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# FlowVisual: Design and Evaluation of a Visualization Tool for Teaching 2D Flow Field Concepts

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## Abstract

Visible as well as invisible fluids exist everywhere in nature and many scientific fields. Most fluids (air, water, etc.) are transparent, thus their flow patterns are invisible to us. Flow visualization is used to make the flow patterns visible so that desired insights can be gleaned. There exist various software tools to perform different flow visualization tasks. However, there is a lack of tools to help students learn important flow visualization concepts. In this paper, we present a visualization tool, FlowVisual, which illustrates basic flow field concepts in 2D. Techniques involving field-line tracing, line drawing, background texture, field-line comparison, and critical point detection are integrated into FlowVisual to serve a comprehensive learning goal targeting both engineering and visualization students. We evaluate and demonstrate the effectiveness of FlowVisual by conducting a formal user study consisting of an introduction and training section, an auto-grading test, and a survey.

## 1. Introduction

Fluid mechanics and computational fluid dynamics are among the core courses in many engineering majors such as mechanical engineering, aerospace engineering, biomedical engineering, chemical engineering, and civil engineering. In these courses, it is important for engineering students to acquire the knowledge of fundamental flow field concepts. Many of those concepts are not straightforward to learn. For instance, it is not easy for beginning-level students to fully understand the differences between various kinds of field-lines and critical points. Commonly, these materials are taught by instructors through explaining concepts and definitions, drawing diagrams and illustrations, and occasionally, playing custom-made animations or video clips. Using intuitive and vivid examples proves to be an excellent way of learning; however, most examples available today are only designed for teaching and demonstration but not for student interaction or self-learning. Developing a pedagogical visualization software tool holds the potential to help engineering students better learn these essential flow field concepts through interactive exploration.

In this paper, we present a visualization tool, FlowVisual, which illustrates basic flow field concepts in 2D. We opt to concentrate on 2D flow field visualization and interaction mainly because it simplifies the development effort and user interaction, while maintaining the same learning goals. Our key deliverable is a portable system for classroom presentation as a demo tool and for self-study by students and professionals. FlowVisual has been used in a classroom environment and its effectiveness was evaluated through a formal user study involving students from mechanical engineering, electrical engineering, and computer science. We have released

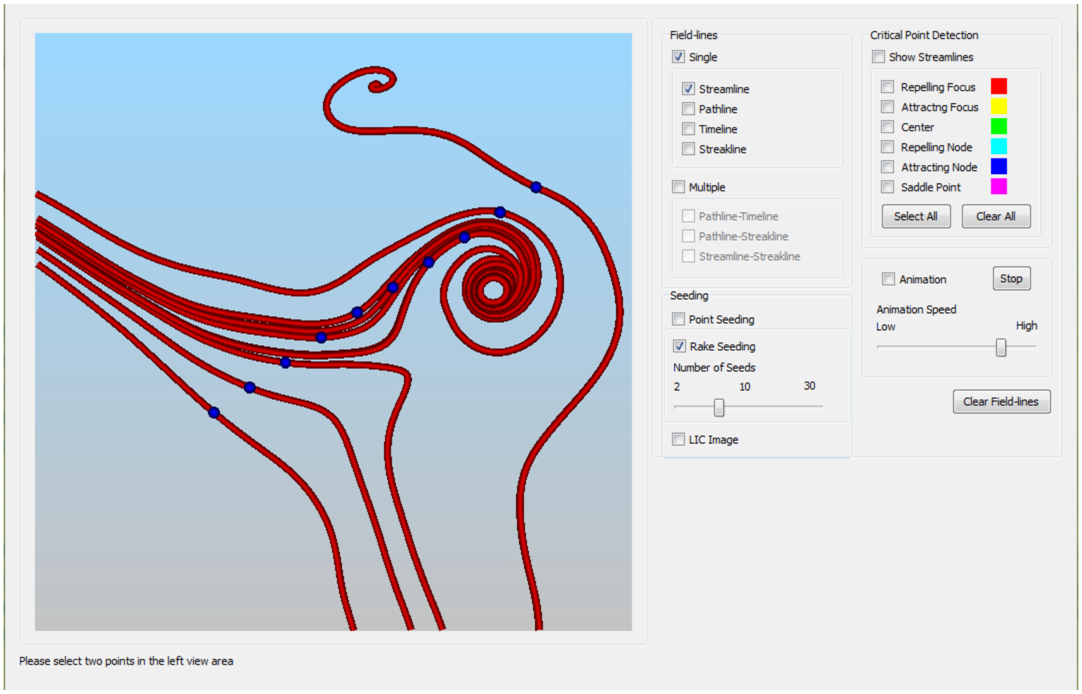
FlowVisual online along with the tutorial and evaluation materials so that other instructors and students who are interested in our work can benefit as well, making it truly useful for teaching and learning fluid dynamics and flow visualization.

The paper is organized as follow. In Section 2, we give an overview of flow visualization techniques and the current status of fluid dynamics related courses. Section 3 describes detailed techniques employed in FlowVisual. Basic ideas of tracing and drawing field-lines as well as important design principles are explained. Section 4 presents an analysis of the user evaluation data we collected to demonstrate the effectiveness of FlowVisual. Finally, we conclude this work in Section 5 and present possible directions for future work.

## 2. Related Work

Flow visualization plays a vital role in many scientific, engineering, and medical disciplines, offering users a graphical representation of their vector data for visual understanding, interpretation, and decision-making. For over two decades, flow visualization has been a central topic in scientific visualization, and a variety of techniques including glyph-based [1], texture-based [2], integration-based [3], topology-based [4], partition-based [5], and illustration-based [6] visualizations have been presented. To design FlowVisual, we focus on integration-based flow visualization as it is most widely used in practice. For integration-based flow visualization, particles or seeds are placed in a vector field and advected over time. The traces or field-lines that the particles follow, e.g., streamlines for steady flow and pathlines for unsteady flow, depict the underlying vector data.

Teaching the core concepts of fluid dynamics has not significantly changed over the years. Only a few published works have discussed some recent advances. Hertzberg and Sweetman [7] designed a flow visualization course to focus on studio/laboratory experiences for mixed teams of students. The course content included fluid flow physics, history of photography with respect to the relationship with science and art, as well as flow visualization and photography techniques. Their course proved to be very successful in attracting both graduate and undergraduate students, engineering women in particular. Settles et al. [8] argued that fluid mechanics is fundamentally visual, and visual topics can be taught by modern multimedia methods. They described a new series of 10-15 minute narrated videos that use flow visualization to illustrate basic fluid mechanics concepts. Rossmann and Skvirsky [9] developed a sophomore-level seminar that exposes students to flow visualization techniques and the science of fluid mechanics, and to the photographic methods needed to create effective images. The fundamentals of fluid flow and photography were taught and practiced in a studio setting. In our work, we prototyped FlowVisual for teaching essential fluid dynamics concepts to engineering students and students learning flow visualization. Our tool thus provides an alternative to the methods mentioned above. Leveraging interactive functions we provide, instructors and students are expected to teach and learn related concepts effectively and efficiently.



