Team 4

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E0271 – GRAPHICS & VISUALIZATION

VISUALIZATION OF VORTEX SHEDDING BEHAVIOUR IN 3D FLOW AROUND A SQUARE CYLINDER USING TRACKING GRAPHS

भारतीय विज्ञान संस्थान

Masavir

AGENDA

- Introduction to Background
- Motivation
- Difficulties & Challenges in Existing Problem
- Problem Identification
- Problem Statement
- Objective
- Approach
- Work done
- Results & Discussion
- Conclusion
- Discussion on Difficulties & Challenges Faced
- Scope for Improvement

PROBLEM WITH LARGE SCIENTIFIC DATASETS

- Identifying and Tracking Features from Large Scientific Data is Challenging
  - Scientific simulations produce large datasets
  - Challenges when using large datasets…
    - Analyzing features
    - Understanding temporal evolution
  - Combustion or Fluid flow simulations
    - TB size data sets
    - Several hundred timesteps
    - Burning of premixed hydrogen
    - 100 timesteps & 400GB in size
  - Can we Identify & track the important regions in time from the large dataset?

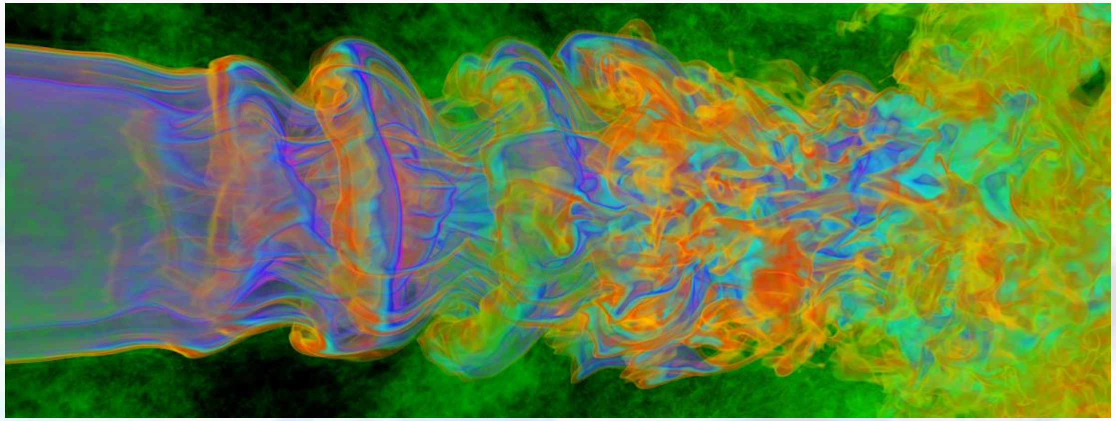

Image Source: https://www.nvidia.com/en-gb/data-center/index-paraview-plugin/

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DIFFICULTIES & CHALLENGES IN EXISTING PROBLEM

- Exploring and analyzing the spatio-temporal evolution of features in largescale time-varying datasets is a common problem in many areas of science and engineering
- For practical data sets creating the corresponding optimal graph layouts that minimize the number of intersections can take hours to compute with existing techniques.
- Defining, extracting and analyzing features in the increasingly large and complex datasets produced by state of the art simulations still poses a significant challenge.
- Furthermore, the resulting graphs are often unmanageably large and complex even with an ideal layout.
- Finally, due to the cost of the layout, changing the feature definition, e.g. by changing an iso-value, or analyzing properly adjusted sub-graphs is infeasible.
- Coupling the corresponding analysis across time steps to understand the temporal evolution of such features increases the difficulty exponentially

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DIFFICULTIES & CHALLENGES IN EXISTING PROBLEM

- First, a temporal analysis multiplies the amount of data that must be considered simultaneously, often exceeding available memory and other resources.
- Second, the resulting data potentially contain information about thousands of features across hundreds of time steps making it challenging to present them in a comprehensible manner.
- Finally, for all but the smallest datasets, even assuming an optimal layout, graphs quickly become too large and convoluted for users to understand.
- Consequently, most existing techniques to visualize and explore time-varying datasets have primarily focused on high dimensional projections, illustration, and change detection

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MOTIVATION

- A new framework that couples hierarchical feature definitions with progressive graph layout algorithms to provide an interactive exploration of dynamically constructed tracking graphs.
- The system enables users to change feature definitions on-the-fly and filter features using arbitrary attributes while providing an interactive view of the resulting tracking graphs.
- Furthermore, the graph display is integrated into a linked view system that provides a traditional 3D view of the current set of features and allows a cross-linked selection to enable a fully flexible spatio-temporal exploration of data.
- Abstract model showing the time evolution of features with interactive modification of their characterization

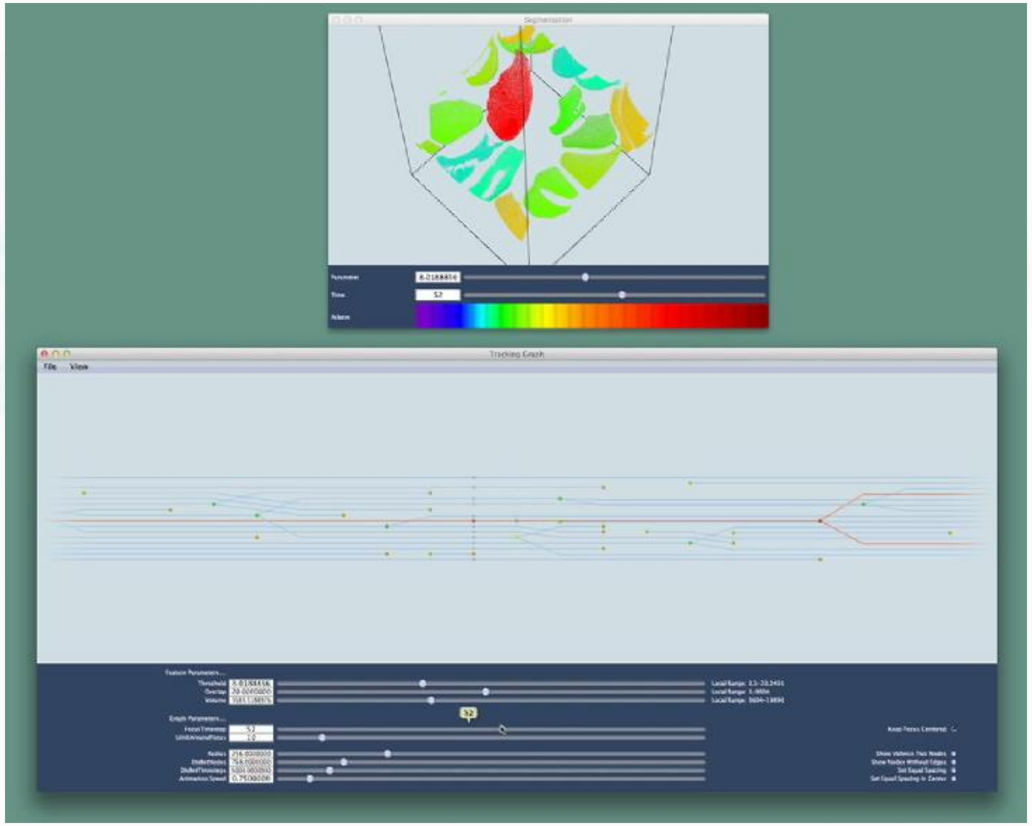

Image Source: Widanagamaachchi et. Al.

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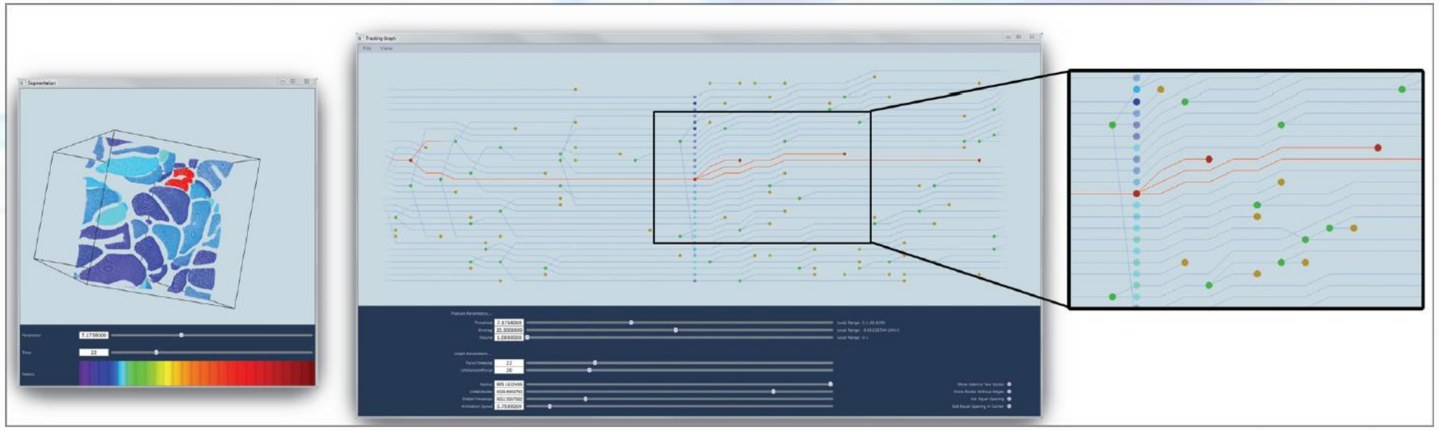
MOTIVATION

A system which allows

- Exploration of features
- Progressive layouts of Graphs
- Modification of feature attributes & correlation criteria
- Interactivity for TB size data
- Mapping dynamics of the dataset with the visualization
- Identification of region of interest

Image Source: Widanagamaachchi et. Al.



INTRODUCTION TO BACKGROUND

- Tracking Graph
- Contour Tree or Merge Tree
- Contour plot vs Contour Tree
- Vortex, Vorticity, Vortex Shedding & Von- Kármán vortex street
- Difference between Eddy & Vortex
- Types of Flow Regimes

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TRACKING GRAPH

- One natural representation of large data is tracking graphs, i.e., constrained graph layouts that use one spatial dimension to indicate time and show the "tracks" of each feature as it evolves, merges or disappears.
- Conceptually, the most natural representation of such data is a tracking graph showing the evolution of all features across time as a collection of feature tracks that may merge or split.
- Given some feature definition a graph is constructed by first extracting all features from all time steps and then correlating those features across time, for example, by considering their spatial overlap

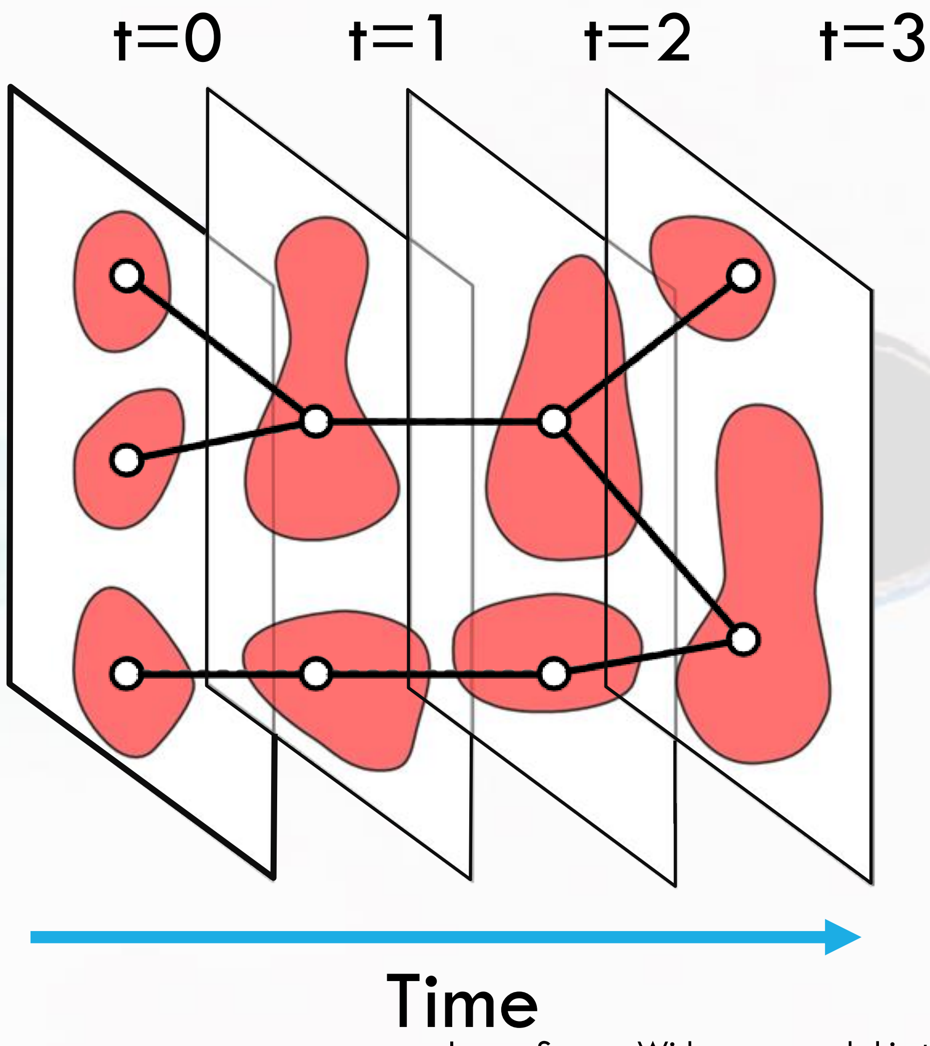

Image Source: Widanagamaachchi et. Al.

