, which a few matrices extra at the end. I'll go with 4 rows of columns with 6 matrices each and an extra column at the end for the last 2 matrices if necessary.

To do this, I just use the index of the current matrix to set the column for that matrix. Qt5's grid layout handles spacing and creating extra columns for me, so I just have to work out which column to put each matrix in.

```
# 8e0f2dfe27fb9629b0f8cd33a25a61f85b5443e8
# src/lintrans/gui/dialogs/misc.py

102 class InfoPanelDialog(FixedSizeDialog):
...
105     def __init__(self, matrix_wrapper: MatrixWrapper, *args, **kwargs):
...
120         for i, name_value_pair in enumerate(self.wrapper.get_defined_matrices()):
121             name, value = name_value_pair
122
123             label_name = QLabel(self)
124             label_name.setText(name)
125             label_name.setFont(bold_font)
126
127             label_equals = QLabel(self)
128             label_equals.setText('=')
```

```
129
130             widget_matrix = self._get_matrix_widget(value)
131
132             column = 3 * (i // 6)
133
134             grid_layout.addWidget(
135                 label_name,
136                 i - 2 * column,
137                 column,
138                 Qt.AlignCenter
139             )
140             grid_layout.addWidget(
141                 label_equals,
142                 i - 2 * column,
143                 column + 1,
144                 Qt.AlignCenter
145             )
146             grid_layout.addWidget(
147                 widget_matrix,
148                 i - 2 * column,
149                 column + 2,
150                 Qt.AlignCenter
151             )
```

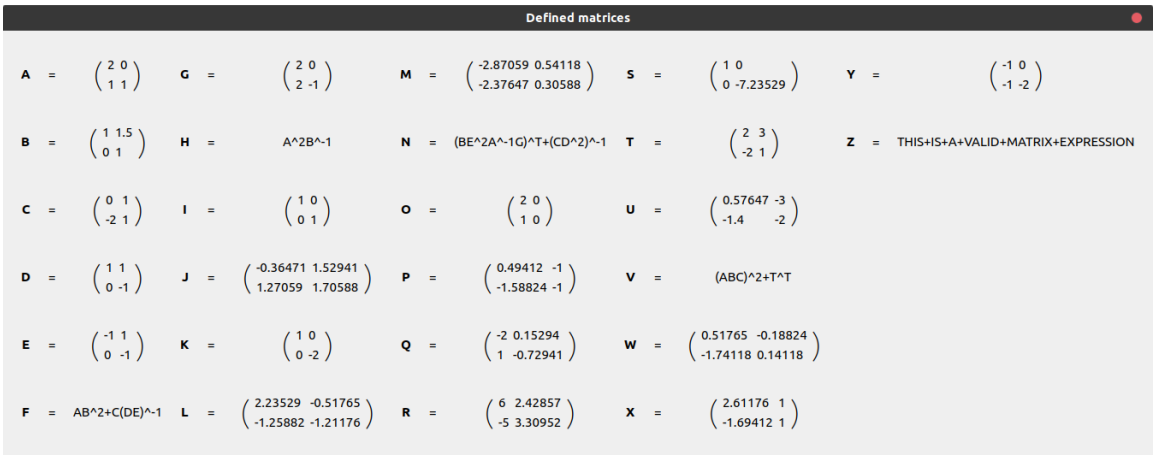


Figure 3.11.4: The info panel with all matrices defined, arranged in multiple columns

3.11.6 Fixing a bug with matrices with a 0 column

Currently, if you set one basis vector to **0**, then it will continue to draw the line for the zeroed basis vector. This doesn't make much sense, since the non-zero basis vector is the only one that has an impact on the matrix. To fix this, I can just check for a zero column and not draw the vector lines in that case.

```
# 37abc3dbb5d99c9ec812e6c887fc6c021f9c91c6
# src/lintrans/gui/plots/classes.py

171 class VectorGridPlot(BackgroundPlot):
...
231     def draw_parallel_lines(self, painter: QPainter, vector: Tuple[float, float], point: Tuple[float, float]) ->
        ↪ None:
...
244         # If the determinant is 0
245         if abs(vector_x * point_y - vector_y * point_x) < 1e-12:
246             rank = np.linalg.matrix_rank(
247                 np.array([
248                     [vector_x, point_x],
249                     [vector_y, point_y]
250                 ])
```

```
            )

            # If the matrix is rank 1, then we can draw the column space line
            if rank == 1:
                # If the vector does not have a 0 x or y component, then we can just draw the line
                if abs(vector_x) > 1e-12 and abs(vector_y) > 1e-12:
                    self.draw_oblique_line(painter, vector_y / vector_x, 0)

                # Otherwise, we have to draw lines along the axes
                elif abs(vector_x) > 1e-12 and abs(vector_y) < 1e-12:
                    painter.drawLine(0, self.height() // 2, self.width(), self.height() // 2)

                elif abs(vector_x) < 1e-12 and abs(vector_y) > 1e-12:
                    painter.drawLine(self.width() // 2, 0, self.width() // 2, self.height())

                # If the vector is (0, 0), then don't draw a line for it
                else:
                    return

            # If the rank is 0, then we don't draw any lines
            else:
                return
```

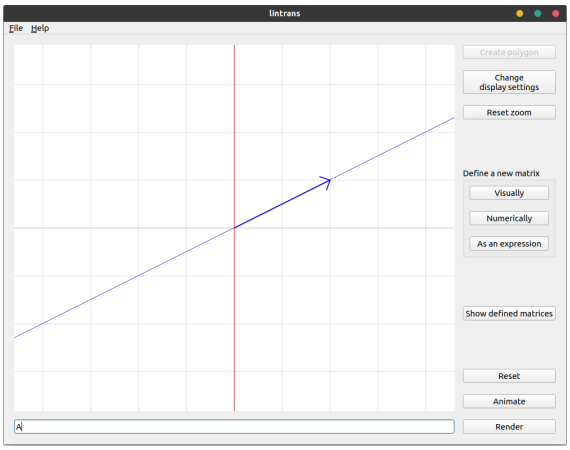


Figure 3.11.5: Before the bug fix

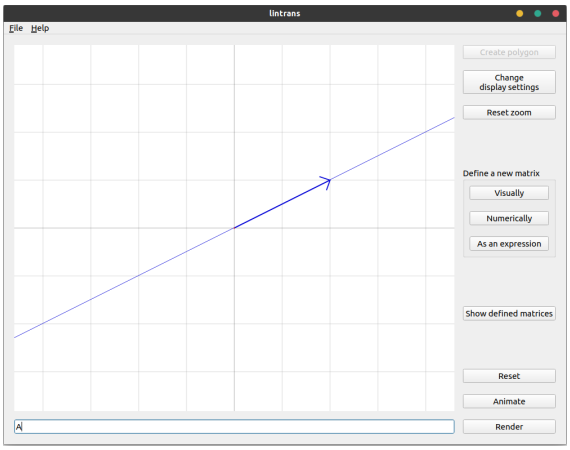


Figure 3.11.6: After the bug fix

4 Post-development Testing

Test ID	Description	Test data	Expected outcome	Actual outcome	Evidence	Comments
T1	The program should run in the Python interpreter and compile with PyInstaller.	N/A	The program runs and compiles with no problem.	As expected.	See Figure 4.1.	None.
T2	The user should be able to define matrices visually.	Approximately $\begin{pmatrix} 2 & 0.5 \\ 1 & 2 \end{pmatrix}$	The matrix should be successfully defined by the visual definition dialog.	The definition works fine with no errors and the defined matrix appears in the info panel.	See Figures 4.2 and 4.4	It's hard to correctly line up the j vector since it's $\begin{pmatrix} 0.5 \\ 2 \end{pmatrix}$ and the dialog only snaps to integer coordinates, but defining i was easy because of this.
T3	The user should be able to define matrices numerically.	$\begin{pmatrix} 2.2 & 18 \\ -0.4529 & 0 \end{pmatrix}$	The matrix should be successfully defined by the numerical definition dialog.	The definition works fine with no errors and the defined matrix appears in the info panel.	See Figures 4.3 and 4.4	Inputting the numbers directly makes it easy to get exactly what you want (such as precise decimals and large numbers that can be inconvenient to zoom out to find in the visual definition dialog) but there's no support for mathematical expressions or fractions, so the user is limited to decimal numbers.
T4	The program should be able to render matrices that the user has defined.	Rendering the previously defined **A** and then **B**.	The program renders the matrices correctly.	As expected.	See Figures 4.5 and 4.6.	Both the button and hotkey work as expected, as does the reset button.
T5	The program should be able to animate matrices that the user has defined.	Resetting, then animating **A**, then resetting and animating **B**>	The program animates smoothly from I to the matrices without any issues.	As expected.	See `pdtest/animate_defined.mp4` in the videos folder.	This test was performed with the default display settings.

T6	The program should be able to render and animate arbitrary rotations created with the `rot()` command.	Trying to render and animate `rot(135)`.	The program renders and animates the rotations correctly.	As expected.	See `pdtest/render_and_animate_rotations.mp4` in the videos folder.	None.
T7	The program should be able to render and animate expressions containing previously defined matrices.	Trying to render and animate **AB** and $\mathbf{A}^{-1}\mathbf{B}^2$.	The program renders and animates the expressions correctly.	As expected.	See `pdtest/render_and_animate_expressions.mp4` in the videos folder.	None.
T8	The program should be able to animate one matrix and then animate a transition to another.	Trying to render and animate **A** and then **B**.	The program animates them correctly, transitioning between them.	As expected.	See `pdtest/animate_multiple_transitional.mp4` in the videos folder.	None.
T9	The program should be able to animate one matrix and then apply another matrix to it.	I will start at **I**, then animate **B**, then apply **A**. This should be equivalent to **AB**, so I will apply $(\mathbf{AB})^{-1}$ to undo it.	The program animates everything correctly.	As expected.	See `pdtest/animate_multiple_applicative.mp4` in the videos folder.	None.
T10	The program should be able to animate a sequence of expressions using transitional animation.	I will animate the expression `"(AB)^-1,A,B"` and it will transition between each expression, right-to-left.	The program animates each expression in turn, transitioning between them.	As expected.	See `pdtest/animate_sequence_transitional.mp4` in the videos folder.	None.

T11	The program should be able to animate a sequence of expressions using applicative animation.	I will animate the expression `"(AB)^-1,A,B"` and it will apply each matrix in turn. The `"(AB)^-1"` at the end will undo the others and return it to the start.	The program animates each expression in turn, applying them from right to left.	As expected.	See `pdtest/animate_sequence_applicative.mp4` in the videos folder.	None.
T12	The program should allow the user to define a matrix as an expression in terms of other matrices.	$\mathbf{C} = 0.2\mathbf{A}^2\mathbf{B}^{-1}$	The matrix $\mathbf{C}$ will be defined as this expression and render properly, as well as showing up in the info panel.	As expected.	See Figures 4.7, 4.8, 4.9 and `pdtest/expression.mp4` in the videos folder.	None.
T13	When a matrix is defined as an expression, it should be re-calculated every time it's used. That means that if the user redefines one of the dependencies of an expression matrix, the expression matrix should update to reflect that the next time it's used.	$\mathbf{C} = 0.2\mathbf{A}^2\mathbf{B}^{-1}$ and then I will change $\mathbf{A}$ and re-render $\mathbf{C}$.	$\mathbf{C}$ will be rendered correctly both times, and both will be different.	As expected.	See `pdtest/change_expression_dependencies.mp4` in the videos folder.	None.

T14	A key part of the display settings is the determinant parallelogram. It should work correctly.	I will enable the determinant parallelogram and try a variety of inputs, including compositions of matrices, expression-based matrices, and a rotation.	The matrix inputs should all be animated correctly, the determinant parallelogram will be visible for all of them, smoothed out during animations, blue for positive determinants, and red for negative determinants.	As expected.	See `pdtest/determinant_parallelogram.mp4` in the videos folder.	None.
T15	A key part of the display settings is displaying eigenvectors and eigenlines. This feature should work correctly.	I will enable eigenvectors and eigenlines and then animate each matrix in turn, resetting between each of them.	Each matrix should be animated correctly and the eigenvectors and eigenlines should be rendered properly at every stage.	As expected.	See `pdtest/eigenlines.mp4` in the videos folder.	Eigenvectors are discontinuous over animation. This means that the eigenvectors start aligned to the axes, and then snap to where they should be on the first frame of animation. This doesn't look great, but there's not much I can do to get around it.

```
(lintrans) dyson@Harold-Ubuntu:~/repos/lintrans [main =]
$ ./compile.py
Created Compiler(filename=lintrans, version_name=0.3.0-alpha, platform=linux)
Compiling for platform=linux
503 INFO: PyInstaller: 5.5
503 INFO: Python: 3.11.0
504 INFO: Platform: Linux-5.19.0-35-generic-x86_64-with-glibc2.35
505 INFO: wrote /home/dyson/repos/lintrans/lintrans.spec
507 INFO: UPX is available.
507 INFO: Removing temporary files and cleaning cache in /home/dyson/.cache/pyinstaller
548 INFO: Extending PYTHONPATH with paths
['/home/dyson/repos/lintrans/src']
821 INFO: checking Analysis
821 INFO: Building Analysis because Analysis-00.toc is non existent
821 INFO: Initializing module dependency graph...
822 INFO: Caching module graph hooks...
826 WARNING: Several hooks defined for module 'numpy'. Please take care they do not conflict.
827 INFO: Analyzing base_library.zip ...
1798 INFO: Loading module hook 'hook-heapq.py' from '/home/dyson/repos/lintrans/venv/lib/python3.11/site-packages/PyInstaller/hooks'...
2095 INFO: Loading module hook 'hook-encodings.py' from '/home/dyson/repos/lintrans/venv/lib/python3.11/site-packages/PyInstaller/hooks'...
3566 INFO: Loading module hook 'hook-pickle.py' from '/home/dyson/repos/lintrans/venv/lib/python3.11/site-packages/PyInstaller/hooks'...
5139 INFO: Caching module dependency graph...
5221 INFO: running Analysis Analysis-00.toc
5233 INFO: Analyzing /home/dyson/repos/lintrans/src/lintrans/__main__.py
5284 INFO: Loading module hook 'hook-numpy.py' from '/home/dyson/repos/lintrans/venv/lib/python3.11/site-packages/numpy/_pyinstaller'...
5650 INFO: Loading module hook 'hook-numpy._pytesttester.py' from '/home/dyson/repos/lintrans/venv/lib/python3.11/site-packages/PyInstaller/hooks'...
5923 INFO: Loading module hook 'hook-difflib.py' from '/home/dyson/repos/lintrans/venv/lib/python3.11/site-packages/PyInstaller/hooks'...
6130 INFO: Loading module hook 'hook-multiprocessing.util.py' from '/home/dyson/repos/lintrans/venv/lib/python3.11/site-packages/PyInstaller/hooks'...
6288 INFO: Loading module hook 'hook-xml.py' from '/home/dyson/repos/lintrans/venv/lib/python3.11/site-packages/PyInstaller/hooks'...
6971 INFO: Loading module hook 'hook-platform.py' from '/home/dyson/repos/lintrans/venv/lib/python3.11/site-packages/PyInstaller/hooks'...
7262 INFO: Loading module hook 'hook-sysconfig.py' from '/home/dyson/repos/lintrans/venv/lib/python3.11/site-packages/PyInstaller/hooks'...
8588 INFO: Processing module hooks...
8638 INFO: Loading module hook 'hook-PyQt5.QtWidgets.py' from '/home/dyson/repos/lintrans/venv/lib/python3.11/site-packages/PyInstaller/hooks'...
8848 INFO: Loading module hook 'hook-PyQt5.QtCore.py' from '/home/dyson/repos/lintrans/venv/lib/python3.11/site-packages/PyInstaller/hooks'...
8905 INFO: Loading module hook 'hook-PyQt5.py' from '/home/dyson/repos/lintrans/venv/lib/python3.11/site-packages/PyInstaller/hooks'...
8905 WARNING: Hidden import "sip" not found!
8936 INFO: Loading module hook 'hook-PyQt5.QtGui.py' from '/home/dyson/repos/lintrans/venv/lib/python3.11/site-packages/PyInstaller/hooks'...
9041 INFO: Looking for ctypes DLLs
9081 INFO: Analyzing run-time hooks ...
9085 INFO: Including run-time hook '/home/dyson/repos/lintrans/venv/lib/python3.11/site-packages/PyInstaller/hooks/rthooks/pyi_rth_inspect.py'
9087 INFO: Including run-time hook '/home/dyson/repos/lintrans/venv/lib/python3.11/site-packages/PyInstaller/hooks/rthooks/pyi_rth_subprocess.py'
9088 INFO: Including run-time hook '/home/dyson/repos/lintrans/venv/lib/python3.11/site-packages/PyInstaller/hooks/rthooks/pyi_rth_pyqt5.py'
9089 INFO: Including run-time hook '/home/dyson/repos/lintrans/venv/lib/python3.11/site-packages/PyInstaller/hooks/rthooks/pyi_rth_pkgutil.py'
9091 INFO: Including run-time hook '/home/dyson/repos/lintrans/venv/lib/python3.11/site-packages/PyInstaller/hooks/rthooks/pyi_rth_multiprocessing.py'
9102 INFO: Looking for dynamic libraries
/home/dyson/repos/lintrans/venv/lib/python3.11/site-packages/PyInstaller/building/build_main.py:173: UserWarning: The numpy.array_api submodule is still experimental. See NEP 47.
  __import__(package)
2120 WARNING: Cannot find libicuuc.so.56 (needed by /home/dyson/repos/lintrans/venv/lib/python3.11/site-packages/PyQt5/Qt5/plugins/wayland-shell-integration/../../lib/libicui18n.so.56)
2120 WARNING: Cannot find libicudata.so.56 (needed by /home/dyson/repos/lintrans/venv/lib/python3.11/site-packages/PyQt5/Qt5/plugins/wayland-shell-integration/../../lib/libicui18n.so.56)
2314 WARNING: Cannot find libicudata.so.56 (needed by /home/dyson/repos/lintrans/venv/lib/python3.11/site-packages/PyQt5/Qt5/plugins/wayland-shell-integration/../../lib/libicuuc.so.56)
3346 WARNING: Cannot find libquadmath-96973f99.so.0.0.0 (needed by /home/dyson/repos/lintrans/venv/lib/python3.11/site-packages/numpy/core/../../numpy.libs/libgfortran-040039e1.so.5.0.0)
3358 WARNING: Cannot find libgfortran-040039e1.so.5.0.0 (needed by /home/dyson/repos/lintrans/venv/lib/python3.11/site-packages/numpy/core/../../numpy.libs/libopenblas64_p-r0-742d56dc.3.20.so)
12731 INFO: Looking for eggs
12731 INFO: Using Python library /home/dyson/.local/lib/libpython3.11.so.1.0
12736 INFO: Warnings written to /home/dyson/repos/lintrans/build/lintrans/warn-lintrans.txt
12770 INFO: Graph cross-reference written to /home/dyson/repos/lintrans/build/lintrans/xref-lintrans.html
12798 INFO: checking PYZ
12798 INFO: Building PYZ because PYZ-00.toc is non existent
12798 INFO: Building PYZ (ZlibArchive) /home/dyson/repos/lintrans/build/lintrans/PYZ-00.pyz
13312 INFO: Building PYZ (ZlibArchive) /home/dyson/repos/lintrans/build/lintrans/PYZ-00.pyz completed successfully.
13318 INFO: checking PKG
13318 INFO: Building PKG because PKG-00.toc is non existent
13318 INFO: Building PKG (CArchive) lintrans.pkg
63256 INFO: Building PKG (CArchive) lintrans.pkg completed successfully.
63260 INFO: Bootloader /home/dyson/repos/lintrans/venv/lib/python3.11/site-packages/PyInstaller/bootloader/Linux-64bit-intel/run
63260 INFO: checking EXE
63261 INFO: Building EXE because EXE-00.toc is non existent
63261 INFO: Building EXE from EXE-00.toc
63261 INFO: Copying bootloader EXE to /home/dyson/repos/lintrans/dist/lintrans
63261 INFO: Appending PKG archive to custom ELF section in EXE
64111 INFO: Building EXE from EXE-00.toc completed successfully.
Compilation finished
Auxiliary files cleaned up
```