☑ Single
☑ Streamline
☐ Pathline
☐ Timeline
☐ Streakline
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☐ Pathline-Timeline
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☐ Attracting Node 🟦
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☐ Animation

Please select two points in the left view area

Figure 1. The user interface of FlowVisual for teaching 2D flow field concepts.

## 3. FlowVisual Design and Functions

We develop FlowVisual to facilitate the teaching and learning of fundamental concepts in fluid dynamics. Given a 2D flow field, our tool allows users to drop seeds into the field. We depict the paths that the seeds will follow at any point in time so that the users can observe the integral lines. Besides point seeding for single field-lines, we also enable rake seeding so that a group of field-lines can be traced simultaneously for efficiency. Our tool includes *streamline* visualization for *steady* flow fields and *pathline*, *timeline*, and *streakline* visualization for *unsteady* flow fields. Visually comparing streamlines with streaklines, pathlines with timelines, and pathlines with streaklines allow students to easily understand the similarities and differences among these integral lines, which may be difficult to comprehend without visual explanation and interrogation. Besides various field-lines, we also compute and display the *line integral convolution* texture so that users can intuitively grasp an overview of the underlying flow data. To enable effective feature identification, we detect and analyze *critical points* of various kinds and highlight them in the visualization via *template-based seeding*. For an explanation of related terms, please refer to Appendix I.

Our visualization interface is implemented using QT 4.0 and OpenGL. Figure 1 shows a screenshot of the user interface. It includes a rendering window on the left and control panels on the right. The operation hint is displayed right below the rendering window. The program also supports hover hints for each option in the panels. In the following, we describe in detail each individual function and its implementation. For the best evaluation of FlowVisual, please refer to the accompanying video.

### 3.1 Field-line Visualization and Comparison

***Field-line Tracing.*** Users can click on the rendering window to drop seeds for field-line tracing. Computing a series of points following the direction of the vector field captures the entire field-line. More precisely, the tangent line to the path at each point is required to be parallel to the vector at that point. In practice, the points are calculated by bilinearly interpolating vectors using the Runge-Kutta fourth order method.

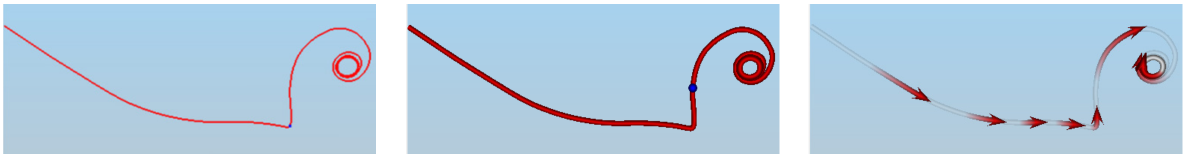

Figure 2. Three visual forms of field-line representation: line, tube, and animated arrow.

***Line Drawing.*** Figure 2 shows an example streamline with all three forms of visual representation we provide for field-lines: *line*, *tube*, and *animated arrow*. The first two forms show the entire streamline statically, while the last one dynamically conveys a vector direction as well as its magnitude along the streamline in an animated fashion. We utilize OpenGL functions for all the drawing.

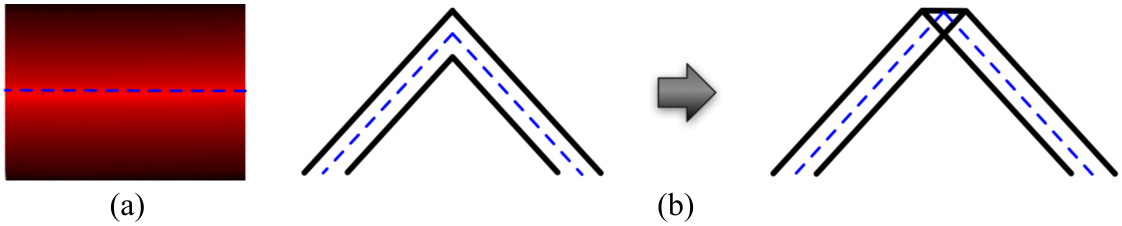

Figure 3. (a) 2D texture for tube drawing where the blue dashed line indicates a segment of the field-line. (b) Maintaining the constant edge width for sharp turning angle.

The line form is depicted by simply connecting the points that we trace along the field-line. Drawing field-lines as tubes is implemented using texture mapping. As shown in Figure 3 (a), we create a texture image to have the pixels along the horizontal middle row being the brightest (as indicated by the blue dashed line), which gradually fade into black to the upper and lower boundaries. In this way, the texture with a specular highlighting effect is generated. We assign different bright colors to indicate different kinds of field-lines.

The next step is to attach the texture to the line segment connecting the points along the field-line. Once we define a certain width of the tube, it is straightforward to apply the texture to the line segment based on the quad shape. However, when neighboring line segments form a sharp angle, we actually draw the edges of the tube in a cross way to maintain the constant edge width. This scenario is illustrated in Figure 3 (b).

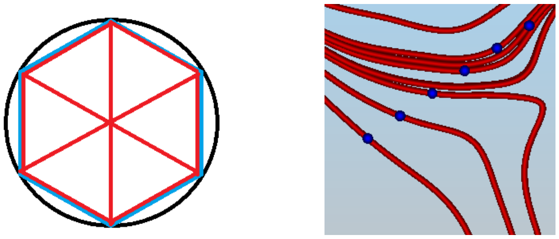
(a) (b)

Figure 4. (a) Drawing the seed point as a triangle fan. (b) The 3D ball effect for seed points.

Animated arrows are the extension of the static tube drawing. The animation shows the flow pattern of each drawn field-line using arrows whose movements indicate vector directions and whose lengths represent vector magnitudes. In contrast to always drawing the entire line, the animation turns solid lines to dashed lines and adds arrowheads to indicate flow directions. Each arrow of a dashed line has the same number of traced points. Therefore, if one arrow is longer than another, then the particle will travel further in the same amount of time. This implies that the vector corresponding to the arrow has a larger magnitude. To make the animation more aesthetically pleasing, we incorporate two effects: *arrow fading* and *arrow injecting*. The arrow fading effect is achieved by gradually increasing the transparency of an arrow from its head to tail. Continuously injecting new arrows along the field-line as old ones move out of the rendering window yields a repeated animation effect.

