CS 5635/6635 Spring Semester 2022 Assignment 4

Due Date: Friday, March 25, 2022

Vector Field Visualization

For **Part 1** of the assignment, we will use data from a simulation of air flow above a heated disk.

For **Part 2** of the assignment, we will use data that was created by the National Center for Atmospheric Research's Weather Research and Forecasting Model.
The Weather Research and Forecasting (WRF) Model is a next-generation mesoscale numerical weather prediction system designed for both atmospheric research and operational forecasting applications:

https://www.mmm.ucar.edu/weather-research-and-forecasting-model

We are going to visualize both scalar and vector fields of WRF forecast simulations of Hurricane Katrina's path:

ftp://ftp.ucar.edu/vapor/data/Katrina/

We are going to use one time step in the forecast simulation, which you can download from the class website:

https://my.eng.utah.edu/~cs6635/hurricanekatrina.vts.gz

This has been converted from WRF format to a format ParaView can read. After loading the Hurricane Katrina data set and clicking Apply, you will see four data fields (T, QCLOUD, QVAPOR, and Wind). T is the Temperature, QCLOUD is the cloud water mixing ratio, QVAPOR is the Column Water Vapor Content, and Wind is Wind Speed.

For **Part 3**, we will use simulation data of the air flow around a moving car.

You will use ParaView to visualize the vector field data in **Parts 1-3**.

Part 1: Streamline Visualization of Air Flow above Heated Disk using Glyphs [20 pts]

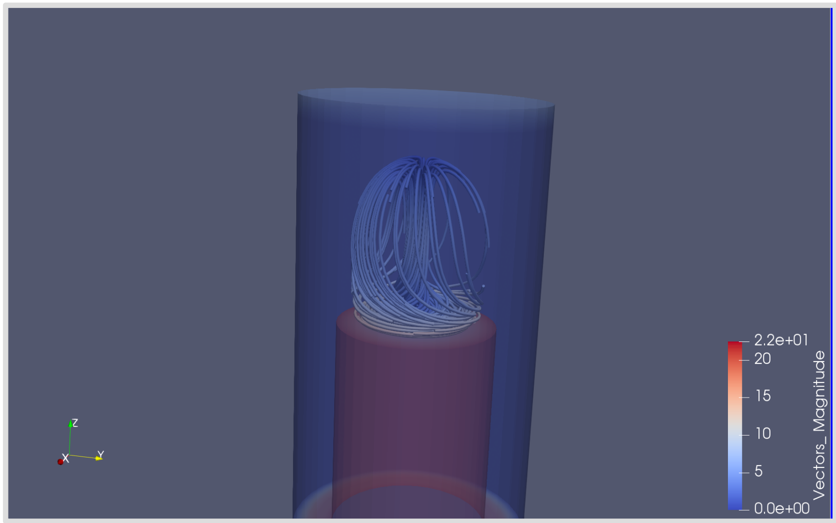
Load the dataset https://my.eng.utah.edu/~cs6635/Assignment4-output.vtu.gz

Find and apply the appropriate filter to:

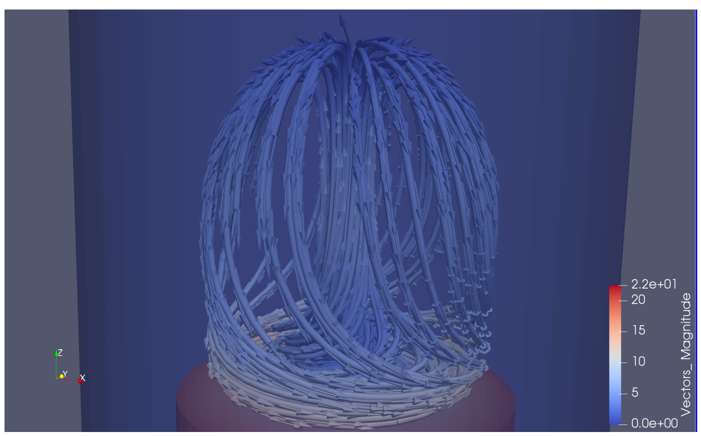
1. Extract streamlines using 'Point Source" seed type.
2. Enhance the rendering by using tubular surfaces.