Figure 4.1: The successful output of compilation

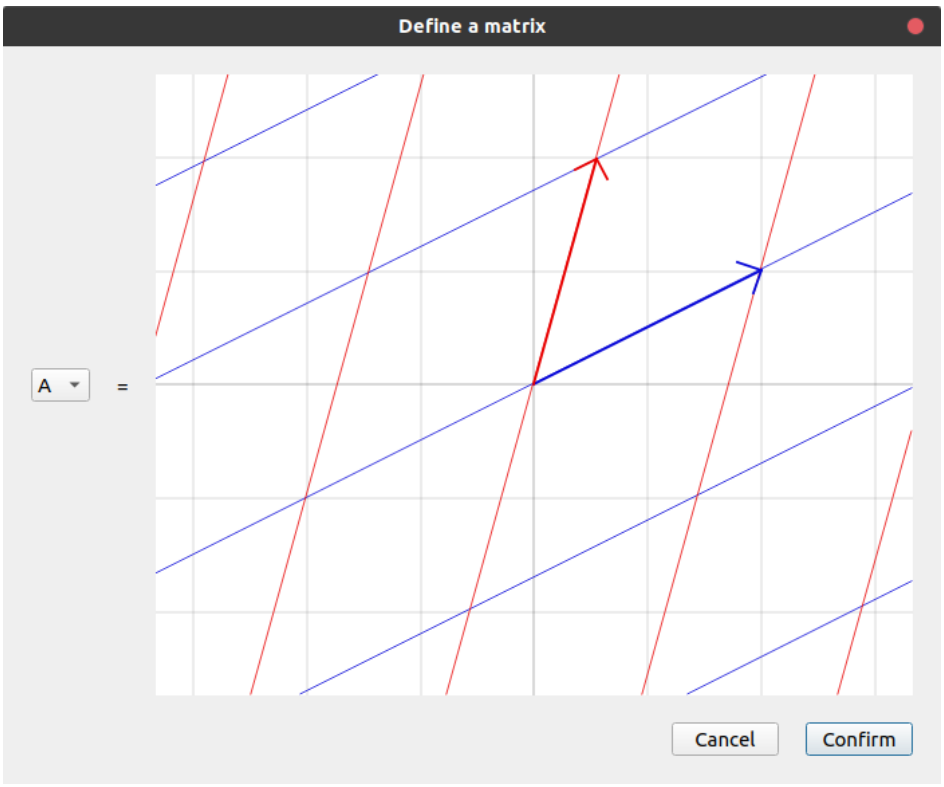


Figure 4.2: The matrix **A** being defined visually

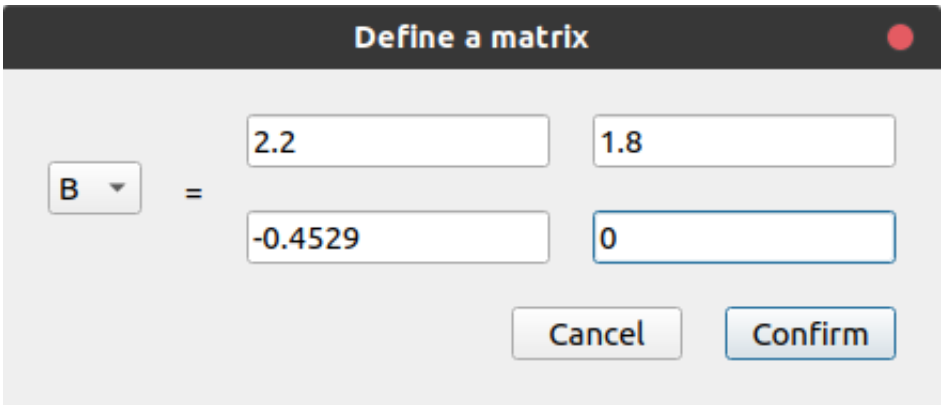


Figure 4.3: The matrix **B** being defined numerically

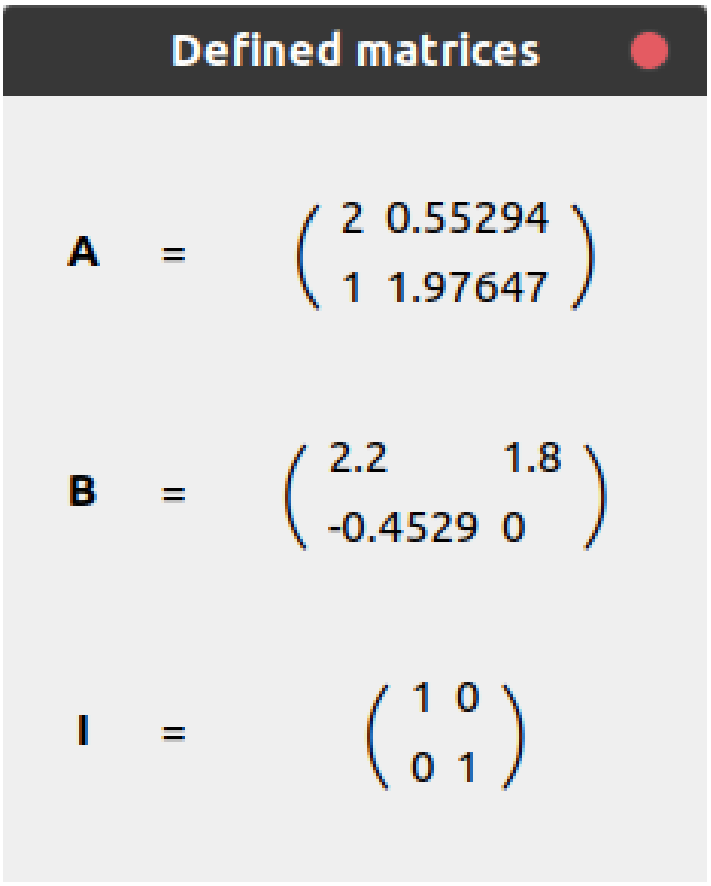


Figure 4.4: The info panel after defining matrices **A** and **B**

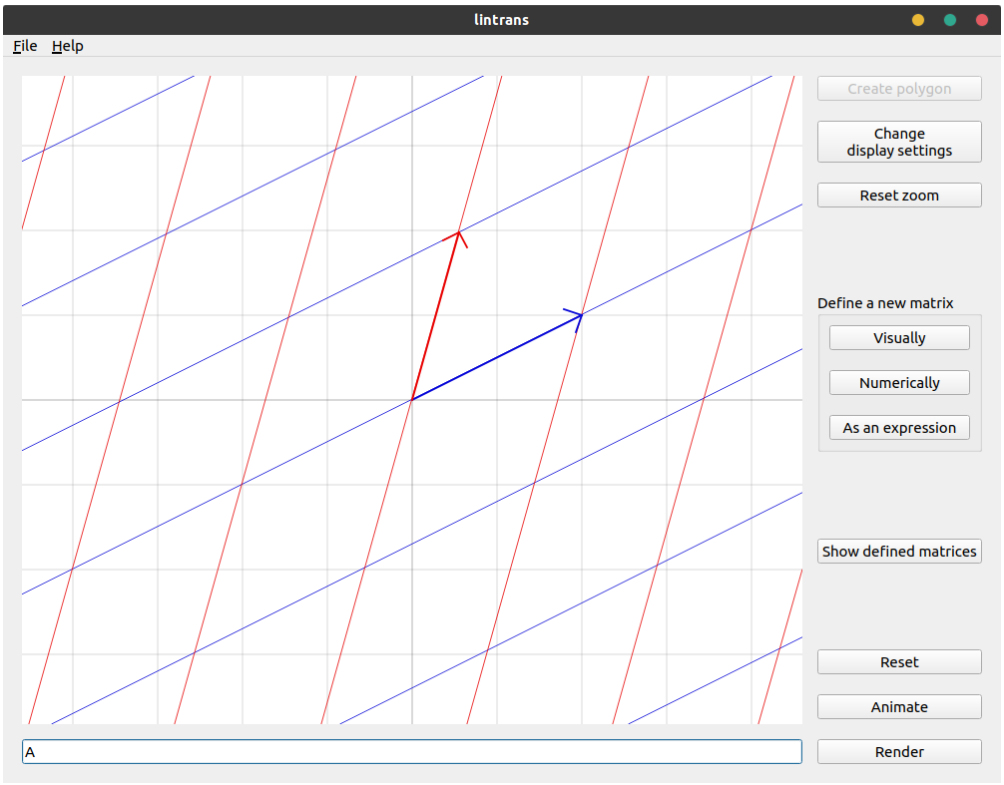


Figure 4.5: The matrix **A** being rendered

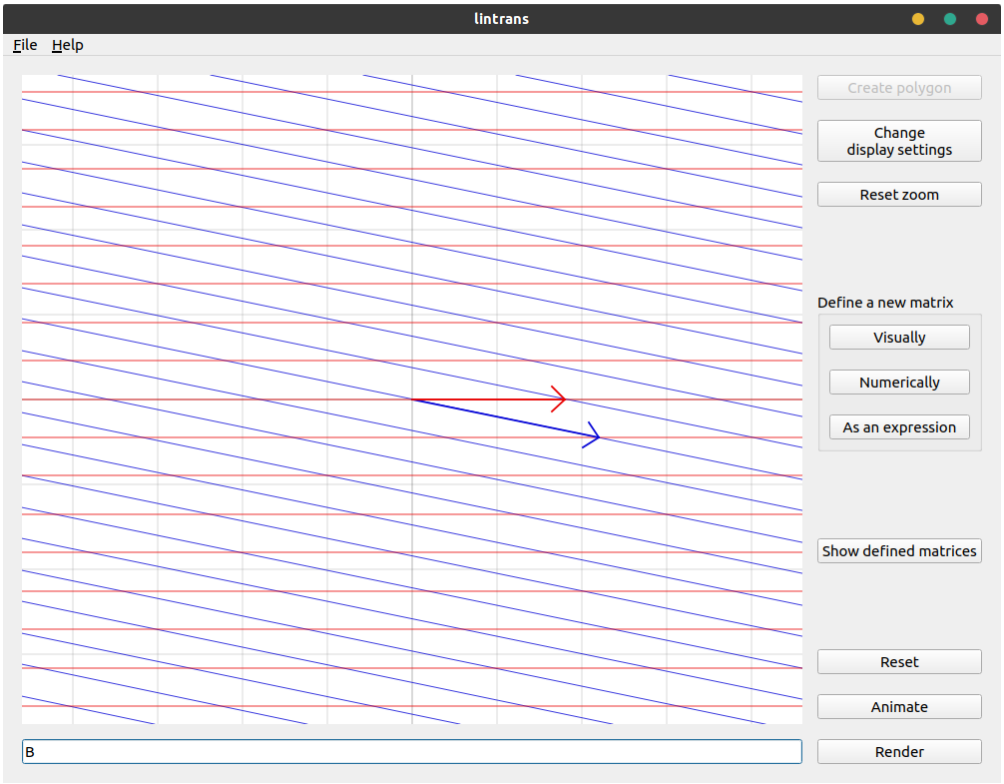


Figure 4.6: The matrix **B** being rendered

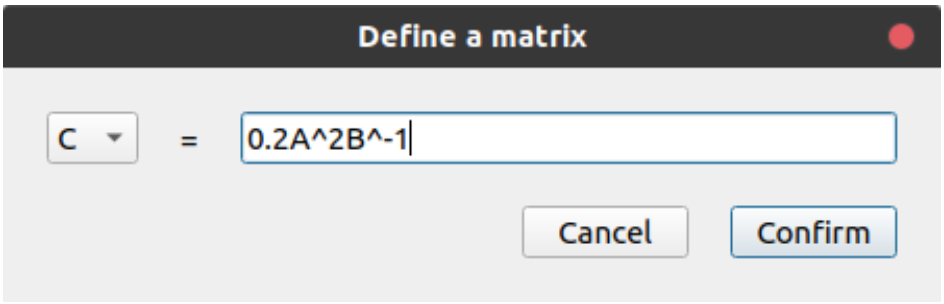


Figure 4.7: The expression matrix **C** being defined

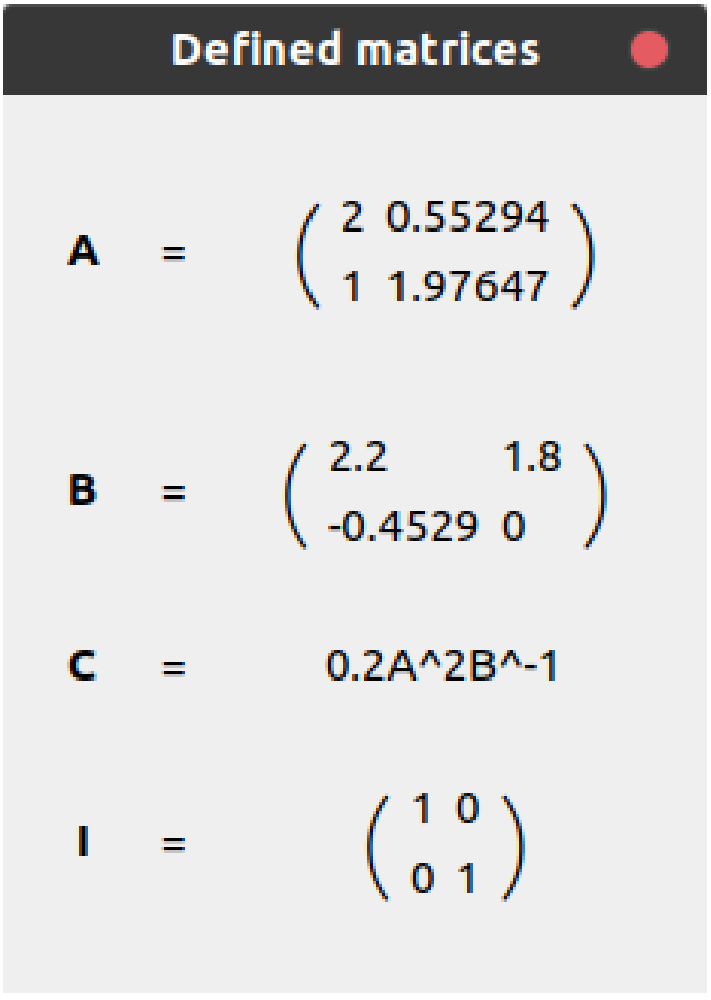


Figure 4.8: The info panel after defining the new matrix **C**

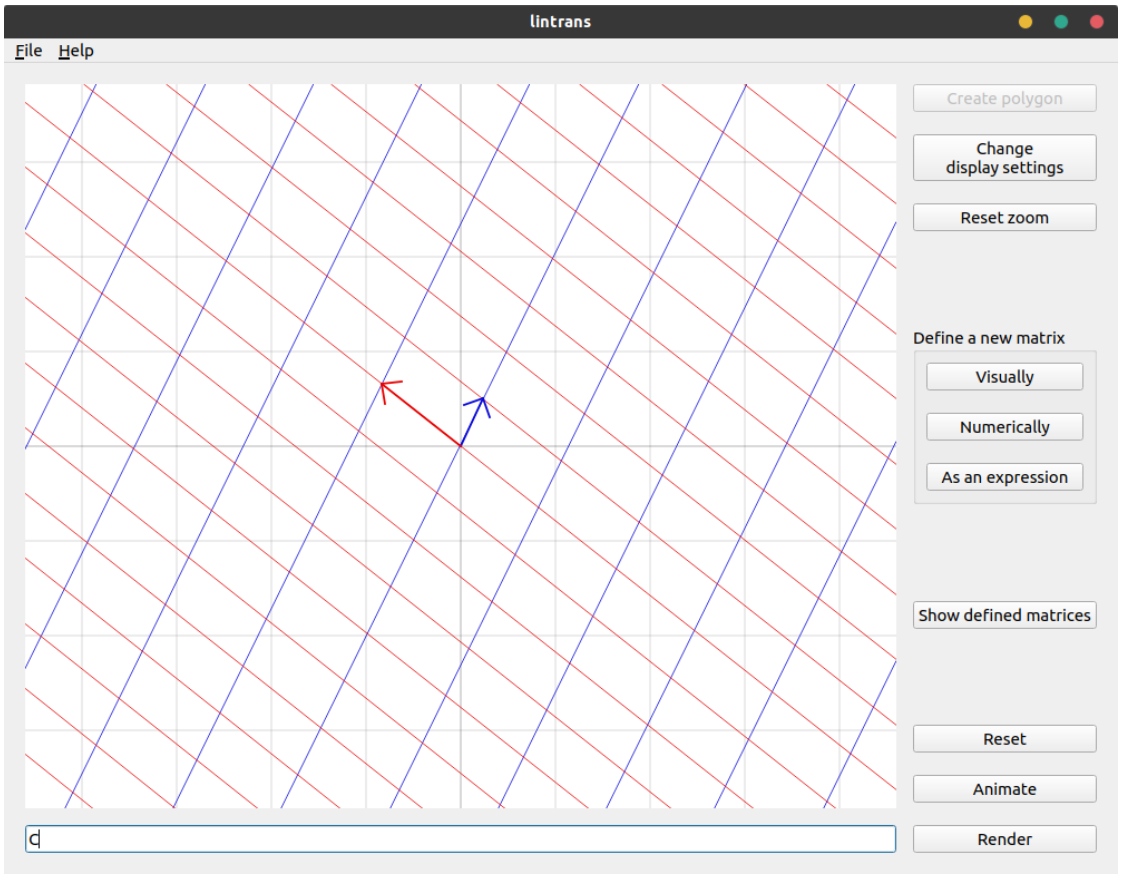


Figure 4.9: The matrix **C** being rendered

5 Evaluation

5.1 Evaluating success criteria

In §1.7, I laid out the success criteria for the project. It is now time to evaluate how well I met these criteria.

5.1.1 Defining multiple matrices

Criterion 1 says that the user must be able to define matrices in at least two different ways. I have been using these dialogs during development and they're quite useful. I would say I have completely fulfilled this criterion.

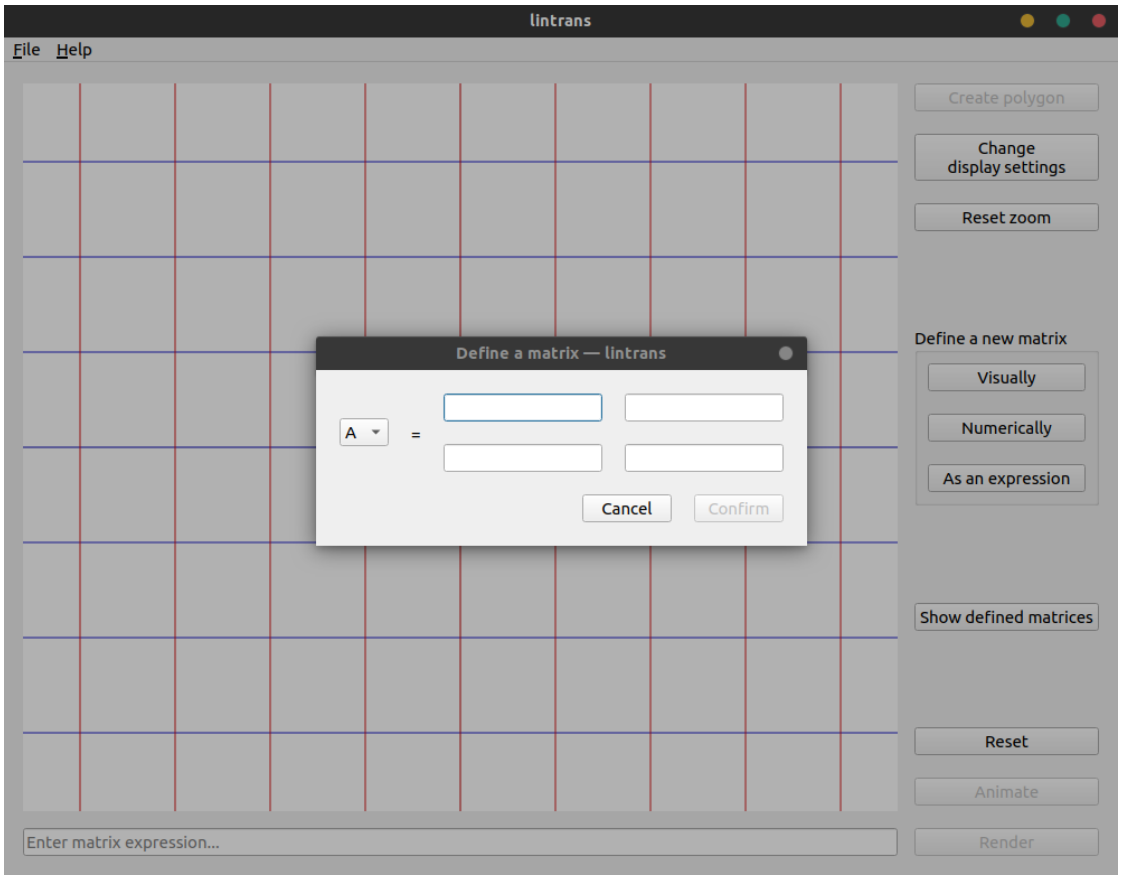


Figure 5.1.1: The numerical definition dialog

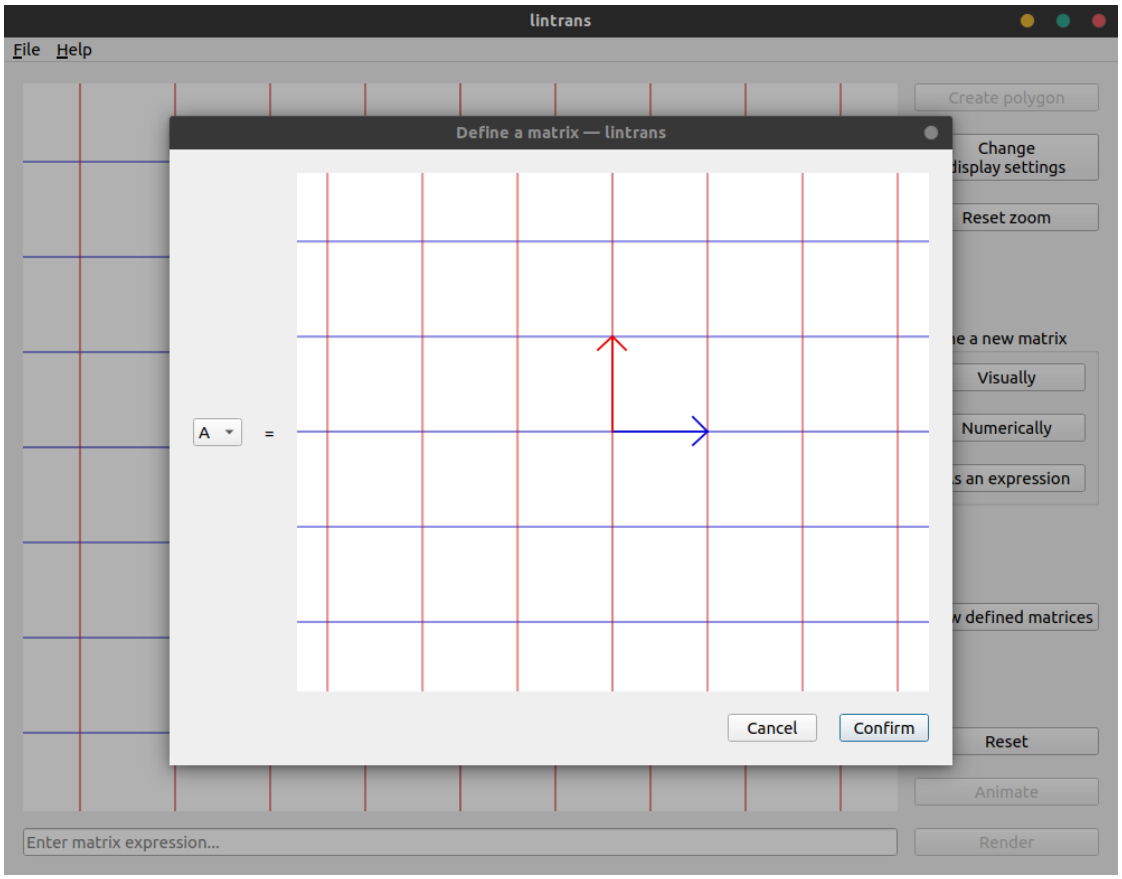


Figure 5.1.2: The visual definition dialog

5.1.2 Validating and parsing matrix expressions

Criterion 2 says that the program must be able to validate arbitrary matrix expressions and criterion 3 says that it must be able to parse any valid expression. As shown in §3.1.2, §3.1.4, and §3.10.7, the parser and validator are both complete and robust. I have fulfilled these success criteria.

5.1.3 Rendering any valid expression

Criterion 4 says that the program must be able to render any valid matrix expression. Rendering is quite simple and I got it sorted early on in §3.3.3 and §3.3.4. I have successfully fulfilled this criterion.

5.1.4 Animating any valid expression

Criterion 5 says that the program must be able to animate from **I** to any valid expression. I expected animation to be difficult but it was surprisingly easy. I just had to draw multiple frames using a `for` loop. I have covered animation in §3.3.5, §3.3.6, and §3.10.9. I have fulfilled this criterion.

5.1.5 Applicative animation

Criterion 6 says that the program must be able to apply a matrix transformation to the current scene. This is essentially the crux of the app. I was initially inspired to create `lintrans` because I wanted a way to demonstrate the non-commutativity of matrix multiplication ($\mathbf{AB} \neq \mathbf{BA}$). For me, the best

demonstration of this fact would be to show that applying two different matrices in different orders produces different results. Once I had the basis of an animation system, making it applicative wasn't as difficult as I expected.

I laid the groundwork for applicative animation in §3.4.9 and §3.4.10 and then I implemented applicative animation by just allowing the user to change the display settings in §3.5.1. I have fulfilled this criterion.

5.1.6 Display matrix info

Criterion 7 says that the program should be able to display information about the currently displayed matrix. I added display settings in §3.5 and these included things like determinants. I then polished determinant text in §3.6.8 and added eigenvectors and eigenlines in §3.7. I also added settings for animation timings in §3.5.1 and §3.10.10.

I'm quite happy with these display settings. I think being able to change colours and label the basis vectors i and j would have been nice, but I got the important parts done. I have fulfilled this criterion.

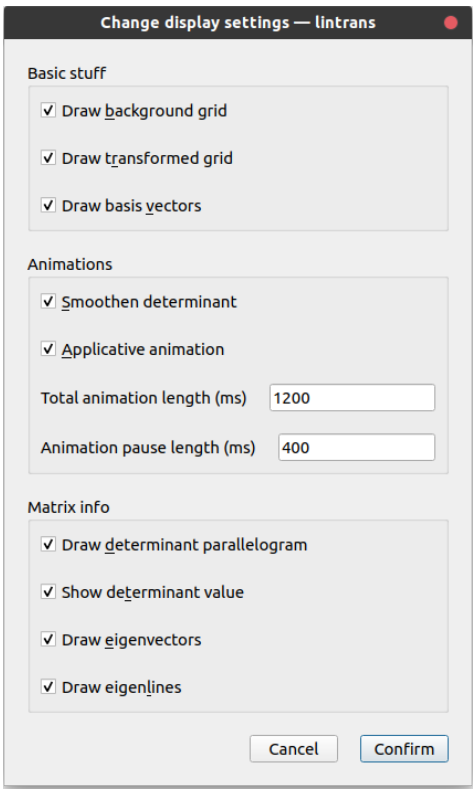


Figure 5.1.3: The display settings dialog

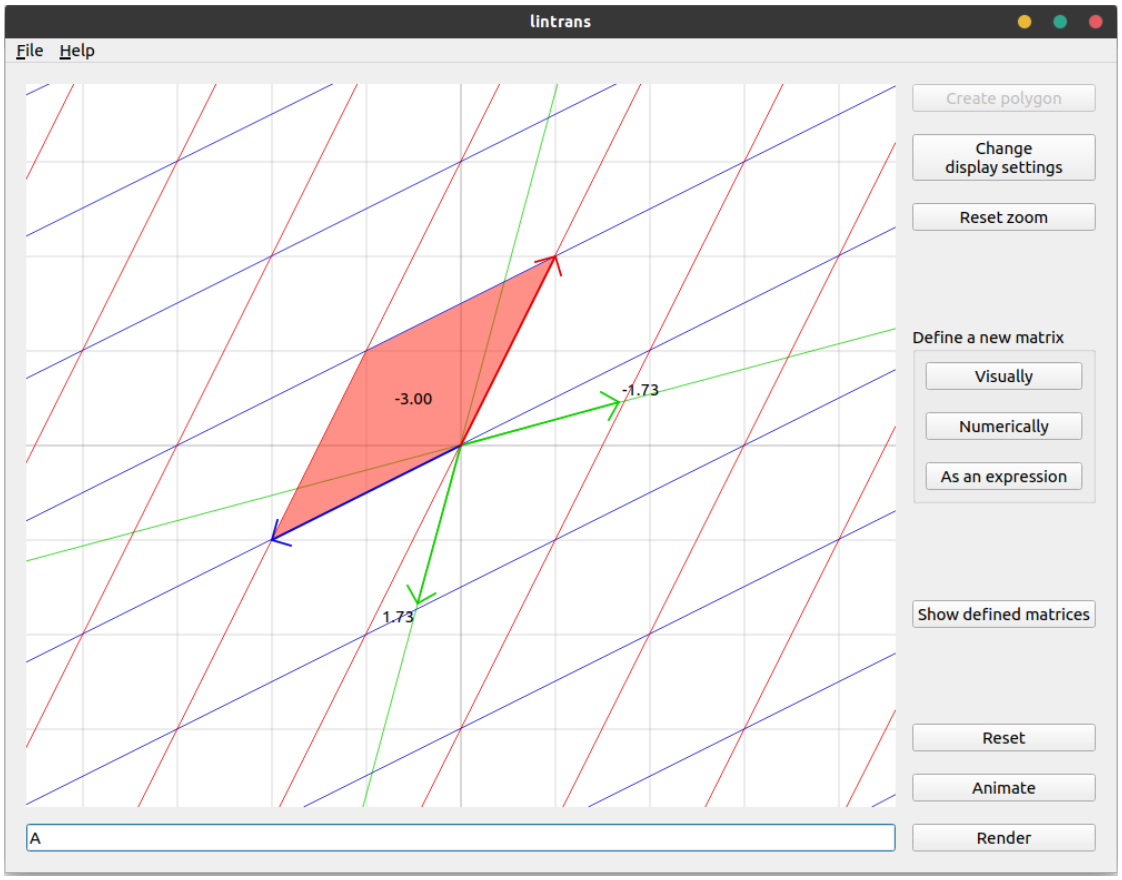


Figure 5.1.4: A matrix being rendered with all the display settings on

5.1.7 Saving and loading sessions

Criterion 8 says that the program should be able to save and load sessions. This was mostly a time restriction, but it shouldn't be particularly difficult to actually implement. I would create a dataclass to contain the data that we want to save, and use Python's `pickle` module to save it to a binary format for saving in a file. I failed to fulfil this criterion, mostly due to time.

5.1.8 Transforming polygons

Criterion 9 says that the program should allow the user to define and transform an arbitrary polygon. I was unable to complete this criterion. I'm not entirely sure how I would've done it. Obviously I'd have a dialog to define a polygon, and that would probably use a list of coordinates, which it would return to the main window when the user confirmed the dialog. Then I would just transform each coordinate one-by-one and draw the before and after versions. I failed to complete this criterion, again mostly due to running out of time.

Overall, I completed 7 out of my 9 criteria. I wish I'd had time to get the polygons done, and maybe I should've focussed on that instead of fixing bugs. But I'm happy with `lintrans` as it is now. I will probably add these missing features in a future release.

5.2 Assessing usability

The main usability features that I discussed in §2.4 were about colours, as well as layout and hotkeys.

The colours of the basis vectors are red and blue, as I said they should be. This allows users with common types of colour-blindness like deuteranopia to still distinguish parts of the UI. Refer to the images below to see that the colour scheme was a success[26]:

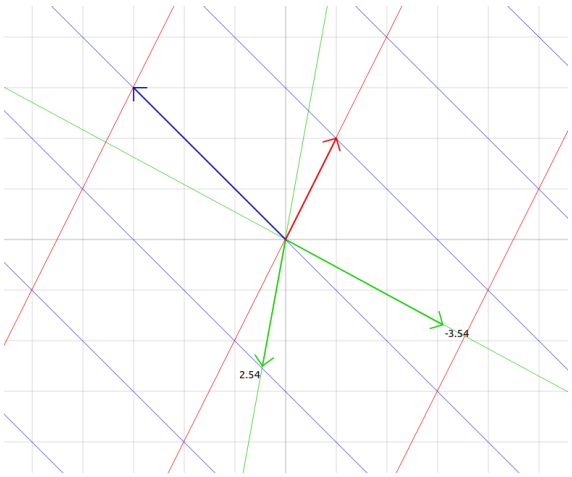


Figure 5.2.1: Normal vision

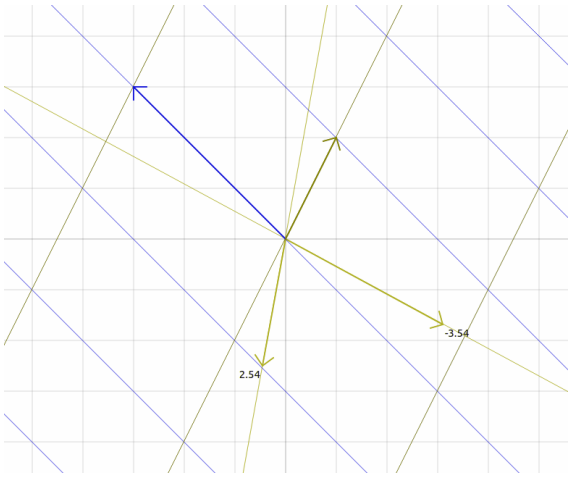


Figure 5.2.2: Deuteranopia (common)

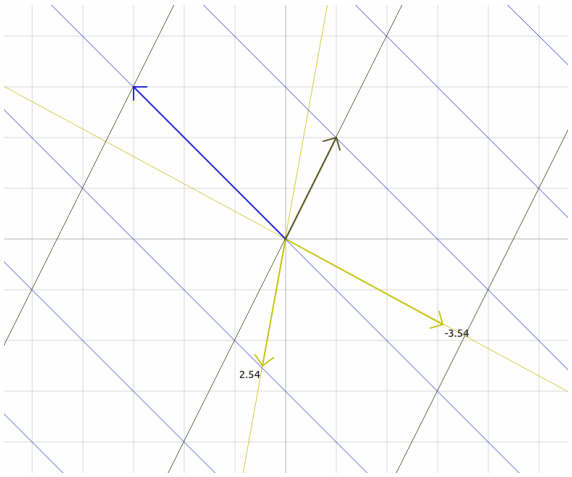


Figure 5.2.3: Protanopia (rare)

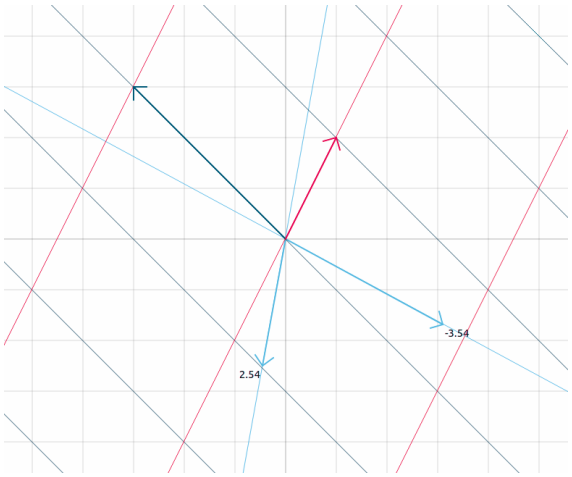


Figure 5.2.4: Tritanopia (very rare)

My other usability features were consistent UI layouts and hotkeys. All dialogs follow the same pattern of having the confirm button in the bottom right corner with the cancel button to the left of it, which is consistent with common menu design. I consider this a success.

Most of the functionality in the app has associated hotkeys. Rendering, animating, resetting, opening dialogs, and toggling display settings all have dedicated hotkeys. I forgot to add a shortcut to open the info panel, but that change is tiny, so I can just do it right now:

```
# 63f569328a1906976d725fa72da02e98e5d73afb
# src/lintrans/gui/main_window.py

39  class LintransMainWindow(QMainWindow):
...
45      def __init__(self):
...
208         self.button_info_panel.clicked.connect(
```

[26] These images were generated using my fork of Color Oracle[2].

```
209             # We have to use a lambda instead of 'InfoPanelDialog(self.matrix_wrapper, self).open' here
210             # because that would create an unnamed instance of InfoPanelDialog when LintransMainWindow is
211             # constructed, but we need to create a new instance every time to keep self.matrix_wrapper up to date
212             lambda: InfoPanelDialog(self.matrix_wrapper, self).open()
213         )
214         self.button_info_panel.setToolTip(
215             'Open an info panel with all matrices that have been defined in this session<br><b>(Ctrl + M)</b>'
216         )
217         QShortcut(QKeySequence('Ctrl+M'), self).activated.connect(self.button_info_panel.click)
```

I would consider my use of hotkeys to be a success.

5.3 Limitations

5.3.1 Feature completeness

As discussed in §5.1.7 and §5.1.8, `lintrans` is not feature complete according to my original success criteria. I attribute my failure to implement these features to me running out of time. If I focussed on implementing them instead of fixing bugs, then I definitely could've done them in time, but I wanted a more robust and bug-free app.

I think a more secure base allows for easier and more efficient expansion in the future. I can easily add these features in new versions, but I want to squash bugs early on so that I don't have to fix them later when the code base is larger. Overall, I wish I had more time to implement these missing features, but the core of the app is there, so I'll just add transforming arbitrary polygons and saving and loading sessions in the future.

5.3.2 Distribution

`lintrans` was surprisingly hard to distribute. I spend most of my time in the terminal, which makes it very easy to set up complete development environments and a virtual environment to manage the Python packages and interpreter needed to run `lintrans`. My stakeholders are teachers who don't even know what a shell is, let alone how to set up a virtual environment for Python. So I had to compile `lintrans` into a single Windows executable. That wasn't massively difficult, but it was certainly a headache. If I did this project again, I'd use a compiled language like Rust, Java, or C++, since those languages are much easier to distribute executables for.

Additionally, Rust can compile to WebAssembly[14], so I could make a web version of `lintrans`, which would avoid anyone having to download anything and would allow students to try it out very easily, perhaps even on their phones.

5.4 Maintenance

5.4.1 Class structure

As you can see from the following internal import graph and class diagram, the class structure isn't fantastic.