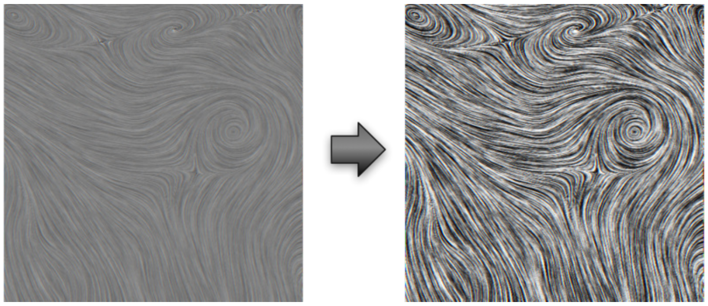
(a) (b)

Figure 5. (a) LIC texture showing the underlying flow data. (b) LIC texture after histogram equalization.

***Seed Drawing.*** As shown in Figure 4 (a), to draw a seed point, we draw a triangle fan with the common vertex as the seed location. If the number of triangles in the fan is large enough, the geometry formed by the triangles approximates a circle. In addition, we add a nice effect to the triangle fan so that a seed point is perceived as a 3D ball. This helps the seed point stand out from the background for visual attention. To achieve this, we use a bright color at the common vertex of each triangle fan and gradually darken the color toward the outline of the circle.

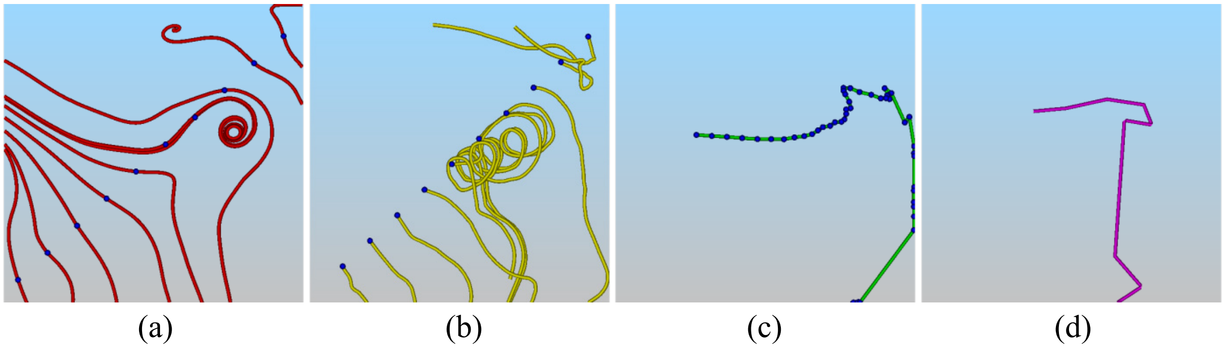
(a) (b) (c) (d)

Figure 6. Single field-lines. (a) streamlines, (b) pathlines, (c) streakline, and (d) timeline.

***LIC Texture.*** We generate the *line integral convolution* (LIC) texture to provide users with a background image showing an overview of the entire vector field. The LIC algorithm was introduced by Cabral and Leedom [10], and has been widely used in flow visualization. Figure 5 shows two versions of the LIC textures with different contrasts. LIC textures are used for both steady and unsteady flow fields. For unsteady flow fields, LIC images will be updated synchronously along with pathline, timeline, and streakline visualization and animation.

***Field-lines.*** FlowVisual includes the visualization of four different types of field-lines: streamline, pathline, streakline, and timeline. Examples are given in Figure 6. To distinguish different field-lines, we employ distinct colors to encode them: red for streamlines, yellow for pathlines, green for streaklines, and magenta for timelines. Streamlines are traced in one single time slice, while all other field-lines are traced throughout multiple time slices.

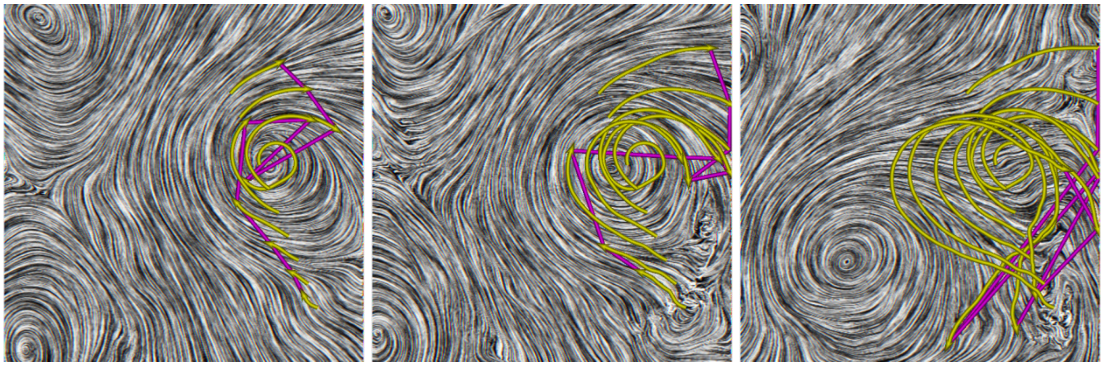
Figure 7. Snapshots of pathline and timeline comparison with LIC texture overlay.

***Multiple Field-line Comparison.*** To demonstrate the concepts of field-lines and the relationship among them, we also provide multiple field-line comparison in conjunction with animation. Two examples are given in Figures 7 and 8. Since timeline and streakline are defined based on pathline, both timeline and pathline comparison and streakline and pathline comparison play a crucial role in helping users understand the formation of timeline and streakline. In addition to the animation of field-lines, we update LIC textures synchronously over time showing the underlying unsteady flow field for reference. Users can adjust the animation speed or pause/resume the animation for careful comparison.