CONTOUR PLOT VS MERGE TREE

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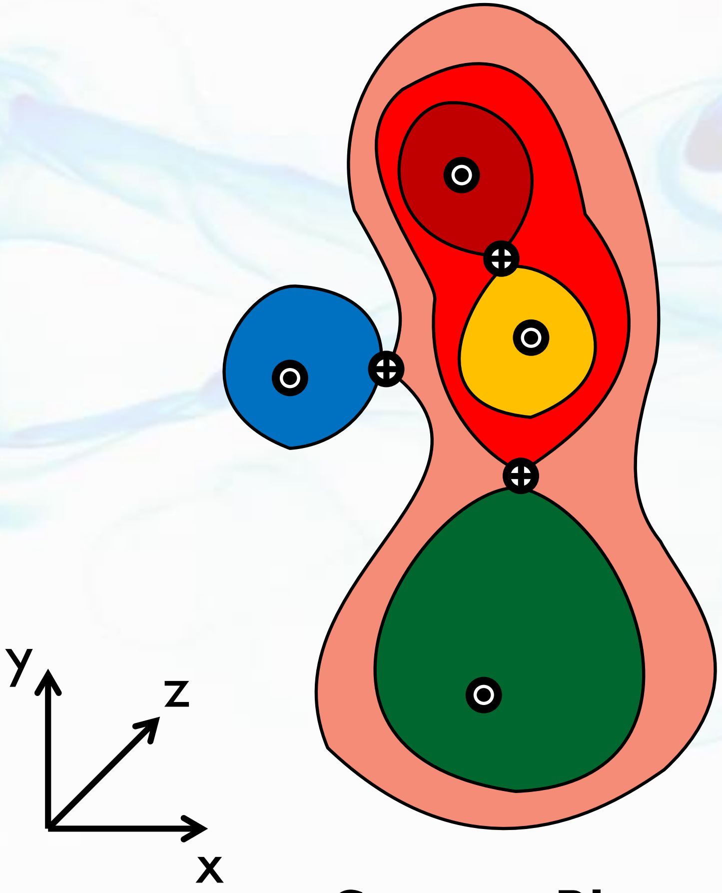
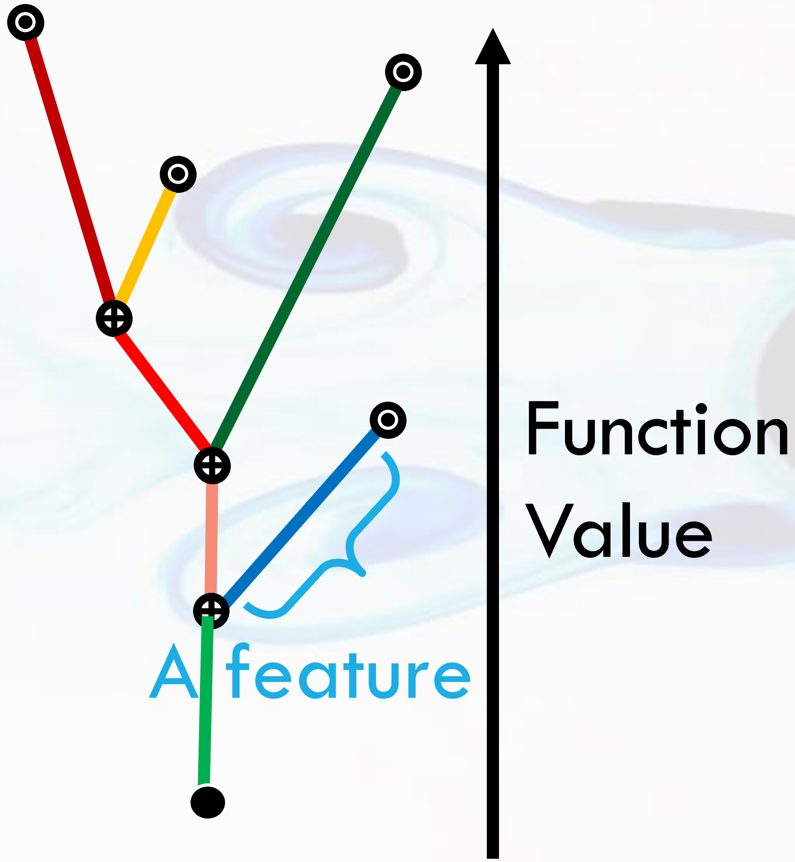
- Contour Plot vs Merge Tree



Contour Plot



Contour Tree or Merge tree

Image Source: Widanagamaachchi et. Al.

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TRACKING GRAPH WITH MERGE TREES

- Tracking Graph with Merge Trees

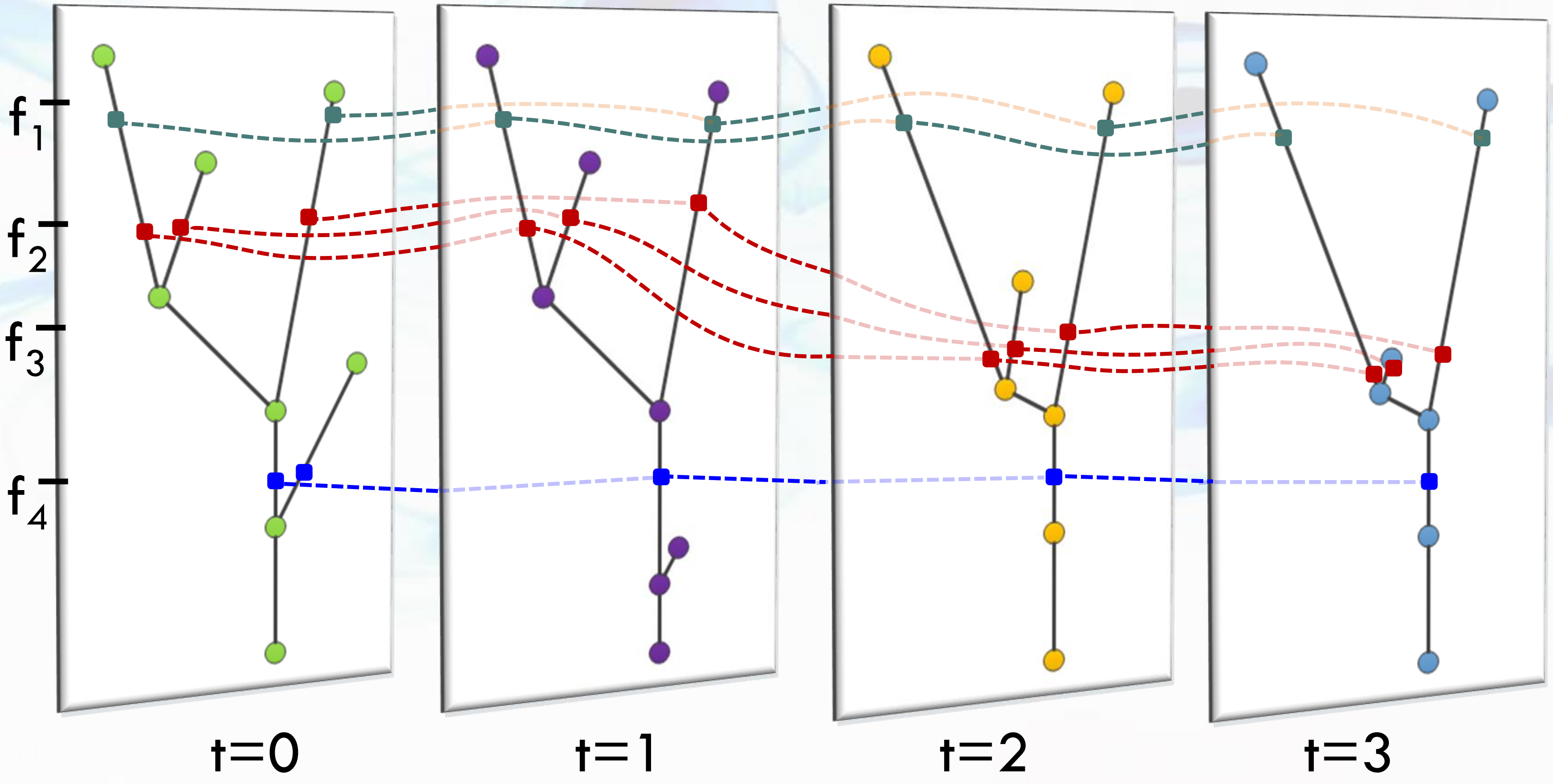

Image Source: Widanagamaachchi et. Al.

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VORTEX & VORTICITY

- In fluid dynamics, a vortex (plural vortices/vortexes) is a region in a fluid in which the flow revolves around an axis line, which may be straight or curved.
- A key concept in the dynamics of vortices is the vorticity, a vector that describes the local rotary motion at a point in the fluid, as would be perceived by an observer that moves along with it.
- Vortices form in stirred fluids, and may be observed in smoke rings, whirlpools in the wake of a boat, and the winds surrounding a tropical cyclone, tornado or dust devil.
- Vortices are a major component of turbulent flow.
- The distribution of velocity, vorticity (the curl of the flow velocity), concept of circulation are used to characterize vortices.
- In most vortices, the fluid flow velocity is greatest next to its axis and decreases in inverse proportion to the distance from the axis.
- Once formed, vortices can move, stretch, twist, and interact in complex ways.
- A moving vortex carries some angular and linear momentum, energy, and mass, with it.

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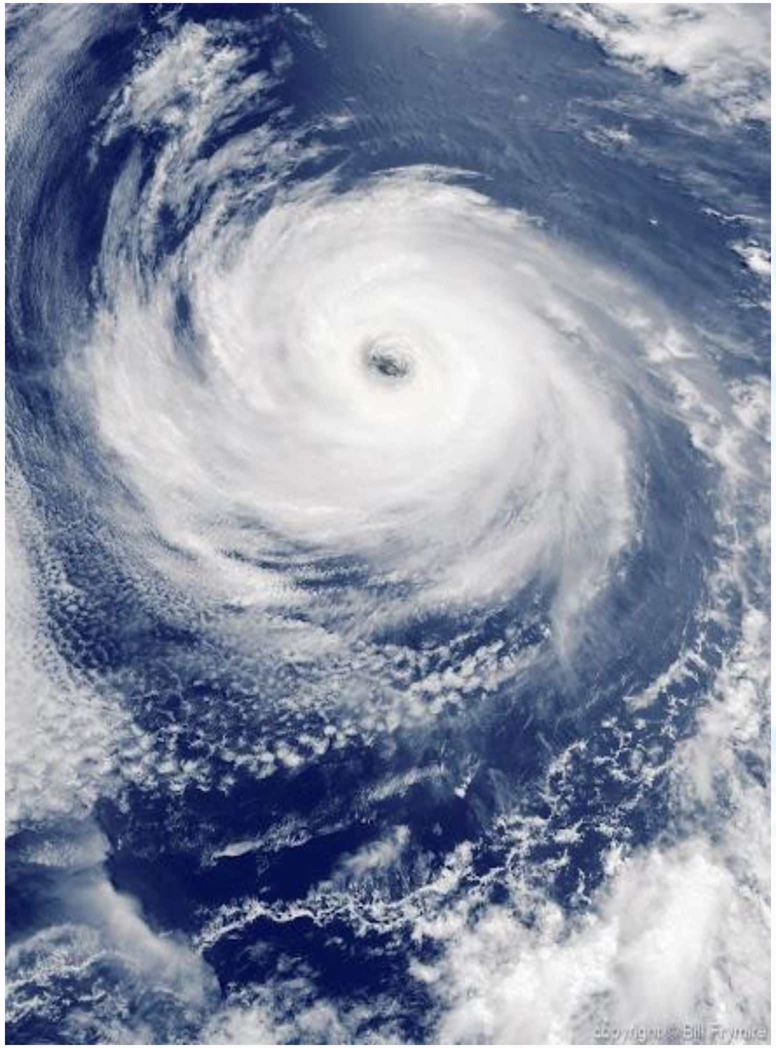
VORTEX & VORTICITY

Image Source: Google Images



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VORTEX SHEDDING

- In fluid dynamics, vortex shedding is an oscillating flow that takes place when a fluid such as air or water flows past a bluff (as opposed to streamlined) body (body that, as a result of its shape, has separated flow over a substantial part of its surface) at certain velocities, depending on the size and shape of the body.
- In this flow, vortices are created at the back of the body and detach periodically from either side of the body forming a Von Kármán vortex street.
- The fluid flow past the object creates alternating low-pressure vortices on the downstream side of the object.
- Vortex Shedding is characterized by Strouhal Number given by, $St = \frac{f\,D}{V}$

where St is the dimensionless Strouhal number, f is the vortex shedding frequency (s^{-1}), D is the diameter of the cylinder (m), and V is the flow velocity (ms^{-1}).