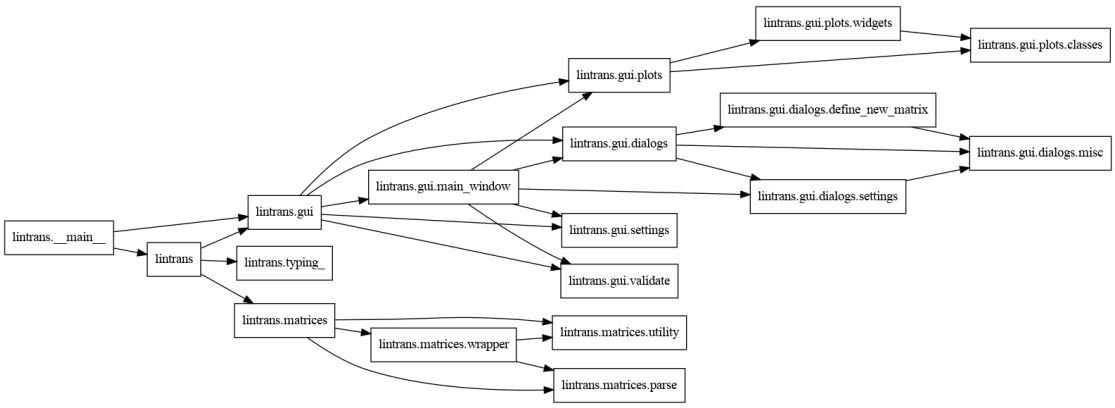


Figure 5.4.1: The final internal import graph

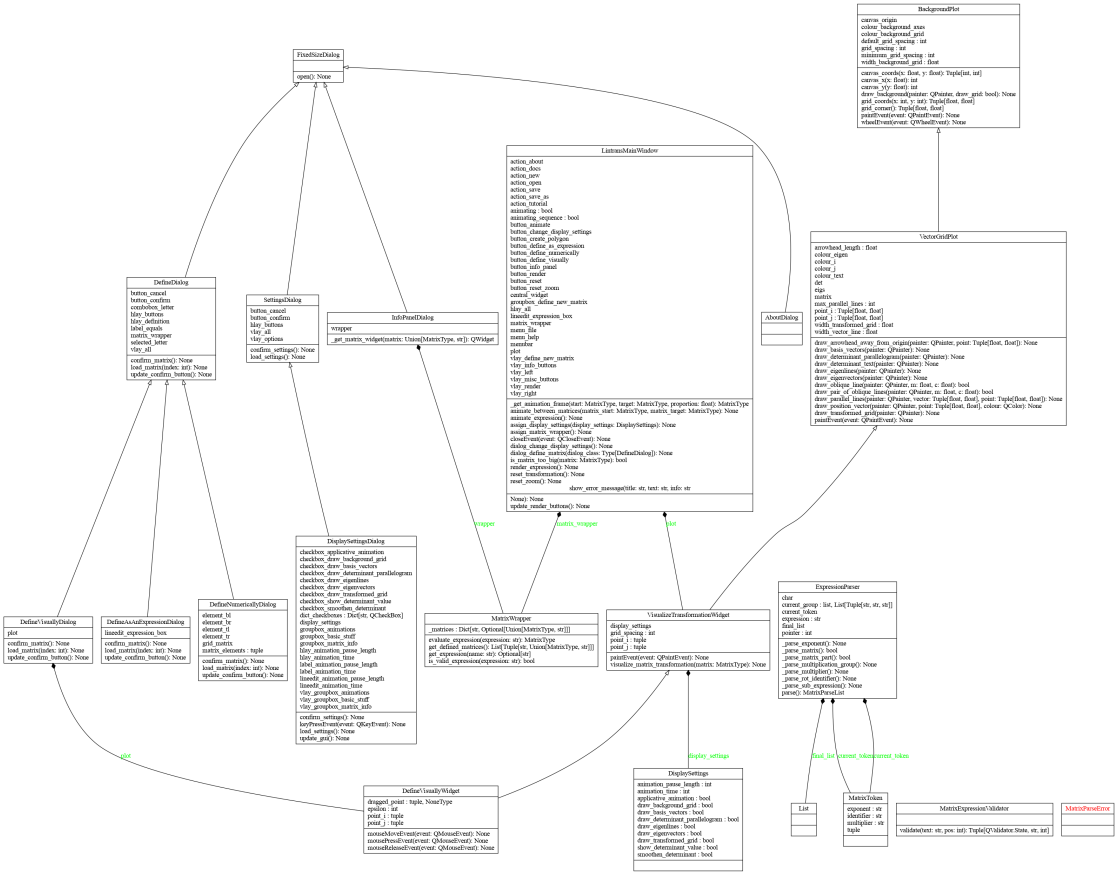


Figure 5.4.2: The final class diagram

However, I believe that the classes are well named and in files which are equally well named. This makes maintaining them easier than you might suspect by looking at these diagrams. Additionally, all my variables and functions have sensible names which identify their purpose. Each class, method, and function is small and individual. The only 'large' class is the main window, which makes sense because it has the most logic and is hard to split up.

Everything else is split into small enough logical chunks to make it pretty easy to maintain. I also have docstrings for every single class, method, and function, as well as comments to explain the complicated parts of algorithms. This annotation makes it much easier to remember what each thing does and how it does it.

Overall, there are a lot of classes and modules, but it's a complex program, so I think this is well justified. The logic is separate and modular.

5.4.2 Type safety

By far, my biggest maintainability problem is Python's lack of type safety. I use `mypy` to statically check the types of variables *before* runtime, but the Python interpreter makes no real guarantees about what the types of variables will be *at* runtime. This makes it much harder to debug things and introduces whole categories of bugs that would be impossible in a compiled, statically and strongly typed language like Rust, Java, or C++.

When I started `lintrans`, I didn't really care about types in a programming language and I was only really familiar with Python, so that's what I used. Since then, I've learned Rust and it's taught me the benefits of a static, strong type system. Rust doesn't even have `null` or exceptions. Python's `None` and hidden exception throwing have caused several bugs already and will undoubtedly cause many more in the future. With Rust, these would be impossible, but in Python, they are seemingly hiding in every dark corner, just waiting to crash the program in some weird edge case.

I will need to stay on top of these types of bugs when maintaining `lintrans`, unless I decide to rewrite the whole thing in a compiled language.

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A Project code

A.1 `__init__.py`

```
# lintrans - The linear transformation visualizer
# Copyright (C) 2021-2022 D. Dyson (DoctorDalek1963)

# This program is licensed under GNU GPLv3, available here:
# <https://www.gnu.org/licenses/gpl-3.0.html>

"""This is the top-level ``lintrans`` package, which contains all the subpackages of the project."""

from . import gui, matrices, typing_

__version__ = '0.3.0-alpha'

__all__ = ['gui', 'matrices', 'typing_', '__version__']
```

A.2 `__main__.py`

```
#!/usr/bin/env python

# lintrans - The linear transformation visualizer
# Copyright (C) 2021-2022 D. Dyson (DoctorDalek1963)

# This program is licensed under GNU GPLv3, available here:
# <https://www.gnu.org/licenses/gpl-3.0.html>

"""This module provides a :func:`main` function to interpret command line arguments and run the program."""

import sys
from argparse import ArgumentParser
from textwrap import dedent
from typing import List

from lintrans import __version__, gui


def main(args: List[str]) -> None:
    """Interpret program-specific command line arguments and run the main window in most cases.

    If the user supplies --help or --version, then we simply respond to that and then return.
    If they don't supply either of these, then we run :func:`lintrans.gui.main_window.main`.

    :param List[str] args: The full argument list (including program name)
    """
    parser = ArgumentParser(add_help=False)

    parser.add_argument(
        '-h',
        '--help',
        default=False,
        action='store_true'
    )

    parser.add_argument(
        '-V',
        '--version',
        default=False,
        action='store_true'
    )

    parsed_args, unparsed_args = parser.parse_known_args()

    if parsed_args.help:
        print(dedent('''
        Usage: lintrans [option]

```

```
        Options:
            -h, --help       Display this help text and exit
            -V, --version    Display the version information and exit

        Any other options will get passed to the QApplication constructor.
        If you don't know what that means, then don't provide any arguments and just the run the program.'''[1:]))
        return

    if parsed_args.version:
        print(dedent(f'''
        lintrans (version {__version__})
        The linear transformation visualizer

        Copyright (C) 2021-2022 D. Dyson (DoctorDalek1963)

        This program is licensed under GNU GPLv3, available here:
        <https://www.gnu.org/licenses/gpl-3.0.html>'''[1:]))
        return

    for arg in unparsed_args:
        print(f'Passing "{arg}" to QApplication. See --help for recognised args')

    gui.main(args[:1] + unparsed_args)


if __name__ == '__main__':
    main(sys.argv)
```

A.3 gui/__init__.py

```
# lintrans - The linear transformation visualizer
# Copyright (C) 2021-2022 D. Dyson (DoctorDalek1963)

# This program is licensed under GNU GPLv3, available here:
# <https://www.gnu.org/licenses/gpl-3.0.html>

"""This package supplies the main GUI and associated dialogs for visualization."""

from . import dialogs, plots, settings, validate
from .main_window import main

__all__ = ['dialogs', 'main', 'plots', 'settings', 'validate']
```

A.4 gui/main_window.py

```
# lintrans - The linear transformation visualizer
# Copyright (C) 2021-2022 D. Dyson (DoctorDalek1963)

# This program is licensed under GNU GPLv3, available here:
# <https://www.gnu.org/licenses/gpl-3.0.html>

"""This module provides the :class:`LintransMainWindow` class, which provides the main window for the GUI."""

from __future__ import annotations

import re
import sys
import webbrowser
from copy import deepcopy
from typing import List, Tuple, Type

import numpy as np
from numpy import linalg
from numpy.linalg import LinAlgError
from PyQt5 import QtWidgets
from PyQt5.QtCore import pyqtSlot, QCoreApplication, QThread
from PyQt5.QtGui import QCloseEvent, QKeySequence
from PyQt5.QtWidgets import (QApplication, QHBoxLayout, QMainWindow, QMessageBox,
```

```
                              QShortcut, QSizePolicy, QSpacerItem, QStyleFactory, QVBoxLayout)

import lintrans
from lintrans.matrices import MatrixWrapper
from lintrans.matrices.parse import validate_matrix_expression
from lintrans.matrices.utility import polar_coords, rotate_coord
from lintrans.typing_ import MatrixType, VectorType
from .dialogs import (AboutDialog, DefineAsAnExpressionDialog, DefineDialog,
                      DefineNumericallyDialog, DefineVisuallyDialog, InfoPanelDialog)
from .dialogs.settings import DisplaySettingsDialog
from .plots import VisualizeTransformationWidget
from .settings import DisplaySettings
from .validate import MatrixExpressionValidator


class LintransMainWindow(QMainWindow):
    """This class provides a main window for the GUI using the Qt framework.

    This class should not be used directly, instead call :func:`lintrans.gui.main_window.main` to create the GUI.
    """

    def __init__(self):
        """Create the main window object, and create and arrange every widget in it.

        This doesn't show the window, it just constructs it.
        Use :func:`lintrans.gui.main_window.main` to show the GUI.
        """
        super().__init__()

        self.matrix_wrapper = MatrixWrapper()

        self.setWindowTitle('lintrans')
        self.setMinimumSize(1000, 750)

        self.animating: bool = False
        self.animating_sequence: bool = False

        # === Create menubar

        self.menubar = QtWidgets.QMenuBar(self)

        self.menu_file = QtWidgets.QMenu(self.menubar)
        self.menu_file.setTitle('&File')

        self.menu_help = QtWidgets.QMenu(self.menubar)
        self.menu_help.setTitle('&Help')

        self.action_new = QtWidgets.QAction(self)
        self.action_new.setText('&New')
        self.action_new.setShortcut('Ctrl+N')
        self.action_new.triggered.connect(lambda: print('new'))

        self.action_open = QtWidgets.QAction(self)
        self.action_open.setText('&Open')
        self.action_open.setShortcut('Ctrl+O')
        self.action_open.triggered.connect(lambda: print('open'))

        self.action_save = QtWidgets.QAction(self)
        self.action_save.setText('&Save')
        self.action_save.setShortcut('Ctrl+S')
        self.action_save.triggered.connect(lambda: print('save'))

        self.action_save_as = QtWidgets.QAction(self)
        self.action_save_as.setText('Save as...')
        self.action_save_as.triggered.connect(lambda: print('save as'))

        self.action_tutorial = QtWidgets.QAction(self)
        self.action_tutorial.setText('&Tutorial')
        self.action_tutorial.setShortcut('F1')
        self.action_tutorial.triggered.connect(lambda: print('tutorial'))

        self.action_docs = QtWidgets.QAction(self)
        self.action_docs.setText('&Docs')
```

```
97
98              # If this is an old release, use the docs for this release. Else, use the latest docs
99              # We use the latest because most use cases for non-stable releases will be in development and testing
100             docs_link = 'https://lintrans.readthedocs.io/en/'
101
102             if re.match(r'^\d+\.\d+\.\d+$', lintrans.__version__):
103                 docs_link += 'v' + lintrans.__version__
104             else:
105                 docs_link += 'latest'
106
107             self.action_docs.triggered.connect(
108                 lambda: webbrowser.open_new_tab(docs_link)
109             )
110
111             self.action_about = QtWidgets.QAction(self)
112             self.action_about.setText('&About')
113             self.action_about.triggered.connect(lambda: AboutDialog(self).open())
114
115             # TODO: Implement these actions and enable them
116             self.action_new.setEnabled(False)
117             self.action_open.setEnabled(False)
118             self.action_save.setEnabled(False)
119             self.action_save_as.setEnabled(False)
120             self.action_tutorial.setEnabled(False)
121
122             self.menu_file.addAction(self.action_new)
123             self.menu_file.addAction(self.action_open)
124             self.menu_file.addSeparator()
125             self.menu_file.addAction(self.action_save)
126             self.menu_file.addAction(self.action_save_as)
127
128             self.menu_help.addAction(self.action_tutorial)
129             self.menu_help.addAction(self.action_docs)
130             self.menu_help.addSeparator()
131             self.menu_help.addAction(self.action_about)
132
133             self.menubar.addAction(self.menu_file.menuAction())
134             self.menubar.addAction(self.menu_help.menuAction())
135
136             self.setMenuBar(self.menubar)
137
138             # === Create widgets
139
140             # Left layout: the plot and input box
141
142             self.plot = VisualizeTransformationWidget(self, display_settings=DisplaySettings())
143
144             self.lineedit_expression_box = QtWidgets.QLineEdit(self)
145             self.lineedit_expression_box.setPlaceholderText('Enter matrix expression...')
146             self.lineedit_expression_box.setValidator(MatrixExpressionValidator(self))
147             self.lineedit_expression_box.textChanged.connect(self.update_render_buttons)
148
149             # Right layout: all the buttons
150
151             # Misc buttons
152
153             self.button_create_polygon = QtWidgets.QPushButton(self)
154             self.button_create_polygon.setText('Create polygon')
155             # self.button_create_polygon.clicked.connect(self.create_polygon)
156             self.button_create_polygon.setToolTip('Define a new polygon to view the transformation of')
157
158             # TODO: Implement this and enable button
159             self.button_create_polygon.setEnabled(False)
160
161             self.button_change_display_settings = QtWidgets.QPushButton(self)
162             self.button_change_display_settings.setText('Change\ndisplay settings')
163             self.button_change_display_settings.clicked.connect(self.dialog_change_display_settings)
164             self.button_change_display_settings.setToolTip(
165                 "Change which things are rendered and how they're rendered<br><b>(Ctrl + D)</b>"
166             )
167             QShortcut(QKeySequence('Ctrl+D'), self).activated.connect(self.button_change_display_settings.click)
168
169             self.button_reset_zoom = QtWidgets.QPushButton(self)
```

```
170             self.button_reset_zoom.setText('Reset zoom')
171             self.button_reset_zoom.clicked.connect(self.reset_zoom)
172             self.button_reset_zoom.setToolTip('Reset the zoom level back to normal<br><b>(Ctrl + Shift + R)</b>')
173             QShortcut(QKeySequence('Ctrl+Shift+R'), self).activated.connect(self.button_reset_zoom.click)
174
175             # Define new matrix buttons and their groupbox
176
177             self.button_define_visually = QtWidgets.QPushButton(self)
178             self.button_define_visually.setText('Visually')
179             self.button_define_visually.setToolTip('Drag the basis vectors<br><b>(Alt + 1)</b>')
180             self.button_define_visually.clicked.connect(lambda: self.dialog_define_matrix(DefineVisuallyDialog))
181             QShortcut(QKeySequence('Alt+1'), self).activated.connect(self.button_define_visually.click)
182
183             self.button_define_numerically = QtWidgets.QPushButton(self)
184             self.button_define_numerically.setText('Numerically')
185             self.button_define_numerically.setToolTip('Define a matrix just with numbers<br><b>(Alt + 2)</b>')
186             self.button_define_numerically.clicked.connect(lambda: self.dialog_define_matrix(DefineNumericallyDialog))
187             QShortcut(QKeySequence('Alt+2'), self).activated.connect(self.button_define_numerically.click)
188
189             self.button_define_as_expression = QtWidgets.QPushButton(self)
190             self.button_define_as_expression.setText('As an expression')
191             self.button_define_as_expression.setToolTip('Define a matrix in terms of other matrices<br><b>(Alt +
                ↪  3)</b>')
192             self.button_define_as_expression.clicked.connect(lambda:
                ↪  self.dialog_define_matrix(DefineAsAnExpressionDialog))
193             QShortcut(QKeySequence('Alt+3'), self).activated.connect(self.button_define_as_expression.click)
194
195             self.vlay_define_new_matrix = QVBoxLayout()
196             self.vlay_define_new_matrix.setSpacing(20)
197             self.vlay_define_new_matrix.addWidget(self.button_define_visually)
198             self.vlay_define_new_matrix.addWidget(self.button_define_numerically)
199             self.vlay_define_new_matrix.addWidget(self.button_define_as_expression)
200
201             self.groupbox_define_new_matrix = QtWidgets.QGroupBox('Define a new matrix', self)
202             self.groupbox_define_new_matrix.setLayout(self.vlay_define_new_matrix)
203
204             # Info panel button
205
206             self.button_info_panel = QtWidgets.QPushButton(self)
207             self.button_info_panel.setText('Show defined matrices')
208             self.button_info_panel.clicked.connect(
209                 # We have to use a lambda instead of 'InfoPanelDialog(self.matrix_wrapper, self).open' here
210                 # because that would create an unnamed instance of InfoPanelDialog when LintransMainWindow is
211                 # constructed, but we need to create a new instance every time to keep self.matrix_wrapper up to date
212                 lambda: InfoPanelDialog(self.matrix_wrapper, self).open()
213             )
214             self.button_info_panel.setToolTip(
215                 'Open an info panel with all matrices that have been defined in this session<br><b>(Ctrl + M)</b>'
216             )
217             QShortcut(QKeySequence('Ctrl+M'), self).activated.connect(self.button_info_panel.click)
218
219             # Render buttons
220
221             self.button_reset = QtWidgets.QPushButton(self)
222             self.button_reset.setText('Reset')
223             self.button_reset.clicked.connect(self.reset_transformation)
224             self.button_reset.setToolTip('Reset the visualized transformation back to the identity<br><b>(Ctrl +
                ↪  R)</b>')
225             QShortcut(QKeySequence('Ctrl+R'), self).activated.connect(self.button_reset.click)
226
227             self.button_render = QtWidgets.QPushButton(self)
228             self.button_render.setText('Render')
229             self.button_render.setEnabled(False)
230             self.button_render.clicked.connect(self.render_expression)
231             self.button_render.setToolTip('Render the expression<br><b>(Ctrl + Enter)</b>')
232             QShortcut(QKeySequence('Ctrl+Return'), self).activated.connect(self.button_render.click)
233
234             self.button_animate = QtWidgets.QPushButton(self)
235             self.button_animate.setText('Animate')
236             self.button_animate.setEnabled(False)
237             self.button_animate.clicked.connect(self.animate_expression)
238             self.button_animate.setToolTip('Animate the expression<br><b>(Ctrl + Shift + Enter)</b>')
239             QShortcut(QKeySequence('Ctrl+Shift+Return'), self).activated.connect(self.button_animate.click)
```

```
240
241             # === Arrange widgets
242
243             self.vlay_left = QVBoxLayout()
244             self.vlay_left.addWidget(self.plot)
245             self.vlay_left.addWidget(self.lineedit_expression_box)
246
247             self.vlay_misc_buttons = QVBoxLayout()
248             self.vlay_misc_buttons.setSpacing(20)
249             self.vlay_misc_buttons.addWidget(self.button_create_polygon)
250             self.vlay_misc_buttons.addWidget(self.button_change_display_settings)
251             self.vlay_misc_buttons.addWidget(self.button_reset_zoom)
252
253             self.vlay_info_buttons = QVBoxLayout()
254             self.vlay_info_buttons.setSpacing(20)
255             self.vlay_info_buttons.addWidget(self.button_info_panel)
256
257             self.vlay_render = QVBoxLayout()
258             self.vlay_render.setSpacing(20)
259             self.vlay_render.addWidget(self.button_reset)
260             self.vlay_render.addWidget(self.button_animate)
261             self.vlay_render.addWidget(self.button_render)
262
263             self.vlay_right = QVBoxLayout()
264             self.vlay_right.setSpacing(50)
265             self.vlay_right.addLayout(self.vlay_misc_buttons)
266             self.vlay_right.addItem(QSpacerItem(100, 2, hPolicy=QSizePolicy.Minimum, vPolicy=QSizePolicy.Expanding))
267             self.vlay_right.addWidget(self.groupbox_define_new_matrix)
268             self.vlay_right.addItem(QSpacerItem(100, 2, hPolicy=QSizePolicy.Minimum, vPolicy=QSizePolicy.Expanding))
269             self.vlay_right.addLayout(self.vlay_info_buttons)
270             self.vlay_right.addItem(QSpacerItem(100, 2, hPolicy=QSizePolicy.Minimum, vPolicy=QSizePolicy.Expanding))
271             self.vlay_right.addLayout(self.vlay_render)
272
273             self.hlay_all = QHBoxLayout()
274             self.hlay_all.setSpacing(15)
275             self.hlay_all.addLayout(self.vlay_left)
276             self.hlay_all.addLayout(self.vlay_right)
277
278             self.central_widget = QtWidgets.QWidget()
279             self.central_widget.setLayout(self.hlay_all)
280             self.central_widget.setContentsMargins(10, 10, 10, 10)
281
282             self.setCentralWidget(self.central_widget)
283
284         def closeEvent(self, event: QCloseEvent) -> None:
285             """Handle a :class:`QCloseEvent` by cancelling animation first."""
286             self.animating = False
287             event.accept()
288
289         def update_render_buttons(self) -> None:
290             """Enable or disable the render and animate buttons according to whether the matrix expression is valid."""
291             text = self.lineedit_expression_box.text()
292
293             # Let's say that the user defines a non-singular matrix A, then defines B as A^-1
294             # If they then redefine A and make it singular, then we get a LinAlgError when
295             # trying to evaluate an expression with B in it
296             # To fix this, we just do naive validation rather than aware validation
297             if ',' in text:
298                 self.button_render.setEnabled(False)
299
300                 try:
301                     valid = all(self.matrix_wrapper.is_valid_expression(x) for x in text.split(','))
302                 except LinAlgError:
303                     valid = all(validate_matrix_expression(x) for x in text.split(','))
304
305                 self.button_animate.setEnabled(valid)
306
307             else:
308                 try:
309                     valid = self.matrix_wrapper.is_valid_expression(text)
310                 except LinAlgError:
311                     valid = validate_matrix_expression(text)
312
```

```
313                 self.button_render.setEnabled(valid)
314                 self.button_animate.setEnabled(valid)
315
316         @pyqtSlot()
317         def reset_zoom(self) -> None:
318             """Reset the zoom level back to normal."""
319             self.plot.grid_spacing = self.plot.default_grid_spacing
320             self.plot.update()
321
322         @pyqtSlot()
323         def reset_transformation(self) -> None:
324             """Reset the visualized transformation back to the identity."""
325             self.plot.visualize_matrix_transformation(self.matrix_wrapper['I'])
326             self.animating = False
327             self.animating_sequence = False
328             self.plot.update()
329
330         @pyqtSlot()
331         def render_expression(self) -> None:
332             """Render the transformation given by the expression in the input box."""
333             try:
334                 matrix = self.matrix_wrapper.evaluate_expression(self.lineedit_expression_box.text())
335
336             except LinAlgError:
337                 self.show_error_message('Singular matrix', 'Cannot take inverse of singular matrix')
338                 return
339
340             if self.is_matrix_too_big(matrix):
341                 self.show_error_message('Matrix too big', "This matrix doesn't fit on the canvas")
342                 return
343
344             self.plot.visualize_matrix_transformation(matrix)
345             self.plot.update()
346
347         @pyqtSlot()
348         def animate_expression(self) -> None:
349             """Animate from the current matrix to the matrix in the expression box."""
350             self.button_render.setEnabled(False)
351             self.button_animate.setEnabled(False)
352
353             matrix_start: MatrixType = np.array([
354                 [self.plot.point_i[0], self.plot.point_j[0]],
355                 [self.plot.point_i[1], self.plot.point_j[1]]
356             ])
357
358             text = self.lineedit_expression_box.text()
359
360             # If there's commas in the expression, then we want to animate each part at a time
361             if ',' in text:
362                 current_matrix = matrix_start
363                 self.animating_sequence = True
364
365                 # For each expression in the list, right multiply it by the current matrix,
366                 # and animate from the current matrix to that new matrix
367                 for expr in text.split(',')[::-1]:
368                     try:
369                         new_matrix = self.matrix_wrapper.evaluate_expression(expr)
370
371                         if self.plot.display_settings.applicative_animation:
372                             new_matrix = new_matrix @ current_matrix
373                     except LinAlgError:
374                         self.show_error_message('Singular matrix', 'Cannot take inverse of singular matrix')
375                         return
376
377                     if not self.animating_sequence:
378                         break
379
380                     self.animate_between_matrices(current_matrix, new_matrix)
381                     current_matrix = new_matrix
382
383                     # Here we just redraw and allow for other events to be handled while we pause
384                     self.plot.update()
385                     QApplication.processEvents()
```

```
                QThread.msleep(self.plot.display_settings.animation_pause_length)

            self.animating_sequence = False

        # If there's no commas, then just animate directly from the start to the target
        else:
            # Get the target matrix and it's determinant
            try:
                matrix_target = self.matrix_wrapper.evaluate_expression(text)

            except LinAlgError:
                self.show_error_message('Singular matrix', 'Cannot take inverse of singular matrix')
                return

            # The concept of applicative animation is explained in /gui/settings.py
            if self.plot.display_settings.applicative_animation:
                matrix_target = matrix_target @ matrix_start

            # If we want a transitional animation and we're animating the same matrix, then restart the animation
            # We use this check rather than equality because of small floating point errors
            elif (abs(matrix_start - matrix_target) < 1e-12).all():
                matrix_start = self.matrix_wrapper['I']

                # We pause here for 200 ms to make the animation look a bit nicer
                self.plot.visualize_matrix_transformation(matrix_start)
                self.plot.update()
                QApplication.processEvents()
                QThread.msleep(200)

            self.animate_between_matrices(matrix_start, matrix_target)

        self.update_render_buttons()

    def _get_animation_frame(self, start: MatrixType, target: MatrixType, proportion: float) -> MatrixType:
        """Get the matrix to render for this frame of the animation.

        This method will smoothen the determinant if that setting in enabled and if the determinant is positive.
        It also animates rotation-like matrices using a logarithmic spiral to rotate around and scale continuously.
        Essentially, it just makes things look good when animating.

        :param MatrixType start: The starting matrix
        :param MatrixType start: The target matrix
        :param float proportion: How far we are through the loop
        """
        det_target = linalg.det(target)
        det_start = linalg.det(start)

        # This is the matrix that we're applying to get from start to target
        # We want to check if it's rotation-like
        if linalg.det(start) == 0:
            matrix_application = None
        else:
            matrix_application = target @ linalg.inv(start)

        # For a matrix to represent a rotation, it must have a positive determinant,
        # its vectors must be perpendicular, and its vectors must be the same length
        # The checks for 'abs(value) < 1e-10' are to account for floating point error
        if matrix_application is not None \
                and self.plot.display_settings.smoothen_determinant \
                and linalg.det(matrix_application) > 0 \
                and abs(np.dot(matrix_application.T[0], matrix_application.T[1])) < 1e-10 \
                and abs(np.hypot(*matrix_application.T[0]) - np.hypot(*matrix_application.T[1])) < 1e-10:
            rotation_vector: VectorType = matrix_application.T[0]  # Take the i column
            radius, angle = polar_coords(*rotation_vector)

            # We want the angle to be in [-pi, pi), so we have to subtract 2pi from it if it's too big
            if angle > np.pi:
                angle -= 2 * np.pi

            i: VectorType = start.T[0]
            j: VectorType = start.T[1]

            # Scale the coords with a list comprehension
```

```
            # It's a bit janky, but rotate_coords() will always return a 2-tuple,
            # so new_i and new_j will always be lists of length 2
            scale = (radius - 1) * proportion + 1
            new_i = [scale * c for c in rotate_coord(i[0], i[1], angle * proportion)]
            new_j = [scale * c for c in rotate_coord(j[0], j[1], angle * proportion)]

            return np.array(
                [
                    [new_i[0], new_j[0]],
                    [new_i[1], new_j[1]]
                ]
            )

        # matrix_a is the start matrix plus some part of the target, scaled by the proportion
        # If we just used matrix_a, then things would animate, but the determinants would be weird
        matrix_a = start + proportion * (target - start)

        if not self.plot.display_settings.smoothen_determinant or det_start * det_target <= 0:
            return matrix_a

        # To fix the determinant problem, we get the determinant of matrix_a and use it to normalize
        det_a = linalg.det(matrix_a)

        # For a 2x2 matrix A and a scalar c, we know that det(cA) = c^2 det(A)
        # We want B = cA such that det(B) = det(S), where S is the start matrix,
        # so then we can scale it with the animation, so we get
        # det(cA) = c^2 det(A) = det(S) => c = sqrt(abs(det(S) / det(A)))
        # Then we scale A to get the determinant we want, and call that matrix_b
        if det_a == 0:
            c = 0
        else:
            c = np.sqrt(abs(det_start / det_a))

        matrix_b = c * matrix_a
        det_b = linalg.det(matrix_b)

        # We want to return B, but we have to scale it over time to have the target determinant

        # We want some C = dB such that det(C) is some target determinant T
        # det(dB) = d^2 det(B) = T => d = sqrt(abs(T / det(B))

        # We're also subtracting 1 and multiplying by the proportion and then adding one
        # This just scales the determinant along with the animation

        # That is all of course, if we can do that
        # We'll crash if we try to do this with det(B) == 0
        if det_b == 0:
            return matrix_a

        scalar = 1 + proportion * (np.sqrt(abs(det_target / det_b)) - 1)
        return scalar * matrix_b

    def animate_between_matrices(self, matrix_start: MatrixType, matrix_target: MatrixType) -> None:
        """Animate from the start matrix to the target matrix."""
        self.animating = True

        # Making steps depend on animation_time ensures a smooth animation without
        # massive overheads for small animation times
        steps = self.plot.display_settings.animation_time // 10

        for i in range(0, steps + 1):
            if not self.animating:
                break

            matrix_to_render = self._get_animation_frame(matrix_start, matrix_target, i / steps)

            if self.is_matrix_too_big(matrix_to_render):
                self.show_error_message('Matrix too big', "This matrix doesn't fit on the canvas")
                self.animating = False
                return

            self.plot.visualize_matrix_transformation(matrix_to_render)