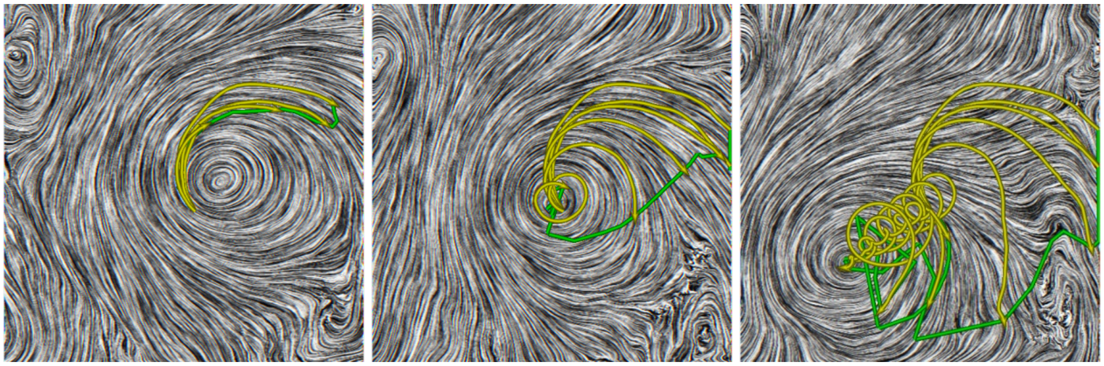

Figure 8. Snapshots of pathline and streakline comparison with LIC texture overlay.

### 3.2 Critical Points

Extracting features from vector fields has been a central research focus for decades. A great deal of work has been conducted to tackle this problem. In FlowVisual, we need to achieve the following two goals: (1) figuring out *locations* and *types* of critical points for a given vector field, and (2) designing *templates* for automatically placing streamlines to effectively highlight different types of critical points.

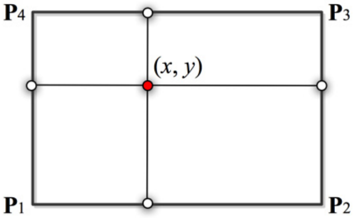

Figure 9. Interpolating a critical point.

***Critical Point Detection.*** As mentioned in the work of Helman and Hesselink [11], the vectors at critical points have to be zero. For discrete vector data, we detect critical points through sign checking and vector interpolation based on vectors defined on grid points. Specifically, for each 2D grid cell, we check whether there is at least one change of sign of the vectors at its four corners. If both the *x* and *y* vector components have sign change, then we interpolate the position of a critical point within the cell. Otherwise, there is no critical point in the cell. To compute the exact location of a critical point as shown in Figure 9, we have the following formula

$$(1-x)(1-y)P_1 + x(1-y)P_2 + xyP_3 + (1-x)yP_4$$

Setting the above formula to zero, we have

$$(1-x)(1-y)P_1 + x(1-y)P_2 + xyP_3 + (1-x)yP_4 = 0$$

Therefore,

$$y = \frac{-P_1 + (P_1 - P_2)x}{(-P_1 + P_4) + (P_1 - P_2 + P_3 - P_4)x}$$

Let $-P_1 = C_1, P_1 - P_2 = C_2, -P_1 + P_4 = C_3$, and $P_1 - P_2 + P_3 - P_4 = C_4$, then

$$y = \frac{C_1 + C_2 x}{C_3 + C_4 x} = \frac{C_2}{C_4} + \frac{C_1 - \frac{C_2 C_3}{C_4}}{C_3 + C_4 x}$$

Thus, all the points with vector of (0, $y$) are on a hyperbola. Symmetrically, all the points with vector of ($x$, 0) are also on a hyperbola. By definition, the critical points in the cell are at the intersection of these two hyperbolas.

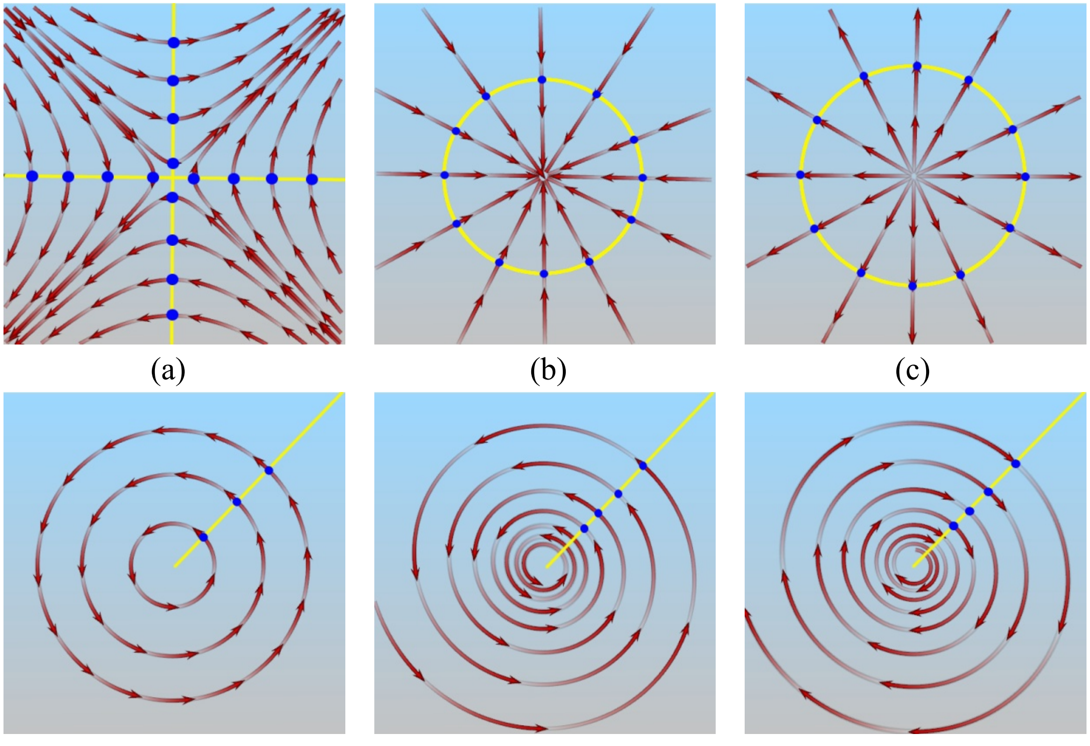
(a) (b) (c)
(d) (e) (f)

Figure 10. Six different types of critical points and their seeding templates: (a) saddle, (b) attracting node, (c) repelling node, (d) center, (e) attracting focus, and (f) repelling focus.

***Critical Point Classification and Visualization.*** As shown in Figure 10, for 2D flow fields, we can classify critical points into six different types. This can be determined by distinguishing different types on the real and imaginary parts of the eigenvalues of the Jacobian matrix in the neighborhood of a critical point [11]. Since imaginary parts demonstrate the circulating flow pattern while real parts represent the repelling or attracting behavior of the flow, a straightforward analysis on both parts would determine the type of critical points. To effectively display critical points, we draw sphere-shape textures at the locations of critical points and add halos of different colors to indicate their types: magenta for saddle, blue for attracting node, cyan for repelling node, green for center, yellow for attracting focus, and red for repelling focus. Figure 11 (a) shows such an example.