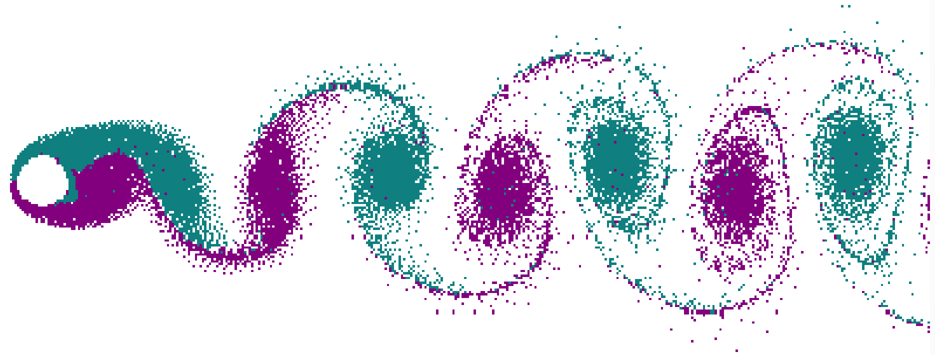

Image Source: Wikipedia

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VON KÁRMÁN VORTEX STREET

- In fluid dynamics, a Kármán vortex street (or a von Kármán vortex street) is a repeating pattern of swirling vortices, caused by a process known as vortex shedding, which is responsible for the unsteady separation of flow of a fluid around blunt bodies.
- A vortex street will form only at a certain range of flow velocities, specified by a range of Reynolds numbers (Re), typically above a limiting Re value of about 90.
- The (global) Reynolds number for a flow is a measure of the ratio of inertial to viscous forces in the flow of a fluid around a body or in a channel which defines the flow to be either Laminar or Turbulent flow
- It may be defined as a nondimensional parameter of the global speed of the whole fluid flow: $\boldsymbol{Re = \frac{\rho\, V\, D}{\mu}}$
- Where ρ is the density of the fluid medium, V is the fluid velocity, D is the Characteristic Dimension of the body, μ is the viscosity of the fluid.

Image Source: Wikipedia

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DIFFERENCE BETWEEN EDDY & VORTEX

- Vortex
  - Vortex is nothing but its a kind of motion of fluid which involves vorticity. Means the fluid elements rotate about its center.
  - There is an angular velocity vector that is associated with that fluid element.
  - Each fluid element continuously keep rotating and deforming too because of shear stress.
- Eddy
  - In fluid dynamics, an eddy is the swirling of a fluid and the reverse current created when the fluid is in a turbulent flow regime.
  - The moving fluid creates a space devoid of downstream-flowing fluid on the downstream side of the object.
  - consider a turbulent flow in which the separation is taking place.
  - Due to separation, the flow downstream produces what we call eddies. it means the fluid elements are already having the vorticity but in addition these fluid elements are circulating locally downstream of the separation point.
  - So these eddies are nothing but circulation or spinning of fluid elements in curvilinear fashion.

STEADY VS UNSTEADY || LAMINAR VS TURBULENT

- Steady vs Unsteady Flow
  - Steady Flow: A flow whose properties are not a function of time is called steady flow. Steady-state flow refers to the condition where the fluid properties at a point in the system do not change over time.
  - Unsteady Flow: Time dependent flow is known as unsteady (also called Transient). Turbulent flows are unsteady by definition. A turbulent flow can, however sometimes, be statistically stationary.
- Laminar vs Turbulent Flow
  - Laminar Flow: Laminar flow or streamline flow in pipes (or tubes) occurs when a fluid flows in parallel layers, with no disruption between the layers. In laminar flow, the motion of the particles of the fluid is very orderly with all particles
  - Turbulent Flow: Turbulence is flow characterized by recirculation, eddies, and apparent randomness or chaos. The presence of eddies or recirculation n alone does not necessarily indicate turbulent flow. flow regime characterized by chaotic property changes. This includes rapid variation of pressure and flow velocity in space and time

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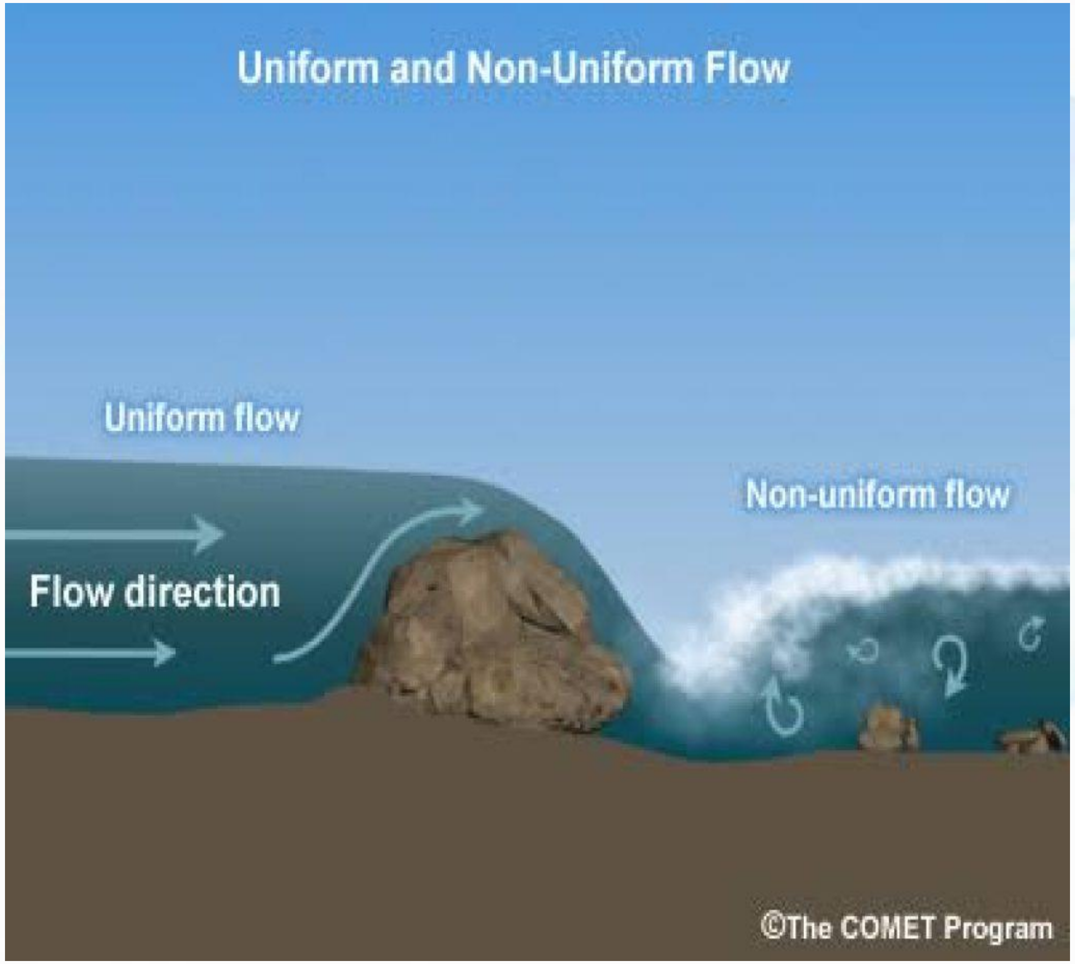
TYPES OF FLOW REGIMES



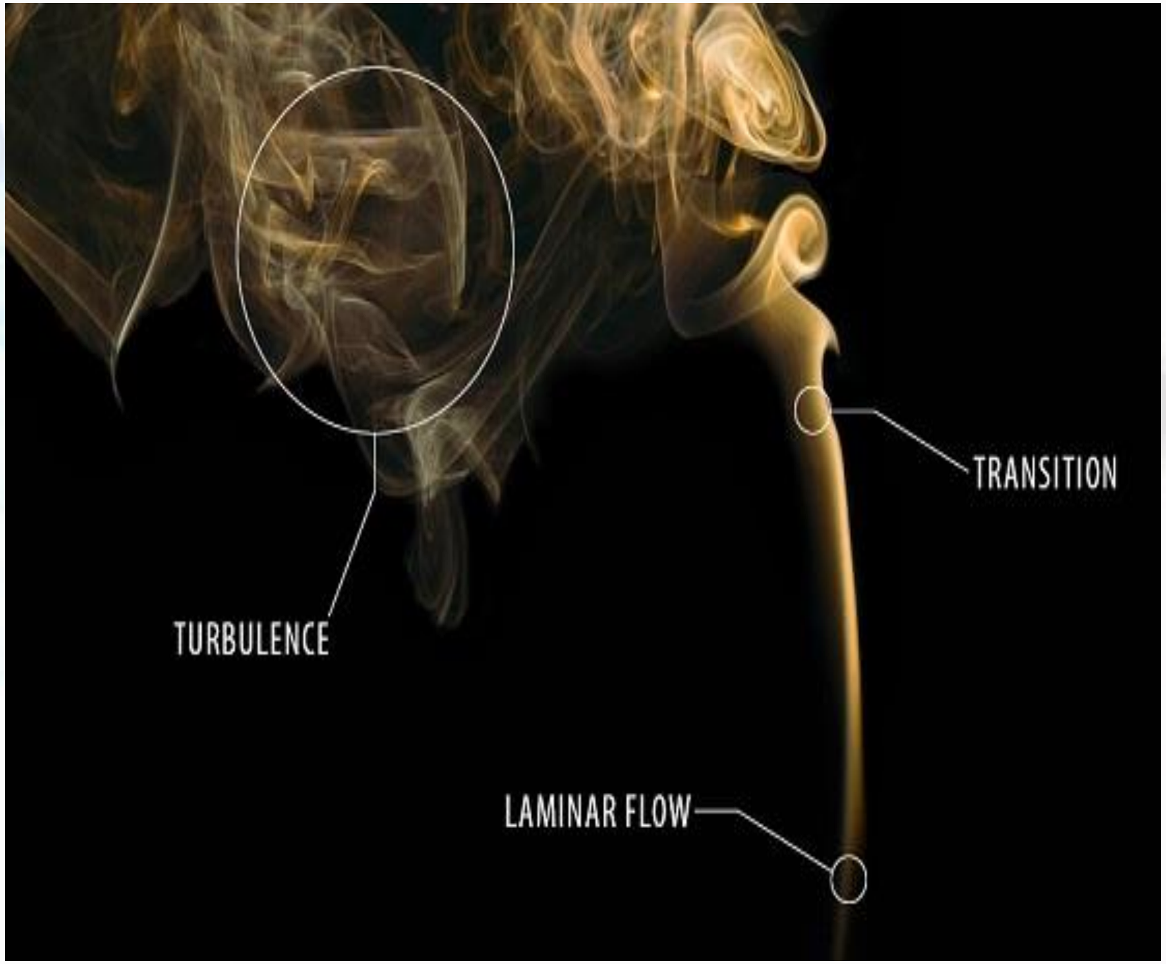


Image Source: Google Images

PROBLEM STATEMENT

- One Engineering area pertaining to the problem of large datasets is the Fluid Mechanics & Combustion Dynamics where the flow of fluids particularly gases have the propensity to demonstrate chaotic unsteady turbulent behavior.
- Advanced Simulations can predict the behavior of the fluids in situations when measuring data in experiments becomes difficult
- The main outcome of doing this lies not only in just solving the Fluid Flow RANS equations but understanding the resulting data of Velocity & Pressure.
- The problem with that is simulations generate mountains of data which makes it difficult & even impossible for the human mind to process them.
- Hence better visualization strategies are needed to understand the data & the spatio-temporal feature attributes.
- Hence we aim to develop a strategy that helps in a streamlined understanding of large dataset & able to track certain physical phenomenon of interest like the Vortex Shedding behavior in the Fluid flow around a Bluff body.