```

```
532                 # We schedule the plot to be updated, tell the event loop to
533                 # process events, and asynchronously sleep for 10ms
534                 # This allows for other events to be processed while animating, like zooming in and out
535                 self.plot.update()
536                 QApplication.processEvents()
537                 QThread.msleep(self.plot.display_settings.animation_time // steps)
538 
539             self.animating = False
540 
541         @pyqtSlot(DefineDialog)
542         def dialog_define_matrix(self, dialog_class: Type[DefineDialog]) -> None:
543             """Open a generic definition dialog to define a new matrix.
544 
545             The class for the desired dialog is passed as an argument. We create an
546             instance of this class and the dialog is opened asynchronously and modally
547             (meaning it blocks interaction with the main window) with the proper method
548             connected to the :meth:`QDialog.accepted` signal.
549 
550             .. note:: ``dialog_class`` must subclass :class:`lintrans.gui.dialogs.define_new_matrix.DefineDialog`.
551 
552             :param dialog_class: The dialog class to instantiate
553             :type dialog_class: Type[lintrans.gui.dialogs.define_new_matrix.DefineDialog]
554             """
555             # We create a dialog with a deepcopy of the current matrix_wrapper
556             # This avoids the dialog mutating this one
557             dialog: DefineDialog
558 
559             if dialog_class == DefineVisuallyDialog:
560                 dialog = DefineVisuallyDialog(
561                     self,
562                     matrix_wrapper=deepcopy(self.matrix_wrapper),
563                     display_settings=self.plot.display_settings
564                 )
565             else:
566                 dialog = dialog_class(self, matrix_wrapper=deepcopy(self.matrix_wrapper))
567 
568             # .open() is asynchronous and doesn't spawn a new event loop, but the dialog is still modal (blocking)
569             dialog.open()
570 
571             # So we have to use the accepted signal to call a method when the user accepts the dialog
572             dialog.accepted.connect(self.assign_matrix_wrapper)
573 
574         @pyqtSlot()
575         def assign_matrix_wrapper(self) -> None:
576             """Assign a new value to ``self.matrix_wrapper`` and give the expression box focus."""
577             self.matrix_wrapper = self.sender().matrix_wrapper
578             self.lineedit_expression_box.setFocus()
579             self.update_render_buttons()
580 
581         @pyqtSlot()
582         def dialog_change_display_settings(self) -> None:
583             """Open the dialog to change the display settings."""
584             dialog = DisplaySettingsDialog(self, display_settings=self.plot.display_settings)
585             dialog.open()
586             dialog.accepted.connect(lambda: self.assign_display_settings(dialog.display_settings))
587 
588         @pyqtSlot(DisplaySettings)
589         def assign_display_settings(self, display_settings: DisplaySettings) -> None:
590             """Assign a new value to ``self.plot.display_settings`` and give the expression box focus."""
591             self.plot.display_settings = display_settings
592             self.plot.update()
593             self.lineedit_expression_box.setFocus()
594             self.update_render_buttons()
595 
596         def show_error_message(self, title: str, text: str, info: str | None = None) -> None:
597             """Show an error message in a dialog box.
598 
599             :param str title: The window title of the dialog box
600             :param str text: The simple error message
601             :param info: The more informative error message
602             :type info: Optional[str]
603             """
604             dialog = QMessageBox(self)
```

```
605             dialog.setIcon(QMessageBox.Critical)
606             dialog.setWindowTitle(title)
607             dialog.setText(text)
608
609             if info is not None:
610                 dialog.setInformativeText(info)
611
612             dialog.open()
613
614             # This is `finished` rather than `accepted` because we want to update the buttons no matter what
615             dialog.finished.connect(self.update_render_buttons)
616
617         def is_matrix_too_big(self, matrix: MatrixType) -> bool:
618             """Check if the given matrix will actually fit onto the canvas.
619
620             Convert the elements of the matrix to canvas coords and make sure they fit within Qt's 32-bit integer limit.
621
622             :param MatrixType matrix: The matrix to check
623             :returns bool: Whether the matrix is too big to fit on the canvas
624             """
625             coords: List[Tuple[int, int]] = [self.plot.canvas_coords(*vector) for vector in matrix.T]
626
627             for x, y in coords:
628                 if not (-2147483648 <= x <= 2147483647 and -2147483648 <= y <= 2147483647):
629                     return True
630
631             return False
632
633
634     def qapp() -> QCoreApplication:
635         """Return the equivalent of the global :class:`qApp` pointer.
636
637         :raises RuntimeError: If :meth:`QCoreApplication.instance` returns ``None``
638         """
639         instance = QCoreApplication.instance()
640
641         if instance is None:
642             raise RuntimeError('qApp undefined')
643
644         return instance
645
646
647     def main(args: List[str]) -> None:
648         """Run the GUI by creating and showing an instance of :class:`LintransMainWindow`.
649
650         :param List[str] args: The args to pass to :class:`QApplication`
651         """
652         app = QApplication(args)
653         app.setApplicationName('lintrans')
654         app.setApplicationVersion(lintrans.__version__)
655
656         qapp().setStyle(QStyleFactory.create('fusion'))
657
658         window = LintransMainWindow()
659         window.show()
660
661         sys.exit(app.exec_())
```

A.5 gui/settings.py

```
1   # lintrans - The linear transformation visualizer
2   # Copyright (C) 2021-2022 D. Dyson (DoctorDalek1963)
3
4   # This program is licensed under GNU GPLv3, available here:
5   # <https://www.gnu.org/licenses/gpl-3.0.html>
6
7   """This module contains the :class:`DisplaySettings` class, which holds configuration for display."""
8
9   from __future__ import annotations
10
```

```python
from dataclasses import dataclass


@dataclass
class DisplaySettings:
    """This class simply holds some attributes to configure display."""

    # === Basic stuff

    draw_background_grid: bool = True
    """This controls whether we want to draw the background grid.

    The background axes will always be drawn. This makes it easy to identify the center of the space.
    """

    draw_transformed_grid: bool = True
    """This controls whether we want to draw the transformed grid. Vectors are handled separately."""

    draw_basis_vectors: bool = True
    """This controls whether we want to draw the transformed basis vectors."""

    # === Animations

    smoothen_determinant: bool = True
    """This controls whether we want the determinant to change smoothly during the animation.

    .. note::
       Even if this is True, it will be ignored if we're animating from a positive det matrix to
       a negative det matrix, or vice versa, because if we try to smoothly animate that determinant,
       things blow up and the app often crashes.
    """

    applicative_animation: bool = True
    """There are two types of simple animation, transitional and applicative.

    Let ``C`` be the matrix representing the currently displayed transformation, and let ``T`` be the target matrix.
    Transitional animation means that we animate directly from ``C`` from ``T``,
    and applicative animation means that we animate from ``C`` to ``TC``, so we apply ``T`` to ``C``.
    """

    animation_time: int = 1200
    """This is the number of milliseconds that an animation takes."""

    animation_pause_length: int = 400
    """This is the number of milliseconds that we wait between animations when using comma syntax."""

    # === Matrix info

    draw_determinant_parallelogram: bool = False
    """This controls whether or not we should shade the parallelogram representing the determinant of the matrix."""

    show_determinant_value: bool = True
    """This controls whether we should write the text value of the determinant inside the parallelogram.

    The text only gets draw if :attr:`draw_determinant_parallelogram` is also True.
    """

    draw_eigenvectors: bool = False
    """This controls whether we should draw the eigenvectors of the transformation."""

    draw_eigenlines: bool = False
    """This controls whether we should draw the eigenlines of the transformation."""
```

A.6 `gui/validate.py`

```python
# lintrans - The linear transformation visualizer
# Copyright (C) 2021-2022 D. Dyson (DoctorDalek1963)

# This program is licensed under GNU GPLv3, available here:
# <https://www.gnu.org/licenses/gpl-3.0.html>
```

```

    """This simple module provides a :class:`MatrixExpressionValidator` class to validate matrix expression input."""

    from __future__ import annotations

    import re
    from typing import Tuple

    from PyQt5.QtGui import QValidator

    from lintrans.matrices import parse


    class MatrixExpressionValidator(QValidator):
        """This class validates matrix expressions in a Qt input box."""

        def validate(self, text: str, pos: int) -> Tuple[QValidator.State, str, int]:
            """Validate the given text according to the rules defined in the :mod:`lintrans.matrices` module."""
            clean_text = re.sub(parse.NAIVE_CHARACTER_CLASS[:-1] + ',]', '', text)

            if clean_text == '':
                if parse.validate_matrix_expression(clean_text):
                    return QValidator.Acceptable, text, pos
                else:
                    return QValidator.Intermediate, text, pos

            return QValidator.Invalid, text, pos
```

A.7 matrices/__init__.py

```

    # lintrans - The linear transformation visualizer
    # Copyright (C) 2021-2022 D. Dyson (DoctorDalek1963)

    # This program is licensed under GNU GPLv3, available here:
    # <https://www.gnu.org/licenses/gpl-3.0.html>

    """This package supplies classes and functions to parse, evaluate, and wrap matrices."""

    from . import parse, utility
    from .utility import create_rotation_matrix
    from .wrapper import MatrixWrapper

    __all__ = ['create_rotation_matrix', 'MatrixWrapper', 'parse', 'utility']
```

A.8 matrices/parse.py

```

    # lintrans - The linear transformation visualizer
    # Copyright (C) 2021-2022 D. Dyson (DoctorDalek1963)

    # This program is licensed under GNU GPLv3, available here:
    # <https://www.gnu.org/licenses/gpl-3.0.html>

    """This module provides functions to parse and validate matrix expressions."""

    from __future__ import annotations

    import re
    from dataclasses import dataclass
    from typing import List, Pattern, Tuple

    from lintrans.typing_ import MatrixParseList

    NAIVE_CHARACTER_CLASS = r'[-+\sA-Z0-9.rot()^{}]'


    class MatrixParseError(Exception):
        """A simple exception to be raised when an error is found when parsing."""

```

```python

def compile_naive_expression_pattern() -> Pattern[str]:
    """Compile the single RegEx pattern that will match a valid matrix expression."""
    digit_no_zero = '[123456789]'
    digits = '\\d+'
    integer_no_zero = digit_no_zero + '(' + digits + ')?'
    real_number = f'({integer_no_zero}(\\.{digits})?|0\\.{digits})'

    index_content = f'(-?{integer_no_zero}|T)'
    index = f'(\\^{{{index_content}}}|\\^{index_content})'
    matrix_identifier = f'([A-Z]|rot\\(-?{real_number}\\)|\\({NAIVE_CHARACTER_CLASS}+\\))'
    matrix = '(' + real_number + '?' + matrix_identifier + index + '?)'
    expression = f'^-?{matrix}+((\\+-?|-){matrix}+)*$'

    return re.compile(expression)


# This is an expensive pattern to compile, so we compile it when this module is initialized
naive_expression_pattern = compile_naive_expression_pattern()


def find_sub_expressions(expression: str) -> List[str]:
    """Find all the sub-expressions in the given expression.

    This function only goes one level deep, so may return strings like ``'A(BC)D'``.

    :raises MatrixParseError: If there are unbalanced parentheses
    """
    sub_expressions: List[str] = []
    string = ''
    paren_depth = 0
    pointer = 0

    while True:
        char = expression[pointer]

        if char == '(' and expression[pointer - 3:pointer] != 'rot':
            paren_depth += 1

            # This is a bit of a manual bodge, but it eliminates extraneous parens
            if paren_depth == 1:
                pointer += 1
                continue

        elif char == ')' and re.match(f'{NAIVE_CHARACTER_CLASS}*?rot\\([-\\d.]+$', expression[:pointer]) is None:
            paren_depth -= 1

        if paren_depth > 0:
            string += char

        if paren_depth == 0 and string:
            sub_expressions.append(string)
            string = ''

        pointer += 1

        if pointer >= len(expression):
            break

    if paren_depth != 0:
        raise MatrixParseError('Unbalanced parentheses in expression')

    return sub_expressions


def validate_matrix_expression(expression: str) -> bool:
    """Validate the given matrix expression.

    This function simply checks the expression against the BNF schema documented in
    :ref:`expression-syntax-docs`. It is not aware of which matrices are actually defined
    in a wrapper. For an aware version of this function, use the
    :meth:`lintrans.matrices.wrapper.MatrixWrapper.is_valid_expression` method.

```

```
96          :param str expression: The expression to be validated
97          :returns bool: Whether the expression is valid according to the schema
98          """
99          # Remove all whitespace
100         expression = re.sub(r'\s', '', expression)
101
102         match = naive_expression_pattern.match(expression)
103
104         if match is None:
105             return False
106
107         # Check that the whole expression was matched against
108         if expression != match.group(0):
109             return False
110
111         try:
112             sub_expressions = find_sub_expressions(expression)
113         except MatrixParseError:
114             return False
115
116         if not sub_expressions:
117             return True
118
119         return all(validate_matrix_expression(m) for m in sub_expressions)
120
121
122     @dataclass
123     class MatrixToken:
124         """A simple dataclass to hold information about a matrix token being parsed."""
125
126         multiplier: str = ''
127         identifier: str = ''
128         exponent: str = ''
129
130         @property
131         def tuple(self) -> Tuple[str, str, str]:
132             """Create a tuple of the token for parsing."""
133             return self.multiplier, self.identifier, self.exponent
134
135
136     class ExpressionParser:
137         """A class to hold state during parsing.
138
139         Most of the methods in this class are class-internal and should not be used from outside.
140
141         This class should be used like this:
142
143         >>> ExpressionParser('3A^-1B').parse()
144         [[('3', 'A', '-1'), ('', 'B', '')]]
145         >>> ExpressionParser('4(M^TA^2)^-2').parse()
146         [[('4', 'M^{T}A^{2}', '-2')]]
147         """
148
149         def __init__(self, expression: str):
150             """Create an instance of the parser with the given expression and initialise variables to use during
                ↪  parsing."""
151             # Remove all whitespace
152             expression = re.sub(r'\s', '', expression)
153
154             # Check if it's valid
155             if not validate_matrix_expression(expression):
156                 raise MatrixParseError('Invalid expression')
157
158             # Wrap all exponents and transposition powers with {}
159             expression = re.sub(r'(?<=\^)(-?\d+|T)(?=[^}]|$)', r'{\g<0>}', expression)
160
161             # Remove any standalone minuses
162             expression = re.sub(r'-(?=[A-Z])', '-1', expression)
163
164             # Replace subtractions with additions
165             expression = re.sub(r'-(?=\d+\.?\d*([A-Z]|rot))', '+-', expression)
166
167             # Get rid of a potential leading + introduced by the last step
```

```
168             expression = re.sub(r'^\+', '', expression)
169
170             self.expression = expression
171             self.pointer: int = 0
172
173             self.current_token = MatrixToken()
174             self.current_group: List[Tuple[str, str, str]] = []
175
176             self.final_list: MatrixParseList = []
177
178         def __repr__(self) -> str:
179             """Return a simple repr containing the expression."""
180             return f'{self.__class__.__module__}.{self.__class__.__name__}("{self.expression}")'
181
182         @property
183         def char(self) -> str:
184             """Return the char pointed to by the pointer."""
185             return self.expression[self.pointer]
186
187         def parse(self) -> MatrixParseList:
188             """Fully parse the instance's matrix expression and return the :attr:`lintrans.typing_.MatrixParseList`.
189
190             This method uses all the private methods of this class to parse the
191             expression in parts. All private methods mutate the instance variables.
192
193             :returns: The parsed expression
194             :rtype: :attr:`lintrans.typing_.MatrixParseList`
195             """
196             self._parse_multiplication_group()
197
198             while self.pointer < len(self.expression):
199                 if self.expression[self.pointer] != '+':
200                     raise MatrixParseError('Expected "+" between multiplication groups')
201
202                 self.pointer += 1
203                 self._parse_multiplication_group()
204
205             return self.final_list
206
207         def _parse_multiplication_group(self) -> None:
208             """Parse a group of matrices to be multiplied together.
209
210             This method just parses matrices until we get to a ``+``.
211             """
212             # This loop continues to parse matrices until we fail to do so
213             while self._parse_matrix():
214                 # Once we get to the end of the multiplication group, we add it the final list and reset the group list
215                 if self.pointer >= len(self.expression) or self.char == '+':
216                     self.final_list.append(self.current_group)
217                     self.current_group = []
218                     self.pointer += 1
219
220         def _parse_matrix(self) -> bool:
221             """Parse a full matrix using :meth:`_parse_matrix_part`.
222
223             This method will parse an optional multiplier, an identifier, and an optional exponent. If we
224             do this successfully, we return True. If we fail to parse a matrix (maybe we've reached the
225             end of the current multiplication group and the next char is ``+``), then we return False.
226
227             :returns bool: Success or failure
228             """
229             self.current_token = MatrixToken()
230
231             while self._parse_matrix_part():
232                 pass  # The actual execution is taken care of in the loop condition
233
234             if self.current_token.identifier == '':
235                 return False
236
237             self.current_group.append(self.current_token.tuple)
238             return True
239
240         def _parse_matrix_part(self) -> bool:
```

```
241             """Parse part of a matrix (multiplier, identifier, or exponent).
242
243             Which part of the matrix we parse is dependent on the current value of the pointer and the expression.
244             This method will parse whichever part of matrix token that it can. If it can't parse a part of a matrix,
245             or it's reached the next matrix, then we just return False. If we succeeded to parse a matrix part, then
246             we return True.
247
248             :returns bool: Success or failure
249             :raises MatrixParseError: If we fail to parse this part of the matrix
250             """
251             if self.pointer >= len(self.expression):
252                 return False
253
254             if self.char.isdigit() or self.char == '-':
255                 if self.current_token.multiplier != '' \
256                         or (self.current_token.multiplier == '' and self.current_token.identifier != ''):
257                     return False
258
259                 self._parse_multiplier()
260
261             elif self.char.isalpha() and self.char.isupper():
262                 if self.current_token.identifier != '':
263                     return False
264
265                 self.current_token.identifier = self.char
266                 self.pointer += 1
267
268             elif self.char == 'r':
269                 if self.current_token.identifier != '':
270                     return False
271
272                 self._parse_rot_identifier()
273
274             elif self.char == '(':
275                 if self.current_token.identifier != '':
276                     return False
277
278                 self._parse_sub_expression()
279
280             elif self.char == '^':
281                 if self.current_token.exponent != '':
282                     return False
283
284                 self._parse_exponent()
285
286             elif self.char == '+':
287                 return False
288
289             else:
290                 raise MatrixParseError(f'Unrecognised character "{self.char}" in matrix expression')
291
292             return True
293
294         def _parse_multiplier(self) -> None:
295             """Parse a multiplier from the expression and pointer.
296
297             This method just parses a numerical multiplier, which can include
298             zero or one ``.`` character and optionally a ``-`` at the start.
299
300             :raises MatrixParseError: If we fail to parse this part of the matrix
301             """
302             multiplier = ''
303
304             while self.char.isdigit() or self.char in ('.', '-'):
305                 multiplier += self.char
306                 self.pointer += 1
307
308             try:
309                 float(multiplier)
310             except ValueError as e:
311                 raise MatrixParseError(f'Invalid multiplier "{multiplier}"') from e
312
313             self.current_token.multiplier = multiplier
```

```
314
315         def _parse_rot_identifier(self) -> None:
316             """Parse a ``rot()``-style identifier from the expression and pointer.
317
318             This method will just parse something like ``rot(12.5)``. The angle number must be a real number.
319
320             :raises MatrixParseError: If we fail to parse this part of the matrix
321             """
322             if match := re.match(r'rot\(([\d.-]+)\)', self.expression[self.pointer:]):
323                 # Ensure that the number in brackets is a valid float
324                 try:
325                     float(match.group(1))
326                 except ValueError as e:
327                     raise MatrixParseError(f'Invalid angle number "{match.group(1)}" in rot-identifier') from e
328
329                 self.current_token.identifier = match.group(0)
330                 self.pointer += len(match.group(0))
331             else:
332                 raise MatrixParseError(f'Invalid rot-identifier "{self.expression[self.pointer:self.pointer + 15]}..."')
333
334         def _parse_sub_expression(self) -> None:
335             """Parse a parenthesized sub-expression as the identifier.
336
337             This method will also validate the expression in the parentheses.
338
339             :raises MatrixParseError: If we fail to parse this part of the matrix
340             """
341             if self.char != '(':
342                 raise MatrixParseError('Sub-expression must start with "("')
343
344             self.pointer += 1
345             paren_depth = 1
346             identifier = ''
347
348             while paren_depth > 0:
349                 if self.char == '(':
350                     paren_depth += 1
351                 elif self.char == ')':
352                     paren_depth -= 1
353
354                 if paren_depth == 0:
355                     self.pointer += 1
356                     break
357
358                 identifier += self.char
359                 self.pointer += 1
360
361             if not validate_matrix_expression(identifier):
362                 raise MatrixParseError(f'Invalid sub-expression identifier "{identifier}"')
363
364             self.current_token.identifier = identifier
365
366         def _parse_exponent(self) -> None:
367             """Parse a matrix exponent from the expression and pointer.
368
369             The exponent must be an integer or ``T`` for transpose.
370
371             :raises MatrixParseError: If we fail to parse this part of the token
372             """
373             if match := re.match(r'\^\{(-?\d+|T)\}', self.expression[self.pointer:]):
374                 exponent = match.group(1)
375
376                 try:
377                     if exponent != 'T':
378                         int(exponent)
379                 except ValueError as e:
380                     raise MatrixParseError(f'Invalid exponent "{match.group(1)}"') from e
381
382                 self.current_token.exponent = exponent
383                 self.pointer += len(match.group(0))
384             else:
385                 raise MatrixParseError(f'Invalid exponent "{self.expression[self.pointer:self.pointer + 10]}..."')
386
```

```
387
388     def parse_matrix_expression(expression: str) -> MatrixParseList:
389         """Parse the matrix expression and return a :data:`lintrans.typing_.MatrixParseList`.
390
391         :Example:
392
393         >>> parse_matrix_expression('A')
394         [[('', 'A', '')]]
395         >>> parse_matrix_expression('-3M^2')
396         [[('-3', 'M', '2')]]
397         >>> parse_matrix_expression('1.2rot(12)^{3}2B^T')
398         [[('1.2', 'rot(12)', '3'), ('2', 'B', 'T')]]
399         >>> parse_matrix_expression('A^2 + 3B')
400         [[('', 'A', '2')], [('3', 'B', '')]]
401         >>> parse_matrix_expression('-3A^{-1}3B^T - 45M^2')
402         [[('-3', 'A', '-1'), ('3', 'B', 'T')], [('-45', 'M', '2')]]
403         >>> parse_matrix_expression('5.3A^{4} 2.6B^{-2} + 4.6D^T 8.9E^{-1}')
404         [[('5.3', 'A', '4'), ('2.6', 'B', '-2')], [('4.6', 'D', 'T'), ('8.9', 'E', '-1')]]
405         >>> parse_matrix_expression('2(A+B^TC)^2D')
406         [[('2', 'A+B^{T}C', '2'), ('', 'D', '')]]
407
408         :param str expression: The expression to be parsed
409         :returns: A list of parsed components
410         :rtype: :data:`lintrans.typing_.MatrixParseList`
411         """
412         return ExpressionParser(expression).parse()
```

A.9 matrices/utility.py

```
1   #  lintrans - The linear transformation visualizer
2   #  Copyright (C) 2022 D. Dyson (DoctorDalek1963)
3   #
4   #  This program is licensed under GNU GPLv3, available here:
5   #  <https://www.gnu.org/licenses/gpl-3.0.html>
6
7   """This module provides simple utility methods for matrix and vector manipulation."""
8
9   from __future__ import annotations
10
11  import math
12  from typing import Tuple
13
14  import numpy as np
15
16  from lintrans.typing_ import MatrixType
17
18
19  def polar_coords(x: float, y: float, *, degrees: bool = False) -> Tuple[float, float]:
20      """Return the polar coordinates of a given (x, y) Cartesian coordinate.
21
22      .. note:: We're returning the angle in the range [0, 2pi)
23      """
24      radius = math.hypot(x, y)
25
26      # PyCharm complains about np.angle taking a complex argument even though that's what it's designed for
27      # noinspection PyTypeChecker
28      angle = float(np.angle(x + y * 1j, degrees))
29
30      if angle < 0:
31          angle += 2 * np.pi
32
33      return radius, angle
34
35
36  def rect_coords(radius: float, angle: float, *, degrees: bool = False) -> Tuple[float, float]:
37      """Return the rectilinear coordinates of a given polar coordinate."""
38      if degrees:
39          angle = np.radians(angle)
40
41      return radius * np.cos(angle), radius * np.sin(angle)
```

```python


def rotate_coord(x: float, y: float, angle: float, *, degrees: bool = False) -> Tuple[float, float]:
    """Rotate a rectilinear coordinate by the given angle."""
    if degrees:
        angle = np.radians(angle)

    r, theta = polar_coords(x, y, degrees=degrees)
    theta = (theta + angle) % (2 * np.pi)

    return rect_coords(r, theta, degrees=degrees)


def create_rotation_matrix(angle: float, *, degrees: bool = True) -> MatrixType:
    """Create a matrix representing a rotation (anticlockwise) by the given angle.

    :Example:

    >>> create_rotation_matrix(30)
    array([[ 0.8660254, -0.5      ],
           [ 0.5      ,  0.8660254]])
    >>> create_rotation_matrix(45)
    array([[ 0.70710678, -0.70710678],
           [ 0.70710678,  0.70710678]])
    >>> create_rotation_matrix(np.pi / 3, degrees=False)
    array([[ 0.5      , -0.8660254],
           [ 0.8660254,  0.5      ]])

    :param float angle: The angle to rotate anticlockwise by
    :param bool degrees: Whether to interpret the angle as degrees (True) or radians (False)
    :returns MatrixType: The resultant matrix
    """
    rad = np.deg2rad(angle % 360) if degrees else angle % (2 * np.pi)
    return np.array([
        [np.cos(rad), -1 * np.sin(rad)],
        [np.sin(rad), np.cos(rad)]
    ])


def is_valid_float(string: str) -> bool:
    """Check if the string is a valid float (or anything that can be cast to a float, such as an int).

    This function simply checks that ``float(string)`` doesn't raise an error.

    .. note:: An empty string is not a valid float, so will return False.

    :param str string: The string to check
    :returns bool: Whether the string is a valid float
    """
    try:
        float(string)
        return True
    except ValueError:
        return False


def round_float(num: float, precision: int = 5) -> str:
    """Round a floating point number to a given number of decimal places for pretty printing.

    :param float num: The number to round
    :param int precision: The number of decimal places to round to
    :returns str: The rounded number for pretty printing
    """
    # Round to ``precision`` number of decimal places
    string = str(round(num, precision))

    # Cut off the potential final zero
    if string.endswith('.0'):
        return string[:-2]

    elif 'e' in string:  # Scientific notation
        split = string.split('e')
        # The leading 0 only happens when the exponent is negative, so we know there'll be a minus sign
```

```
115             return split[0] + 'e-' + split[1][1:].lstrip('0')
116
117         else:
118             return string
```

