INTERACTIVE FOCUS+CONTEXT GLYPH AND STREAMLINE VECTOR VISUALIZATION

by

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The following individuals read and discussed the thesis submitted by student Joshua Joseph Anghel, and they evaluated his presentation and response to questions during the final oral examination. They found that the student passed the final oral examination.

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ABSTRACT

With data sets growing in size, more efficient methods of visualizing and analyzing data are required. A user can become overwhelmed if too much data is displayed at once and be distracted from identifying potentially important features. This thesis presents methods for *focus+context visualization* of vector fields. Users can interact with the data in real time to choose which regions should have more emphasis through a mouse or touch interface. Streamlines and hedgehog based visualizations are used to change the level-of-detail based on the importance value at each data point to provide focus+context to vector visualizations. The presented visualization methods are shown to be more computationally efficient and are shown to scale well to smaller resource platforms (such as tablets), while user evaluations indicate user performance for feature analysis and particle advection was similar to existing techniques.

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LIST OF ABBREVIATIONS

CPU – Central Processing Unit

GPU – Graphics Processing Unit

LOD – Level of Detail

LIC – Line Integral Convolution

OLIC – Oriented Line Integral Convolution

FROLIC – Fast Rendering Oriented Line Integral Convolution

LIST OF SYMBOLS

$\vec{\mathbf{V}}$	Vector field
$\mathbf{I}$	Importance field
p	Focus point location
w	Focus point weight
r_f	Focus point radius
$\mathbf{\Phi}$	Focus point wave equation
d_s	Step size used in streamline integration
d_{min}	Minimum streamline separation distance
d_{max}	Maximum streamline separation distance
d_{test}	Streamline separation distance test value
t_s	Maximum streamline thickness

CHAPTER 1

INTRODUCTION

1.1 Context

With the size of simulated and measured data sets growing, a more efficient method of analyzing that data is needed. Data visualization is a way of filtering data and displaying it in a way that allows more intuitive analysis. Data visualization is used in many technical fields such as physics, math, chemistry, and engineering; however, it is not limited to those fields. Figure 1.1 shows how data visualization can be used to create a visual representation of recent wind trends across the United States.

A sub-domain of data visualization is vector field visualization. Vector fields map a direction to every point in space and can be used to describe flow or movement of a material (air or water for example) as well as represent vector potentials (such as electric or magnetic fields). Many fields use numerical techniques to produce vector data ranging from wind velocity in a hurricane to water currents around the world. Vector visualization gives form to the data and allows more interactive and intuitive analysis.

Vector fields are commonly described by their turbulence, a measure of how steady or violent the flow of the field is, and by their critical points. *Critical points* are regions where the value of the vector field becomes ambiguous. They include sources, sinks, centers, and saddles.

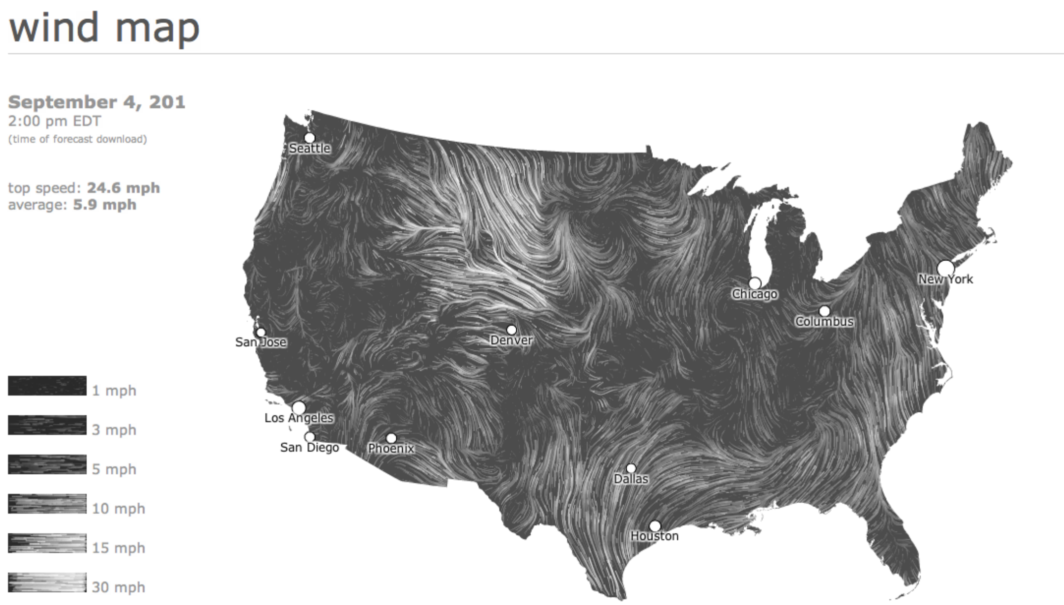


Figure 1.1: Shows recent wind patterns across the United States [16].