Phani

OBJECTIVE

- To Develop Visualizations that demonstrates the Spatial-Time Evolving Features in 3D Flow around a Confined Cylinder dataset using the concept of Tracking Graph
- To able to track the transition from Laminar to Turbulent flow regime along the different timesteps
- To figure out the important subset region of interest out of the entire set of 4D volume of data 192x64x48x102
- To understand the behaviour of Vortex Shedding Phenomenon (Von Kármán Vortex Street) by tracking each & every vortex separately
- To understand how different Visualization techniques perform under the increasing unsteadiness of the fluid flow
- To demonstrate the Streamlines, Glyphs, Sliced Representation & Pathlines in a 3D Visualization

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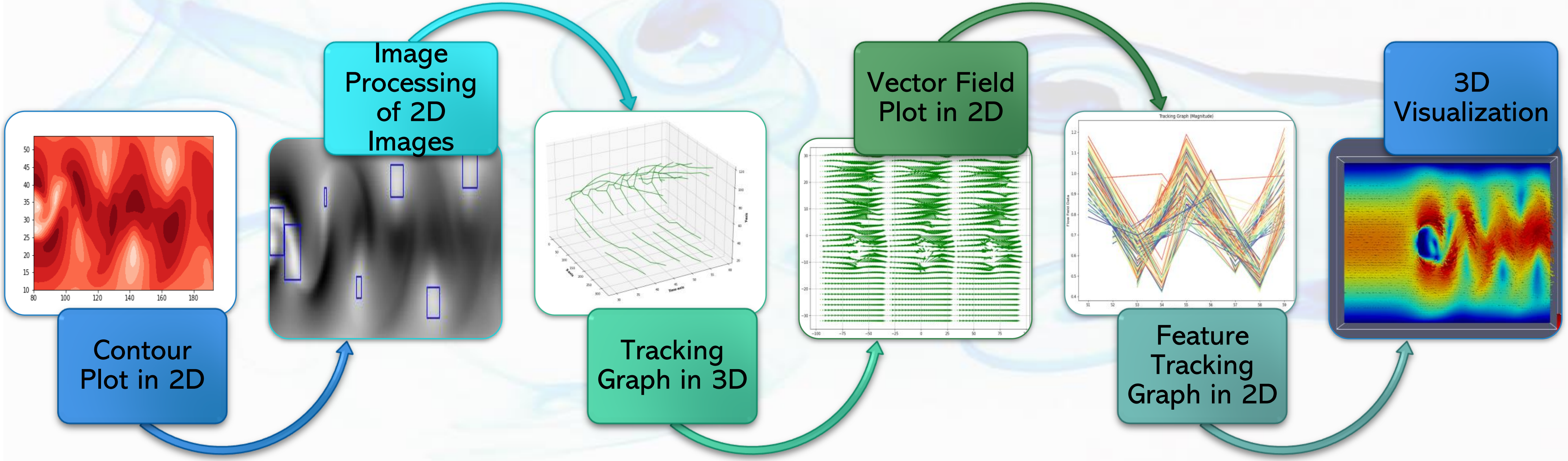
APPROACH



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WORK DONE

S. No.	Work Done	Why?	Tools Used
1.	Exploring Dataset – 3D Flow around a confined Square Cylinder	To Read the Amira mesh format & convert to data files & then covert to VTK file format	C++, Amira mesh
2.	Contour Plot for all the 102 timesteps with span of 192 x 64 for a mid plane Z slice = 24	To identify the various feature regions in the dataset including vortex & visualize the Von Karman Street Phenomenon	Python, Matplotlib
3.	Image Processing of all the Contour Plots	To identify & track the movement of each and every vortex separately	Python, OpenCV
4.	Tracking Graph in 3D	To plot the birth & death of vortex & visualize the Vortex Shedding	Python, Matplotlib

Phani

WORK DONE

S. No.	Work Done	Why?	Tools Used
5.	Vector Field Plot	To deduce the region of interest to focus more on to identify the behaviour of one vortex	Python, Matplotlib
6.	Feature Tracking Graph in 2D	To identify the critical timestep & region of interest & the pattern of repetitive behaviour of the Vortex	Python, Matplotlib
7.	VTK File Dataset	To convert the data files created earlier into VTK file format – Structured Points + Vector Field	C++
8.	3D Visualization of Vector Field & Streamlines	To Visualize the Behaviour of Laminar & Turbulent flow behaviour at a particular timestep	VTK, Paraview

Phani

DATASET - 3D FLOW AROUND A CONFINED SQUARE CYLINDER

- This is a 3D time-dependent flow field resampled onto a uniform structured grid of 192 x 64 x 48 for 102 timesteps.
- It is an incompressible solution with a Reynolds number of 200 and the square cylinder has been positioned symmetrically between two parallel walls.
- The flow has periodic boundary conditions in spanwise Z-direction. It exhibits periodic vortex shedding leading to the well known von Kármán vortex street.
- In contrast to most flow data sets, this simulation is initiated from an impulsive start-up and the periodic vortex shedding develops with time.
- In order to show the alternating behavior of the vortex shedding, two smoke surfaces were seeded such that the red one passes above the cylinder and the blue one passes below.
- Each time step is written as a single file in AmiraMesh format.

Dataset Courtesy: S.Camarri, M.-V. Salvetti, M. Buffoni, and A. Iollo. Simulation of the three-dimensional flow around a square cylinder between parallel walls at moderate Reynolds numbers. In *XVII Congresso di Meccanica Teorica ed Applicata*, 11-15 September 2005, Firenze

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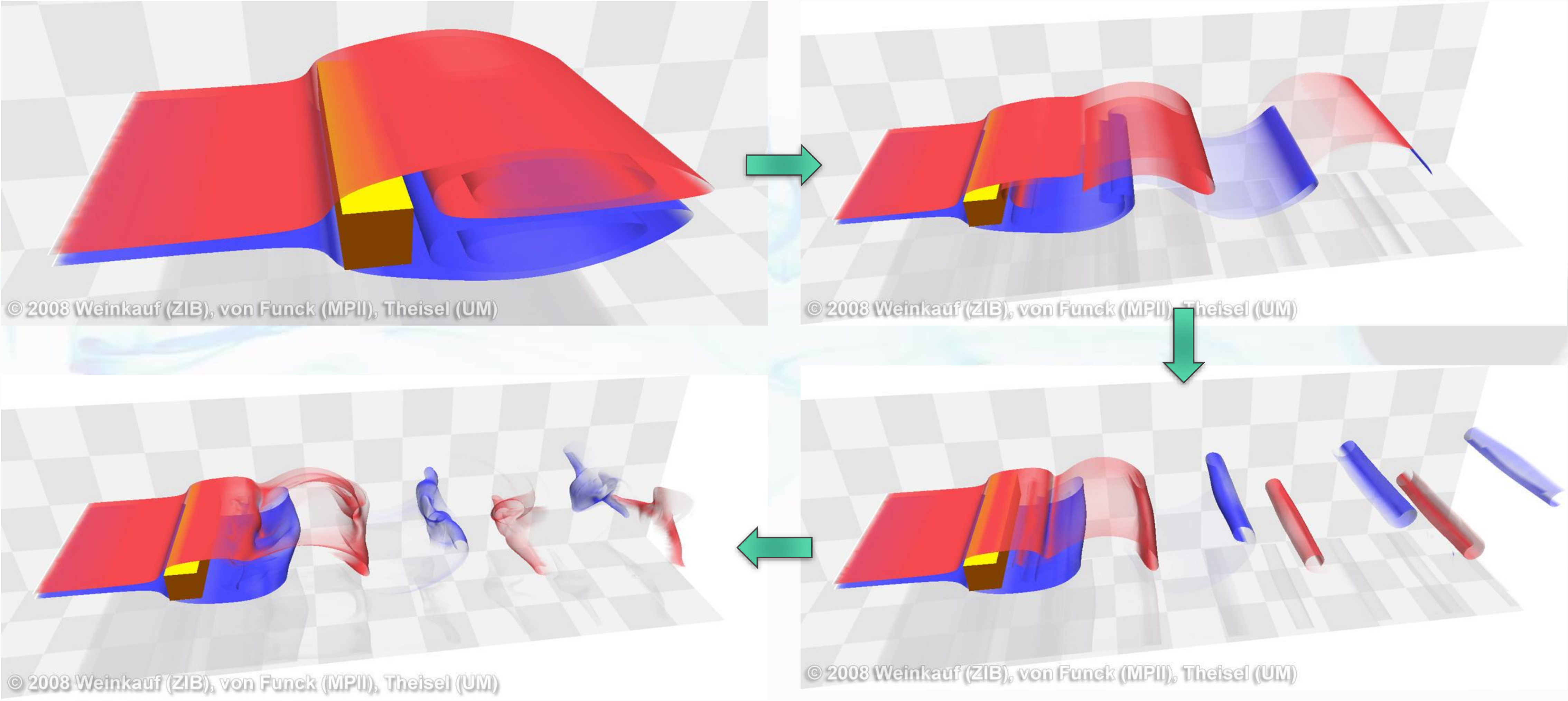
DATASET - 3D FLOW AROUND A CONFINED SQUARE CYLINDER



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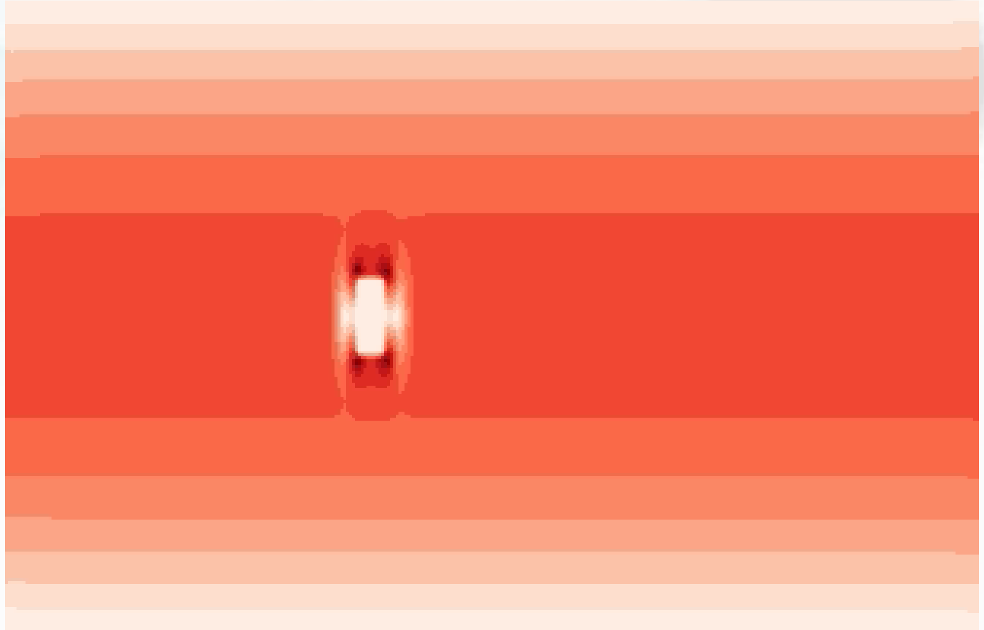
CONTOUR PLOT

- A 2D Slice along the Z axis was taken at the midplane section as the flow has periodic boundary conditions in the spanwise direction
- A 10 level iso contour plot was plotted & animated to see the generation of vortex & the vortex shedding behaviour leading to a Von Karman Vortex Street.
- Vortex have higher velocity vector close to the axis of rotation which is evident from the dark patches at the centre of each vortex being generated
- As the fluid hits the square cylinder a sudden drop in velocity can be seen by the white region in front of the block
- The top & bottom region of the square cylinder experience maximum velocity & the separation of flow can be visualized by the large formation of dark region
- As the vortex loses its energy, the vector field can be observed to be dissipating seen by the lightening of the dark regions towards white