A.10 matrices/wrapper.py

```
1   # lintrans - The linear transformation visualizer
2   # Copyright (C) 2021-2022 D. Dyson (DoctorDalek1963)
3
4   # This program is licensed under GNU GPLv3, available here:
5   # <https://www.gnu.org/licenses/gpl-3.0.html>
6
7   """This module contains the main :class:`MatrixWrapper` class and a function to create a matrix from an angle."""
8
9   from __future__ import annotations
10
11  import re
12  from copy import copy
13  from functools import reduce
14  from operator import add, matmul
15  from typing import Any, Dict, List, Optional, Tuple, Union
16
17  import numpy as np
18
19  from lintrans.typing_ import is_matrix_type, MatrixType
20  from .parse import parse_matrix_expression, validate_matrix_expression
21  from .utility import create_rotation_matrix
22
23
24  class MatrixWrapper:
25      """A wrapper class to hold all possible matrices and allow access to them.
26
27      .. note::
28         When defining a custom matrix, its name must be a capital letter and cannot be ``I``.
29
30      The contained matrices can be accessed and assigned to using square bracket notation.
31
32      :Example:
33
34      >>> wrapper = MatrixWrapper()
35      >>> wrapper['I']
36      array([[1., 0.],
37             [0., 1.]])
38      >>> wrapper['M']  # Returns None
39      >>> wrapper['M'] = np.array([[1, 2], [3, 4]])
40      >>> wrapper['M']
41      array([[1., 2.],
42             [3., 4.]])
43      """
44
45      def __init__(self):
46          """Initialize a :class:`MatrixWrapper` object with a dictionary of matrices which can be accessed."""
47          self._matrices: Dict[str, Optional[Union[MatrixType, str]]] = {
48              'A': None, 'B': None, 'C': None, 'D': None,
49              'E': None, 'F': None, 'G': None, 'H': None,
50              'I': np.eye(2),  # I is always defined as the identity matrix
51              'J': None, 'K': None, 'L': None, 'M': None,
52              'N': None, 'O': None, 'P': None, 'Q': None,
53              'R': None, 'S': None, 'T': None, 'U': None,
54              'V': None, 'W': None, 'X': None, 'Y': None,
55              'Z': None
56          }
57
58      def __repr__(self) -> str:
59          """Return a nice string repr of the :class:`MatrixWrapper` for debugging."""
60          defined_matrices = ''.join([k for k, v in self._matrices.items() if v is not None])
61          return f'<{self.__class__.__module__}.{self.__class__.__name__} object with ' \
62                 f"{len(defined_matrices)} defined matrices: '{defined_matrices}'>"
63
```

```
64          def __eq__(self, other: Any) -> bool:
65              """Check for equality in wrappers by comparing dictionaries.
66
67              :param Any other: The object to compare this wrapper to
68              """
69              if not isinstance(other, self.__class__):
70                  return NotImplemented
71
72              # We loop over every matrix and check if every value is equal in each
73              for name in self._matrices:
74                  s_matrix = self[name]
75                  o_matrix = other[name]
76
77                  if s_matrix is None and o_matrix is None:
78                      continue
79
80                  elif (s_matrix is None and o_matrix is not None) or \
81                       (s_matrix is not None and o_matrix is None):
82                      return False
83
84                  # This is mainly to satisfy mypy, because we know these must be matrices
85                  elif not is_matrix_type(s_matrix) or not is_matrix_type(o_matrix):
86                      return False
87
88                  # Now we know they're both NumPy arrays
89                  elif np.array_equal(s_matrix, o_matrix):
90                      continue
91
92                  else:
93                      return False
94
95              return True
96
97          def __hash__(self) -> int:
98              """Return the hash of the matrices dictionary."""
99              return hash(self._matrices)
100
101         def __getitem__(self, name: str) -> Optional[MatrixType]:
102             """Get the matrix with the given name.
103
104             If it is a simple name, it will just be fetched from the dictionary. If the name is ``rot(x)``, with
105             a given angle in degrees, then we return a new matrix representing a rotation by that angle.
106
107             .. note::
108                If the named matrix is defined as an expression, then this method will return its evaluation.
109                If you want the expression itself, use :meth:`get_expression`.
110
111             :param str name: The name of the matrix to get
112             :returns Optional[MatrixType]: The value of the matrix (could be None)
113
114             :raises NameError: If there is no matrix with the given name
115             """
116             # Return a new rotation matrix
117             if (match := re.match(r'^rot\((-?\d*\.?\d*)\)$', name)) is not None:
118                 return create_rotation_matrix(float(match.group(1)))
119
120             if name not in self._matrices:
121                 if validate_matrix_expression(name):
122                     return self.evaluate_expression(name)
123
124                 raise NameError(f'Unrecognised matrix name "{name}"')
125
126             # We copy the matrix before we return it so the user can't accidentally mutate the matrix
127             matrix = copy(self._matrices[name])
128
129             if isinstance(matrix, str):
130                 return self.evaluate_expression(matrix)
131
132             return matrix
133
134         def __setitem__(self, name: str, new_matrix: Optional[Union[MatrixType, str]]) -> None:
135             """Set the value of matrix ``name`` with the new_matrix.
136
```

```
137             The new matrix may be a simple 2x2 NumPy array, or it could be a string, representing an
138             expression in terms of other, previously defined matrices.
139
140             :param str name: The name of the matrix to set the value of
141             :param Optional[Union[MatrixType, str]] new_matrix: The value of the new matrix (could be None)
142
143             :raises NameError: If the name isn't a legal matrix name
144             :raises TypeError: If the matrix isn't a valid 2x2 NumPy array or expression in terms of other defined
                ↪  matrices
145             :raises ValueError: If you attempt to define a matrix in terms of itself
146             """
147             if not (name in self._matrices and name != 'I'):
148                 raise NameError('Matrix name is illegal')
149
150             if new_matrix is None:
151                 self._matrices[name] = None
152                 return
153
154             if isinstance(new_matrix, str):
155                 if self.is_valid_expression(new_matrix):
156                     if name not in new_matrix:
157                         self._matrices[name] = new_matrix
158                         return
159                     else:
160                         raise ValueError('Cannot define a matrix recursively')
161
162             if not is_matrix_type(new_matrix):
163                 raise TypeError('Matrix must be a 2x2 NumPy array')
164
165             # All matrices must have float entries
166             a = float(new_matrix[0][0])
167             b = float(new_matrix[0][1])
168             c = float(new_matrix[1][0])
169             d = float(new_matrix[1][1])
170
171             self._matrices[name] = np.array([[a, b], [c, d]])
172
173         def get_expression(self, name: str) -> Optional[str]:
174             """If the named matrix is defined as an expression, return that expression, else return None.
175
176             :param str name: The name of the matrix
177             :returns Optional[str]: The expression that the matrix is defined as, or None
178
179             :raises NameError: If the name is invalid
180             """
181             if name not in self._matrices:
182                 raise NameError('Matrix must have a legal name')
183
184             matrix = self._matrices[name]
185             if isinstance(matrix, str):
186                 return matrix
187
188             return None
189
190         def is_valid_expression(self, expression: str) -> bool:
191             """Check if the given expression is valid, using the context of the wrapper.
192
193             This method calls :func:`lintrans.matrices.parse.validate_matrix_expression`, but also
194             ensures that all the matrices in the expression are defined in the wrapper.
195
196             :param str expression: The expression to validate
197             :returns bool: Whether the expression is valid in this wrapper
198
199             :raises LinAlgError: If a matrix is defined in terms of the inverse of a singular matrix
200             """
201             # Get rid of the transposes to check all capital letters
202             new_expression = expression.replace('^T', '').replace('^{T}', '')
203
204             # Make sure all the referenced matrices are defined
205             for matrix in [x for x in new_expression if re.match('[A-Z]', x)]:
206                 if self[matrix] is None:
207                     return False
208
```

```
            if (expr := self.get_expression(matrix)) is not None:
                if not self.is_valid_expression(expr):
                    return False

        return validate_matrix_expression(expression)

    def evaluate_expression(self, expression: str) -> MatrixType:
        """Evaluate a given expression and return the matrix evaluation.

        :param str expression: The expression to be parsed
        :returns MatrixType: The matrix result of the expression

        :raises ValueError: If the expression is invalid
        """
        if not self.is_valid_expression(expression):
            raise ValueError('The expression is invalid')

        parsed_result = parse_matrix_expression(expression)
        final_groups: List[List[MatrixType]] = []

        for group in parsed_result:
            f_group: List[MatrixType] = []

            for multiplier, identifier, index in group:
                if index == 'T':
                    m = self[identifier]

                    # This assertion is just so mypy doesn't complain
                    # We know this won't be None, because we know that this matrix is defined in this wrapper
                    assert m is not None
                    matrix_value = m.T

                else:
                    matrix_value = np.linalg.matrix_power(self[identifier], 1 if index == '' else int(index))

                matrix_value *= 1 if multiplier == '' else float(multiplier)
                f_group.append(matrix_value)

            final_groups.append(f_group)

        return reduce(add, [reduce(matmul, group) for group in final_groups])

    def get_defined_matrices(self) -> List[Tuple[str, Union[MatrixType, str]]]:
        """Return a list of tuples containing the name and value of all defined matrices in the wrapper.

        :returns: A list of tuples where the first element is the name, and the second element is the value
        :rtype: List[Tuple[str, Union[MatrixType, str]]]
        """
        matrices = []

        for name, value in self._matrices.items():
            if value is not None:
                matrices.append((name, value))

        return matrices
```

A.11 `typing_/__init__.py`

```
# lintrans - The linear transformation visualizer
# Copyright (C) 2021-2022 D. Dyson (DoctorDalek1963)

# This program is licensed under GNU GPLv3, available here:
# <https://www.gnu.org/licenses/gpl-3.0.html>

"""This package supplies type aliases for linear algebra and transformations.

.. note::
   This package is called ``typing_`` and not ``typing`` to avoid name collisions with the
   builtin :mod:`typing`. I don't quite know how this collision occurs, but renaming
   this module fixed the problem.
```

```
    """

    from __future__ import annotations

    from sys import version_info
    from typing import Any, List, Tuple

    from numpy import ndarray
    from nptyping import NDArray, Float

    if version_info >= (3, 10):
        from typing import TypeGuard

    __all__ = ['is_matrix_type', 'MatrixType', 'MatrixParseList', 'VectorType']

    MatrixType = NDArray[(2, 2), Float]
    """This type represents a 2x2 matrix as a NumPy array."""

    VectorType = NDArray[(2,), Float]
    """This type represents a 2D vector as a NumPy array, for use with :attr:`MatrixType`."""

    MatrixParseList = List[List[Tuple[str, str, str]]]
    """This is a list containing lists of tuples. Each tuple represents a matrix and is ``(multiplier,
    matrix_identifier, index)`` where all of them are strings. These matrix-representing tuples are
    contained in lists which represent multiplication groups. Every matrix in the group should be
    multiplied together, in order. These multiplication group lists are contained by a top level list,
    which is this type. Once these multiplication group lists have been evaluated, they should be summed.

    In the tuples, the multiplier is a string representing a real number, the matrix identifier
    is a capital letter or ``rot(x)`` where x is a real number angle, and the index is a string
    representing an integer, or it's the letter ``T`` for transpose.
    """


    def is_matrix_type(matrix: Any) -> TypeGuard[NDArray[(2, 2), Float]]:
        """Check if the given value is a valid matrix type.

        .. note::
           This function is a TypeGuard, meaning if it returns True, then the
           passed value must be a :attr:`lintrans.typing_.MatrixType`.
        """
        return isinstance(matrix, ndarray) and matrix.shape == (2, 2)
```

A.12 gui/dialogs/__init__.py

```
    # lintrans - The linear transformation visualizer
    # Copyright (C) 2021-2022 D. Dyson (DoctorDalek1963)

    # This program is licensed under GNU GPLv3, available here:
    # <https://www.gnu.org/licenses/gpl-3.0.html>

    """This package provides separate dialogs for the main GUI.

    These dialogs are for defining new matrices in different ways and editing settings.
    """

    from .define_new_matrix import DefineAsAnExpressionDialog, DefineDialog, DefineNumericallyDialog,
    ↪  DefineVisuallyDialog
    from .misc import AboutDialog, InfoPanelDialog
    from .settings import DisplaySettingsDialog

    __all__ = ['AboutDialog', 'DefineAsAnExpressionDialog', 'DefineDialog', 'DefineNumericallyDialog',
               'DefineVisuallyDialog', 'DisplaySettingsDialog', 'InfoPanelDialog']
```

A.13 gui/dialogs/define_new_matrix.py

```
    # lintrans - The linear transformation visualizer
    # Copyright (C) 2021-2022 D. Dyson (DoctorDalek1963)
```

```
3
4   # This program is licensed under GNU GPLv3, available here:
5   # <https://www.gnu.org/licenses/gpl-3.0.html>
6
7   """This module provides an abstract :class:`DefineDialog` class and subclasses, allowing definition of new
    ↪  matrices."""
8
9   from __future__ import annotations
10
11  import abc
12
13  from numpy import array
14  from PyQt5 import QtWidgets
15  from PyQt5.QtCore import pyqtSlot
16  from PyQt5.QtGui import QDoubleValidator, QKeySequence
17  from PyQt5.QtWidgets import QGridLayout, QHBoxLayout, QShortcut, QSizePolicy, QSpacerItem, QVBoxLayout
18
19  from lintrans.gui.dialogs.misc import FixedSizeDialog
20  from lintrans.gui.plots import DefineVisuallyWidget
21  from lintrans.gui.settings import DisplaySettings
22  from lintrans.gui.validate import MatrixExpressionValidator
23  from lintrans.matrices import MatrixWrapper
24  from lintrans.matrices.utility import is_valid_float, round_float
25  from lintrans.typing_ import MatrixType
26
27  ALPHABET_NO_I = 'ABCDEFGHJKLMNOPQRSTUVWXYZ'
28
29
30  class DefineDialog(FixedSizeDialog):
31      """An abstract superclass for definitions dialogs.
32
33      .. warning:: This class should never be directly instantiated, only subclassed.
34
35      .. note::
36         I would make this class have ``metaclass=abc.ABCMeta``, but I can't because it subclasses :class:`QDialog`,
37         and every superclass of a class must have the same metaclass, and :class:`QDialog` is not an abstract class.
38      """
39
40      def __init__(self, *args, matrix_wrapper: MatrixWrapper, **kwargs):
41          """Create the widgets and layout of the dialog.
42
43          .. note:: ``*args`` and ``**kwargs`` are passed to the super constructor (:class:`QDialog`).
44
45          :param MatrixWrapper matrix_wrapper: The MatrixWrapper that this dialog will mutate
46          """
47          super().__init__(*args, **kwargs)
48
49          self.matrix_wrapper = matrix_wrapper
50          self.setWindowTitle('Define a matrix')
51
52          # === Create the widgets
53
54          self.button_confirm = QtWidgets.QPushButton(self)
55          self.button_confirm.setText('Confirm')
56          self.button_confirm.setEnabled(False)
57          self.button_confirm.clicked.connect(self.confirm_matrix)
58          self.button_confirm.setToolTip('Confirm this as the new matrix<br><b>(Ctrl + Enter)</b>')
59          QShortcut(QKeySequence('Ctrl+Return'), self).activated.connect(self.button_confirm.click)
60
61          self.button_cancel = QtWidgets.QPushButton(self)
62          self.button_cancel.setText('Cancel')
63          self.button_cancel.clicked.connect(self.reject)
64          self.button_cancel.setToolTip('Cancel this definition<br><b>(Escape)</b>')
65
66          self.label_equals = QtWidgets.QLabel()
67          self.label_equals.setText('=')
68
69          self.combobox_letter = QtWidgets.QComboBox(self)
70
71          for letter in ALPHABET_NO_I:
72              self.combobox_letter.addItem(letter)
73
74          self.combobox_letter.activated.connect(self.load_matrix)
```

```
75
76              # === Arrange the widgets
77
78              self.setContentsMargins(10, 10, 10, 10)
79
80              self.hlay_buttons = QHBoxLayout()
81              self.hlay_buttons.setSpacing(20)
82              self.hlay_buttons.addItem(QSpacerItem(50, 5, hPolicy=QSizePolicy.Expanding, vPolicy=QSizePolicy.Minimum))
83              self.hlay_buttons.addWidget(self.button_cancel)
84              self.hlay_buttons.addWidget(self.button_confirm)
85
86              self.hlay_definition = QHBoxLayout()
87              self.hlay_definition.setSpacing(20)
88              self.hlay_definition.addWidget(self.combobox_letter)
89              self.hlay_definition.addWidget(self.label_equals)
90
91              self.vlay_all = QVBoxLayout()
92              self.vlay_all.setSpacing(20)
93
94              self.setLayout(self.vlay_all)
95
96          @property
97          def selected_letter(self) -> str:
98              """Return the letter currently selected in the combo box."""
99              return str(self.combobox_letter.currentText())
100
101         @abc.abstractmethod
102         @pyqtSlot()
103         def update_confirm_button(self) -> None:
104             """Enable the confirm button if it should be enabled, else, disable it."""
105
106         @pyqtSlot(int)
107         def load_matrix(self, index: int) -> None:
108             """Load the selected matrix into the dialog.
109
110             This method is optionally able to be overridden. If it is not overridden,
111             then no matrix is loaded when selecting a name.
112
113             We have this method in the superclass so that we can define it as the slot
114             for the :meth:`QComboBox.activated` signal in this constructor, rather than
115             having to define that in the constructor of every subclass.
116             """
117
118         @abc.abstractmethod
119         @pyqtSlot()
120         def confirm_matrix(self) -> None:
121             """Confirm the inputted matrix and assign it.
122
123             .. note:: When subclassing, this method should mutate ``self.matrix_wrapper`` and then call
                ↪  ``self.accept()``.
124             """
125
126
127 class DefineVisuallyDialog(DefineDialog):
128     """The dialog class that allows the user to define a matrix visually."""
129
130     def __init__(self, *args, matrix_wrapper: MatrixWrapper, display_settings: DisplaySettings, **kwargs):
131         """Create the widgets and layout of the dialog.
132
133         :param MatrixWrapper matrix_wrapper: The MatrixWrapper that this dialog will mutate
134         """
135         super().__init__(*args, matrix_wrapper=matrix_wrapper, **kwargs)
136
137         self.setMinimumSize(700, 550)
138
139         # === Create the widgets
140
141         self.plot = DefineVisuallyWidget(self, display_settings=display_settings)
142
143         # === Arrange the widgets
144
145         self.hlay_definition.addWidget(self.plot)
146         self.hlay_definition.setStretchFactor(self.plot, 1)
```

```
147
148             self.vlay_all.addLayout(self.hlay_definition)
149             self.vlay_all.addLayout(self.hlay_buttons)
150
151             # We load the default matrix A into the plot
152             self.load_matrix(0)
153
154             # We also enable the confirm button, because any visually defined matrix is valid
155             self.button_confirm.setEnabled(True)
156
157         @pyqtSlot()
158         def update_confirm_button(self) -> None:
159             """Enable the confirm button.
160
161             .. note::
162                The confirm button is always enabled in this dialog and this method is never actually used,
163                so it's got an empty body. It's only here because we need to implement the abstract method.
164             """
165
166         @pyqtSlot(int)
167         def load_matrix(self, index: int) -> None:
168             """Show the selected matrix on the plot. If the matrix is None, show the identity."""
169             matrix = self.matrix_wrapper[self.selected_letter]
170
171             if matrix is None:
172                 matrix = self.matrix_wrapper['I']
173
174             self.plot.visualize_matrix_transformation(matrix)
175             self.plot.update()
176
177         @pyqtSlot()
178         def confirm_matrix(self) -> None:
179             """Confirm the matrix that's been defined visually."""
180             matrix: MatrixType = array([
181                 [self.plot.point_i[0], self.plot.point_j[0]],
182                 [self.plot.point_i[1], self.plot.point_j[1]]
183             ])
184
185             self.matrix_wrapper[self.selected_letter] = matrix
186             self.accept()
187
188
189     class DefineNumericallyDialog(DefineDialog):
190         """The dialog class that allows the user to define a new matrix numerically."""
191
192         def __init__(self, *args, matrix_wrapper: MatrixWrapper, **kwargs):
193             """Create the widgets and layout of the dialog.
194
195             :param MatrixWrapper matrix_wrapper: The MatrixWrapper that this dialog will mutate
196             """
197             super().__init__(*args, matrix_wrapper=matrix_wrapper, **kwargs)
198
199             # === Create the widgets
200
201             # tl = top left, br = bottom right, etc.
202             self.element_tl = QtWidgets.QLineEdit(self)
203             self.element_tl.textChanged.connect(self.update_confirm_button)
204             self.element_tl.setValidator(QDoubleValidator())
205
206             self.element_tr = QtWidgets.QLineEdit(self)
207             self.element_tr.textChanged.connect(self.update_confirm_button)
208             self.element_tr.setValidator(QDoubleValidator())
209
210             self.element_bl = QtWidgets.QLineEdit(self)
211             self.element_bl.textChanged.connect(self.update_confirm_button)
212             self.element_bl.setValidator(QDoubleValidator())
213
214             self.element_br = QtWidgets.QLineEdit(self)
215             self.element_br.textChanged.connect(self.update_confirm_button)
216             self.element_br.setValidator(QDoubleValidator())
217
218             self.matrix_elements = (self.element_tl, self.element_tr, self.element_bl, self.element_br)
219
```

```
220             # === Arrange the widgets
221
222             self.grid_matrix = QGridLayout()
223             self.grid_matrix.setSpacing(20)
224             self.grid_matrix.addWidget(self.element_tl, 0, 0)
225             self.grid_matrix.addWidget(self.element_tr, 0, 1)
226             self.grid_matrix.addWidget(self.element_bl, 1, 0)
227             self.grid_matrix.addWidget(self.element_br, 1, 1)
228
229             self.hlay_definition.addLayout(self.grid_matrix)
230
231             self.vlay_all.addLayout(self.hlay_definition)
232             self.vlay_all.addLayout(self.hlay_buttons)
233
234             # We load the default matrix A into the boxes
235             self.load_matrix(0)
236
237             self.element_tl.setFocus()
238
239         @pyqtSlot()
240         def update_confirm_button(self) -> None:
241             """Enable the confirm button if there are valid floats in every box."""
242             for elem in self.matrix_elements:
243                 if not is_valid_float(elem.text()):
244                     # If they're not all numbers, then we can't confirm it
245                     self.button_confirm.setEnabled(False)
246                     return
247
248             # If we didn't find anything invalid
249             self.button_confirm.setEnabled(True)
250
251         @pyqtSlot(int)
252         def load_matrix(self, index: int) -> None:
253             """If the selected matrix is defined, load its values into the boxes."""
254             matrix = self.matrix_wrapper[self.selected_letter]
255
256             if matrix is None:
257                 for elem in self.matrix_elements:
258                     elem.setText('')
259
260             else:
261                 self.element_tl.setText(round_float(matrix[0][0]))
262                 self.element_tr.setText(round_float(matrix[0][1]))
263                 self.element_bl.setText(round_float(matrix[1][0]))
264                 self.element_br.setText(round_float(matrix[1][1]))
265
266             self.update_confirm_button()
267
268         @pyqtSlot()
269         def confirm_matrix(self) -> None:
270             """Confirm the matrix in the boxes and assign it to the name in the combo box."""
271             matrix: MatrixType = array([
272                 [float(self.element_tl.text()), float(self.element_tr.text())],
273                 [float(self.element_bl.text()), float(self.element_br.text())]
274             ])
275
276             self.matrix_wrapper[self.selected_letter] = matrix
277             self.accept()
278
279
280     class DefineAsAnExpressionDialog(DefineDialog):
281         """The dialog class that allows the user to define a matrix as an expression of other matrices."""
282
283         def __init__(self, *args, matrix_wrapper: MatrixWrapper, **kwargs):
284             """Create the widgets and layout of the dialog.
285
286             :param MatrixWrapper matrix_wrapper: The MatrixWrapper that this dialog will mutate
287             """
288             super().__init__(*args, matrix_wrapper=matrix_wrapper, **kwargs)
289
290             self.setMinimumWidth(450)
291
292             # === Create the widgets
```

```
293
294             self.lineedit_expression_box = QtWidgets.QLineEdit(self)
295             self.lineedit_expression_box.setPlaceholderText('Enter matrix expression...')
296             self.lineedit_expression_box.textChanged.connect(self.update_confirm_button)
297             self.lineedit_expression_box.setValidator(MatrixExpressionValidator())
298
299             # === Arrange the widgets
300
301             self.hlay_definition.addWidget(self.lineedit_expression_box)
302
303             self.vlay_all.addLayout(self.hlay_definition)
304             self.vlay_all.addLayout(self.hlay_buttons)
305
306             # Load the matrix if it's defined as an expression
307             self.load_matrix(0)
308
309             self.lineedit_expression_box.setFocus()
310
311         @pyqtSlot()
312         def update_confirm_button(self) -> None:
313             """Enable the confirm button if the matrix expression is valid in the wrapper."""
314             text = self.lineedit_expression_box.text()
315             valid_expression = self.matrix_wrapper.is_valid_expression(text)
316
317             self.button_confirm.setEnabled(valid_expression and self.selected_letter not in text)
318
319         @pyqtSlot(int)
320         def load_matrix(self, index: int) -> None:
321             """If the selected matrix is defined an expression, load that expression into the box."""
322             if (expr := self.matrix_wrapper.get_expression(self.selected_letter)) is not None:
323                 self.lineedit_expression_box.setText(expr)
324             else:
325                 self.lineedit_expression_box.setText('')
326
327         @pyqtSlot()
328         def confirm_matrix(self) -> None:
329             """Evaluate the matrix expression and assign its value to the name in the combo box."""
330             self.matrix_wrapper[self.selected_letter] = self.lineedit_expression_box.text()
331             self.accept()
```

A.14 gui/dialogs/misc.py

```
1   #  lintrans - The linear transformation visualizer
2   #  Copyright (C) 2022 D. Dyson (DoctorDalek1963)
3   #
4   #  This program is licensed under GNU GPLv3, available here:
5   #  <https://www.gnu.org/licenses/gpl-3.0.html>
6
7   """This module provides miscellaneous dialog classes like :class:`AboutDialog`."""
8
9   from __future__ import annotations
10
11  import platform
12  from typing import Union
13
14  from PyQt5.QtCore import PYQT_VERSION_STR, QT_VERSION_STR, Qt
15  from PyQt5.QtWidgets import QDialog, QGridLayout, QLabel, QVBoxLayout, QWidget
16
17  import lintrans
18  from lintrans.matrices.utility import round_float
19  from lintrans.matrices import MatrixWrapper
20  from lintrans.typing_ import is_matrix_type, MatrixType
21
22
23  class FixedSizeDialog(QDialog):
24      """A simple superclass to create modal dialog boxes with fixed size.
25
26      We override the :meth:`open` method to set the fixed size as soon as the dialog is opened modally.
27      """
28
```

```
29          def open(self) -> None:
30              """Override :meth:`QDialog.open` to set the dialog to a fixed size."""
31              super().open()
32              self.setFixedSize(self.size())
33
34
35      class AboutDialog(FixedSizeDialog):
36          """A simple dialog class to display information about the app to the user.
37
38          It only has an :meth:`__init__` method because it only has label widgets, so no other methods are necessary
            ↪ here.
39          """
40
41          def __init__(self, *args, **kwargs):
42              """Create an :class:`AboutDialog` object with all the label widgets."""
43              super().__init__(*args, **kwargs)
44
45              self.setWindowTitle('About lintrans')
46
47              # === Create the widgets
48
49              label_title = QLabel(self)
50              label_title.setText(f'lintrans (version {lintrans.__version__})')
51              label_title.setAlignment(Qt.AlignCenter)
52
53              font_title = label_title.font()
54              font_title.setPointSize(font_title.pointSize() * 2)
55              label_title.setFont(font_title)
56
57              label_version_info = QLabel(self)
58              label_version_info.setText(
59                  f'With Python version {platform.python_version()}\n'
60                  f'Qt version {QT_VERSION_STR} and PyQt5 version {PYQT_VERSION_STR}\n'
61                  f'Running on {platform.platform()}'
62              )
63              label_version_info.setAlignment(Qt.AlignCenter)
64
65              label_info = QLabel(self)
66              label_info.setText(
67                  'lintrans is a program designed to help visualise<br>'
68                  '2D linear transformations represented with matrices.<br><br>'
69                  "It's designed for teachers and students and any feedback<br>"
70                  'is greatly appreciated at <a href="https://github.com/DoctorDalek1963/lintrans" '
71                  'style="color: black;">my GitHub page</a><br>or via email '
72                  '(<a href="mailto:dyson.dyson@icloud.com" style="color: black;">dyson.dyson@icloud.com</a>).'
73              )
74              label_info.setAlignment(Qt.AlignCenter)
75              label_info.setTextFormat(Qt.RichText)
76              label_info.setOpenExternalLinks(True)
77
78              label_copyright = QLabel(self)
79              label_copyright.setText(
80                  'This program is free software.<br>Copyright 2021-2022 D. Dyson (DoctorDalek1963).<br>'
81                  'This program is licensed under GPLv3, which can be found '
82                  '<a href="https://www.gnu.org/licenses/gpl-3.0.html" style="color: black;">here</a>.'
83              )
84              label_copyright.setAlignment(Qt.AlignCenter)
85              label_copyright.setTextFormat(Qt.RichText)
86              label_copyright.setOpenExternalLinks(True)
87
88              # === Arrange the widgets
89
90              self.setContentsMargins(10, 10, 10, 10)
91
92              vlay = QVBoxLayout()
93              vlay.setSpacing(20)
94              vlay.addWidget(label_title)
95              vlay.addWidget(label_version_info)
96              vlay.addWidget(label_info)
97              vlay.addWidget(label_copyright)
98
99              self.setLayout(vlay)
100
```

```
101
102     class InfoPanelDialog(FixedSizeDialog):
103         """A simple dialog class to display an info panel that shows all currently defined matrices."""
104
105         def __init__(self, matrix_wrapper: MatrixWrapper, *args, **kwargs):
106             """Create the dialog box with all the widgets needed to show the information."""
107             super().__init__(*args, **kwargs)
108             self.wrapper = matrix_wrapper
109
110             self.setWindowTitle('Defined matrices')
111
112             grid_layout = QGridLayout()
113             grid_layout.setSpacing(20)
114
115             bold_font = self.font()
116             bold_font.setBold(True)
117
118             name_value_pair: tuple[str, Union[MatrixType, str]]
119
120             # Each defined matrix will get a widget group. Each group will be a label for the name,
121             # a label for '=', and a container widget to either show the matrix numerically, or to
122             # show the expression that it's defined as
123             for i, name_value_pair in enumerate(self.wrapper.get_defined_matrices()):
124                 name, value = name_value_pair
125
126                 # Create all the widgets first
127                 label_name = QLabel(self)
128                 label_name.setText(name)
129                 label_name.setFont(bold_font)
130
131                 label_equals = QLabel(self)
132                 label_equals.setText('=')
133
134                 widget_matrix = self._get_matrix_widget(value)
135
136                 # We want columns of at most 6 widget groups
137                 # This column variable manages which column of defined matrices we're on
138                 # It's multiplied by 3 because all the widgets are in a single grid layout
139                 # I could factor out each triplet of widgets for a defined matrix into a container widget,
140                 # but I prefer to keep the widget count lower to reduce any possible lag
141                 column = 3 * (i // 6)
142
143                 grid_layout.addWidget(
144                     label_name,
145                     i - 2 * column,
146                     column,
147                     Qt.AlignCenter
148                 )
149                 grid_layout.addWidget(
150                     label_equals,
151                     i - 2 * column,
152                     column + 1,
153                     Qt.AlignCenter
154                 )
155                 grid_layout.addWidget(
156                     widget_matrix,
157                     i - 2 * column,
158                     column + 2,
159                     Qt.AlignCenter
160                 )
161
162             self.setContentsMargins(10, 10, 10, 10)
163             self.setLayout(grid_layout)
164
165         def _get_matrix_widget(self, matrix: Union[MatrixType, str]) -> QWidget:
166             """Return a :class:`QWidget` containing the value of the matrix.
167
168             If the matrix is defined as an expression, it will be a simple :class:`QLabel`.
169             If the matrix is defined as a matrix, it will be a :class:`QWidget` container
170             with multiple :class:`QLabel` objects in it.
171             """
172             if isinstance(matrix, str):
173                 label = QLabel(self)
```

```
            label.setText(matrix)
            return label

        elif is_matrix_type(matrix):
            # tl = top left, br = bottom right, etc.
            label_tl = QLabel(self)
            label_tl.setText(round_float(matrix[0][0]))

            label_tr = QLabel(self)
            label_tr.setText(round_float(matrix[0][1]))

            label_bl = QLabel(self)
            label_bl.setText(round_float(matrix[1][0]))

            label_br = QLabel(self)
            label_br.setText(round_float(matrix[1][1]))

            # The parens need to be bigger than the numbers, but increasing the font size also
            # makes the font thicker, so we have to reduce the font weight by the same factor
            font_parens = self.font()
            font_parens.setPointSize(int(font_parens.pointSize() * 2.5))
            font_parens.setWeight(int(font_parens.weight() / 2.5))

            label_paren_left = QLabel(self)
            label_paren_left.setText('(')
            label_paren_left.setFont(font_parens)

            label_paren_right = QLabel(self)
            label_paren_right.setText(')')
            label_paren_right.setFont(font_parens)

            container = QWidget(self)
            grid_layout = QGridLayout()

            grid_layout.addWidget(label_paren_left, 0, 0, -1, 1)
            grid_layout.addWidget(label_tl, 0, 1)
            grid_layout.addWidget(label_tr, 0, 2)
            grid_layout.addWidget(label_bl, 1, 1)
            grid_layout.addWidget(label_br, 1, 2)
            grid_layout.addWidget(label_paren_right, 0, 3, -1, 1)

            container.setLayout(grid_layout)

            return container

        raise ValueError('Matrix was not MatrixType or str')
```