Since streamline patterns around distinct types of critical points are quite different from one another, streamline placement becomes important in order to effectively highlight the characteristics of critical points. We adopt a similar strategy proposed by Verma et al. [12] that applies a different seeding template for each type of critical point, as shown in Figure 10. For a saddle point, the template has the seeds distributed along the bisector of the hyperbola. But for an attracting/repelling focus or a center, the pattern forms a circular or spiral shape. Therefore, seeding on circles with an increasing radius is a good strategy. As for an attracting/repelling node, the streamlines are either toward/away from the critical point. The corresponding strategy is to place seeds evenly on a circle in a good distance from the critical point. The visualization of critical points with template-based seeding is shown in Figure 11 (b) and (c).

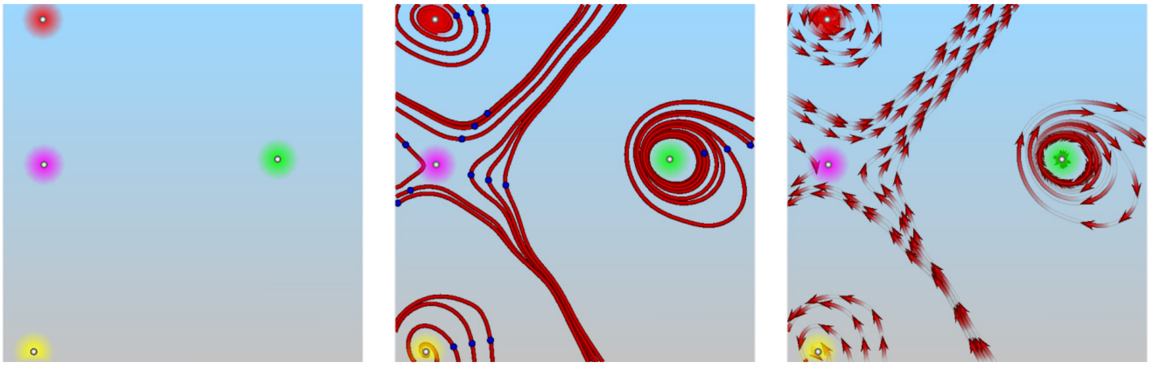
(a) (b) (c)

Figure 11. Visualization of critical points. (a) Critical point highlighting. (b) Static streamlines around critical points via template-based seeding. (c) Dynamic streamlines with animated arrows.

### 3.3 Auto-grading

Auto-grading is a special component within FlowVisual that we design to evaluate a students' understanding of flow field concepts. We provide three kinds of questions as follows:

- The first kind is the text-based questions asking about the core concepts involved.
- The second kind lists some visualization results generated from the tool and asks which one corresponds to which type of field-line. Here the visualization results use a different field-line coloring scheme in order to eliminate the possible memorization of field-line color encoding by students.

- The third kind asks students to classify the type for a given critical point or locate a critical point with a given type. Students need to trace streamlines over the flow field in order to answer these questions.

The auto-grading function is used for user study in our work. It could also be used in class for assignment or quiz to enhance students' understanding. Figure 12 shows an example of the third kind of questions.


Please locate a repelling node in the data. (Right click to confirm the location. Left click two points to trace streamlines.)

Figure 12. The user locates a repelling node (indicated by the red circle) in the data using rake seeding.

## 4. Evaluation

We conducted a user study to evaluate the effectiveness of FlowVisual. This study consists of two parts, a paper-based survey and an auto-grading test using our tool. The survey has 22 rating questions and eight open questions for detailed comments. For the auto-grading test, students interacted with FlowVisual to answer questions posted by the tool which automatically recorded the time spent on each question and graded the answers. The students were informed that how the tool can improve their understanding of flow field concepts was the most important factor to consider.

### 4.1 General Information

This study was conducted in our lab using standard PCs of the same configuration. At most two students participated in a study at the same time. The students were seated in front of 27-inch monitors with screen resolution 1920×1080 and the rendering window occupied an 850×850 area. All participants had access to the introduction and the tool a week before the user study. Before a test started, the students were first briefed with an introduction to the flow field concepts and our tool, and given time to freely explore our tool using a *xy*-slice over the entire 48 time steps from the hurricane data set. Then, they could perform the auto-grading test and the survey whenever they felt comfortable with the concepts and the tool. During the test, the students were only allowed to ask questions regarding the use of the tool. The questions of the test were presented one by one, and once moved to the next question they were not be able to go back.

Twenty-two students from computer science and electrical engineering (EECS) and mechanical engineering (ME) participated in this study. Of these 22 students, 12 were in EECS with one undergraduate student, and 10 were in ME with six undergraduate students. All the students had some flow field background. The EECS and ME students learned flow field concepts from a graduate level visualization course and a fluid dynamics course, respectively. For the visualization course, the students were introduced basic flow field concepts and various visualization methods including glyph-based, geometry-based, and texture-based techniques. The students also learned different field-lines and seed placement solutions. Many of these techniques were presented from a visualization point of view, placing their focus on visual outcomes and interpretation. For the fluid dynamics course, the students learned the basic concepts for kinematics and dynamics of a fluid. The flow field concepts such as streamline and streakline were introduced at the beginning, followed by the introduction of the Navier-Stokes equations. The course focused on the methods to analyze engineering problems, such as control volume analysis and non-dimensional analysis.

### 4.2 Questions

As shown in Appendix II, of the 22 rating questions, 11 are for flow-lines, five for critical points, and the remaining six related to the user interface (UI) design. Each function (e.g., streamline point seeding, streamline rake seeding, streakline animation, etc.) has a question that asks the students to rate how much they agree with this particular function helping them understand the concept. The available choices are 5: strongly agree, 4: agree, 3: neutral, 2: disagree, and 1: strongly disagree. Based on the nature of the contents, these questions are further grouped into the following groups: flow field, streamline, pathline, streakline, timeline, animation, critical point, UI color, and UI size, where the UI size category has questions regarding to the size of seeds and critical points and the width of lines. Each group has two to five questions, and each question may appear in multiple groups. For example, a question asking the students to rate the streamline animation capability also appears in both streamline group and animation group.