Please include screenshots with appropriate title or caption, and a PSVM file.

If you got it right, you should be visualizing something like this:



Find and apply the appropriate filters to provide visual insights about the orientation and magnitude of the vector field in this region of space. This could be similar as follows:



Part 2: Hurricane Visualization [30 pts]

Step 1:

1. Create streamlines of the wind flow within the hurricane. Seed the streamlines so as to get a good overview of the flow.
2. Create stream tubes of the wind flow within the hurricane.
3. Add cone glyphs to the stream tubes so you can see direction of the flow (see pages 35-36 of the ParaView Tutorial).

Do this with two types of seeds (i.e. cloud vs. line) and describe the different trends you can identity in the data with different seed types such as rotation of flow or how the air travels into and out of the center of the hurricane.

Step 2:

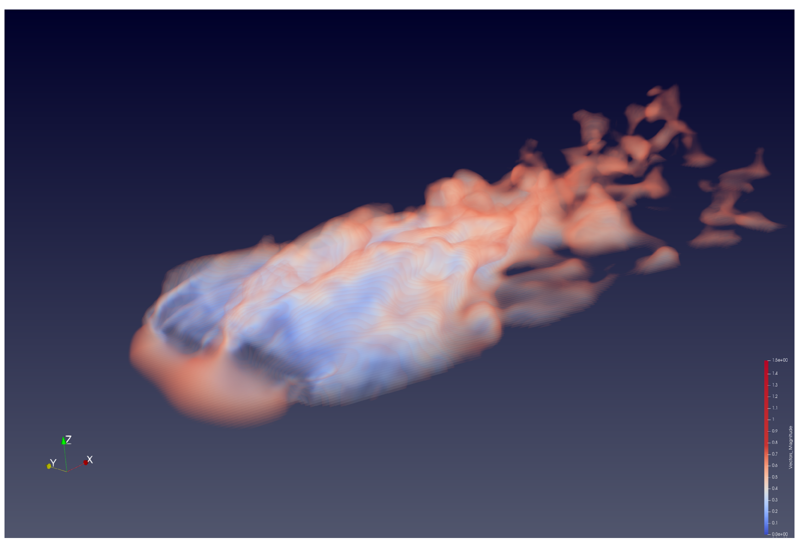
4. To see a big picture of the direction of the wind flow within the hurricane, create a visualization using arrow glyphs at randomly sampled places throughout the volume. You should use enough arrow glyphs to get a good overview, but not so many arrow glyphs that the view is cluttered.
5. Now scale the vectors proportional to their speed and add a colormap for the speed. What happens, why should we do this? Explain the flow in this visualization and compare to any trends you observed in Step 1.

<u>Please include screenshots with appropriate title or caption, and a PSVM file</u>

Part 3: Visualization of Air Flow around a Moving Car [30 pts]

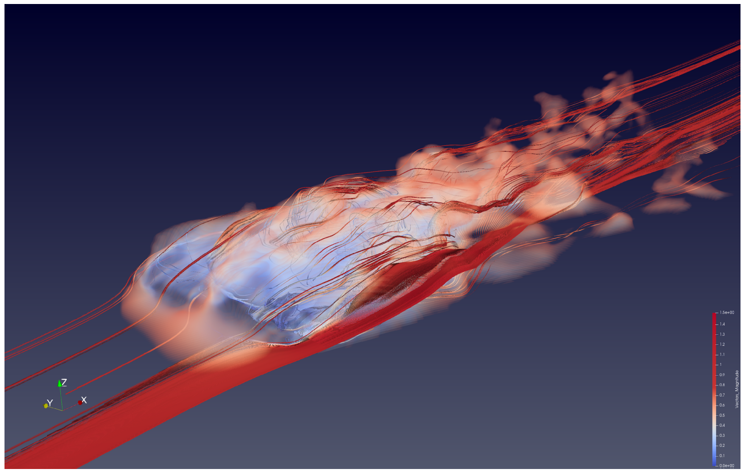
1. Load the dataset: https://my.eng.utah.edu/~cs6635/Assignment4-output.vti.gz