A.15 gui/dialogs/settings.py

```
# lintrans - The linear transformation visualizer
# Copyright (C) 2021-2022 D. Dyson (DoctorDalek1963)

# This program is licensed under GNU GPLv3, available here:
# <https://www.gnu.org/licenses/gpl-3.0.html>

"""This module provides dialogs to edit settings within the app."""

from __future__ import annotations

import abc
from typing import Dict

from PyQt5 import QtWidgets
from PyQt5.QtGui import QIntValidator, QKeyEvent, QKeySequence
from PyQt5.QtWidgets import QCheckBox, QGroupBox, QHBoxLayout, QShortcut, QSizePolicy, QSpacerItem, QVBoxLayout

from lintrans.gui.dialogs.misc import FixedSizeDialog
from lintrans.gui.settings import DisplaySettings


```

```python
class SettingsDialog(FixedSizeDialog):
    """An abstract superclass for other simple dialogs."""

    def __init__(self, *args, **kwargs):
        """Create the widgets and layout of the dialog, passing ``*args`` and ``**kwargs`` to super."""
        super().__init__(*args, **kwargs)

        # === Create the widgets

        self.button_confirm = QtWidgets.QPushButton(self)
        self.button_confirm.setText('Confirm')
        self.button_confirm.clicked.connect(self.confirm_settings)
        self.button_confirm.setToolTip('Confirm these new settings<br><b>(Ctrl + Enter)</b>')
        QShortcut(QKeySequence('Ctrl+Return'), self).activated.connect(self.button_confirm.click)

        self.button_cancel = QtWidgets.QPushButton(self)
        self.button_cancel.setText('Cancel')
        self.button_cancel.clicked.connect(self.reject)
        self.button_cancel.setToolTip('Revert these settings<br><b>(Escape)</b>')

        # === Arrange the widgets

        self.setContentsMargins(10, 10, 10, 10)

        self.hlay_buttons = QHBoxLayout()
        self.hlay_buttons.setSpacing(20)
        self.hlay_buttons.addItem(QSpacerItem(50, 5, hPolicy=QSizePolicy.Expanding, vPolicy=QSizePolicy.Minimum))
        self.hlay_buttons.addWidget(self.button_cancel)
        self.hlay_buttons.addWidget(self.button_confirm)

        self.vlay_options = QVBoxLayout()
        self.vlay_options.setSpacing(20)

        self.vlay_all = QVBoxLayout()
        self.vlay_all.setSpacing(20)
        self.vlay_all.addLayout(self.vlay_options)
        self.vlay_all.addLayout(self.hlay_buttons)

        self.setLayout(self.vlay_all)

    @abc.abstractmethod
    def load_settings(self) -> None:
        """Load the current settings into the widgets."""

    @abc.abstractmethod
    def confirm_settings(self) -> None:
        """Confirm the settings chosen in the dialog."""


class DisplaySettingsDialog(SettingsDialog):
    """The dialog to allow the user to edit the display settings."""

    def __init__(self, *args, display_settings: DisplaySettings, **kwargs):
        """Create the widgets and layout of the dialog.

        :param DisplaySettings display_settings: The :class:`lintrans.gui.settings.DisplaySettings` object to mutate
        """
        super().__init__(*args, **kwargs)

        self.display_settings = display_settings
        self.setWindowTitle('Change display settings')

        self.dict_checkboxes: Dict[str, QCheckBox] = dict()

        # === Create the widgets

        # Basic stuff

        self.checkbox_draw_background_grid = QCheckBox(self)
        self.checkbox_draw_background_grid.setText('Draw &background grid')
        self.checkbox_draw_background_grid.setToolTip(
            'Draw the background grid (axes are always drawn)'
        )
```

```
95              self.dict_checkboxes['b'] = self.checkbox_draw_background_grid
96
97              self.checkbox_draw_transformed_grid = QCheckBox(self)
98              self.checkbox_draw_transformed_grid.setText('Draw t&ransformed grid')
99              self.checkbox_draw_transformed_grid.setToolTip(
100                 'Draw the transformed grid (vectors are handled separately)'
101             )
102             self.dict_checkboxes['r'] = self.checkbox_draw_transformed_grid
103
104             self.checkbox_draw_basis_vectors = QCheckBox(self)
105             self.checkbox_draw_basis_vectors.setText('Draw basis &vectors')
106             self.checkbox_draw_basis_vectors.setToolTip(
107                 'Draw the transformed basis vectors'
108             )
109             self.dict_checkboxes['v'] = self.checkbox_draw_basis_vectors
110
111             # Animations
112
113             self.checkbox_smoothen_determinant = QCheckBox(self)
114             self.checkbox_smoothen_determinant.setText('&Smoothen determinant')
115             self.checkbox_smoothen_determinant.setToolTip(
116                 'Smoothly animate the determinant transition during animation (if possible)'
117             )
118             self.dict_checkboxes['s'] = self.checkbox_smoothen_determinant
119
120             self.checkbox_applicative_animation = QCheckBox(self)
121             self.checkbox_applicative_animation.setText('&Applicative animation')
122             self.checkbox_applicative_animation.setToolTip(
123                 'Animate the new transformation applied to the current one,\n'
124                 'rather than just that transformation on its own'
125             )
126             self.dict_checkboxes['a'] = self.checkbox_applicative_animation
127
128             self.label_animation_time = QtWidgets.QLabel(self)
129             self.label_animation_time.setText('Total animation length (ms)')
130             self.label_animation_time.setToolTip(
131                 'How long it takes for an animation to complete'
132             )
133
134             self.lineedit_animation_time = QtWidgets.QLineEdit(self)
135             self.lineedit_animation_time.setValidator(QIntValidator(1, 9999, self))
136
137             self.label_animation_pause_length = QtWidgets.QLabel(self)
138             self.label_animation_pause_length.setText('Animation pause length (ms)')
139             self.label_animation_pause_length.setToolTip(
140                 'How many milliseconds to pause for in comma-separated animations'
141             )
142
143             self.lineedit_animation_pause_length = QtWidgets.QLineEdit(self)
144             self.lineedit_animation_pause_length.setValidator(QIntValidator(1, 999, self))
145
146             # Matrix info
147
148             self.checkbox_draw_determinant_parallelogram = QCheckBox(self)
149             self.checkbox_draw_determinant_parallelogram.setText('Draw &determinant parallelogram')
150             self.checkbox_draw_determinant_parallelogram.setToolTip(
151                 'Shade the parallelogram representing the determinant of the matrix'
152             )
153             self.checkbox_draw_determinant_parallelogram.clicked.connect(self.update_gui)
154             self.dict_checkboxes['d'] = self.checkbox_draw_determinant_parallelogram
155
156             self.checkbox_show_determinant_value = QCheckBox(self)
157             self.checkbox_show_determinant_value.setText('Show de&terminant value')
158             self.checkbox_show_determinant_value.setToolTip(
159                 'Show the value of the determinant inside the parallelogram'
160             )
161             self.dict_checkboxes['t'] = self.checkbox_show_determinant_value
162
163             self.checkbox_draw_eigenvectors = QCheckBox(self)
164             self.checkbox_draw_eigenvectors.setText('Draw &eigenvectors')
165             self.checkbox_draw_eigenvectors.setToolTip('Draw the eigenvectors of the transformations')
166             self.dict_checkboxes['e'] = self.checkbox_draw_eigenvectors
167
```

```
168             self.checkbox_draw_eigenlines = QCheckBox(self)
169             self.checkbox_draw_eigenlines.setText('Draw eigen&lines')
170             self.checkbox_draw_eigenlines.setToolTip('Draw the eigenlines (invariant lines) of the transformations')
171             self.dict_checkboxes['l'] = self.checkbox_draw_eigenlines
172 
173             # === Arrange the widgets in QGroupBoxes
174 
175             # Basic stuff
176 
177             self.vlay_groupbox_basic_stuff = QVBoxLayout()
178             self.vlay_groupbox_basic_stuff.setSpacing(20)
179             self.vlay_groupbox_basic_stuff.addWidget(self.checkbox_draw_background_grid)
180             self.vlay_groupbox_basic_stuff.addWidget(self.checkbox_draw_transformed_grid)
181             self.vlay_groupbox_basic_stuff.addWidget(self.checkbox_draw_basis_vectors)
182 
183             self.groupbox_basic_stuff = QGroupBox('Basic stuff', self)
184             self.groupbox_basic_stuff.setLayout(self.vlay_groupbox_basic_stuff)
185 
186             # Animations
187 
188             self.hlay_animation_time = QHBoxLayout()
189             self.hlay_animation_time.addWidget(self.label_animation_time)
190             self.hlay_animation_time.addWidget(self.lineedit_animation_time)
191 
192             self.hlay_animation_pause_length = QHBoxLayout()
193             self.hlay_animation_pause_length.addWidget(self.label_animation_pause_length)
194             self.hlay_animation_pause_length.addWidget(self.lineedit_animation_pause_length)
195 
196             self.vlay_groupbox_animations = QVBoxLayout()
197             self.vlay_groupbox_animations.setSpacing(20)
198             self.vlay_groupbox_animations.addWidget(self.checkbox_smoothen_determinant)
199             self.vlay_groupbox_animations.addWidget(self.checkbox_applicative_animation)
200             self.vlay_groupbox_animations.addLayout(self.hlay_animation_time)
201             self.vlay_groupbox_animations.addLayout(self.hlay_animation_pause_length)
202 
203             self.groupbox_animations = QGroupBox('Animations', self)
204             self.groupbox_animations.setLayout(self.vlay_groupbox_animations)
205 
206             # Matrix info
207 
208             self.vlay_groupbox_matrix_info = QVBoxLayout()
209             self.vlay_groupbox_matrix_info.setSpacing(20)
210             self.vlay_groupbox_matrix_info.addWidget(self.checkbox_draw_determinant_parallelogram)
211             self.vlay_groupbox_matrix_info.addWidget(self.checkbox_show_determinant_value)
212             self.vlay_groupbox_matrix_info.addWidget(self.checkbox_draw_eigenvectors)
213             self.vlay_groupbox_matrix_info.addWidget(self.checkbox_draw_eigenlines)
214 
215             self.groupbox_matrix_info = QGroupBox('Matrix info', self)
216             self.groupbox_matrix_info.setLayout(self.vlay_groupbox_matrix_info)
217 
218             # Now arrange the groupboxes
219             self.vlay_options.addWidget(self.groupbox_basic_stuff)
220             self.vlay_options.addWidget(self.groupbox_animations)
221             self.vlay_options.addWidget(self.groupbox_matrix_info)
222 
223             # Finally, we load the current settings and update the GUI
224             self.load_settings()
225             self.update_gui()
226 
227         def load_settings(self) -> None:
228             """Load the current display settings into the widgets."""
229             # Basic stuff
230             self.checkbox_draw_background_grid.setChecked(self.display_settings.draw_background_grid)
231             self.checkbox_draw_transformed_grid.setChecked(self.display_settings.draw_transformed_grid)
232             self.checkbox_draw_basis_vectors.setChecked(self.display_settings.draw_basis_vectors)
233 
234             # Animations
235             self.checkbox_smoothen_determinant.setChecked(self.display_settings.smoothen_determinant)
236             self.checkbox_applicative_animation.setChecked(self.display_settings.applicative_animation)
237             self.lineedit_animation_time.setText(str(self.display_settings.animation_time))
238             self.lineedit_animation_pause_length.setText(str(self.display_settings.animation_pause_length))
239 
240             # Matrix info
```

```
241             self.checkbox_draw_determinant_parallelogram.setChecked(self.display_settings.draw_determinant
                ↪  _parallelogram)
242             self.checkbox_show_determinant_value.setChecked(self.display_settings.show_determinant_value)
243             self.checkbox_draw_eigenvectors.setChecked(self.display_settings.draw_eigenvectors)
244             self.checkbox_draw_eigenlines.setChecked(self.display_settings.draw_eigenlines)
245
246         def confirm_settings(self) -> None:
247             """Build a :class:`lintrans.gui.settings.DisplaySettings` object and assign it."""
248             # Basic stuff
249             self.display_settings.draw_background_grid = self.checkbox_draw_background_grid.isChecked()
250             self.display_settings.draw_transformed_grid = self.checkbox_draw_transformed_grid.isChecked()
251             self.display_settings.draw_basis_vectors = self.checkbox_draw_basis_vectors.isChecked()
252
253             # Animations
254             self.display_settings.smoothen_determinant = self.checkbox_smoothen_determinant.isChecked()
255             self.display_settings.applicative_animation = self.checkbox_applicative_animation.isChecked()
256             self.display_settings.animation_time = int(self.lineedit_animation_time.text())
257             self.display_settings.animation_pause_length = int(self.lineedit_animation_pause_length.text())
258
259             # Matrix info
260             self.display_settings.draw_determinant_parallelogram =
                ↪  self.checkbox_draw_determinant_parallelogram.isChecked()
261             self.display_settings.show_determinant_value = self.checkbox_show_determinant_value.isChecked()
262             self.display_settings.draw_eigenvectors = self.checkbox_draw_eigenvectors.isChecked()
263             self.display_settings.draw_eigenlines = self.checkbox_draw_eigenlines.isChecked()
264
265             self.accept()
266
267         def update_gui(self) -> None:
268             """Update the GUI according to other widgets in the GUI.
269
270             For example, this method updates which checkboxes are enabled based on the values of other checkboxes.
271             """
272             self.checkbox_show_determinant_value.setEnabled(self.checkbox_draw_determinant_parallelogram.isChecked())
273
274         def keyPressEvent(self, event: QKeyEvent) -> None:
275             """Handle a :class:`QKeyEvent` by manually activating toggling checkboxes.
276
277             Qt handles these shortcuts automatically and allows the user to do ``Alt + Key``
278             to activate a simple shortcut defined with ``&``. However, I like to be able to
279             just hit ``Key`` and have the shortcut activate.
280             """
281             letter = event.text().lower()
282             key = event.key()
283
284             if letter in self.dict_checkboxes:
285                 self.dict_checkboxes[letter].animateClick()
286
287             # Return or keypad enter
288             elif key == 0x01000004 or key == 0x01000005:
289                 self.button_confirm.click()
290
291             # Escape
292             elif key == 0x01000000:
293                 self.button_cancel.click()
294
295             else:
296                 event.ignore()
```

A.16 gui/plots/__init__.py

```
1   # lintrans - The linear transformation visualizer
2   # Copyright (C) 2021-2022 D. Dyson (DoctorDalek1963)
3
4   # This program is licensed under GNU GPLv3, available here:
5   # <https://www.gnu.org/licenses/gpl-3.0.html>
6
7   """This package provides widgets for the visualization plot in the main window and the visual definition dialog."""
8
9   from .classes import BackgroundPlot, VectorGridPlot
```

```
10  from .widgets import DefineVisuallyWidget, VisualizeTransformationWidget
11
12  __all__ = ['BackgroundPlot', 'DefineVisuallyWidget', 'VectorGridPlot', 'VisualizeTransformationWidget']
```

A.17 gui/plots/classes.py

```
1   # lintrans - The linear transformation visualizer
2   # Copyright (C) 2021-2022 D. Dyson (DoctorDalek1963)
3
4   # This program is licensed under GNU GPLv3, available here:
5   # <https://www.gnu.org/licenses/gpl-3.0.html>
6
7   """This module provides superclasses for plotting transformations."""
8
9   from __future__ import annotations
10
11  from abc import abstractmethod
12  from typing import Iterable, List, Tuple
13
14  import numpy as np
15  from nptyping import Float, NDArray
16  from PyQt5.QtCore import QPoint, QRectF, Qt
17  from PyQt5.QtGui import QBrush, QColor, QPainter, QPainterPath, QPaintEvent, QPen, QWheelEvent
18  from PyQt5.QtWidgets import QWidget
19
20  from lintrans.typing_ import MatrixType
21
22
23  class BackgroundPlot(QWidget):
24      """This class provides a background for plotting, as well as setup for a Qt widget.
25
26      This class provides a background (untransformed) plane, and all the backend
27      details for a Qt application, but does not provide useful functionality. To
28      be useful, this class must be subclassed and behaviour must be implemented
29      by the subclass.
30
31      .. warning:: This class should never be directly instantiated, only subclassed.
32
33      .. note::
34         I would make this class have ``metaclass=abc.ABCMeta``, but I can't because it subclasses :class:`QWidget`,
35         and every superclass of a class must have the same metaclass, and :class:`QWidget` is not an abstract class.
36      """
37
38      default_grid_spacing: int = 85
39      minimum_grid_spacing: int = 5
40
41      def __init__(self, *args, **kwargs):
42          """Create the widget and setup backend stuff for rendering.
43
44          .. note:: ``*args`` and ``**kwargs`` are passed the superclass constructor (:class:`QWidget`).
45          """
46          super().__init__(*args, **kwargs)
47
48          self.setAutoFillBackground(True)
49
50          # Set the background to white
51          palette = self.palette()
52          palette.setColor(self.backgroundRole(), Qt.white)
53          self.setPalette(palette)
54
55          # Set the grid colour to grey and the axes colour to black
56          self.colour_background_grid = QColor('#808080')
57          self.colour_background_axes = QColor('#000000')
58
59          self.grid_spacing = BackgroundPlot.default_grid_spacing
60          self.width_background_grid: float = 0.3
61
62      @property
63      def canvas_origin(self) -> Tuple[int, int]:
64          """Return the canvas coords of the grid origin.
```

```
65
66              The return value is intended to be unpacked and passed to a :meth:`QPainter.drawLine:iiii` call.
67
68              See :meth:`canvas_coords`.
69
70              :returns: The canvas coordinates of the grid origin
71              :rtype: Tuple[int, int]
72              """
73              return self.width() // 2, self.height() // 2
74
75          def canvas_x(self, x: float) -> int:
76              """Convert an x coordinate from grid coords to canvas coords."""
77              return int(self.canvas_origin[0] + x * self.grid_spacing)
78
79          def canvas_y(self, y: float) -> int:
80              """Convert a y coordinate from grid coords to canvas coords."""
81              return int(self.canvas_origin[1] - y * self.grid_spacing)
82
83          def canvas_coords(self, x: float, y: float) -> Tuple[int, int]:
84              """Convert a coordinate from grid coords to canvas coords.
85
86              This method is intended to be used like
87
88              .. code::
89
90                 painter.drawLine(*self.canvas_coords(x1, y1), *self.canvas_coords(x2, y2))
91
92              or like
93
94              .. code::
95
96                 painter.drawLine(*self.canvas_origin, *self.canvas_coords(x, y))
97
98              See :attr:`canvas_origin`.
99
100             :param float x: The x component of the grid coordinate
101             :param float y: The y component of the grid coordinate
102             :returns: The resultant canvas coordinates
103             :rtype: Tuple[int, int]
104             """
105             return self.canvas_x(x), self.canvas_y(y)
106
107         def grid_corner(self) -> Tuple[float, float]:
108             """Return the grid coords of the top right corner."""
109             return self.width() / (2 * self.grid_spacing), self.height() / (2 * self.grid_spacing)
110
111         def grid_coords(self, x: int, y: int) -> Tuple[float, float]:
112             """Convert a coordinate from canvas coords to grid coords.
113
114             :param int x: The x component of the canvas coordinate
115             :param int y: The y component of the canvas coordinate
116             :returns: The resultant grid coordinates
117             :rtype: Tuple[float, float]
118             """
119             # We get the maximum grid coords and convert them into canvas coords
120             return (x - self.canvas_origin[0]) / self.grid_spacing, (-y + self.canvas_origin[1]) / self.grid_spacing
121
122         @abstractmethod
123         def paintEvent(self, event: QPaintEvent) -> None:
124             """Handle a :class:`QPaintEvent`.
125
126             .. note:: This method is abstract and must be overridden by all subclasses.
127             """
128
129         def draw_background(self, painter: QPainter, draw_grid: bool) -> None:
130             """Draw the background grid.
131
132             .. note:: This method is just a utility method for subclasses to use to render the background grid.
133
134             :param QPainter painter: The painter to draw the background with
135             :param bool draw_grid: Whether to draw the grid lines
136             """
137             if draw_grid:
```

```
138                 painter.setPen(QPen(self.colour_background_grid, self.width_background_grid))
139
140                 # Draw equally spaced vertical lines, starting in the middle and going out
141                 # We loop up to half of the width. This is because we draw a line on each side in each iteration
142                 for x in range(self.width() // 2 + self.grid_spacing, self.width(), self.grid_spacing):
143                     painter.drawLine(x, 0, x, self.height())
144                     painter.drawLine(self.width() - x, 0, self.width() - x, self.height())
145
146                 # Same with the horizontal lines
147                 for y in range(self.height() // 2 + self.grid_spacing, self.height(), self.grid_spacing):
148                     painter.drawLine(0, y, self.width(), y)
149                     painter.drawLine(0, self.height() - y, self.width(), self.height() - y)
150
151             # Now draw the axes
152             painter.setPen(QPen(self.colour_background_axes, self.width_background_grid))
153             painter.drawLine(self.width() // 2, 0, self.width() // 2, self.height())
154             painter.drawLine(0, self.height() // 2, self.width(), self.height() // 2)
155
156         def wheelEvent(self, event: QWheelEvent) -> None:
157             """Handle a :class:`QWheelEvent` by zooming in or our of the grid."""
158             # angleDelta() returns a number of units equal to 8 times the number of degrees rotated
159             degrees = event.angleDelta() / 8
160
161             if degrees is not None:
162                 new_spacing = max(1, self.grid_spacing + degrees.y())
163
164                 if new_spacing >= self.minimum_grid_spacing:
165                     self.grid_spacing = new_spacing
166
167             event.accept()
168             self.update()
169
170
171     class VectorGridPlot(BackgroundPlot):
172         """This class represents a background plot, with vectors and their grid drawn on top.
173
174         This class should be subclassed to be used for visualization and matrix definition widgets.
175         All useful behaviour should be implemented by any subclass.
176
177         .. warning:: This class should never be directly instantiated, only subclassed.
178         """
179
180         def __init__(self, *args, **kwargs):
181             """Create the widget with ``point_i`` and ``point_j`` attributes.
182
183             .. note:: ``*args`` and ``**kwargs`` are passed to the superclass constructor (:class:`BackgroundPlot`).
184             """
185             super().__init__(*args, **kwargs)
186
187             self.point_i: Tuple[float, float] = (1., 0.)
188             self.point_j: Tuple[float, float] = (0., 1.)
189
190             self.colour_i = QColor('#0808d8')
191             self.colour_j = QColor('#e90000')
192             self.colour_eigen = QColor('#13cf00')
193             self.colour_text = QColor('#000000')
194
195             self.width_vector_line = 1.8
196             self.width_transformed_grid = 0.8
197
198             self.arrowhead_length = 0.15
199
200             self.max_parallel_lines = 150
201
202         @property
203         def matrix(self) -> MatrixType:
204             """Return the assembled matrix of the basis vectors."""
205             return np.array([
206                 [self.point_i[0], self.point_j[0]],
207                 [self.point_i[1], self.point_j[1]]
208             ])
209
210         @property
```

```
        def det(self) -> float:
            """Return the determinant of the assembled matrix."""
            return float(np.linalg.det(self.matrix))

        @property
        def eigs(self) -> Iterable[Tuple[float, NDArray[(1, 2), Float]]]:
            """Return the eigenvalues and eigenvectors zipped together to be iterated over.

            :rtype: Iterable[Tuple[float, NDArray[(1, 2), Float]]]
            """
            values, vectors = np.linalg.eig(self.matrix)
            return zip(values, vectors.T)

        @abstractmethod
        def paintEvent(self, event: QPaintEvent) -> None:
            """Handle a :class:`QPaintEvent`.

            .. note:: This method is abstract and must be overridden by all subclasses.
            """

        def draw_parallel_lines(self, painter: QPainter, vector: Tuple[float, float], point: Tuple[float, float]) ->
        ↪  None:
            """Draw a set of evenly spaced grid lines parallel to ``vector`` intersecting ``point``.

            :param QPainter painter: The painter to draw the lines with
            :param vector: The vector to draw the grid lines parallel to
            :type vector: Tuple[float, float]
            :param point: The point for the lines to intersect with
            :type point: Tuple[float, float]
            """
            max_x, max_y = self.grid_corner()
            vector_x, vector_y = vector
            point_x, point_y = point

            # If the determinant is 0
            if abs(vector_x * point_y - vector_y * point_x) < 1e-12:
                rank = np.linalg.matrix_rank(
                    np.array([
                        [vector_x, point_x],
                        [vector_y, point_y]
                    ])
                )

                # If the matrix is rank 1, then we can draw the column space line
                if rank == 1:
                    # If the vector does not have a 0 x or y component, then we can just draw the line
                    if abs(vector_x) > 1e-12 and abs(vector_y) > 1e-12:
                        self.draw_oblique_line(painter, vector_y / vector_x, 0)

                    # Otherwise, we have to draw lines along the axes
                    elif abs(vector_x) > 1e-12 and abs(vector_y) < 1e-12:
                        painter.drawLine(0, self.height() // 2, self.width(), self.height() // 2)

                    elif abs(vector_x) < 1e-12 and abs(vector_y) > 1e-12:
                        painter.drawLine(self.width() // 2, 0, self.width() // 2, self.height())

                    # If the vector is (0, 0), then don't draw a line for it
                    else:
                        return

                # If the rank is 0, then we don't draw any lines
                else:
                    return

            elif abs(vector_x) < 1e-12 and abs(vector_y) < 1e-12:
                # If both components of the vector are practically 0, then we can't render any grid lines
                return

            # Draw vertical lines
            elif abs(vector_x) < 1e-12:
                painter.drawLine(self.canvas_x(0), 0, self.canvas_x(0), self.height())

                for i in range(max(abs(int(max_x / point_x)), self.max_parallel_lines)):
```

```
                painter.drawLine(
                    self.canvas_x((i + 1) * point_x),
                    0,
                    self.canvas_x((i + 1) * point_x),
                    self.height()
                )
                painter.drawLine(
                    self.canvas_x(-1 * (i + 1) * point_x),
                    0,
                    self.canvas_x(-1 * (i + 1) * point_x),
                    self.height()
                )

        # Draw horizontal lines
        elif abs(vector_y) < 1e-12:
            painter.drawLine(0, self.canvas_y(0), self.width(), self.canvas_y(0))

            for i in range(max(abs(int(max_y / point_y)), self.max_parallel_lines)):
                painter.drawLine(
                    0,
                    self.canvas_y((i + 1) * point_y),
                    self.width(),
                    self.canvas_y((i + 1) * point_y)
                )
                painter.drawLine(
                    0,
                    self.canvas_y(-1 * (i + 1) * point_y),
                    self.width(),
                    self.canvas_y(-1 * (i + 1) * point_y)
                )

        # If the line is oblique, then we can use y = mx + c
        else:
            m = vector_y / vector_x
            c = point_y - m * point_x

            self.draw_oblique_line(painter, m, 0)

            # We don't want to overshoot the max number of parallel lines,
            # but we should also stop looping as soon as we can't draw any more lines
            for i in range(1, self.max_parallel_lines + 1):
                if not self.draw_pair_of_oblique_lines(painter, m, i * c):
                    break

    def draw_pair_of_oblique_lines(self, painter: QPainter, m: float, c: float) -> bool:
        """Draw a pair of oblique lines, using the equation y = mx + c.

        This method just calls :meth:`draw_oblique_line` with ``c`` and ``-c``,
        and returns True if either call returned True.

        :param QPainter painter: The painter to draw the vectors and grid lines with
        :param float m: The gradient of the lines to draw
        :param float c: The y-intercept of the lines to draw. We use the positive and negative versions
        :returns bool: Whether we were able to draw any lines on the canvas
        """
        return any([
            self.draw_oblique_line(painter, m, c),
            self.draw_oblique_line(painter, m, -c)
        ])

    def draw_oblique_line(self, painter: QPainter, m: float, c: float) -> bool:
        """Draw an oblique line, using the equation y = mx + c.

        We only draw the part of the line that fits within the canvas, returning True if
        we were able to draw a line within the boundaries, and False if we couldn't draw a line

        :param QPainter painter: The painter to draw the vectors and grid lines with
        :param float m: The gradient of the line to draw
        :param float c: The y-intercept of the line to draw
        :returns bool: Whether we were able to draw a line on the canvas
        """
        max_x, max_y = self.grid_corner()