A *source* is a region where the field appears to originate and diverge from. A *sink* is a region where the field appears to converge upon. *Saddles* occur along boundaries in a vector field between regions of opposing direction. *Centers* are regions where the vector field rotates about, but never converges or diverges from. Each critical point type can be further classified based on rotation direction or other properties. Figure 1.2 shows a few examples of a saddle, a spiraling source (repelling focus), a spiraling sink (attracting focus), a source which emits mainly in two directions (repelling node), and a similar sink which absorbs mostly along two directions (attracting node).

Vector fields can be stored as functions or a map of positions to directions, but are commonly stored in a structured grid format. Each point in the grid (either 2D or 3D) stores a 2D or 3D value representing the direction at that point. Advances in computational capabilities allow massive parallel computations of higher resolution

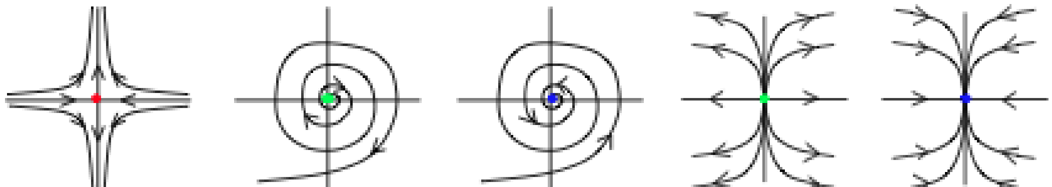


Figure 1.2: Example of feature types from left to right: simple saddle, a spiraling source (repelling focus), a spiraling sink (attracting focus), a source emitting only in two directions (repelling node), and a sink absorbing only in two directions (attracting node) [14].

grids resulting in vast amounts of vector data. For simplicity it is tempting to visualize entire vector fields as a grid of values, but what if many of those values are null or the user is uninterested in those regions? The result is a loss of computing time and possibly cluttering a screen with information that will only distract the user.

With data set sizes growing it becomes more important to efficiently filter out some of the data visualized. Many techniques for vector visualization currently exist including streamlines, hedgehogs, and line integral convolution (LIC). All of these techniques have been researched and improved over time, but the focus has been on uniform density visualizations and not on the emphasis of specified regions of interest. Doing so would allow interactive visualization of larger data sets more efficiently as well as allowing the user to have a sense of context around a higher resolution viewing region. This work proposes *methods for adaptive importance-driven vector visualization.*

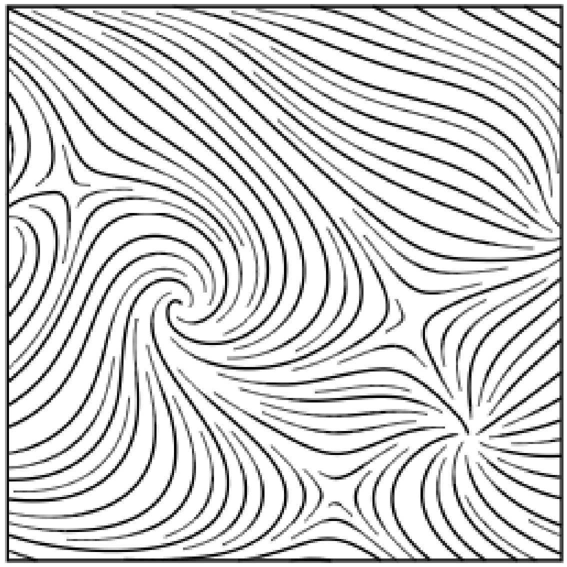


Figure 1.3: Example of streamlines without orientation indications. [9]

1.2 Prior Research

1.2.1 Streamlines

Streamlines [9, 15, 23, 27] are smooth lines that follow the gradient of a vector field. *Streaklines* are lines representing movement of particles (dye advection) at any point. *Pathlines or particle traces* are lines representing the past history of a single particle. These appear to be similar, but the gradient is not equivalent to a particle trace or advection and thus produces slightly different results, but the lines themselves are commonly visualized in a similar way. These methods of visualization result in smooth visualizations, but present challenges with spatial and temporal (for animation) coherence. Figure 1.3 shows an example of a simple streamline visualization. Note that basic streamlines do not show which direction along the streamline the vector field points.