2. Design a transfer function for direct volume rendering of flow velocity magnitudes to create a visualization similar to the following (Red: relatively high magnitudes, Blue: relatively low magnitudes)



3. Apply the Stream Tracer filter to output.vti. Please orient a seed line orthogonal to the moving direction and keep it horizontal **before applying the filter.**

4. Apply the ribbon filter to stream lines. Set ribbon width parameter such that the resulting visualization has a pleasing appearance. Note the ribbons, in contrast to tubes, enable to better illustrate small-scale helicoidal trajectories (in turbulent areas). The image looks similar to the following:



5. Create visualizations similar to image in question 4 for **two more** seed configurations of your choice. Please include screenshots with brief description, and a PSVM file.

6. Note any interesting observations for flow visualizations.

Part 4: The Reading Questions [Chapter 12, visualization handbook] [20 pts] (Only for CS 6635 students)

Please answer succinctly in YOUR OWN words:

- DO NOT write the same thing as in the source material with only slight changes in phrasing.
- DO NOT simply rewrite the same sentences as in the source material.
- You should be aiming to *summarize*, maybe with a little bit of *paraphrasing*, and you can also use some *quotations*. But even if you are paraphrasing, it cannot be too similar to the source material. You should be able to write your answer without simultaneously looking at the original text. E.g., see this guide on appropriate paraphrasing/summarizing: https://owl.purdue.edu/owl/research_and_citation/using_research/quoting_paraphrasing_and_summarizing/index.html

1. What are steady and unsteady state flows? What are pathlines and streamlines?

2. Briefly describe any three classifications of vector-field visualization techniques.

3. State any three features for feature-based vector field visualizations. Describe any two features in detail. Why is feature-based visualization important for vector field data?

Extra Credit: Numerical Integration Methods [30 points]

We will be simulating the orbit of Earth around the Sun using our own implementations of Euler, RK-4, and Leapfrog integration methods. These are the same methods that work under the hood in ParaView to generate your visualizations such as stream lines. It is best to carefully review the lecture notes for Integration Techniques before attempting this.

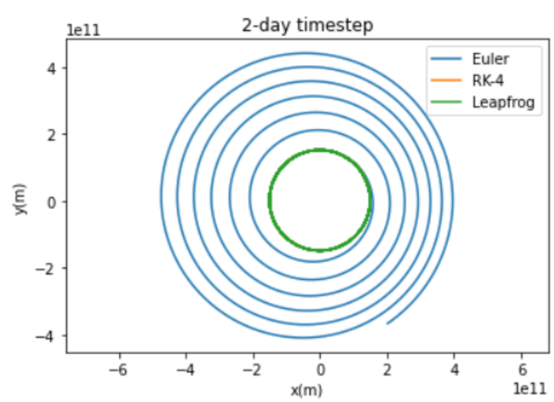
1. Create your ODE system for an orbit in 2D. It is best to write things in the form of state vector. In this case, your state vector is $u = [x, y, v_x, v_y]$. Additionally, you will need to use the equations $F = ma$ and $F = -\frac{Gm_1m_2}{r^2}\hat{r}, \hat{r}$ is a unit vector since you'll need the acceleration in x and y separately. It is also possible to do this problem with other coordinate systems, but we recommend cartesian. In code, this system can be written as a function with input of u and output $[v_x, v_y, a_x, a_y]$ at a given step using the previous equations to get a_x, a_y.
2. Write a function that takes one integration step for each method (Euler, RK-4, and Leapfrog). This means you want to update your state vector from u_i to u_{i+1}. You will need to call the previous function here.
3. Finally, write a function that steps through a given timeseries using your previous two functions.
4. We will be working in SI base units, i.e., meters-seconds-kilograms, keep your units straight. Our constants and initial conditions needed will be

$$
\begin{gathered}
G = 6.674 * 10^{-11} Nm^2kg^{-2} \\
M_{earth} = 5.97 * 10^{23} kg \\
M_{sun} = 1.98 * 10^{30} kg \\
d_{aphelion} = 1.52 * 10^{11} m \\
v_{aphelion} = 29290 ms^{-1}
\end{gathered}
$$

Note: 1 day is 86400 seconds and a year is 365 days. Per our units, you must the times in seconds.