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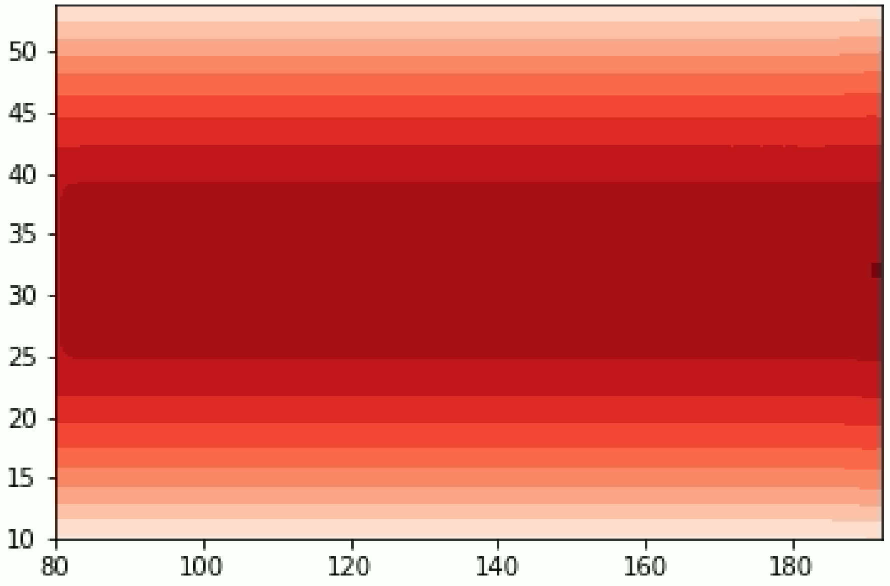
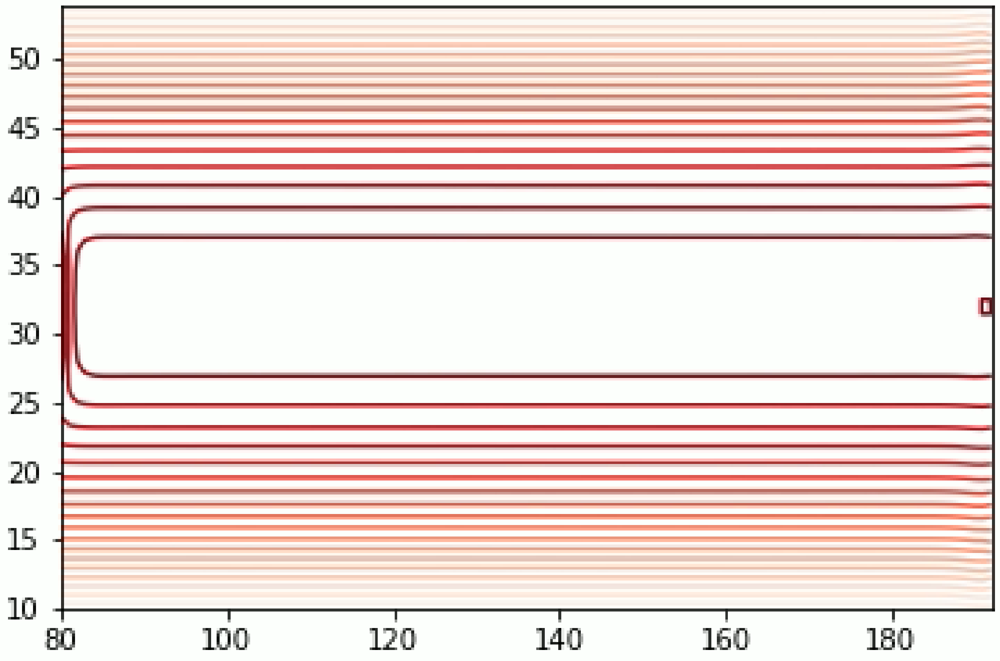
CONTOUR PLOT



Coloured Surface Plot

Coloured Contour Plot

- The vortex shedding starts to happen after a little time from the moment when the flow separation starts to happen.



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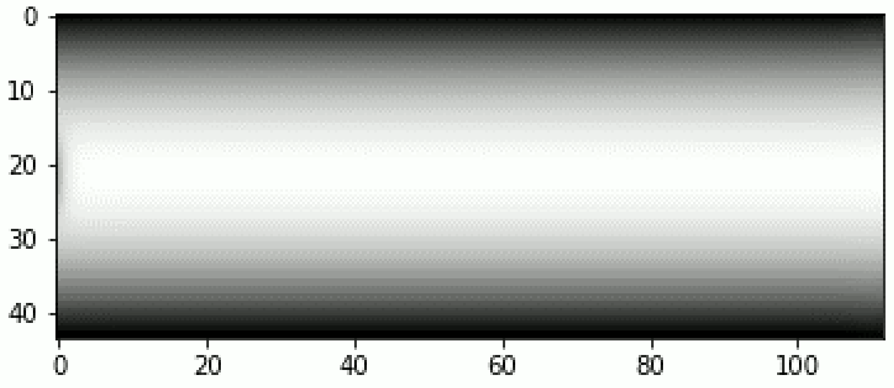
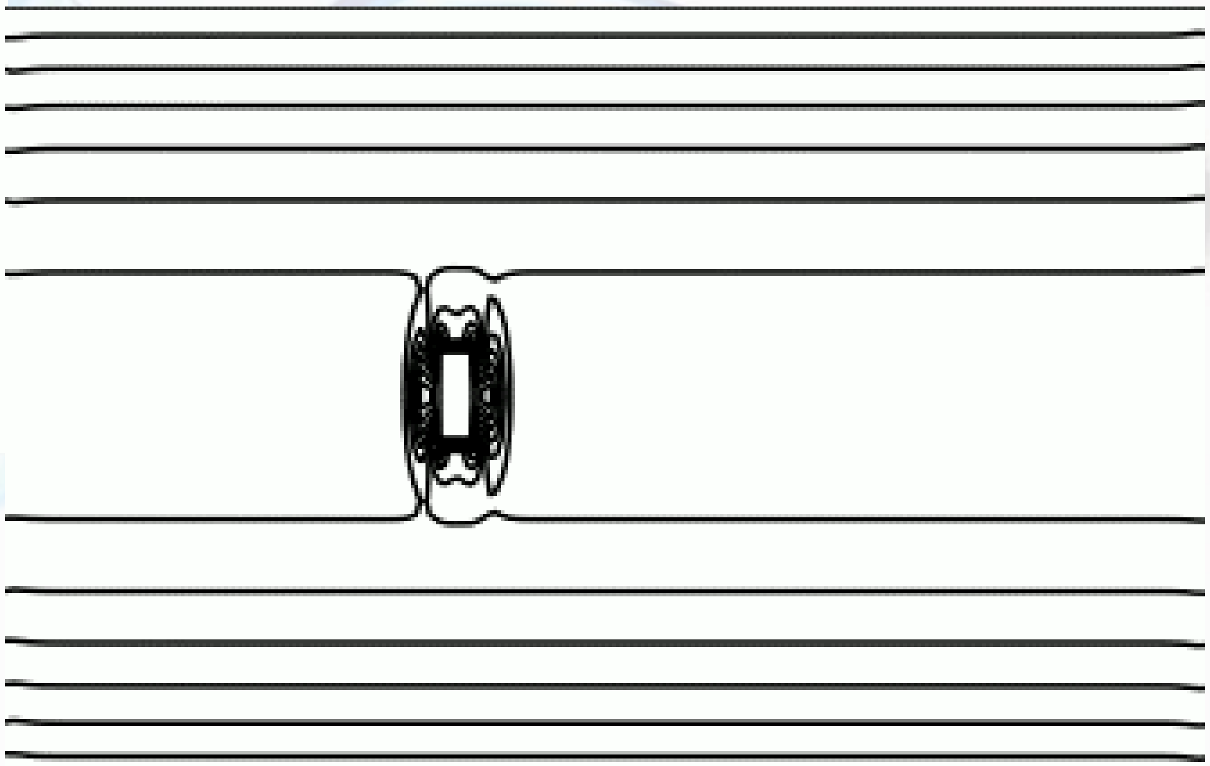
CONTOUR PLOT



Binary Smoke Surface Plot

Binary Contour Plot



- The alternating behaviour of vortex formation & the eddy motion can be clearly seen here

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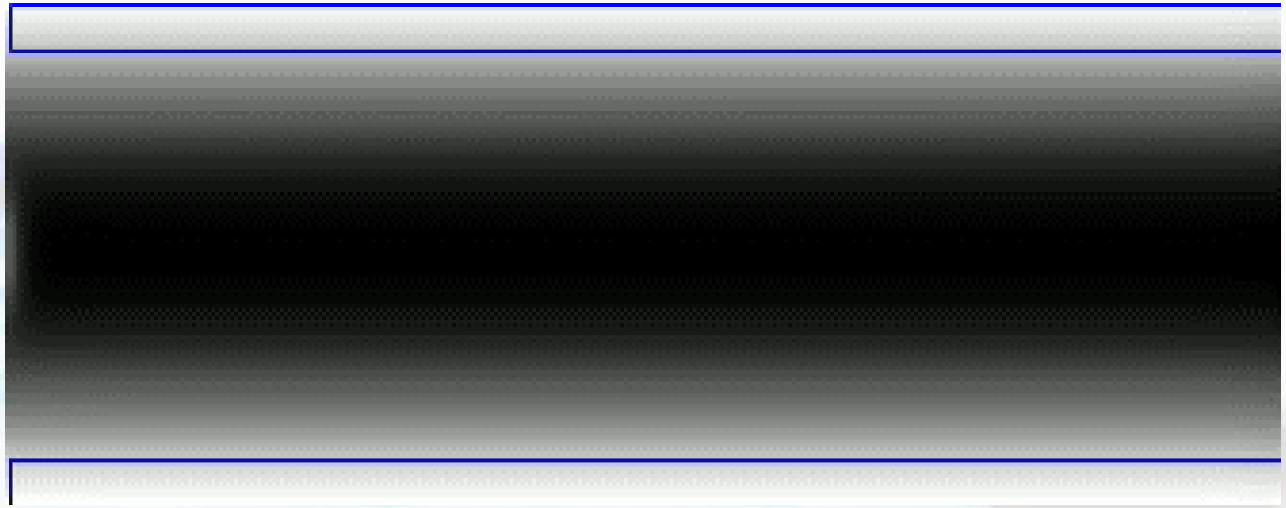
IMAGE PROCESSING OF CONTOUR PLOTS

- The alternating behaviour of vortex formation & the respective circular eddy motion can be clearly seen here
- The Binary surface plot was taken to track the eddy.
- Image Processing was performed on these images using OpenCV.
- A Threshold value of 200 was given to separate the vortex by identifying the eye of the vortex
- As the vortex starts dissipating its energy the rectangular region of recognition is enlarged
- A parabolic motion of the eddies can be seen here.