```

```
356             # These variable names are shortened for convenience
357             # myi is max_y_intersection, mmyi is minus_max_y_intersection, etc.
358             myi = (max_y - c) / m
359             mmyi = (-max_y - c) / m
360             mxi = max_x * m + c
361             mmxi = -max_x * m + c
362
363             # The inner list here is a list of coords, or None
364             # If an intersection fits within the bounds, then we keep its coord,
365             # else it is None, and then gets discarded from the points list
366             # By the end, points is a list of two coords, or an empty list
367             points: List[Tuple[float, float]] = [
368                 x for x in [
369                     (myi, max_y) if -max_x < myi < max_x else None,
370                     (mmyi, -max_y) if -max_x < mmyi < max_x else None,
371                     (max_x, mxi) if -max_y < mxi < max_y else None,
372                     (-max_x, mmxi) if -max_y < mmxi < max_y else None
373                 ] if x is not None
374             ]
375
376             # If no intersections fit on the canvas
377             if len(points) < 2:
378                 return False
379
380             # If we can, then draw the line
381             else:
382                 painter.drawLine(
383                     *self.canvas_coords(*points[0]),
384                     *self.canvas_coords(*points[1])
385                 )
386                 return True
387
388         def draw_transformed_grid(self, painter: QPainter) -> None:
389             """Draw the transformed version of the grid, given by the basis vectors.
390
391             .. note:: This method draws the grid, but not the basis vectors. Use :meth:`draw_basis_vectors` to draw
                ↪  them.
392
393             :param QPainter painter: The painter to draw the grid lines with
394             """
395             # Draw all the parallel lines
396             painter.setPen(QPen(self.colour_i, self.width_transformed_grid))
397             self.draw_parallel_lines(painter, self.point_i, self.point_j)
398             painter.setPen(QPen(self.colour_j, self.width_transformed_grid))
399             self.draw_parallel_lines(painter, self.point_j, self.point_i)
400
401         def draw_arrowhead_away_from_origin(self, painter: QPainter, point: Tuple[float, float]) -> None:
402             """Draw an arrowhead at ``point``, pointing away from the origin.
403
404             :param QPainter painter: The painter to draw the arrowhead with
405             :param point: The point to draw the arrowhead at, given in grid coords
406             :type point: Tuple[float, float]
407             """
408             # This algorithm was adapted from a C# algorithm found at
409             # http://csharphelper.com/blog/2014/12/draw-lines-with-arrowheads-in-c/
410
411             # Get the x and y coords of the point, and then normalize them
412             # We have to normalize them, or else the size of the arrowhead will
413             # scale with the distance of the point from the origin
414             x, y = point
415             vector_length = np.sqrt(x * x + y * y)
416
417             if vector_length < 1e-12:
418                 return
419
420             nx = x / vector_length
421             ny = y / vector_length
422
423             # We choose a length and find the steps in the x and y directions
424             length = min(
425                 self.arrowhead_length * self.default_grid_spacing / self.grid_spacing,
426                 vector_length
427             )
```

```
            dx = length * (-nx - ny)
            dy = length * (nx - ny)

            # Then we just plot those lines
            painter.drawLine(*self.canvas_coords(x, y), *self.canvas_coords(x + dx, y + dy))
            painter.drawLine(*self.canvas_coords(x, y), *self.canvas_coords(x - dy, y + dx))

        def draw_position_vector(self, painter: QPainter, point: Tuple[float, float], colour: QColor) -> None:
            """Draw a vector from the origin to the given point.

            :param QPainter painter: The painter to draw the position vector with
            :param point: The tip of the position vector in grid coords
            :type point: Tuple[float, float]
            :param QColor colour: The colour to draw the position vector in
            """
            painter.setPen(QPen(colour, self.width_vector_line))
            painter.drawLine(*self.canvas_origin, *self.canvas_coords(*point))
            self.draw_arrowhead_away_from_origin(painter, point)

        def draw_basis_vectors(self, painter: QPainter) -> None:
            """Draw arrowheads at the tips of the basis vectors.

            :param QPainter painter: The painter to draw the basis vectors with
            """
            self.draw_position_vector(painter, self.point_i, self.colour_i)
            self.draw_position_vector(painter, self.point_j, self.colour_j)

        def draw_determinant_parallelogram(self, painter: QPainter) -> None:
            """Draw the parallelogram of the determinant of the matrix.

            :param QPainter painter: The painter to draw the parallelogram with
            """
            if self.det == 0:
                return

            path = QPainterPath()
            path.moveTo(*self.canvas_origin)
            path.lineTo(*self.canvas_coords(*self.point_i))
            path.lineTo(*self.canvas_coords(self.point_i[0] + self.point_j[0], self.point_i[1] + self.point_j[1]))
            path.lineTo(*self.canvas_coords(*self.point_j))

            color = (16, 235, 253) if self.det > 0 else (253, 34, 16)
            brush = QBrush(QColor(*color, alpha=128), Qt.SolidPattern)

            painter.fillPath(path, brush)

        def draw_determinant_text(self, painter: QPainter) -> None:
            """Write the string value of the determinant in the middle of the parallelogram.

            :param QPainter painter: The painter to draw the determinant text with
            """
            painter.setPen(QPen(self.colour_text, self.width_vector_line))

            # We're building a QRect that encloses the determinant parallelogram
            # Then we can center the text in this QRect
            coords: List[Tuple[float, float]] = [
                (0, 0),
                self.point_i,
                self.point_j,
                (
                    self.point_i[0] + self.point_j[0],
                    self.point_i[1] + self.point_j[1]
                )
            ]

            xs = [t[0] for t in coords]
            ys = [t[1] for t in coords]

            top_left = QPoint(*self.canvas_coords(min(xs), max(ys)))
            bottom_right = QPoint(*self.canvas_coords(max(xs), min(ys)))

            rect = QRectF(top_left, bottom_right)
```

```
            painter.drawText(
                rect,
                Qt.AlignHCenter | Qt.AlignVCenter,
                f'{self.det:.2f}'
            )

        def draw_eigenvectors(self, painter: QPainter) -> None:
            """Draw the eigenvectors of the displayed matrix transformation.

            :param QPainter painter: The painter to draw the eigenvectors with
            """
            for value, vector in self.eigs:
                x = value * vector[0]
                y = value * vector[1]

                if x.imag != 0 or y.imag != 0:
                    continue

                self.draw_position_vector(painter, (x, y), self.colour_eigen)

                # Now we need to draw the eigenvalue at the tip of the eigenvector

                offset = 3
                top_left: QPoint
                bottom_right: QPoint
                alignment_flags: int

                if x >= 0 and y >= 0:  # Q1
                    top_left = QPoint(self.canvas_x(x) + offset, 0)
                    bottom_right = QPoint(self.width(), self.canvas_y(y) - offset)
                    alignment_flags = Qt.AlignLeft | Qt.AlignBottom

                elif x < 0 and y >= 0:  # Q2
                    top_left = QPoint(0, 0)
                    bottom_right = QPoint(self.canvas_x(x) - offset, self.canvas_y(y) - offset)
                    alignment_flags = Qt.AlignRight | Qt.AlignBottom

                elif x < 0 and y < 0:  # Q3
                    top_left = QPoint(0, self.canvas_y(y) + offset)
                    bottom_right = QPoint(self.canvas_x(x) - offset, self.height())
                    alignment_flags = Qt.AlignRight | Qt.AlignTop

                else:  # Q4
                    top_left = QPoint(self.canvas_x(x) + offset, self.canvas_y(y) + offset)
                    bottom_right = QPoint(self.width(), self.height())
                    alignment_flags = Qt.AlignLeft | Qt.AlignTop

                painter.setPen(QPen(self.colour_text, self.width_vector_line))
                painter.drawText(QRectF(top_left, bottom_right), alignment_flags, f'{value:.2f}')

        def draw_eigenlines(self, painter: QPainter) -> None:
            """Draw the eigenlines (invariant lines).

            :param QPainter painter: The painter to draw the eigenlines with
            """
            painter.setPen(QPen(self.colour_eigen, self.width_transformed_grid))

            for value, vector in self.eigs:
                if value.imag != 0:
                    continue

                x, y = vector

                if x == 0:
                    x_mid = int(self.width() / 2)
                    painter.drawLine(x_mid, 0, x_mid, self.height())

                elif y == 0:
                    y_mid = int(self.height() / 2)
                    painter.drawLine(0, y_mid, self.width(), y_mid)

                else:
                    self.draw_oblique_line(painter, y / x, 0)
```

A.18 gui/plots/widgets.py

```python
# lintrans - The linear transformation visualizer
# Copyright (C) 2021-2022 D. Dyson (DoctorDalek1963)

# This program is licensed under GNU GPLv3, available here:
# <https://www.gnu.org/licenses/gpl-3.0.html>

"""This module provides the actual widgets that can be used to visualize transformations in the GUI."""

from __future__ import annotations

from math import ceil, dist, floor
from typing import List, Tuple

from PyQt5.QtCore import Qt
from PyQt5.QtGui import QMouseEvent, QPainter, QPaintEvent

from lintrans.typing_ import MatrixType
from lintrans.gui.settings import DisplaySettings
from .classes import VectorGridPlot


class VisualizeTransformationWidget(VectorGridPlot):
    """This class is the widget that is used in the main window to visualize transformations.

    It handles all the rendering itself, and the only method that the user needs to
    worry about is :meth:`visualize_matrix_transformation`, which allows you to visualize
    the given matrix transformation.
    """

    def __init__(self, *args, display_settings: DisplaySettings, **kwargs):
        """Create the widget and assign its display settings, passing ``*args`` and ``**kwargs`` to super."""
        super().__init__(*args, **kwargs)

        self.display_settings = display_settings

    def visualize_matrix_transformation(self, matrix: MatrixType) -> None:
        """Transform the grid by the given matrix.

        .. warning:: This method does not call ``update()``. This must be done by the caller.

        .. note::
           This method transforms the background grid, not the basis vectors. This
           means that it cannot be used to compose transformations. Compositions
           should be done by the user.

        :param MatrixType matrix: The matrix to transform by
        """
        self.point_i = (matrix[0][0], matrix[1][0])
        self.point_j = (matrix[0][1], matrix[1][1])

    def paintEvent(self, event: QPaintEvent) -> None:
        """Handle a :class:`QPaintEvent` by drawing the background grid and the transformed grid.

        The transformed grid is defined by the basis vectors i and j, which can
        be controlled with the :meth:`visualize_matrix_transformation` method.
        """
        painter = QPainter()
        painter.begin(self)

        painter.setRenderHint(QPainter.Antialiasing)
        painter.setBrush(Qt.NoBrush)

        self.draw_background(painter, self.display_settings.draw_background_grid)

        if self.display_settings.draw_eigenlines:
            self.draw_eigenlines(painter)

        if self.display_settings.draw_eigenvectors:
            self.draw_eigenvectors(painter)

```

```
71              if self.display_settings.draw_determinant_parallelogram:
72                  self.draw_determinant_parallelogram(painter)
73
74                  if self.display_settings.show_determinant_value:
75                      self.draw_determinant_text(painter)
76
77              if self.display_settings.draw_transformed_grid:
78                  self.draw_transformed_grid(painter)
79
80              if self.display_settings.draw_basis_vectors:
81                  self.draw_basis_vectors(painter)
82
83              painter.end()
84              event.accept()
85
86
87      class DefineVisuallyWidget(VisualizeTransformationWidget):
88          """This class is the widget that allows the user to visually define a matrix.
89
90          This is just the widget itself. If you want the dialog, use
91          :class:`lintrans.gui.dialogs.define_new_matrix.DefineVisuallyDialog`.
92          """
93
94          def __init__(self, *args, display_settings: DisplaySettings, **kwargs):
95              """Create the widget and enable mouse tracking. ``*args`` and ``**kwargs`` are passed to ``super()``."""
96              super().__init__(*args, display_settings=display_settings, **kwargs)
97
98              self.dragged_point: Tuple[float, float] | None = None
99
100             # This is the distance that the cursor needs to be from the point to drag it
101             self.epsilon: int = 5
102
103         def mousePressEvent(self, event: QMouseEvent) -> None:
104             """Handle a :class:`QMouseEvent` when the user presses a button."""
105             mx = event.x()
106             my = event.y()
107             button = event.button()
108
109             if button != Qt.LeftButton:
110                 event.ignore()
111                 return
112
113             for point in (self.point_i, self.point_j):
114                 px, py = self.canvas_coords(*point)
115                 if abs(px - mx) <= self.epsilon and abs(py - my) <= self.epsilon:
116                     self.dragged_point = point[0], point[1]
117
118             event.accept()
119
120         def mouseReleaseEvent(self, event: QMouseEvent) -> None:
121             """Handle a :class:`QMouseEvent` when the user releases a button."""
122             if event.button() == Qt.LeftButton:
123                 self.dragged_point = None
124                 event.accept()
125             else:
126                 event.ignore()
127
128         def mouseMoveEvent(self, event: QMouseEvent) -> None:
129             """Handle the mouse moving on the canvas."""
130             mx = event.x()
131             my = event.y()
132
133             if self.dragged_point is None:
134                 event.ignore()
135                 return
136
137             x, y = self.grid_coords(mx, my)
138
139             possible_snaps: List[Tuple[int, int]] = [
140                 (floor(x), floor(y)),
141                 (floor(x), ceil(y)),
142                 (ceil(x), floor(y)),
143                 (ceil(x), ceil(y))
```

```
144             ]
145
146             snap_distances: List[Tuple[float, Tuple[int, int]]] = [
147                 (dist((x, y), coord), coord)
148                 for coord in possible_snaps
149             ]
150
151             for snap_dist, coord in snap_distances:
152                 if snap_dist < 0.1:
153                     x, y = coord
154
155             if self.dragged_point == self.point_i:
156                 self.point_i = x, y
157
158             elif self.dragged_point == self.point_j:
159                 self.point_j = x, y
160
161             self.dragged_point = x, y
162
163             self.update()
164
165             event.accept()
```

B Testing code

B.1 `matrices/test_parse_and_validate_expression.py`

```python
# lintrans - The linear transformation visualizer
# Copyright (C) 2021-2022 D. Dyson (DoctorDalek1963)

# This program is licensed under GNU GPLv3, available here:
# <https://www.gnu.org/licenses/gpl-3.0.html>

"""Test the :mod:`matrices.parse` module validation and parsing."""

from typing import List, Tuple

import pytest

from lintrans.matrices.parse import (
    MatrixParseError, find_sub_expressions, parse_matrix_expression, validate_matrix_expression
)
from lintrans.typing_ import MatrixParseList

expected_sub_expressions: List[Tuple[str, List[str]]] = [
    ('2(AB)^-1', ['AB']),
    ('-3(A+B)^2-C(B^TA)^-1', ['A+B', 'B^TA']),
    ('rot(45)', []),
    ('()', []),
    ((()), ['()']),
    ('2.3A^-1(AB)^-1+(BC)^2', ['AB', 'BC']),
    ('(2.3A^-1(AB)^-1+(BC)^2)', ['2.3A^-1(AB)^-1+(BC)^2']),
]


def test_find_sub_expressions() -> None:
    """Test the :func:`lintrans.matrices.parse.find_sub_expressions` function."""
    for inp, output in expected_sub_expressions:
        assert find_sub_expressions(inp) == output


valid_inputs: List[str] = [
    'A', 'AB', '3A', '1.2A', '-3.4A', 'A^2', 'A^-1', 'A^{-1}',
    'A^12', 'A^T', 'A^{5}', 'A^{T}', '4.3A^7', '9.2A^{18}', '0.1A'

    'rot(45)', 'rot(12.5)', '3rot(90)',
    'rot(135)^3', 'rot(51)^T', 'rot(-34)^-1',

    'A+B', 'A+2B', '4.3A+9B', 'A^2+B^T', '3A^7+0.8B^{16}',
    'A-B', '3A-4B', '3.2A^3-16.79B^T', '4.752A^{17}-3.32B^{36}',
    'A-1B', '-A', '-1A'

    '3A4B', 'A^TB', 'A^{T}B', '4A^6B^3',
    '2A^{3}4B^5', '4rot(90)^3', 'rot(45)rot(13)',
    'Arot(90)', 'AB^2', 'A^2B^2', '8.36A^T3.4B^12',

    '3.5A^{4}5.6rot(19.2)^T-B^{-1}4.1C^5',

    '(A)', '(AB)^-1', '2.3(3B^TA)^2', '-3.4(9D^{2}3F^-1)^T+C', '(AB)(C)',
    '3(rot(34)^-7A)^-1+B', '3A^2B+4A(B+C)^-1D^T-A(C(D+E)B)'
]

invalid_inputs: List[str] = [
    '', 'rot()', 'A^', 'A^1.2', 'A^{3.4}', '1,2A', 'ro(12)', '5', '12^2', '^T', '^{12}', '.1A',
    'A^{13', 'A^3}', 'A^A', '^2', 'A--B', '--A', '+A', '--1A', 'A--B', 'A--1B', '.A', '1.A',
    '2.3AB)^T', '(AB+)', '-4.6(9A', '-2(3.4A^{-1}-C^)^2', '9.2)', '3A^2B+4A(B+C)^-1D^T-A(C(D+EB)',
    '3()^2', '4(your mum)^T', 'rot()', 'rot(10.1.1)', 'rot(--2)',

    'This is 100% a valid matrix expression, I swear'
]


@pytest.mark.parametrize('inputs,output', [(valid_inputs, True), (invalid_inputs, False)])
def test_validate_matrix_expression(inputs: List[str], output: bool) -> None:
```

```
68          """Test the validate_matrix_expression() function."""
69          for inp in inputs:
70              assert validate_matrix_expression(inp) == output
71
72
73      expressions_and_parsed_expressions: List[Tuple[str, MatrixParseList]] = [
74          # Simple expressions
75          ('A', [[('', 'A', '')]]),
76          ('A^2', [[('', 'A', '2')]]),
77          ('A^{2}', [[('', 'A', '2')]]),
78          ('3A', [[('3', 'A', '')]]),
79          ('1.4A^3', [[('1.4', 'A', '3')]]),
80          ('0.1A', [[('0.1', 'A', '')]]),
81          ('0.1A', [[('0.1', 'A', '')]]),
82          ('A^12', [[('', 'A', '12')]]),
83          ('A^234', [[('', 'A', '234')]]),
84
85          # Multiplications
86          ('A 0.1B', [[('', 'A', ''), ('0.1', 'B', '')]]),
87          ('A^2 3B', [[('', 'A', '23'), ('', 'B', '')]]),
88          ('4A^{3} 6B^2', [[('4', 'A', '3'), ('6', 'B', '2')]]),
89          ('4.2A^{T} 6.1B^-1', [[('4.2', 'A', 'T'), ('6.1', 'B', '-1')]]),
90          ('-1.2A^2 rot(45)^2', [[('-1.2', 'A', '2'), ('', 'rot(45)', '2')]]),
91          ('3.2A^T 4.5B^{5} 9.6rot(121.3)', [[('3.2', 'A', 'T'), ('4.5', 'B', '5'), ('9.6', 'rot(121.3)', '')]]),
92          ('-1.18A^{-2} 0.1B^{2} 9rot(-34.6)^-1', [[('-1.18', 'A', '-2'), ('0.1', 'B', '2'), ('9', 'rot(-34.6)', '-1')]]),
93
94          # Additions
95          ('A + B', [[('', 'A', '')], [('', 'B', '')]]),
96          ('A + B - C', [[('', 'A', '')], [('', 'B', '')], [('-1', 'C', '')]]),
97          ('A^2 + 0.5B', [[('', 'A', '2')], [('0.5', 'B', '')]]),
98          ('2A^3 + 8B^T - 3C^-1', [[('2', 'A', '3')], [('8', 'B', 'T')], [('-3', 'C', '-1')]]),
99          ('4.9A^2 - 3rot(134.2)^-1 + 7.6B^8', [[('4.9', 'A', '2')], [('-3', 'rot(134.2)', '-1')], [('7.6', 'B', '8')]]),
100
101         # Additions with multiplication
102         ('2.14A^{3} 4.5rot(14.5)^-1 + 8B^T - 3C^-1', [[('2.14', 'A', '3'), ('4.5', 'rot(14.5)', '-1')],
103                                                       [('8', 'B', 'T')], [('-3', 'C', '-1')]]),
104         ('2.14A^{3} 4.5rot(14.5)^-1 + 8.5B^T 5.97C^14 - 3.14D^{-1} 6.7E^T',
105          [[('2.14', 'A', '3'), ('4.5', 'rot(14.5)', '-1')], [('8.5', 'B', 'T'), ('5.97', 'C', '14')],
106           [('-3.14', 'D', '-1'), ('6.7', 'E', 'T')]]),
107
108         # Parenthesized expressions
109         ('(AB)^-1', [[('', 'AB', '-1')]]),
110         ('-3(A+B)^2-C(B^TA)^-1', [[('-3', 'A+B', '2')], [('-1', 'C', ''), ('', 'B^{T}A', '-1')]]),
111         ('2.3(3B^TA)^2', [[('2.3', '3B^{T}A', '2')]]),
112         ('-3.4(9D^{2}3F^-1)^T+C', [[('-3.4', '9D^{2}3F^{-1}', 'T')], [('', 'C', '')]]),
113         ('2.39(3.1A^{-1}2.3B(CD)^-1)^T + (AB^T)^-1', [[('2.39', '3.1A^{-1}2.3B(CD)^{-1}', 'T')], [('', 'AB^{T}',
        ↪  '-1')]])
114     ]
115
116
117     def test_parse_matrix_expression() -> None:
118         """Test the parse_matrix_expression() function."""
119         for expression, parsed_expression in expressions_and_parsed_expressions:
120             # Test it with and without whitespace
121             assert parse_matrix_expression(expression) == parsed_expression
122             assert parse_matrix_expression(expression.replace(' ', '')) == parsed_expression
123
124
125     def test_parse_error() -> None:
126         """Test that parse_matrix_expression() raises a MatrixParseError."""
127         for expression in invalid_inputs:
128             with pytest.raises(MatrixParseError):
129                 parse_matrix_expression(expression)
```

B.2 `matrices/matrix_wrapper/conftest.py`

```
1       # lintrans - The linear transformation visualizer
2       # Copyright (C) 2021-2022 D. Dyson (DoctorDalek1963)
3
4       # This program is licensed under GNU GPLv3, available here:
```

```
    # <https://www.gnu.org/licenses/gpl-3.0.html>

    """A simple conftest.py containing some re-usable fixtures."""

    import numpy as np
    import pytest

    from lintrans.matrices import MatrixWrapper


    def get_test_wrapper() -> MatrixWrapper:
        """Return a new MatrixWrapper object with some preset values."""
        wrapper = MatrixWrapper()

        root_two_over_two = np.sqrt(2) / 2

        wrapper['A'] = np.array([[1, 2], [3, 4]])
        wrapper['B'] = np.array([[6, 4], [12, 9]])
        wrapper['C'] = np.array([[-1, -3], [4, -12]])
        wrapper['D'] = np.array([[13.2, 9.4], [-3.4, -1.8]])
        wrapper['E'] = np.array([
            [root_two_over_two, -1 * root_two_over_two],
            [root_two_over_two, root_two_over_two]
        ])
        wrapper['F'] = np.array([[-1, 0], [0, 1]])
        wrapper['G'] = np.array([[np.pi, np.e], [1729, 743.631]])

        return wrapper


    @pytest.fixture
    def test_wrapper() -> MatrixWrapper:
        """Return a new MatrixWrapper object with some preset values."""
        return get_test_wrapper()


    @pytest.fixture
    def new_wrapper() -> MatrixWrapper:
        """Return a new MatrixWrapper with no initialized values."""
        return MatrixWrapper()
```