5. Initial conditions: Given a timeseries starting at t = 0, ending at 20 years, with a timestep of two days and an initial state vector u_0 of $[0, d_{aphelion}, v_{aphelion}, 0]$,

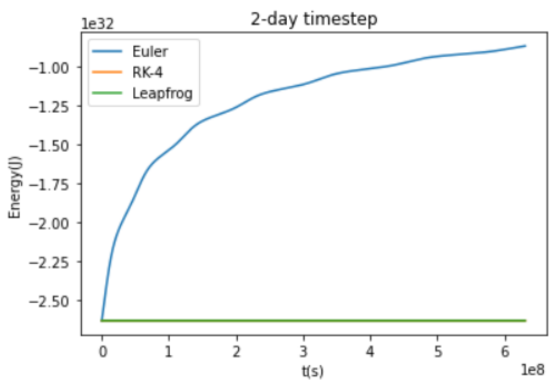
   Simulate this system using all three numerical methods and plot the timeseries of position in x-y space for all methods on one plot. It should look like this:

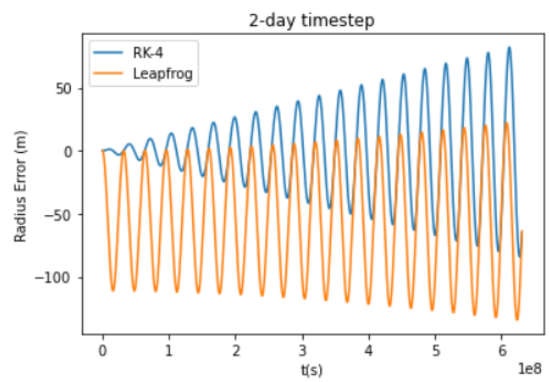


Note: You may have to round down by one step when making the timeseries if the end time isn't perfectly divisible by the timestep.

6. Plot the energy of these three systems over time. It is common to use a higher fidelity (smaller step size) to approximate the exact solution for the error. Run RK-4 again but use a step size of $\frac{1}{16}$ days instead of two. Using this as the exact solution, compare the error of the radius of leapfrog and the low fidelity RK-4. These should look like the plots below:

$$E_{tot} = KE + PE = \frac{1}{2}M_e v^2 - \frac{GM_eM_s}{r}$$

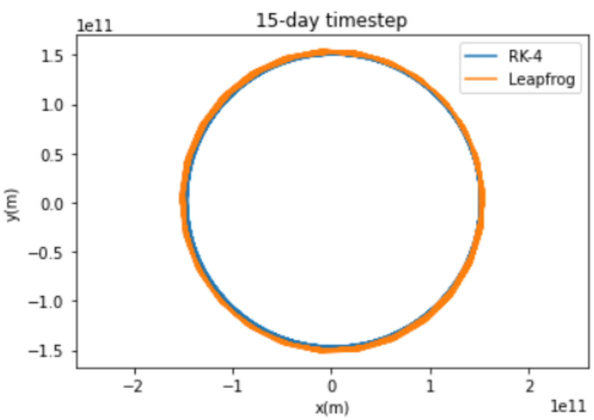


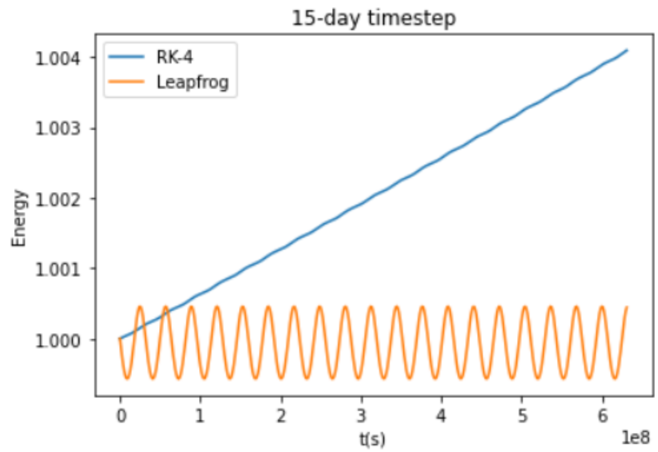


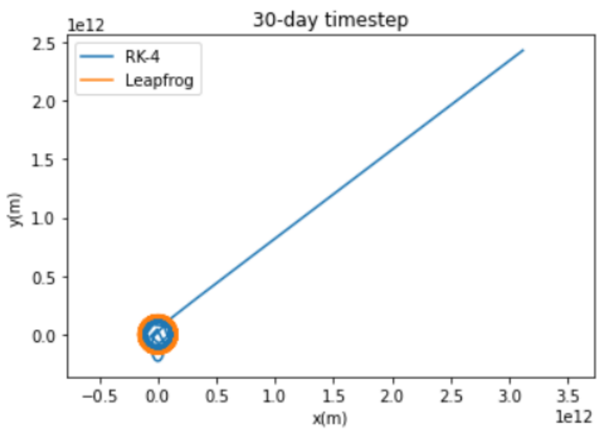
Describe what you can tell from these three plots and why would we want to visualize them? Why is energy negative? What do you think of Euler vs. RK-4 vs. leapfrog?

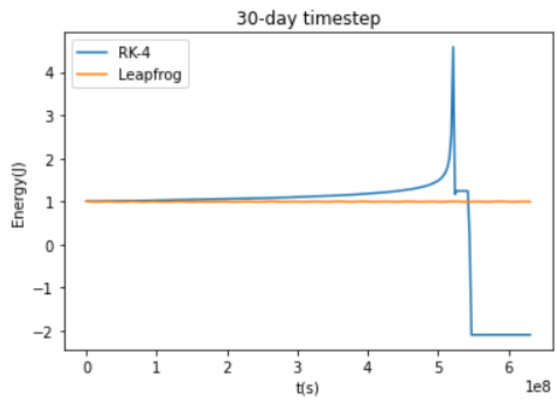
7. Now, run RK-4 and leapfrog for an initial state vector of $[0, d_{aphelion}, v_{aphelion}, 500]$. Run for 20 years as before but now try two more timesteps of 15 days and 30 days. To see the difference between a symplectic integrator and non-symplectic we must use larger timesteps and or timescales. We increase the timestep and not the timescale here because in the other case it would be very computationally expensive. Show the position and energy over time for these systems as before. Also, normalize the energy by the initial energy.

They should look like:









Describe what you see. Compare with all three timesteps (2, 15, 30 days), what happened? Analyze the interplay between the non-symplectic 4th order of accuracy of RK-4 and the symplectic 2nd order accuracy of leapfrog using the plots we made as evidence. **Include the code in your submission.**

What to turn in:

Write a ***short*** report documenting your results, including any necessary plots/figures, and answering any questions asked above. Be sure to explain any figures you submit and to write a **conclusion** at the end of your report. Explanation of a figure should be close to the actual figure. In the Discussion section, compare and contrast results and note any interesting observations when exploring data. You can also elaborate on challenges faces when implementing the project. In the conclusion tell us what you learned from this assignment and add references, if any.

Your homework is primarily graded upon your report. Please submit your report on Canvas in PDF format. Submit your code and any other files in a ZIP archive. Your PDF and ZIP should be separate on Canvas.

Note: Any figures/plots in the report should be captioned appropriately. Also be sure to include axis labels in all plots.