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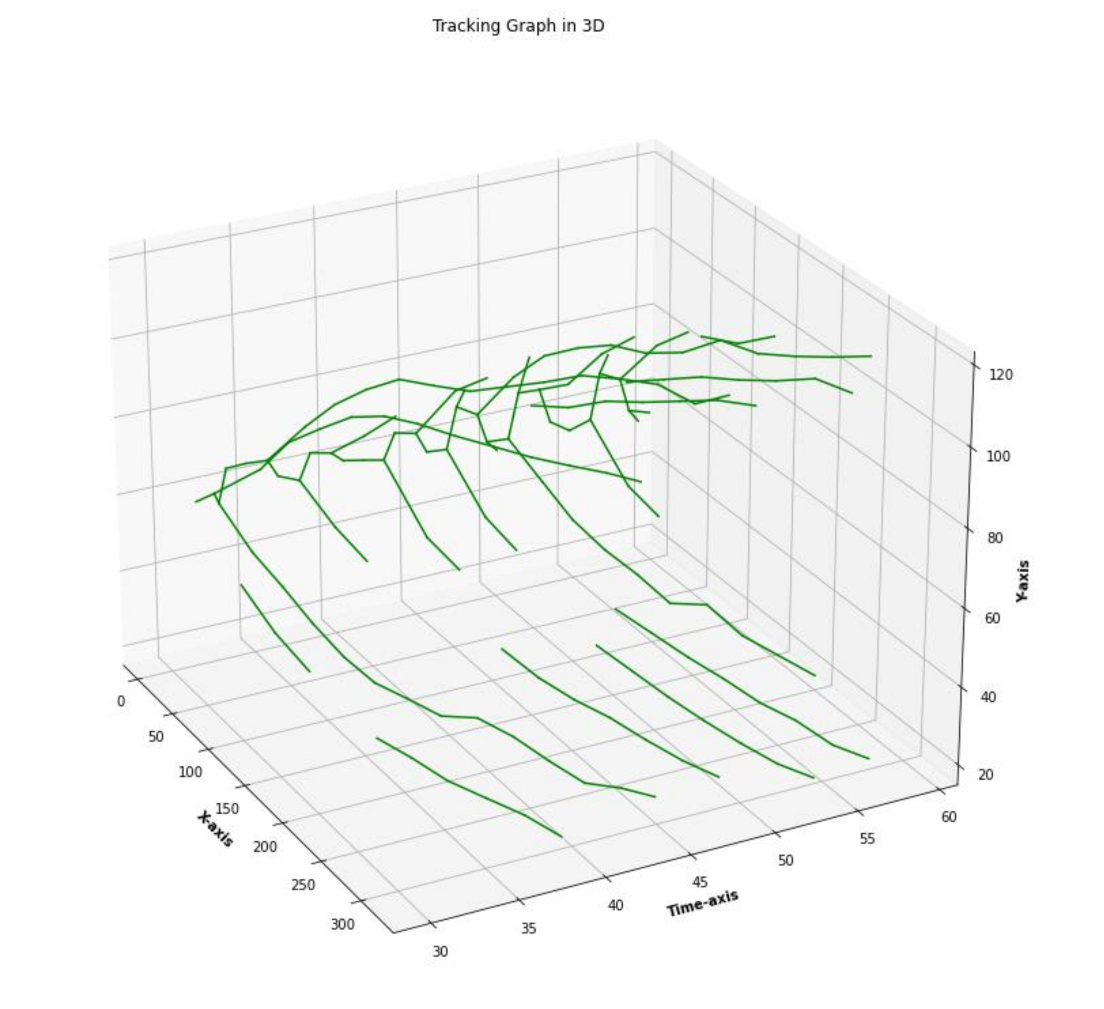
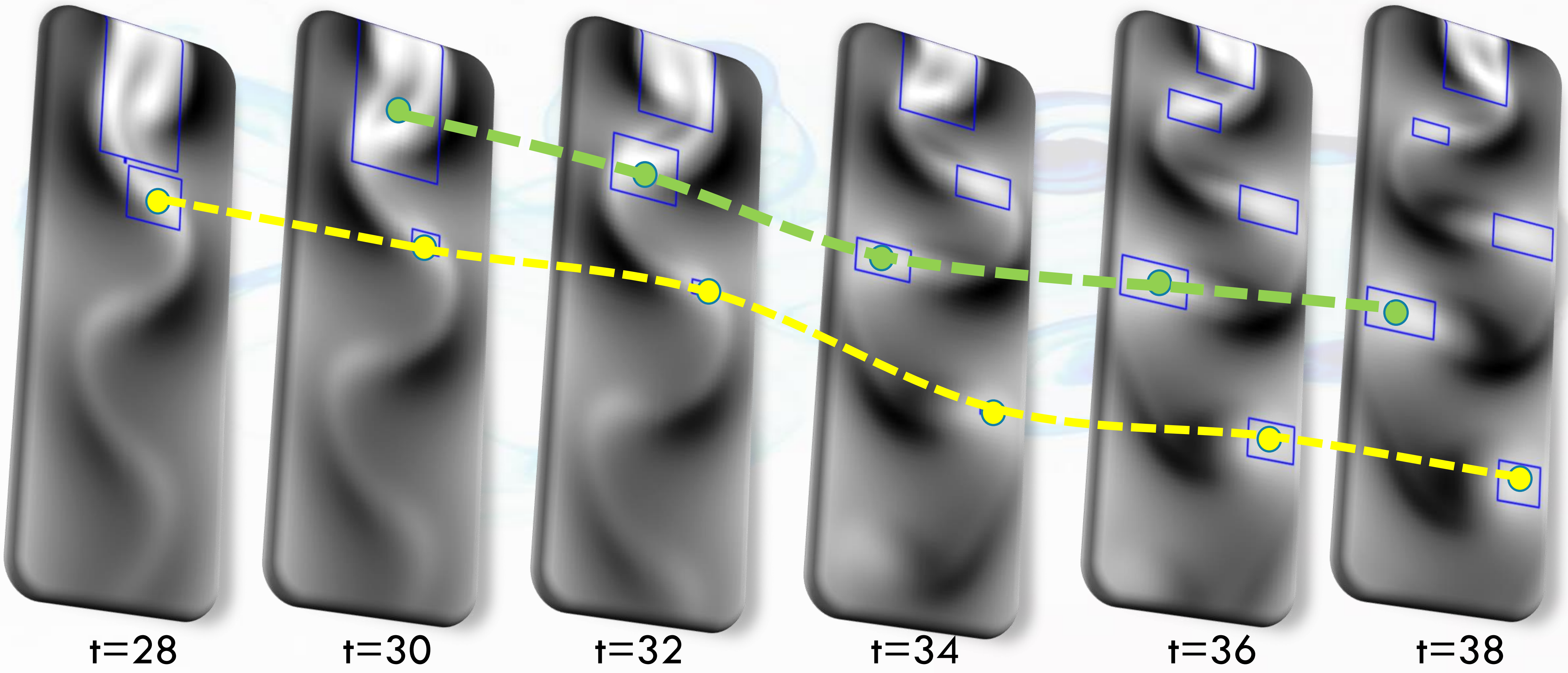
TRACKING GRAPH IN 3D

- In order to track the motion of vortices which were identified in the previous slides over the entire period of timestep
- The centroid of the rectangular region for subsequent timesteps are plotted over a 3D axis, where X and Y represents the XY Plane as in the contour plot and the Z axis represents time.
- It is very clear that several vortices starts forming from the central location i.e. around the square cylinder block and traverses outwards towards the wall in a parabolic fashion.
- There are certain intermittent gaps in the formation of vortices which signifies a loss in energy of those small eddies & also the OpenCV is not able to detect certain images.



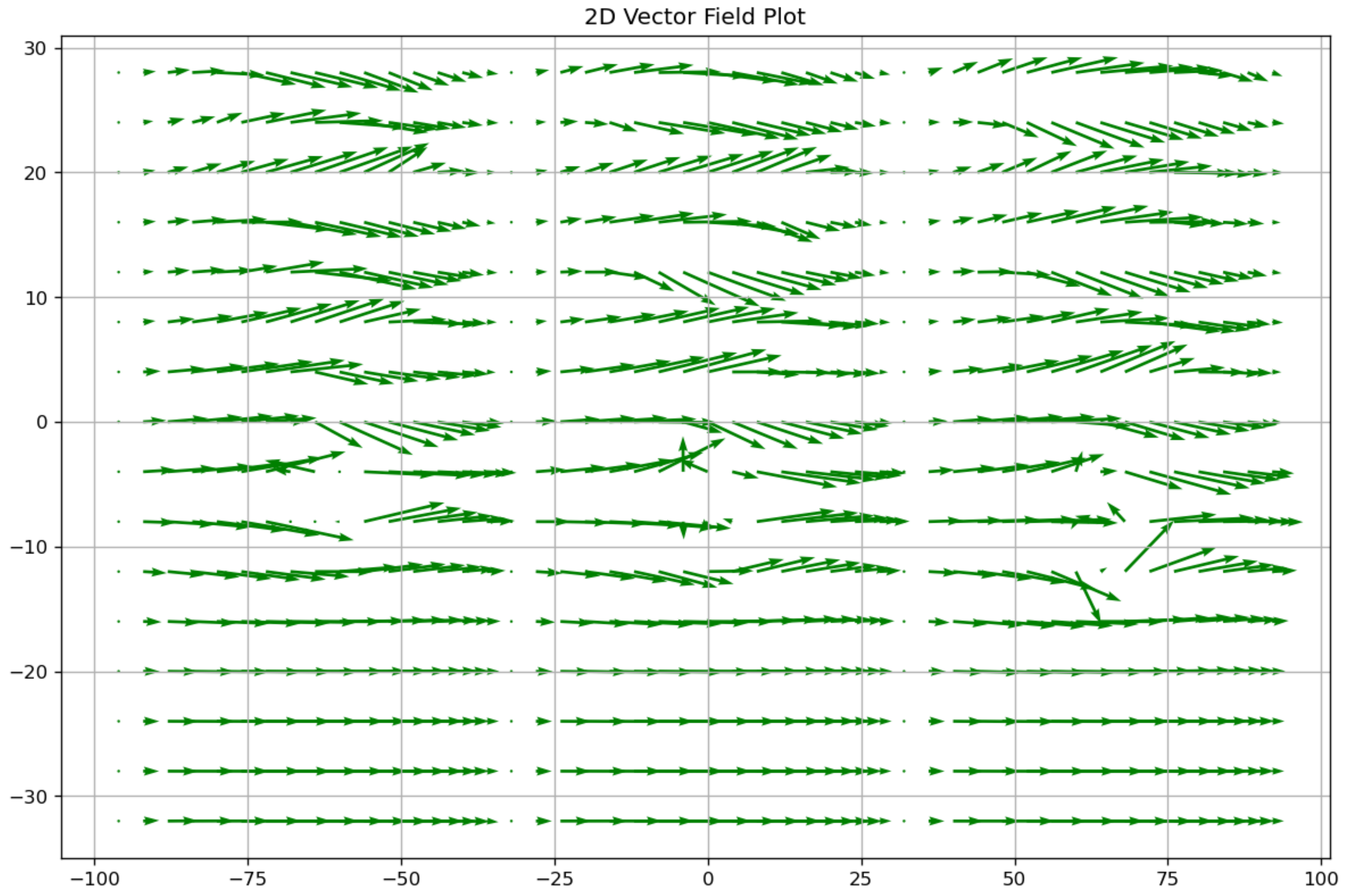
TRACKING GRAPH WITH OPENCV BASED CONTOUR PLOT

- Tracking Graph in 3D with Vortex Detection using OpenCV from Binary Contour Plots



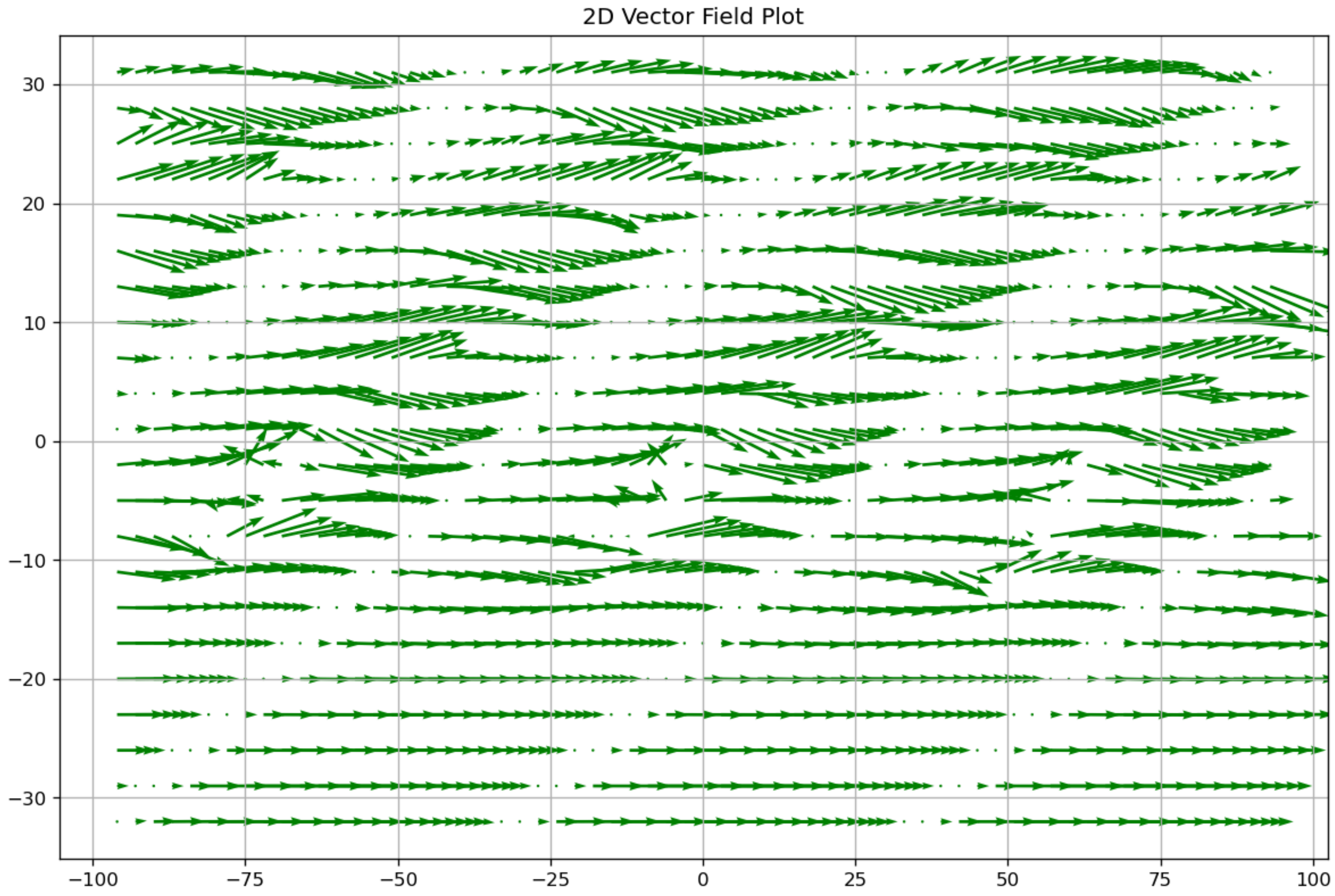
VECTOR FIELD PLOT

- A Vector field plot was drawn for a particular timestep was drawn.
- Equal spacing of grids on both positive & negative axes were taken.
- It is clear that there is region where there is no change in the v velocity vector & only unit velocity vector along u direction which signifies a steady streamlined laminar flow



VECTOR FIELD PLOT

- A Vector field plot was drawn for a another timestep where the vortices have grown fully.
- Equal spacing of grids on both positive & negative axes were taken.
- As the loci of each arrow mark can be joined together, it will show the Streaklines of the flow.
- Alternating repetitive flow pattern can be seen from this plot.