B.3 matrices/matrix_wrapper/test_evaluate_expression.py

```
    # lintrans - The linear transformation visualizer
    # Copyright (C) 2021-2022 D. Dyson (DoctorDalek1963)

    # This program is licensed under GNU GPLv3, available here:
    # <https://www.gnu.org/licenses/gpl-3.0.html>

    """Test the MatrixWrapper evaluate_expression() method."""

    import numpy as np
    from numpy import linalg as la
    import pytest
    from pytest import approx

    from lintrans.matrices import MatrixWrapper, create_rotation_matrix
    from lintrans.typing_ import MatrixType

    from conftest import get_test_wrapper


    def test_simple_matrix_addition(test_wrapper: MatrixWrapper) -> None:
        """Test simple addition and subtraction of two matrices."""

        # NOTE: We assert that all of these values are not None just to stop mypy complaining
        # These values will never actually be None because they're set in the wrapper() fixture
        # There's probably a better way  do this, because this method is a bit of a bodge, but this works for now
        assert test_wrapper['A'] is not None and test_wrapper['B'] is not None and test_wrapper['C'] is not None and \
               test_wrapper['D'] is not None and test_wrapper['E'] is not None and test_wrapper['F'] is not None and \
```

```
28              test_wrapper['G'] is not None
29
30          assert (test_wrapper.evaluate_expression('A+B') == test_wrapper['A'] + test_wrapper['B']).all()
31          assert (test_wrapper.evaluate_expression('E+F') == test_wrapper['E'] + test_wrapper['F']).all()
32          assert (test_wrapper.evaluate_expression('G+D') == test_wrapper['G'] + test_wrapper['D']).all()
33          assert (test_wrapper.evaluate_expression('C+C') == test_wrapper['C'] + test_wrapper['C']).all()
34          assert (test_wrapper.evaluate_expression('D+A') == test_wrapper['D'] + test_wrapper['A']).all()
35          assert (test_wrapper.evaluate_expression('B+C') == test_wrapper['B'] + test_wrapper['C']).all()
36
37          assert test_wrapper == get_test_wrapper()
38
39
40      def test_simple_two_matrix_multiplication(test_wrapper: MatrixWrapper) -> None:
41          """Test simple multiplication of two matrices."""
42          assert test_wrapper['A'] is not None and test_wrapper['B'] is not None and test_wrapper['C'] is not None and \
43                 test_wrapper['D'] is not None and test_wrapper['E'] is not None and test_wrapper['F'] is not None and \
44                 test_wrapper['G'] is not None
45
46          assert (test_wrapper.evaluate_expression('AB') == test_wrapper['A'] @ test_wrapper['B']).all()
47          assert (test_wrapper.evaluate_expression('BA') == test_wrapper['B'] @ test_wrapper['A']).all()
48          assert (test_wrapper.evaluate_expression('AC') == test_wrapper['A'] @ test_wrapper['C']).all()
49          assert (test_wrapper.evaluate_expression('DA') == test_wrapper['D'] @ test_wrapper['A']).all()
50          assert (test_wrapper.evaluate_expression('ED') == test_wrapper['E'] @ test_wrapper['D']).all()
51          assert (test_wrapper.evaluate_expression('FD') == test_wrapper['F'] @ test_wrapper['D']).all()
52          assert (test_wrapper.evaluate_expression('GA') == test_wrapper['G'] @ test_wrapper['A']).all()
53          assert (test_wrapper.evaluate_expression('CF') == test_wrapper['C'] @ test_wrapper['F']).all()
54          assert (test_wrapper.evaluate_expression('AG') == test_wrapper['A'] @ test_wrapper['G']).all()
55
56          assert test_wrapper.evaluate_expression('A2B') == approx(test_wrapper['A'] @ (2 * test_wrapper['B']))
57          assert test_wrapper.evaluate_expression('2AB') == approx((2 * test_wrapper['A']) @ test_wrapper['B'])
58          assert test_wrapper.evaluate_expression('C3D') == approx(test_wrapper['C'] @ (3 * test_wrapper['D']))
59          assert test_wrapper.evaluate_expression('4.2E1.2A') == approx((4.2 * test_wrapper['E']) @ (1.2 *
            ↪  test_wrapper['A']))
60
61          assert test_wrapper == get_test_wrapper()
62
63
64      def test_identity_multiplication(test_wrapper: MatrixWrapper) -> None:
65          """Test that multiplying by the identity doesn't change the value of a matrix."""
66          assert test_wrapper['A'] is not None and test_wrapper['B'] is not None and test_wrapper['C'] is not None and \
67                 test_wrapper['D'] is not None and test_wrapper['E'] is not None and test_wrapper['F'] is not None and \
68                 test_wrapper['G'] is not None
69
70          assert (test_wrapper.evaluate_expression('I') == test_wrapper['I']).all()
71          assert (test_wrapper.evaluate_expression('AI') == test_wrapper['A']).all()
72          assert (test_wrapper.evaluate_expression('IA') == test_wrapper['A']).all()
73          assert (test_wrapper.evaluate_expression('GI') == test_wrapper['G']).all()
74          assert (test_wrapper.evaluate_expression('IG') == test_wrapper['G']).all()
75
76          assert (test_wrapper.evaluate_expression('EID') == test_wrapper['E'] @ test_wrapper['D']).all()
77          assert (test_wrapper.evaluate_expression('IED') == test_wrapper['E'] @ test_wrapper['D']).all()
78          assert (test_wrapper.evaluate_expression('EDI') == test_wrapper['E'] @ test_wrapper['D']).all()
79          assert (test_wrapper.evaluate_expression('IEIDI') == test_wrapper['E'] @ test_wrapper['D']).all()
80          assert (test_wrapper.evaluate_expression('EI^3D') == test_wrapper['E'] @ test_wrapper['D']).all()
81
82          assert test_wrapper == get_test_wrapper()
83
84
85      def test_simple_three_matrix_multiplication(test_wrapper: MatrixWrapper) -> None:
86          """Test simple multiplication of two matrices."""
87          assert test_wrapper['A'] is not None and test_wrapper['B'] is not None and test_wrapper['C'] is not None and \
88                 test_wrapper['D'] is not None and test_wrapper['E'] is not None and test_wrapper['F'] is not None and \
89                 test_wrapper['G'] is not None
90
91          assert (test_wrapper.evaluate_expression('ABC') == test_wrapper['A'] @ test_wrapper['B'] @
            ↪  test_wrapper['C']).all()
92          assert (test_wrapper.evaluate_expression('ACB') == test_wrapper['A'] @ test_wrapper['C'] @
            ↪  test_wrapper['B']).all()
93          assert (test_wrapper.evaluate_expression('BAC') == test_wrapper['B'] @ test_wrapper['A'] @
            ↪  test_wrapper['C']).all()
94          assert (test_wrapper.evaluate_expression('EFG') == test_wrapper['E'] @ test_wrapper['F'] @
            ↪  test_wrapper['G']).all()
```

```
95          assert (test_wrapper.evaluate_expression('DAC') == test_wrapper['D'] @ test_wrapper['A'] @
            ↪  test_wrapper['C']).all()
96          assert (test_wrapper.evaluate_expression('GAE') == test_wrapper['G'] @ test_wrapper['A'] @
            ↪  test_wrapper['E']).all()
97          assert (test_wrapper.evaluate_expression('FAG') == test_wrapper['F'] @ test_wrapper['A'] @
            ↪  test_wrapper['G']).all()
98          assert (test_wrapper.evaluate_expression('GAF') == test_wrapper['G'] @ test_wrapper['A'] @
            ↪  test_wrapper['F']).all()
99
100         assert test_wrapper == get_test_wrapper()
101
102
103     def test_matrix_inverses(test_wrapper: MatrixWrapper) -> None:
104         """Test the inverses of single matrices."""
105         assert test_wrapper['A'] is not None and test_wrapper['B'] is not None and test_wrapper['C'] is not None and \
106                test_wrapper['D'] is not None and test_wrapper['E'] is not None and test_wrapper['F'] is not None and \
107                test_wrapper['G'] is not None
108
109         assert (test_wrapper.evaluate_expression('A^{-1}') == la.inv(test_wrapper['A'])).all()
110         assert (test_wrapper.evaluate_expression('B^{-1}') == la.inv(test_wrapper['B'])).all()
111         assert (test_wrapper.evaluate_expression('C^{-1}') == la.inv(test_wrapper['C'])).all()
112         assert (test_wrapper.evaluate_expression('D^{-1}') == la.inv(test_wrapper['D'])).all()
113         assert (test_wrapper.evaluate_expression('E^{-1}') == la.inv(test_wrapper['E'])).all()
114         assert (test_wrapper.evaluate_expression('F^{-1}') == la.inv(test_wrapper['F'])).all()
115         assert (test_wrapper.evaluate_expression('G^{-1}') == la.inv(test_wrapper['G'])).all()
116
117         assert (test_wrapper.evaluate_expression('A^-1') == la.inv(test_wrapper['A'])).all()
118         assert (test_wrapper.evaluate_expression('B^-1') == la.inv(test_wrapper['B'])).all()
119         assert (test_wrapper.evaluate_expression('C^-1') == la.inv(test_wrapper['C'])).all()
120         assert (test_wrapper.evaluate_expression('D^-1') == la.inv(test_wrapper['D'])).all()
121         assert (test_wrapper.evaluate_expression('E^-1') == la.inv(test_wrapper['E'])).all()
122         assert (test_wrapper.evaluate_expression('F^-1') == la.inv(test_wrapper['F'])).all()
123         assert (test_wrapper.evaluate_expression('G^-1') == la.inv(test_wrapper['G'])).all()
124
125         assert test_wrapper == get_test_wrapper()
126
127
128     def test_matrix_powers(test_wrapper: MatrixWrapper) -> None:
129         """Test that matrices can be raised to integer powers."""
130         assert test_wrapper['A'] is not None and test_wrapper['B'] is not None and test_wrapper['C'] is not None and \
131                test_wrapper['D'] is not None and test_wrapper['E'] is not None and test_wrapper['F'] is not None and \
132                test_wrapper['G'] is not None
133
134         assert (test_wrapper.evaluate_expression('A^2') == la.matrix_power(test_wrapper['A'], 2)).all()
135         assert (test_wrapper.evaluate_expression('B^4') == la.matrix_power(test_wrapper['B'], 4)).all()
136         assert (test_wrapper.evaluate_expression('C^{12}') == la.matrix_power(test_wrapper['C'], 12)).all()
137         assert (test_wrapper.evaluate_expression('D^12') == la.matrix_power(test_wrapper['D'], 12)).all()
138         assert (test_wrapper.evaluate_expression('E^8') == la.matrix_power(test_wrapper['E'], 8)).all()
139         assert (test_wrapper.evaluate_expression('F^{-6}') == la.matrix_power(test_wrapper['F'], -6)).all()
140         assert (test_wrapper.evaluate_expression('G^-2') == la.matrix_power(test_wrapper['G'], -2)).all()
141
142         assert test_wrapper == get_test_wrapper()
143
144
145     def test_matrix_transpose(test_wrapper: MatrixWrapper) -> None:
146         """Test matrix transpositions."""
147         assert test_wrapper['A'] is not None and test_wrapper['B'] is not None and test_wrapper['C'] is not None and \
148                test_wrapper['D'] is not None and test_wrapper['E'] is not None and test_wrapper['F'] is not None and \
149                test_wrapper['G'] is not None
150
151         assert (test_wrapper.evaluate_expression('A^{T}') == test_wrapper['A'].T).all()
152         assert (test_wrapper.evaluate_expression('B^{T}') == test_wrapper['B'].T).all()
153         assert (test_wrapper.evaluate_expression('C^{T}') == test_wrapper['C'].T).all()
154         assert (test_wrapper.evaluate_expression('D^{T}') == test_wrapper['D'].T).all()
155         assert (test_wrapper.evaluate_expression('E^{T}') == test_wrapper['E'].T).all()
156         assert (test_wrapper.evaluate_expression('F^{T}') == test_wrapper['F'].T).all()
157         assert (test_wrapper.evaluate_expression('G^{T}') == test_wrapper['G'].T).all()
158
159         assert (test_wrapper.evaluate_expression('A^T') == test_wrapper['A'].T).all()
160         assert (test_wrapper.evaluate_expression('B^T') == test_wrapper['B'].T).all()
161         assert (test_wrapper.evaluate_expression('C^T') == test_wrapper['C'].T).all()
162         assert (test_wrapper.evaluate_expression('D^T') == test_wrapper['D'].T).all()
163         assert (test_wrapper.evaluate_expression('E^T') == test_wrapper['E'].T).all()
```

```
164         assert (test_wrapper.evaluate_expression('F^T') == test_wrapper['F'].T).all()
165         assert (test_wrapper.evaluate_expression('G^T') == test_wrapper['G'].T).all()
166
167         assert test_wrapper == get_test_wrapper()
168
169
170     def test_rotation_matrices(test_wrapper: MatrixWrapper) -> None:
171         """Test that 'rot(angle)' can be used in an expression."""
172         assert (test_wrapper.evaluate_expression('rot(90)') == create_rotation_matrix(90)).all()
173         assert (test_wrapper.evaluate_expression('rot(180)') == create_rotation_matrix(180)).all()
174         assert (test_wrapper.evaluate_expression('rot(270)') == create_rotation_matrix(270)).all()
175         assert (test_wrapper.evaluate_expression('rot(360)') == create_rotation_matrix(360)).all()
176         assert (test_wrapper.evaluate_expression('rot(45)') == create_rotation_matrix(45)).all()
177         assert (test_wrapper.evaluate_expression('rot(30)') == create_rotation_matrix(30)).all()
178
179         assert (test_wrapper.evaluate_expression('rot(13.43)') == create_rotation_matrix(13.43)).all()
180         assert (test_wrapper.evaluate_expression('rot(49.4)') == create_rotation_matrix(49.4)).all()
181         assert (test_wrapper.evaluate_expression('rot(-123.456)') == create_rotation_matrix(-123.456)).all()
182         assert (test_wrapper.evaluate_expression('rot(963.245)') == create_rotation_matrix(963.245)).all()
183         assert (test_wrapper.evaluate_expression('rot(-235.24)') == create_rotation_matrix(-235.24)).all()
184
185         assert test_wrapper == get_test_wrapper()
186
187
188     def test_multiplication_and_addition(test_wrapper: MatrixWrapper) -> None:
189         """Test multiplication and addition of matrices together."""
190         assert test_wrapper['A'] is not None and test_wrapper['B'] is not None and test_wrapper['C'] is not None and \
191                test_wrapper['D'] is not None and test_wrapper['E'] is not None and test_wrapper['F'] is not None and \
192                test_wrapper['G'] is not None
193
194         assert (test_wrapper.evaluate_expression('AB+C') ==
195                 test_wrapper['A'] @ test_wrapper['B'] + test_wrapper['C']).all()
196         assert (test_wrapper.evaluate_expression('DE-D') ==
197                 test_wrapper['D'] @ test_wrapper['E'] - test_wrapper['D']).all()
198         assert (test_wrapper.evaluate_expression('FD+AB') ==
199                 test_wrapper['F'] @ test_wrapper['D'] + test_wrapper['A'] @ test_wrapper['B']).all()
200         assert (test_wrapper.evaluate_expression('BA-DE') ==
201                 test_wrapper['B'] @ test_wrapper['A'] - test_wrapper['D'] @ test_wrapper['E']).all()
202
203         assert (test_wrapper.evaluate_expression('2AB+3C') ==
204                 (2 * test_wrapper['A']) @ test_wrapper['B'] + (3 * test_wrapper['C'])).all()
205         assert (test_wrapper.evaluate_expression('4D7.9E-1.2A') ==
206                 (4 * test_wrapper['D']) @ (7.9 * test_wrapper['E']) - (1.2 * test_wrapper['A'])).all()
207
208         assert test_wrapper == get_test_wrapper()
209
210
211     def test_complicated_expressions(test_wrapper: MatrixWrapper) -> None:
212         """Test evaluation of complicated expressions."""
213         assert test_wrapper['A'] is not None and test_wrapper['B'] is not None and test_wrapper['C'] is not None and \
214                test_wrapper['D'] is not None and test_wrapper['E'] is not None and test_wrapper['F'] is not None and \
215                test_wrapper['G'] is not None
216
217         assert (test_wrapper.evaluate_expression('-3.2A^T 4B^{-1} 6C^{-1} + 8.1D^{2} 3.2E^4') ==
218                 (-3.2 * test_wrapper['A'].T) @ (4 * la.inv(test_wrapper['B'])) @ (6 * la.inv(test_wrapper['C']))
219                 + (8.1 * la.matrix_power(test_wrapper['D'], 2)) @ (3.2 * la.matrix_power(test_wrapper['E'], 4))).all()
220
221         assert (test_wrapper.evaluate_expression('53.6D^{2} 3B^T - 4.9F^{2} 2D + A^3 B^-1') ==
222                 (53.6 * la.matrix_power(test_wrapper['D'], 2)) @ (3 * test_wrapper['B'].T)
223                 - (4.9 * la.matrix_power(test_wrapper['F'], 2)) @ (2 * test_wrapper['D'])
224                 + la.matrix_power(test_wrapper['A'], 3) @ la.inv(test_wrapper['B'])).all()
225
226         assert test_wrapper == get_test_wrapper()
227
228
229     def test_parenthesized_expressions(test_wrapper: MatrixWrapper) -> None:
230         """Test evaluation of parenthesized expressions."""
231         assert test_wrapper['A'] is not None and test_wrapper['B'] is not None and test_wrapper['C'] is not None and \
232                test_wrapper['D'] is not None and test_wrapper['E'] is not None and test_wrapper['F'] is not None and \
233                test_wrapper['G'] is not None
234
235         assert (test_wrapper.evaluate_expression('(A^T)^2') == la.matrix_power(test_wrapper['A'].T, 2)).all()
236         assert (test_wrapper.evaluate_expression('(B^T)^3') == la.matrix_power(test_wrapper['B'].T, 3)).all()
```

```
        assert (test_wrapper.evaluate_expression('(C^T)^4') == la.matrix_power(test_wrapper['C'].T, 4)).all()
        assert (test_wrapper.evaluate_expression('(D^T)^5') == la.matrix_power(test_wrapper['D'].T, 5)).all()
        assert (test_wrapper.evaluate_expression('(E^T)^6') == la.matrix_power(test_wrapper['E'].T, 6)).all()
        assert (test_wrapper.evaluate_expression('(F^T)^7') == la.matrix_power(test_wrapper['F'].T, 7)).all()
        assert (test_wrapper.evaluate_expression('(G^T)^8') == la.matrix_power(test_wrapper['G'].T, 8)).all()

        assert (test_wrapper.evaluate_expression('(rot(45)^1)^T') == create_rotation_matrix(45).T).all()
        assert (test_wrapper.evaluate_expression('(rot(45)^2)^T') == la.matrix_power(create_rotation_matrix(45),
        ↪  2).T).all()
        assert (test_wrapper.evaluate_expression('(rot(45)^3)^T') == la.matrix_power(create_rotation_matrix(45),
        ↪  3).T).all()
        assert (test_wrapper.evaluate_expression('(rot(45)^4)^T') == la.matrix_power(create_rotation_matrix(45),
        ↪  4).T).all()
        assert (test_wrapper.evaluate_expression('(rot(45)^5)^T') == la.matrix_power(create_rotation_matrix(45),
        ↪  5).T).all()

        assert (test_wrapper.evaluate_expression('D^3(A+6.2F-0.397G^TE)^-2+A') ==
                la.matrix_power(test_wrapper['D'], 3) @ la.matrix_power(
                    test_wrapper['A'] + 6.2 * test_wrapper['F'] - 0.397 * test_wrapper['G'].T @ test_wrapper['E'],
                    -2
                ) + test_wrapper['A']).all()

        assert (test_wrapper.evaluate_expression('-1.2F^{3}4.9D^T(A^2(B+3E^TF)^-1)^2') ==
                -1.2 * la.matrix_power(test_wrapper['F'], 3) @ (4.9 * test_wrapper['D'].T) @
                la.matrix_power(
                    la.matrix_power(test_wrapper['A'], 2) @ la.matrix_power(
                        test_wrapper['B'] + 3 * test_wrapper['E'].T @ test_wrapper['F'],
                        -1
                    ),
                    2
                )).all()


    def test_value_errors(test_wrapper: MatrixWrapper) -> None:
        """Test that evaluate_expression() raises a ValueError for any malformed input."""
        invalid_expressions = ['', '+', '-', 'This is not a valid expression', '3+4',
                               'A+2', 'A^', '^2', 'A^-', 'At', 'A^t', '3^2']

        for expression in invalid_expressions:
            with pytest.raises(ValueError):
                test_wrapper.evaluate_expression(expression)


    def test_linalgerror() -> None:
        """Test that certain expressions raise np.linalg.LinAlgError."""
        matrix_a: MatrixType = np.array([
            [0, 0],
            [0, 0]
        ])

        matrix_b: MatrixType = np.array([
            [1, 2],
            [1, 2]
        ])

        wrapper = MatrixWrapper()
        wrapper['A'] = matrix_a
        wrapper['B'] = matrix_b

        assert (wrapper.evaluate_expression('A') == matrix_a).all()
        assert (wrapper.evaluate_expression('B') == matrix_b).all()

        with pytest.raises(np.linalg.LinAlgError):
            wrapper.evaluate_expression('A^-1')

        with pytest.raises(np.linalg.LinAlgError):
            wrapper.evaluate_expression('B^-1')

        assert (wrapper['A'] == matrix_a).all()
        assert (wrapper['B'] == matrix_b).all()
```

B.4 matrices/matrix_wrapper/test_misc.py

```python
# lintrans - The linear transformation visualizer
# Copyright (C) 2021-2022 D. Dyson (DoctorDalek1963)

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# <https://www.gnu.org/licenses/gpl-3.0.html>

"""Test the miscellaneous methods of the MatrixWrapper class."""

from lintrans.matrices import MatrixWrapper


def test_get_expression(test_wrapper: MatrixWrapper) -> None:
    """Test the get_expression method of the MatrixWrapper class."""
    test_wrapper['N'] = 'A^2'
    test_wrapper['O'] = '4B'
    test_wrapper['P'] = 'A+C'

    test_wrapper['Q'] = 'N^-1'
    test_wrapper['R'] = 'P-4O'
    test_wrapper['S'] = 'NOP'

    assert test_wrapper.get_expression('A') is None
    assert test_wrapper.get_expression('B') is None
    assert test_wrapper.get_expression('C') is None
    assert test_wrapper.get_expression('D') is None
    assert test_wrapper.get_expression('E') is None
    assert test_wrapper.get_expression('F') is None
    assert test_wrapper.get_expression('G') is None

    assert test_wrapper.get_expression('N') == 'A^2'
    assert test_wrapper.get_expression('O') == '4B'
    assert test_wrapper.get_expression('P') == 'A+C'

    assert test_wrapper.get_expression('Q') == 'N^-1'
    assert test_wrapper.get_expression('R') == 'P-4O'
    assert test_wrapper.get_expression('S') == 'NOP'
```

B.5 matrices/matrix_wrapper/test_setitem_and_getitem.py

```python
# lintrans - The linear transformation visualizer
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# <https://www.gnu.org/licenses/gpl-3.0.html>

"""Test the MatrixWrapper __setitem__() and __getitem__() methods."""

from typing import Any, List

import numpy as np
import pytest
from numpy import linalg as la

from lintrans.matrices import MatrixWrapper
from lintrans.typing_ import MatrixType

valid_matrix_names = 'ABCDEFGHJKLMNOPQRSTUVWXYZ'
invalid_matrix_names = ['bad name', '123456', 'Th15 Is an 1nV@l1D n@m3', 'abc', 'a']

test_matrix: MatrixType = np.array([[1, 2], [4, 3]])


def test_basic_get_matrix(new_wrapper: MatrixWrapper) -> None:
    """Test MatrixWrapper().__getitem__()."""
    for name in valid_matrix_names:
        assert new_wrapper[name] is None

```

```
        assert (new_wrapper['I'] == np.array([[1, 0], [0, 1]])).all()


    def test_get_name_error(new_wrapper: MatrixWrapper) -> None:
        """Test that MatrixWrapper().__getitem__() raises a NameError if called with an invalid name."""
        for name in invalid_matrix_names:
            with pytest.raises(NameError):
                _ = new_wrapper[name]


    def test_basic_set_matrix(new_wrapper: MatrixWrapper) -> None:
        """Test MatrixWrapper().__setitem__()."""
        for name in valid_matrix_names:
            new_wrapper[name] = test_matrix
            assert (new_wrapper[name] == test_matrix).all()

            new_wrapper[name] = None
            assert new_wrapper[name] is None


    def test_set_expression(test_wrapper: MatrixWrapper) -> None:
        """Test that MatrixWrapper.__setitem__() can accept a valid expression."""
        test_wrapper['N'] = 'A^2'
        test_wrapper['O'] = 'BA+2C'
        test_wrapper['P'] = 'E^T'
        test_wrapper['Q'] = 'C^-1B'
        test_wrapper['R'] = 'A^{2}3B'
        test_wrapper['S'] = 'N^-1'
        test_wrapper['T'] = 'PQP^-1'

        with pytest.raises(TypeError):
            test_wrapper['U'] = 'A+1'

        with pytest.raises(TypeError):
            test_wrapper['V'] = 'K'

        with pytest.raises(TypeError):
            test_wrapper['W'] = 'L^2'

        with pytest.raises(TypeError):
            test_wrapper['X'] = 'M^-1'


    def test_simple_dynamic_evaluation(test_wrapper: MatrixWrapper) -> None:
        """Test that expression-defined matrices are evaluated dynamically."""
        test_wrapper['N'] = 'A^2'
        test_wrapper['O'] = '4B'
        test_wrapper['P'] = 'A+C'

        assert (test_wrapper['N'] == test_wrapper.evaluate_expression('A^2')).all()
        assert (test_wrapper['O'] == test_wrapper.evaluate_expression('4B')).all()
        assert (test_wrapper['P'] == test_wrapper.evaluate_expression('A+C')).all()

        assert (test_wrapper.evaluate_expression('N^2 + 3O') ==
                la.matrix_power(test_wrapper.evaluate_expression('A^2'), 2) +
                3 * test_wrapper.evaluate_expression('4B')
                ).all()
        assert (test_wrapper.evaluate_expression('P^-1 - 3NO^2') ==
                la.inv(test_wrapper.evaluate_expression('A+C')) -
                (3 * test_wrapper.evaluate_expression('A^2')) @
                la.matrix_power(test_wrapper.evaluate_expression('4B'), 2)
                ).all()

        test_wrapper['A'] = np.array([
            [19, -21.5],
            [84, 96.572]
        ])
        test_wrapper['B'] = np.array([
            [-0.993, 2.52],
            [1e10, 0]
        ])
        test_wrapper['C'] = np.array([
            [0, 19512],
```

```
            [1.414, 19]
        ])

        assert (test_wrapper['N'] == test_wrapper.evaluate_expression('A^2')).all()
        assert (test_wrapper['O'] == test_wrapper.evaluate_expression('4B')).all()
        assert (test_wrapper['P'] == test_wrapper.evaluate_expression('A+C')).all()

        assert (test_wrapper.evaluate_expression('N^2 + 3O') ==
                la.matrix_power(test_wrapper.evaluate_expression('A^2'), 2) +
                3 * test_wrapper.evaluate_expression('4B')
                ).all()
        assert (test_wrapper.evaluate_expression('P^-1 - 3NO^2') ==
                la.inv(test_wrapper.evaluate_expression('A+C')) -
                (3 * test_wrapper.evaluate_expression('A^2')) @
                la.matrix_power(test_wrapper.evaluate_expression('4B'), 2)
                ).all()


    def test_recursive_dynamic_evaluation(test_wrapper: MatrixWrapper) -> None:
        """Test that dynamic evaluation works recursively."""
        test_wrapper['N'] = 'A^2'
        test_wrapper['O'] = '4B'
        test_wrapper['P'] = 'A+C'

        test_wrapper['Q'] = 'N^-1'
        test_wrapper['R'] = 'P-4O'
        test_wrapper['S'] = 'NOP'

        assert test_wrapper['Q'] == pytest.approx(test_wrapper.evaluate_expression('A^-2'))
        assert test_wrapper['R'] == pytest.approx(test_wrapper.evaluate_expression('A + C - 16B'))
        assert test_wrapper['S'] == pytest.approx(test_wrapper.evaluate_expression('A^{2}4BA + A^{2}4BC'))


    def test_set_identity_error(new_wrapper: MatrixWrapper) -> None:
        """Test that MatrixWrapper().__setitem__() raises a NameError when trying to assign to the identity matrix."""
        with pytest.raises(NameError):
            new_wrapper['I'] = test_matrix


    def test_set_name_error(new_wrapper: MatrixWrapper) -> None:
        """Test that MatrixWrapper().__setitem__() raises a NameError when trying to assign to an invalid name."""
        for name in invalid_matrix_names:
            with pytest.raises(NameError):
                new_wrapper[name] = test_matrix


    def test_set_type_error(new_wrapper: MatrixWrapper) -> None:
        """Test that MatrixWrapper().__setitem__() raises a TypeError when trying to set a non-matrix."""
        invalid_values: List[Any] = [
                                     12,
                                     [1, 2, 3, 4, 5],
                                     [[1, 2], [3, 4]],
                                     True,
                                     24.3222,
                                     'This is totally a matrix, I swear',
                                     MatrixWrapper,
                                     MatrixWrapper(),
                                     np.array([[1, 2, 3], [4, 5, 6], [7, 8, 9]]),
                                     np.eye(100)
                                     ]

        for value in invalid_values:
            with pytest.raises(TypeError):
                new_wrapper['M'] = value
```

B.6 `matrices/utility/test_coord_conversion.py`

```
#  lintrans - The linear transformation visualizer
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#
```

```
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#  <https://www.gnu.org/licenses/gpl-3.0.html>

"""Test conversion between polar and rectilinear coordinates in :mod:`lintrans.matrices.utility`."""

from typing import List, Tuple

from numpy import pi, sqrt
from pytest import approx

from lintrans.matrices.utility import polar_coords, rect_coords

expected_coords: List[Tuple[Tuple[float, float], Tuple[float, float]]] = [
    ((0, 0), (0, 0)),
    ((1, 1), (sqrt(2), pi / 4)),
    ((0, 1), (1, pi / 2)),
    ((1, 0), (1, 0)),
    ((sqrt(2), sqrt(2)), (2, pi / 4)),
    ((-3, 4), (5, 2.214297436)),
    ((4, -3), (5, 5.639684198)),
    ((5, -0.2), (sqrt(626) / 5, 6.24320662)),
    ((-1.3, -10), (10.08414597, 4.583113976)),
    ((23.4, 0), (23.4, 0)),
    ((pi, -pi), (4.442882938, 1.75 * pi))
]


def test_polar_coords() -> None:
    """Test that :func:`lintrans.matrices.utility.polar_coords` works as expected."""
    for rect, polar in expected_coords:
        assert polar_coords(*rect) == approx(polar)


def test_rect_coords() -> None:
    """Test that :func:`lintrans.matrices.utility.rect_coords` works as expected."""
    for rect, polar in expected_coords:
        assert rect_coords(*polar) == approx(rect)

    assert rect_coords(1, 0) == approx((1, 0))
    assert rect_coords(1, pi) == approx((-1, 0))
    assert rect_coords(1, 2 * pi) == approx((1, 0))
    assert rect_coords(1, 3 * pi) == approx((-1, 0))
    assert rect_coords(1, 4 * pi) == approx((1, 0))
    assert rect_coords(1, 5 * pi) == approx((-1, 0))
    assert rect_coords(1, 6 * pi) == approx((1, 0))
    assert rect_coords(20, 100) == approx(rect_coords(20, 100 % (2 * pi)))
```

B.7 `matrices/utility/test_float_utility_functions.py`

```
# lintrans - The linear transformation visualizer
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"""Test the utility functions for GUI dialog boxes."""

from typing import List, Tuple

import numpy as np
import pytest

from lintrans.matrices.utility import is_valid_float, round_float

valid_floats: List[str] = [
    '0', '1', '3', '-2', '123', '-208', '1.2', '-3.5', '4.252634', '-42362.352325',
    '1e4', '-2.59e3', '4.13e-6', '-5.5244e-12'
]

invalid_floats: List[str] = [
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    '', 'pi', 'e', '1.2.3', '1,2', '-', '.', 'None', 'no', 'yes', 'float'
]


@pytest.mark.parametrize('inputs,output', [(valid_floats, True), (invalid_floats, False)])
def test_is_valid_float(inputs: List[str], output: bool) -> None:
    """Test the is_valid_float() function."""
    for inp in inputs:
        assert is_valid_float(inp) == output


def test_round_float() -> None:
    """Test the round_float() function."""
    expected_values: List[Tuple[float, int, str]] = [
        (1.0, 4, '1'), (1e-6, 4, '0'), (1e-5, 6, '1e-5'), (6.3e-8, 5, '0'), (3.2e-8, 10, '3.2e-8'),
        (np.sqrt(2) / 2, 5, '0.70711'), (-1 * np.sqrt(2) / 2, 5, '-0.70711'),
        (np.pi, 1, '3.1'), (np.pi, 2, '3.14'), (np.pi, 3, '3.142'), (np.pi, 4, '3.1416'), (np.pi, 5, '3.14159'),
        (1.23456789, 2, '1.23'), (1.23456789, 3, '1.235'), (1.23456789, 4, '1.2346'), (1.23456789, 5, '1.23457'),
        (12345.678, 1, '12345.7'), (12345.678, 2, '12345.68'), (12345.678, 3, '12345.678'),
    ]

    for num, precision, answer in expected_values:
        assert round_float(num, precision) == answer
```

B.8 matrices/utility/test_rotation_matrices.py

```
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"""Test functions for rotation matrices."""

from typing import List, Tuple

import numpy as np
import pytest

from lintrans.matrices import create_rotation_matrix
from lintrans.typing_ import MatrixType

angles_and_matrices: List[Tuple[float, float, MatrixType]] = [
    (0, 0, np.array([[1, 0], [0, 1]])),
    (90, np.pi / 2, np.array([[0, -1], [1, 0]])),
    (180, np.pi, np.array([[-1, 0], [0, -1]])),
    (270, 3 * np.pi / 2, np.array([[0, 1], [-1, 0]])),
    (360, 2 * np.pi, np.array([[1, 0], [0, 1]])),

    (45, np.pi / 4, np.array([
        [np.sqrt(2) / 2, -1 * np.sqrt(2) / 2],
        [np.sqrt(2) / 2, np.sqrt(2) / 2]
    ])),
    (135, 3 * np.pi / 4, np.array([
        [-1 * np.sqrt(2) / 2, -1 * np.sqrt(2) / 2],
        [np.sqrt(2) / 2, -1 * np.sqrt(2) / 2]
    ])),
    (225, 5 * np.pi / 4, np.array([
        [-1 * np.sqrt(2) / 2, np.sqrt(2) / 2],
        [-1 * np.sqrt(2) / 2, -1 * np.sqrt(2) / 2]
    ])),
    (315, 7 * np.pi / 4, np.array([
        [np.sqrt(2) / 2, np.sqrt(2) / 2],
        [-1 * np.sqrt(2) / 2, np.sqrt(2) / 2]
    ])),

    (30, np.pi / 6, np.array([
        [np.sqrt(3) / 2, -1 / 2],
        [1 / 2, np.sqrt(3) / 2]
    ])),
```

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        (60, np.pi / 3, np.array([
            [1 / 2, -1 * np.sqrt(3) / 2],
            [np.sqrt(3) / 2, 1 / 2]
        ])),
        (120, 2 * np.pi / 3, np.array([
            [-1 / 2, -1 * np.sqrt(3) / 2],
            [np.sqrt(3) / 2, -1 / 2]
        ])),
        (150, 5 * np.pi / 6, np.array([
            [-1 * np.sqrt(3) / 2, -1 / 2],
            [1 / 2, -1 * np.sqrt(3) / 2]
        ])),
        (210, 7 * np.pi / 6, np.array([
            [-1 * np.sqrt(3) / 2, 1 / 2],
            [-1 / 2, -1 * np.sqrt(3) / 2]
        ])),
        (240, 4 * np.pi / 3, np.array([
            [-1 / 2, np.sqrt(3) / 2],
            [-1 * np.sqrt(3) / 2, -1 / 2]
        ])),
        (300, 10 * np.pi / 6, np.array([
            [1 / 2, np.sqrt(3) / 2],
            [-1 * np.sqrt(3) / 2, 1 / 2]
        ])),
        (330, 11 * np.pi / 6, np.array([
            [np.sqrt(3) / 2, 1 / 2],
            [-1 / 2, np.sqrt(3) / 2]
        ]))
    ]


    def test_create_rotation_matrix() -> None:
        """Test that create_rotation_matrix() works with given angles and expected matrices."""
        for degrees, radians, matrix in angles_and_matrices:
            assert create_rotation_matrix(degrees, degrees=True) == pytest.approx(matrix)
            assert create_rotation_matrix(radians, degrees=False) == pytest.approx(matrix)

            assert create_rotation_matrix(-1 * degrees, degrees=True) == pytest.approx(np.linalg.inv(matrix))
            assert create_rotation_matrix(-1 * radians, degrees=False) == pytest.approx(np.linalg.inv(matrix))

        assert (create_rotation_matrix(-90, degrees=True) ==
                create_rotation_matrix(270, degrees=True)).all()
        assert (create_rotation_matrix(-0.5 * np.pi, degrees=False) ==
                create_rotation_matrix(1.5 * np.pi, degrees=False)).all()
```