### 4.3 General Findings

Table 1 shows the mean and standard deviation of each question group. In general, student reactions to FlowVisual were positive with mean values larger than 4. The flow field, pathline, timeline, and UI color groups all received average ratings higher than 4.5. Among all the question groups, streakline was rated the lowest with a score of 4.08 and the largest standard deviation of 0.92. This is perhaps because the concept of streaklines is the most difficult to understand. Other questions received scores between 4.2 and 4.5.

We also investigated the differences of student groups. Table 2 summarizes the ratings from EECS, ME, UG (undergraduate), and Grad (graduate) students. The mean values are between 4.3 and 4.5 and the standard deviations are between 0.6 and 0.8. The group-specific mean values for each question group are shown in Table 3. Every group rated the flow field with the highest scores and streakline the lowest. The correlations between the EECS and ME groups and between undergraduate and graduate students were 0.82 and 0.79, respectively. This suggested that student ratings were very similar in spite of their discipline and level of education differences.

Table 1. Mean and standard deviation of question groups

| | Flow Field | Streamline | Pathline | Streakline | Timeline | Animation | Critical Point | UI Color | UI Size |
|---|---|---|---|---|---|---|---|---|---|
| Mean | 4.68 | 4.33 | 4.53 | 4.08 | 4.57 | 4.42 | 4.49 | 4.53 | 4.20 |
| S. Dev | 0.50 | 0.83 | 0.68 | 0.92 | 0.62 | 0.77 | 0.60 | 0.68 | 0.67 |

Table 2. Mean and standard deviation of student groups

| | EECS | ME | UG | Grad |
|---|---|---|---|---|
| Mean | 4.51 | 4.39 | 4.34 | 4.50 |
| S. Dev | 0.69 | 0.73 | 0.79 | 0.66 |

Table 3. Student group-specific summary

| | Flow Field | Streamline | Pathline | Streakline | Timeline | Animation | Critical Point | UI Color | UI Size |
|---|---|---|---|---|---|---|---|---|---|
| CS | 4.69 | 4.31 | 4.56 | 4.17 | 4.67 | 4.54 | 4.55 | 4.56 | 4.33 |
| ME | 4.61 | 4.28 | 4.50 | 3.94 | 4.42 | 4.29 | 4.33 | 4.39 | 4.00 |
| UG | 4.75 | 4.50 | 4.50 | 4.00 | 4.50 | 4.25 | 4.55 | 4.67 | 4.13 |
| Grad | 4.67 | 4.37 | 4.50 | 3.97 | 4.45 | 4.28 | 4.42 | 4.50 | 4.05 |

Most correlations among individual questions were positive, with 79.2% of the correlation values larger than 0 and 98.6% larger than -0.25. This suggested that the trend of rating were reasonably positive although some personal preferences may cause the correlations to become slightly negative. The most negative correlations were found to be between “pathline and timeline animation” and “streamline and streakline animation” (-0.23), “pathline and streakline animation” and “streamline and streakline animation” (-0.28), and “pathline and streakline animation” and “animation with arrows” (-0.24). The reason might be that the definitions of timeline and streakline are closely related to pathline instead of streamline, and many students favored the timeline/streakline animation with pathline over streamline. The highest correlations were found to be between “pathline point seeding” and “pathline rake seeding” (0.62), “timeline animation” and “streakline animation” (0.62), and “pathline and timeline animation” and “pathline and streakline animation” (0.60). Timeline and streakline were rated similarly perhaps because the concepts of timeline and streakline are more complicated, and their definitions are both based on pathline. Thus, the animations showing timeline and streakline together with the underlying pathlines were considered to have a similar effect.

### 4.4 Study of Student Group Differences with MANOVA

Since similar questions were grouped together (Section 4.2), student ratings to questions of the same group may be correlated, and MANOVA (Multivariate ANOVA) rather than ANOVA was used to perform significance tests. For each group of questions, we investigated the significance of mean difference between EECS and ME, between UG and Grad, and between ME undergraduate students (MEUG) and ME graduate students (MEG) by applying MANOVA using the Wilk's Lambda test. Although MANOVA requires that the samples are normally distributed and with similar variances and covariances, violating these conditions does not cause much harm [13,14].

The null hypothesis for question group $Q = \{q_0, q_1, \ldots, q_n\}$, where the $q_i$'s are questions, between two student groups $G_1$ and $G_2$ is $H_{0,Q}$: $\text{mean}_{q0,G1} = \text{mean}_{q0,G2}$, $\text{mean}_{q1,G1} = \text{mean}_{q1,G2}$, …, $\text{mean}_{qn,G1} = \text{mean}_{qn,G2}$ (i.e., the mean value of $G_1$ and the mean value of $G_2$ being equal for all questions). The alternative hypothesis is that $G_1$ and $G_2$ have different mean values for some questions. We used the significance level of 0.05, meaning the null hypothesis is rejected if the $p$-value is smaller than 0.05.

Table 4 shows the $p$-values of each question group between student group pairs. No significant difference was found for any question groups. This further verified our findings stated earlier that student ratings were very similar in spite of their discipline and level of education differences.

Table 4. $p$-values of MANOVA

| | EECS-ME | UG-Grad | MEUG-MEG |
|---|---|---|---|
| Flow Field | 0.84 | 0.54 | 0.38 |
| Streamline | 0.96 | 0.74 | 0.94 |
| Pathline | 1.00 | 0.32 | 0.62 |
| Streakline | 0.63 | 0.57 | 0.84 |
| Timeline | 0.46 | 0.12 | 0.68 |
| Animation | 0.77 | 0.13 | 0.64 |
| Critical Point | 0.87 | 0.98 | 0.86 |
| UI Color | 0.45 | 0.27 | 0.43 |
| UI Size | 0.42 | 0.46 | 0.92 |

### 4.5 Student Comments

The eight open questions were designed to allow the students to provide detailed comments about the reasoning behind their ratings and suggestions for future development of our tool. We emphasized the following issues: (1) whether the students felt satisfactory with the functions of our tool, (2) whether the user interface was easy to use, (3) which operating system the students used to run the tool before the study, and (4) installation and runtime issues.

We found that the student feedbacks to the timeline and streakline were very positive. Some ME students mentioned that video clips were used to demonstrate the concepts of timeline and streakline in their class. These video clips did not reveal the relationship between timeline and pathline or streakline and pathline, and they were not able to interact with the video. They felt that the concepts were much easier to understand with FlowVisual. They indicated "*I thought that it was very helpful in understanding unsteady flow of a system*", "*The animation was one of the most helpful features because it was hard to think about how the flow moved with time*" and "*Images and animations in the software provided a more vivid and easy feeling while textbook definitions are much more abstract and difficult to understand*". Some students also mentioned that they would like to recommend this tool to others by commenting "*I showed it to my friends*" and "*This is a wonderful teaching tool.* [*Recommend*] *allowing public use*".