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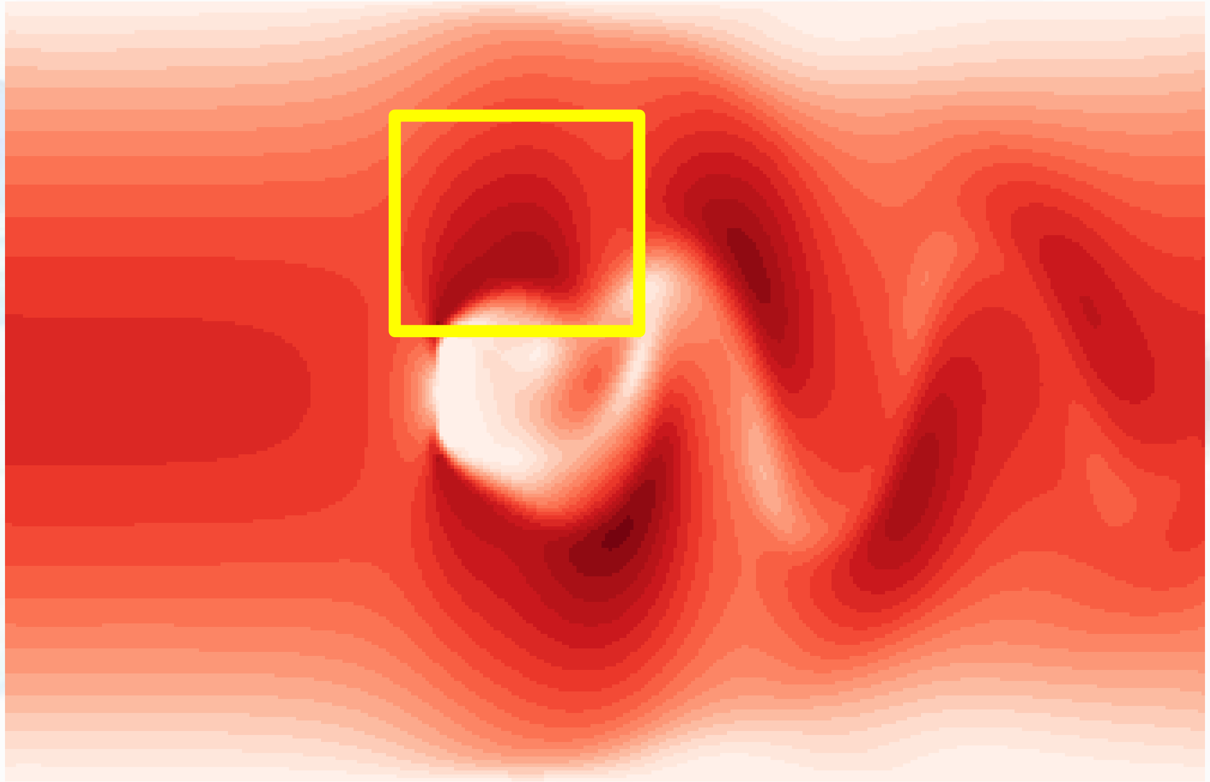
FEATURE TRACKING GRAPH IN 2D

- With all the previous visualizations, a region of interest can be identified based on the expertise of the Scientist
- Hence a region of X_{min} – X_{max} and Y_{min} - Y_{max} and for a certain timestep starting from $time_{min}$ – $time_{max}$ is chosen
- With these data for region selection, the vector field values are queried only for these regions from the pre-loaded entire dataset & are plotted as Tracking graphs shown here.
- The X-axis represents the timesteps and Y-axis represents the magnitude of the vector field data.



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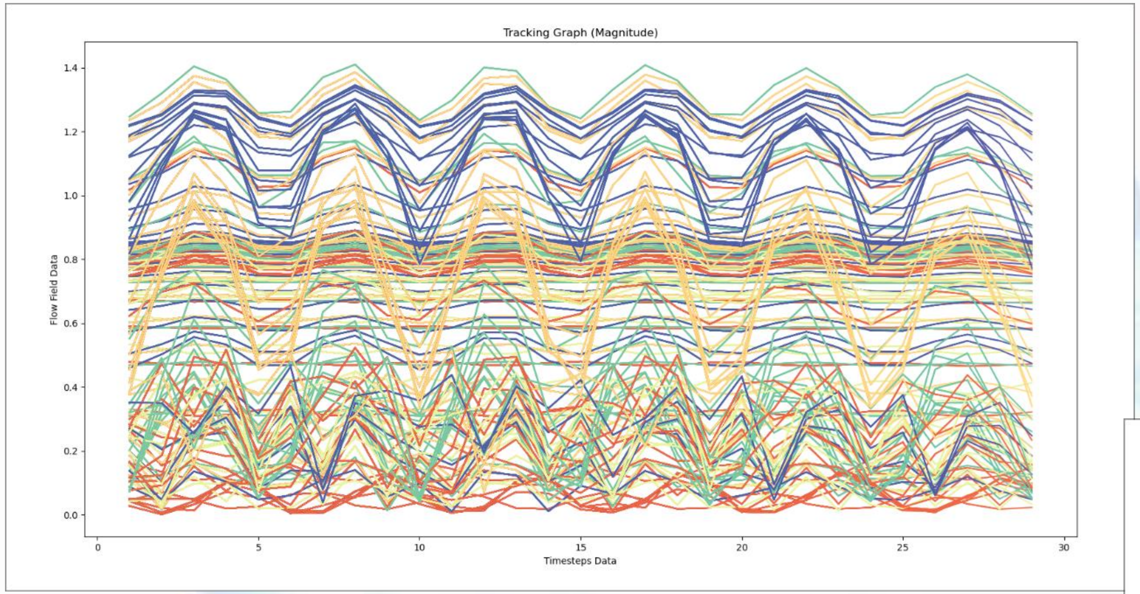
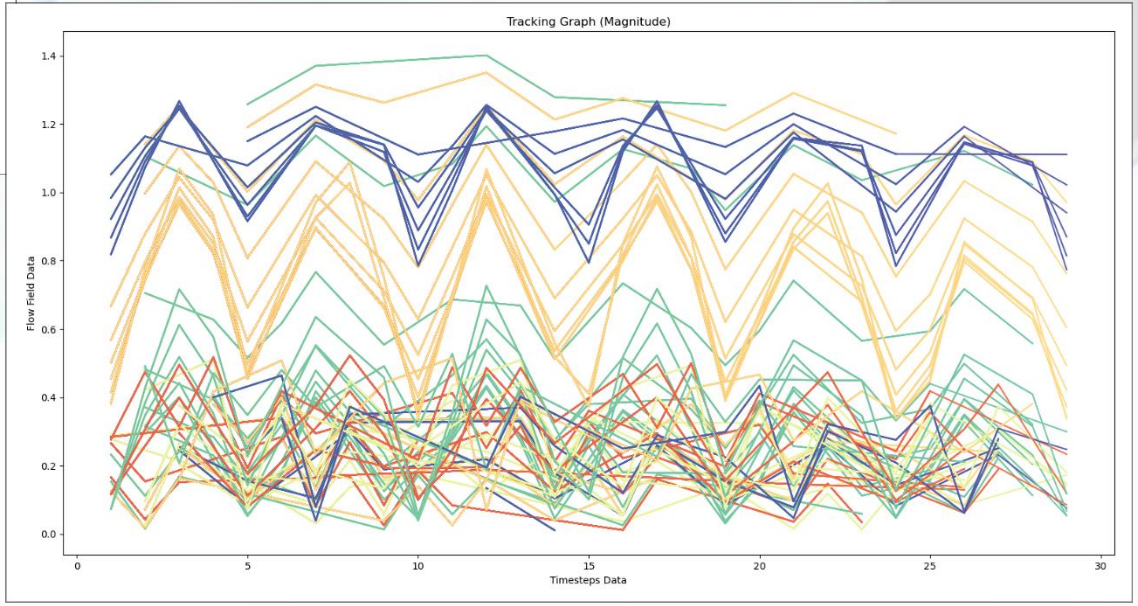
FEATURE TRACKING GRAPH IN 2D