Streamlines can get very cluttered if allowed to overlap or occlude other stream-

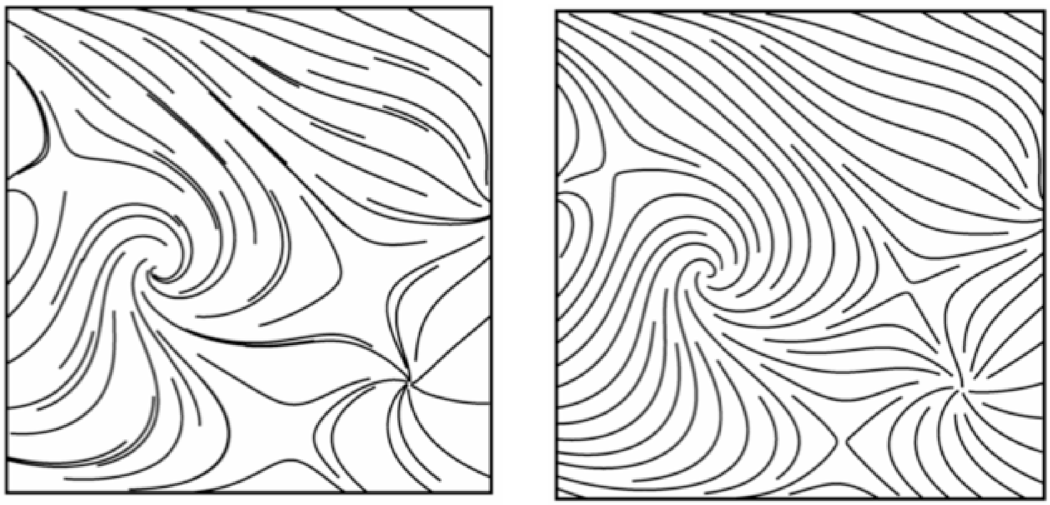


Figure 1.4: The left image shows streamlines placed on a grid. The right image shows streamlines after the seed point positions have been optimized based on the method presented by Turk et al. [15].

lines, so early work began with solving this problem. Turk et al. proposed a method of image guided streamline placement [15]. Their method begins by placing a number of seed points in the image space. Each seed point is integrated outwards to form a streamline that terminates near another streamline, a critical point, or the edge of the image. The seed points are shifted slightly in an attempt to maximize the distances between streamlines. This results in an optimization problem that is iterated until this distance metric is above a threshold set by the user or until the iteration limit has been reached.

Figure 1.4 shows how streamline placement is a crucial factor in the visualization method. Because the method is an optimization problem, it is often non-deterministic and can result in different images if ran for a different number of iterations. Furthermore, Laidlaw et al. demonstrates this method to be less effective than LIC when identifying locations of critical points [10].