Most students were satisfied with the user interface. We also received some valuable suggestions. The most mentioned one was that FlowVisual did not show the first clicked point for rake seeding. Other suggestions included adding hover information for each button and providing hints for the current operation. Both suggestions have been incorporated into the latest version of our tool. Some students also wished us to provide a detailed user guide.

Among the 12 students who used our tool before the user study, 10 of them ran the tool on Windows machines and 2 on Linux machines. None of the students reported system problems, crashes, or any installation issues.

### 4.6 Auto-grading Test

The auto-grading test assessed student learning and automatically provided timing and correctness of their work. For each student, his/her aggregated test score was rescaled to a 0-to-100 scale: if there are $N$ questions and a student answers $M$ of them correctly, then the score is $(M/N)*100$. The text-based questions can be found in Appendix III. We are not able to present all questions in this paper due to the use of animation or user interaction. The missing questions are: three questions based on image/animation, six questions to classify a given critical point, and two questions to locate a certain type of critical point in a given 2D flow field. Table 5 shows that ME graduate students had the highest average score of 84.72 with the smallest standard deviation of 9.49, and the EECS students had the lowest average score of 76.39 with a larger standard deviation 14.24. Generally, ME students performed better than the EECS students. This may be because ME students have more flow field knowledge. However, the scores were reasonably close with an overall average score of 79.80. We also grouped the questions into 12 groups: text-based, image/animation-based, flow field basics, streamline, streakline, pathline, timeline, straightforward concepts, profound understanding, classification of saddle points, classification of other critical points, and location of critical points. MANOVA tests did not report significant differences for question groups between EECS and ME, between UG and Grad, or between MEUG and MEG. We also tested the significance among these student groups for each individual question using ANOVA. The only significant difference was found between EECS and ME for matching streakline with its text description.

Table 5. Mean and standard deviation of auto-grading test result

| | EECS | ME | Grad | UG | MEUG | MEG | ALL |
|---|---|---|---|---|---|---|---|
| Mean | 76.39 | 83.89 | 84.13 | 77.78 | 83.33 | 84.72 | 79.80 |
| S. Dev | 14.24 | 16.66 | 19.36 | 13.61 | 21.08 | 9.49 | 15.48 |

The correlations between EECS and ME (0.74) and between UG and Grad (0.62) showed that the students with different majors and education levels answered the questions similarly. We also investigated the possible differences caused by major and education level using MANOVA on question groups. We did not find a significant difference at the 0.05-level. Therefore, we are confident that the EECS students performed as well as the ME students after using our tool, even though the former had less flow field background.

### 4.7 User Study Summary

Our user study indicated that FlowVisual was very effective in facilitating learning 2D flow field concepts and that the students were able to quickly pick up the concepts. Therefore, regardless of the background of the students (with or without prior fluid dynamics knowledge), our visualization tool turns out to be effective and helpful for classroom teaching and self-learning.

The rating scores indicated that reactions from the students were very positive, with all the average scores for all the functions higher than 4. Although the rating scores for streakline were lower than other functions, students pointed out that it was very useful to improve their understanding by animating the growth of a streakline together with the corresponding pathlines. The low score was probably due to the inherent difficulty in understanding the concept of streakline.

During our user study, some mechanical engineering students informed us that there was no interactive tool to use in their fluid dynamics class when they were introduced to those concepts. As a result, most of them only had some vague impression. It is quite common that videos are often used in classroom teaching. However, there are concerns from students that they would easily lose interest since there was no interaction involved. As the video content is fixed, it is difficult to know what would happen if they placed some seeds at certain spots in the flow field. These concerns no longer exist if an interactive visualization tool is used to aid teaching.

Therefore, FlowVisual not only provides a valuable tool for classroom teaching and demonstration, but also serves as an effective and efficient aid for self-study after the class.

## 5. Conclusions and Future Work

Our 2D FlowVisual provides various ways of visualizing and comparing different fluid dynamics concepts. The single field-line visualization states individual concepts correctly and clearly. The comparisons between related field-lines present the formations of complicated field-lines. FlowVisual helps to clarify the idea that timelines and streaklines are built based on pathlines. Furthermore, users are able to learn and explore field-lines interactively. Besides the basic concepts related to field-lines, our tool also provides critical point detection and classification. Seeding templates are applied to critical points to visualize the essential pattern of the streamlines in the neighborhood, presenting the unique influence of each type of critical point to the flow field.

FlowVisual is fairly lightweight and runs on various operating systems (Windows, Linux, and MacOS). All rendering and drawing functions are implemented using OpenGL, thus eliminating the need to use advanced graphics hardware. We have published FlowVisual, along with tutorial and evaluation materials online at http://www.cs.mtu.edu/~chaoliw/2dflowvis.html. This will provide other instructors with a useful teaching aid, allowing them to revise their curricula and teaching practices. Due to its simplicity of operation, we plan to further develop a tablet version of this tool for use at museums, science centers and similar institutions to develop exhibits in science and engineering.