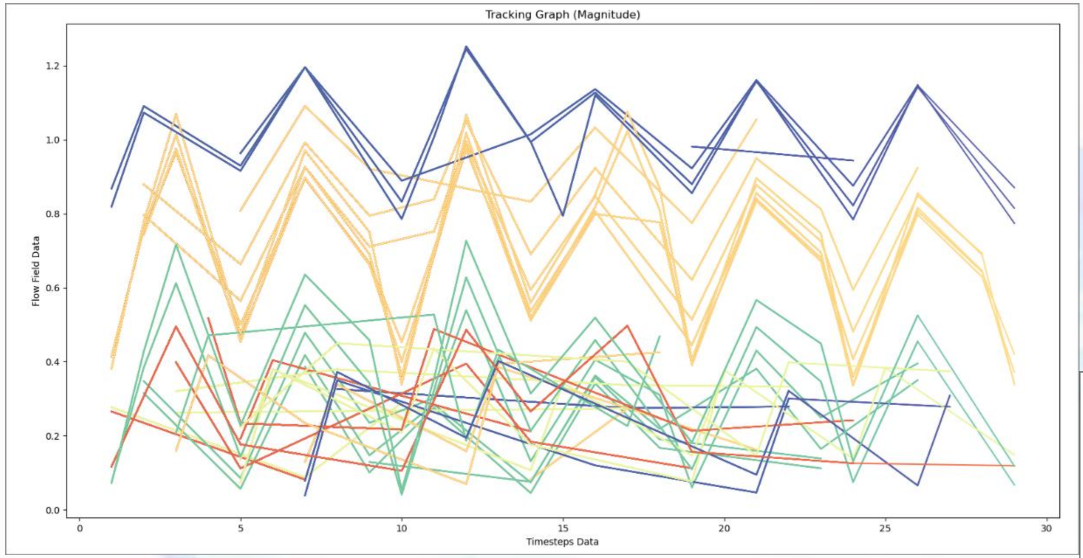


Without Thresholding

Threshold Value – 0.1

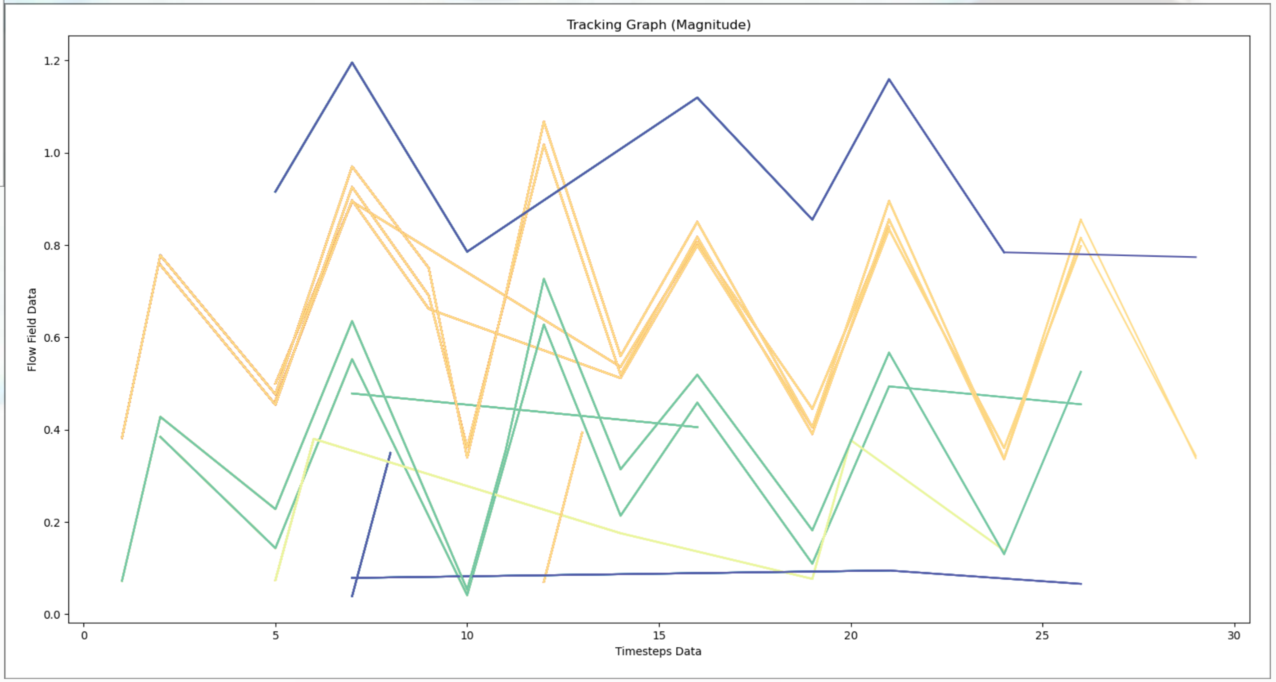


FEATURE TRACKING GRAPH IN 2D



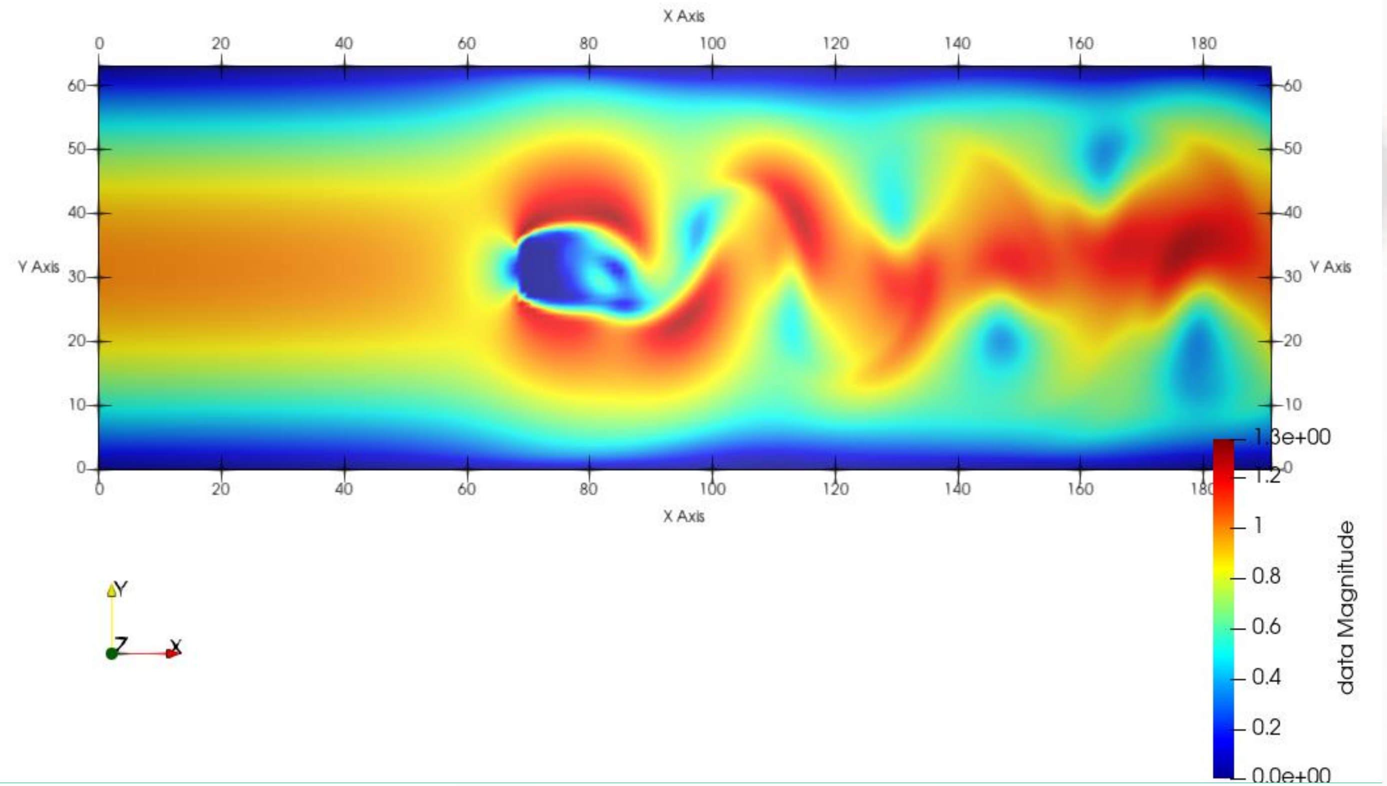
Threshold Value – 0.2

Threshold Value – 0.25



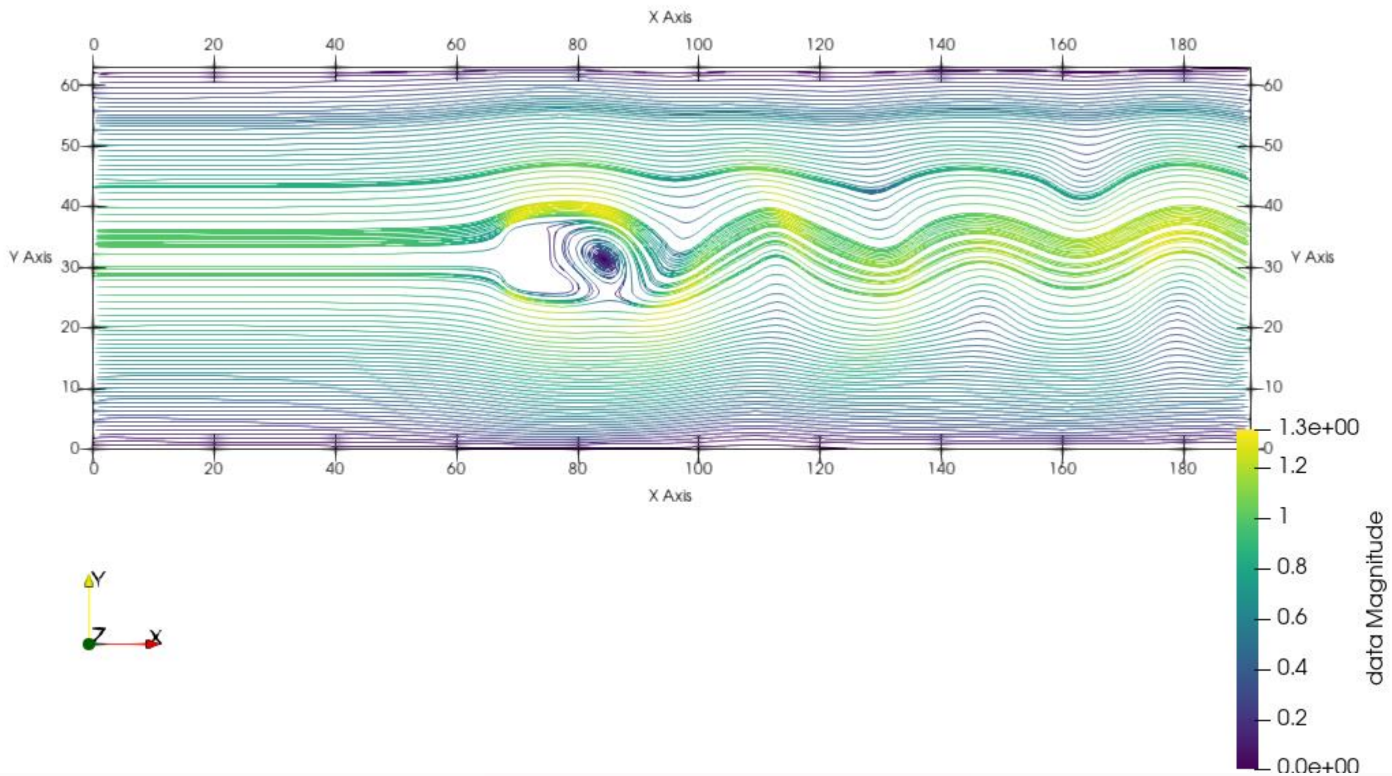
3D VISUALIZATION

- The data file got as a result of converting from amira mesh file is now converted to VTK file format in order to be able to read it using Paraview software
- Structured Points datatype is used with vectors u, v, w is stored over the entire grid set for each time step separately.
- Once the VTK file is loaded onto the Paraview software, first a slice filter is applied and the iso surface stream for the magnitude of the vector field is visualized
- The slices is made along XY plane perpendicular to Z axis. The slice plane is moved along the entire Z axis and no significant change in the w vector can be found thereby justifying the way to visualize in 2D instead of 3D



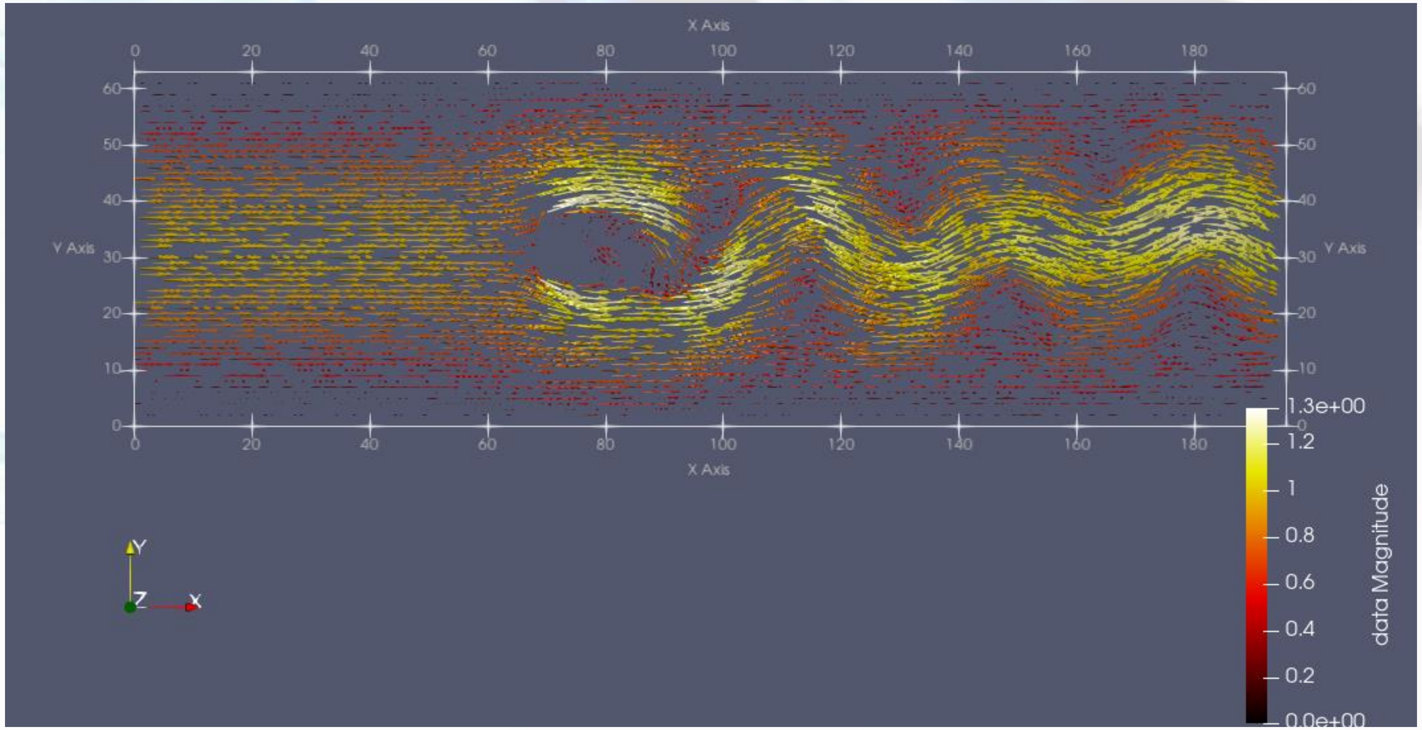
3D VISUALIZATION

- Then Streamlines are plotted onto the same slice.
- Streamlines are a family of curves that are instantaneously tangent to the velocity vector of the flow. These show the direction in which a massless fluid element will travel at any point in time
- The Stream lines clearly show the wavy pattern of movement of the vortex downstream
- It is clear that there is whirlpool formed adjacent to the square cylinder in the downstream region clearly indicating that there is a low pressure region formed



3D VISUALIZATION

- Then path lines are plotted as arrow marks.
- Path lines are the trajectories that individual fluid particles follow. These can be thought of as "recording" the path of a fluid element in the flow over a certain period. The direction the path takes will be determined by the streamlines of the fluid at each moment in time.
- The colour map shows the region of high magnitude of the vector field.
- The straight line path along the walls clearly indicate the steady streamlined laminar flow



Masavir

CONCLUSION

- Explored the dataset
- Understood the formation & dissipation of Vortices & the phenomenon of Vortex Shedding (Von Karman Vortex Street)
- Visualized the Vector field flow around a bluff body
- Able to distinguish the flow regimes from laminar to turbulent and the transition regions
- Implemented our approach on the OpenCV based Tracking Graph Plotting in 3D using Vortex Detection in contour plots
- Understood the importance of optimizing layout in the Feature Tracking graph in 2D
- Found the critical regions downstream behind the square cylinder block where the flow becomes unsteady

Masavir

DISCUSSION ON DIFFICULTIES & CHALLENGES FACED

- The runtime to initially load the entire data set of 102 timesteps was 716 seconds
- Drawing contour tree or merge tree
- Combining all the dataset for different timesteps into a single dataset with time as the 4^{th} dimension
- Using Inviwo to create a interactive dashboard with different visualizations
- Implementing the concept of meta graph structure
- Tracking the centroid of the vortices detected during the image processing
- The image processing is missing certain small vortices during its birth

Masavir

SCOPE FOR IMPROVEMENT

- There are lots of intersections in the tracking graph in 2D even after limiting the region of interest, hence in order to minimize intersections optimization of the layout has to be carried out
- There is no connectivity between different visualizations & there is no interactive exploration in the visualization which can be added

BE CREATIVE

BE UNIQUE

BE YOU!