Another method was later developed by Jobard and Lefer that produces similar

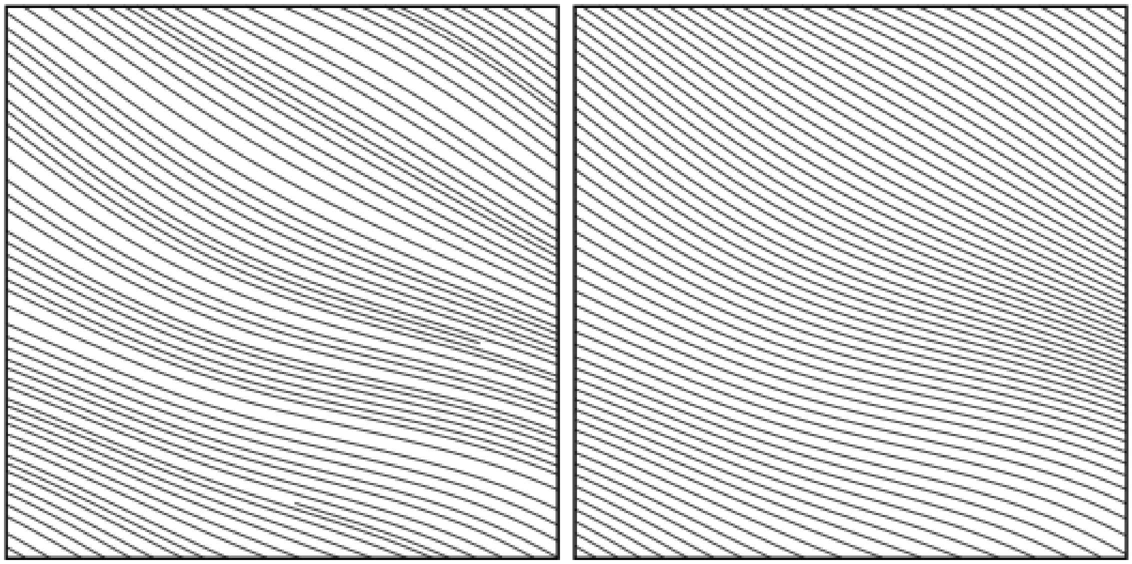


Figure 1.5: The left image shows streamlines created using randomly chosen and optimized streamlines, the image on the right uses the method presented in [9].

results to Turk's method, but is not modeled as an optimization problem and produces deterministic results [9]. This method used a similar approach of attempting to find optimal seed point placement, but it instead creates streamlines sequentially. A seed point is chosen and a streamline is created from it. The next seed point is chosen such that it is the fixed separation distance away from the current streamline and no closer than the separation distance from any other streamline. This process continues until there are no more candidate seed points. By "growing" streamlines outward, an image can be generated in a single pass. Figure 1.5 demonstrates that this method is not only faster, but produces longer, more consistent streamlines.

Heckel et al. later developed streamline hierarchy maps. They present an algorithm for clustering streamlines in 2D and 3D into larger domains of similar flow [8]. This method produces adaptive visualization with focus drawn to regions where the flow changes most. The limitation of this algorithm is that it can only group streamlines based on similar direction and the regions of higher density cannot be specified by the user.

With the advancement of graphics hardware, GPUs and their application to vector visualization has also been investigated. Weiskopf et al. present a method of creating 2D and 3D vector field visualizations by creating streaklines from particle advection calculations computed using per pixel GPU operations [22]. Unfortunately due to the nature of the advection operations, this method lacks the ability to control the resulting distribution of streamlines like those from previous works [9, 15].

Work with variable vector field visualization using streamlines includes that of Schroeder et al. [11]. They developed an interactive software tool that allows for creating illustrative streamline visualizations using sketch-like gestures. This results in varying LOD (level-of-detail) for regions of greater interest; however, this method is not automated and does not actually visualize regions of interest directly. Rather, the interface allows for more intuitive visualization through manual customization by a user. Figure 1.6 displays some visualizations created using "Drawing with the Flow." These visualizations are a great example of importance-driven visualization with emphasis placed on the turbulent region behind the obstacle, but were not created by the software directly, but by a user manually placing and editing the streamlines.

Streamline visualization produces smooth results that provide a greater continuity than other methods, but suffers from the inability to demonstrate flow direction. This problem can be overcome with the use of oriented streamlines. Oriented streamlines use stylized line rendering to represent direction. Figure 1.7 shows how *sawtooth modulation* of the widths of streamlines can provide indication as to which direction along the streamlines the vector field points by mimicking the appearance of a *glyph*