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## References

[1] Z. Peng and R. S. Laramee. Higher Dimensional Vector Field Visualization: A Survey. *Theory and Practice of Computer Graphics*, pages 149-163, 2009.
[2] R. S. Laramee, H. Hauser, H. Doleisch, B. Vrolijk, F. H. Post, and D. Weiskopf. The State of the Art in Flow Visualization: Dense and Texture-based Techniques. *Computer Graphics Forum*, 23(2):203-222, 2004.
[3] T. McLoughlin, R. S. Laramee, R. Peikert, F. H. Post, and M. Chen. Over Two Decades of Integration-based, Geometric Flow Visualization. *Computer Graphics Forum*, 29(6):1807-1829, 2010.
[4] R .S. Laramee, H. Hauser, L. Zhao, and F. H. Post. Topology-based Flow Visualization, the State of the Art. *Topology-based Methods in Visualization*, H. Hauser, H. Hagen, and H. Theisel, eds., chapter 1, pages 1-19, Springer, 2007.
[5] T. Salzbrunn, H. Jänicke, T. Wischgoll, and G. Scheuermann. The State of the Art in Flow Visualization: Partition-based Techniques. In *Proceedings of Simulation and Visualization Conference*, pages 75-92, 2008.
[6] A. Brambilla, R. Carnecky, R. Peikert, I. Viola, and H. Hauser. Illustrative Flow Visualization: State of the Art, Trends and Challenges. In *Eurographics State-of-the-Art Reports*, pages 75-94, 2012.
[7] J. Hertzberg and A. Sweetman. A Course in Flow Visualization: the Art and Physics of Fluid Flow. In *Proceedings of American Society for Engineering Education Annual Conference*, pages 2449-2459, 2004.
[8] G. S. Settles, G. Tremblay, J. M. Cimbala, L. J. Dodson, and J. D. Miller. Teaching Fluid Mechanics with Flow Visualization Videos. In *Proceedings of International Symposium on Flow Visualization*, 2006.
[9] J. S. Rossmann and K. A. Skvirsky. You Don't Need a Weatherman to Know Which Way the Wind Blows: The Art & Science of Flow Visualization. In *Proceedings of ASEE/IEEE Frontiers in Education Conference*, pages F2F-1-F2F-4, 2010.
[10] B. Cabral and L. C. Leedom. Imaging Vector Fields Using Line Integral Convolution. In *Proceedings of ACM SIGGRAPH Conference*, pages 263-270, 1993.
[11] J. L. Helman and L. Hesselink. Representation and Display of Vector Field Topology in Fluid Flow Data Sets. *IEEE Computer*, 22(8): 27-36, 1989.
[12] V. Verma, D. Kao, and A. Pang. A Flow-guided Streamline Seeding Strategy. In *Proceedings IEEE Visualization Conference,* pages 163-170, 2000.
[13] K. Ito. On the Effect of Heteroscedasticity and Nonnormality Upon Some Multivariate Test Procedures. *Multivariate Analysis II*, edited by P. R. Krishnaiah, Academic Press, 1969.
[14] K. Ito and W. Schull. On the Robustness of the $T^2$ Test in Multivariate Analysis of Variance When Variance-Covariance Matrices Are Not Equal. *Biometrika*, 51(1-2):71-82, 1964.

## Appendix I. Fluid Dynamics and Visualization Terms

1. **Steady Flow vs. Unsteady Flow**: When all the time derivatives of a flow field vanish, the flow is considered to be a *steady* flow. In other words, steady flow refers to the condition where the fluid properties at a point in the system do not change over time. Otherwise, the flow is called an *unsteady* flow.
2. **Streamline**: A streamline is the path that a messless particle will follow if released in a steady flow field. It is also known as the curve that is tangent to the flow field everywhere.
3. **Pathline**: A pathline is the trajectory that an individual fluid particle will follow in an unsteady flow field.

4. **Streakline**: A streakline is the locus of points of all the fluid particles that have passed continuously through a particular spatial point in the past.
5. **Timeline**: A timeline is a line formed by a set of fluid particles that were marked at a previous instant in time, creating a curve that is displaced over time as the particles move.
6. **Line Integral Convolution (LIC)**: A LIC imge uses a dense texture to depict a complete overview of a 2D flow field. It works by adding a random static pattern of black-and-white paint sources to visualize the flow field. As the flow passes by the sources each fluid particle picks up some of the source intensity. The result is a random striped texture where points along the same streamline tends to have similar intensities.

## Appendix II. Rating Questions

### Field-lines

1. The **streamline point seeding** in the 2DFlowVisual facilitated the understanding of the definition of streamline.
2. The **streamline rake seeding** in the 2DFlowVisual facilitated the understanding of both local and global overviews of the underlying vector field.
3. The **pathline point seeding** helped the understanding of the definition of pathline.
4. The **pathline rake seeding** helped the understanding of the movements of several seed points in a local area as time evolves.
5. The **streakline animation** made it easier to understand the concept streakline.
6. The **timeline animation** made it easier to understand the concept timeline.
7. The **pathline and timeline animation** helped understanding the relationship of these two types of field-line and showed how the field-lines formed correctly and clearly.
8. The **pathline and streakline animation** helped understanding the relationship of these two types of field-line and showed how the field-lines formed correctly and clearly.
9. The **streamline and streakline animation** helped understanding the relationship of these two types of field-line and showed how the field-lines formed correctly and clearly.
10. The **animation with arrows** eased the comprehension of both the magnitude and direction information of vectors.
11. The **LIC image** increased the comprehension of both local detail and overall pattern of the vector field.

### Critical Point

1. The **critical point detection** indicated the location of critical points correctly.
2. Different types of critical points are clearly distinguished by the tool.
3. The **streamlines templates** of different types of critical points showed the flow pattern around the vicinity of critical points correctly and clearly.
4. The **LIC image** presented a great advantage in helping verify the correctness of the critical point detection.
5. The critical point detection helped find the crucial information in the vector field.

### UI Design

1. The **representation and layout** of the tool is easily understandable and unambiguous.
2. The **use of colors** in the visualization clearly distinguishes different items.
3. The **background color and fading effect** help the items drawn in the area stand out.
4. The **width of the tube** shown as field-lines is in a proper size.
5. The **seeds** (indicated as blue balls) on field-lines are in a proper size (easily visible).
6. The different **available operations** after selecting one item in the user interface show the corresponding concept and its relationship with other concepts correctly and clearly.

## Appendix III. Auto-grading Questions

### Text-based

1. Please select the one that does not exist in steady flow.
    a) Timeline
    b) Streamline
2. Please select the one that fits into the concept of streakline best.
    a) The trajectory of a ball in the flowing water.
    b) The curve formed by oil particles dripping from a tap drifted in a stream for a while.
3. Please tell which type is the field-line described as "The trajectory of an individual element of fluid as function of time".
    a) Streamline
    b) Pathline
    c) Streakline
    d) Timeline
4. Please tell which type is the field-line described as "The locus of all fluid elements that have previously passed through a given point".
    a) Streamline
    b) Pathline
    c) Streakline
    d) Timeline
5. Please tell which type is the field-line described as "A continuous line within a fluid such that the tangent at each point is the direction of the velocity vector at that point".
    a) Streamline
    b) Pathline
    c) Streakline
    d) Timeline
6. Please tell which type is the field-line described as "Set of fluid packets that form a line at some instant in time".
    a) Streamline
    b) Pathline
    c) Streakline
    d) Timeline
7. The LIC image depicts the pattern of:
    a) Streamline
    b) Pathline
    c) Streakline
    d) Timeline

### Image/Animation-based

1. Please select the image in which the red field-line could be a streamline.
2. Please select the image in which the red field-line is a timeline.
3. Please select the image in which the red field-line is a streakline.

### Critical Point Classification

1. Please select the type of critical point highlighted in the red circle.

### Critical Point Identification

1. Please locate a repelling node in the data.
2. Please locate a saddle point in the data.