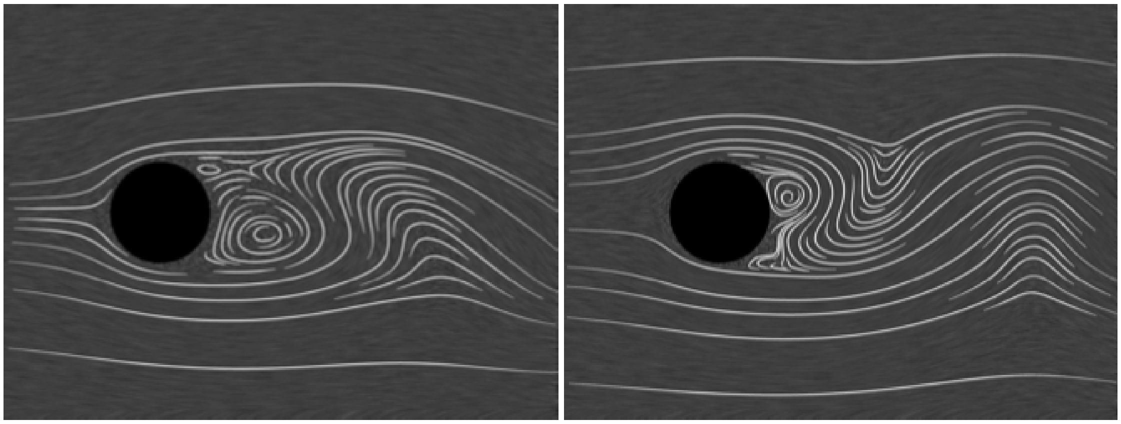


Figure 1.6: Sample visualizations creating using Drawing with the Flow to manually place and alter streamlines [11].

(commonly arrows or triangles) based visualization. Oriented streamlines have been shown to allow users to conduct particle advection tasks faster and more efficiently that other LIC or glyph based techniques [10].

1.2.2 Hedgehogs

Hedgehogs [24] are a method which uses glyphs to represent the direction at various points which can be chosen by any means, but are commonly chosen along a grid of some kind. Hedgehogs produce a clear indication of the vector field direction at various points. Because the glyphs are disjoint they lack the ability to give any strong indication as to flow of the field, but do not suffer from spatial or temporal coherence issues and do not require as much computation as streamlines or streaklines do.

Glyphs can also be used to visualize uncertainty as shown by Wittenbrink et al. Figure 1.8 demonstrates how varying the lengths of the arrow glyph can be used to indicate magnitude while varying the width of the arrow can be used to indicate error associated with the data at that point all within the same vector visualization [24].

Figure 1.7: Oriented streamlines can be adapted to visualize direction along streamlines [10].

Glyph based visualizations can produce very different results depending on the placement of the glyphs. A common and simple approach is to place glyphs at regular intervals along a uniform grid. This produces consistent visualizations and most accurately reflects the file data's structure; however, user studies have shown that jittering the location of the glyphs off a regular grid by some random amount can improve the ability to locate critical points [10]. Figure 1.9 demonstrates the difference between using a uniform or jittered grid to place glyphs along. As can be seen, critical points are more clearly visible/pronounced in the right image.

Randomly jittering a grid can improve user performance, but is hardly a universal solution. Some vector fields may have configurations that a random jittering still does not compensate for (i.e. large number of critical points clustered together on one side of the scene). Telea et al. investigated the use of a level-of-detail approach to glyph visualization [13]. By creating a tree of vector field clusters (regions of similar

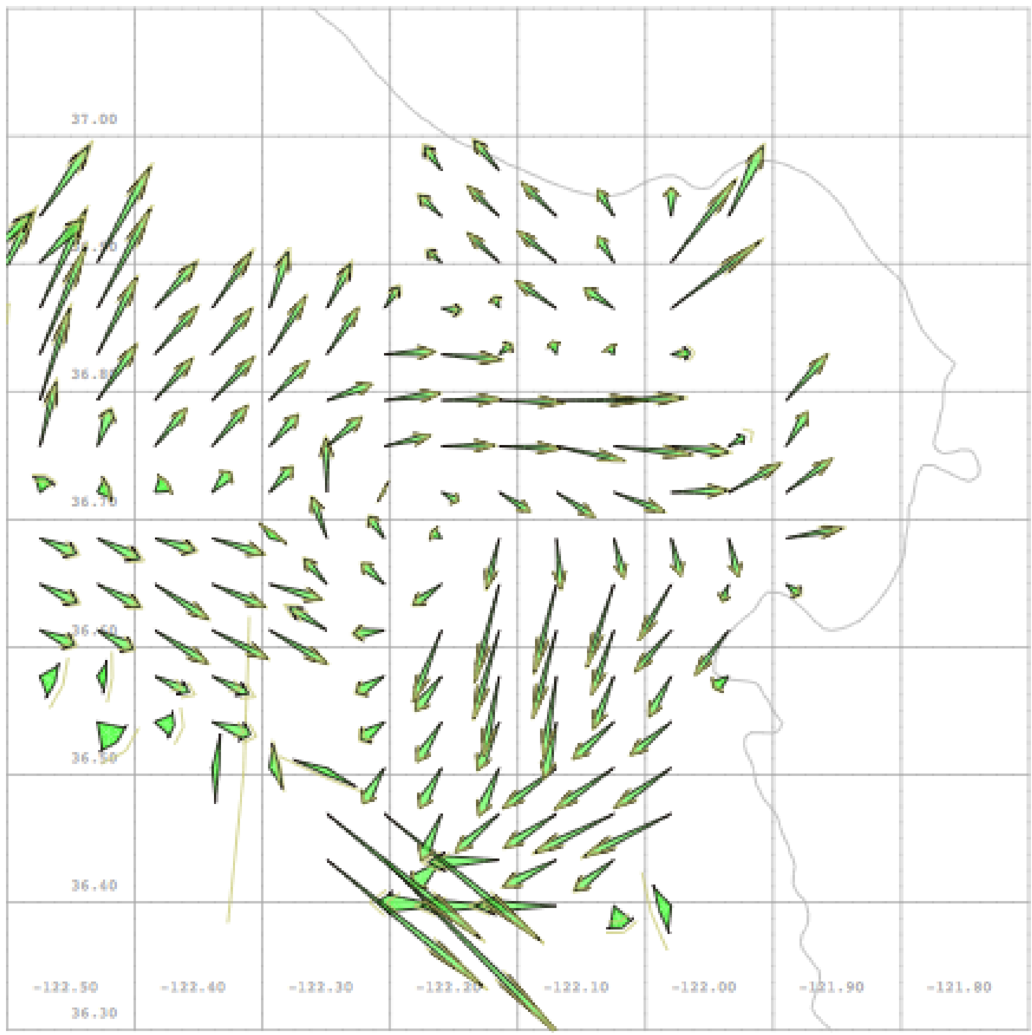


Figure 1.8: Arrow glyph width is used to encode uncertainty while length encodes magnitude to give a complete vector field visualization while conveying the uncertainty of data [24].

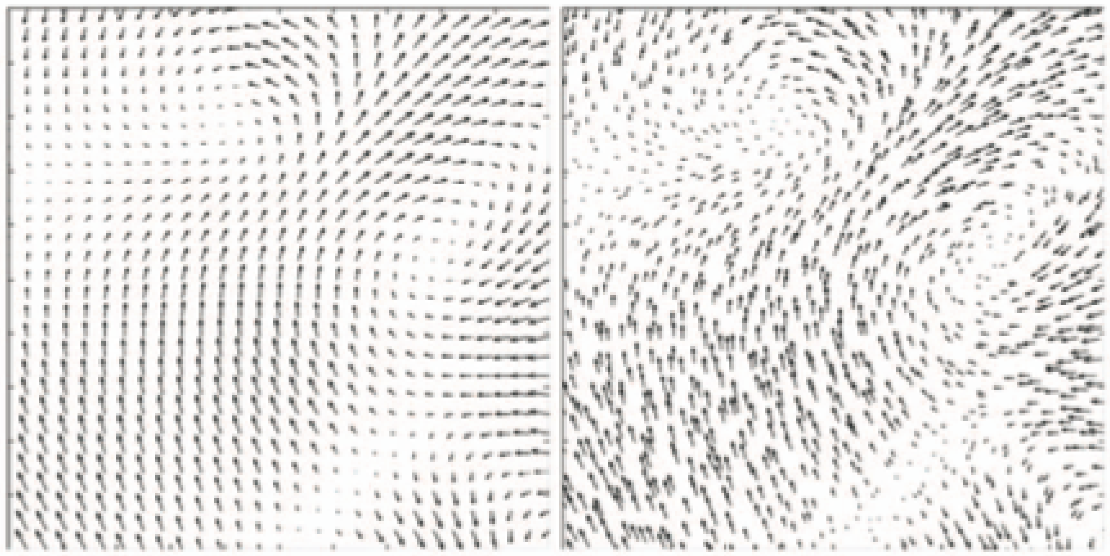


Figure 1.9: The same vector field visualized with hedgehogs on a uniform (left) and jittered (right) grid [10]

direction and magnitude), each level of the tree represents a level-of-detail for the visualization. By choosing a fixed number of glyphs to display, a level of the tree is chosen and rendered. Larger glyphs are used to represent clustered regions while smaller glyphs represent less clustered and more unique regions. An example of two vector fields rendered at different levels of detail is seen in Figure 1.10. Although this approach provides excellent automated level-of-detail support based on features within a vector field, it lacks any interactive component. The user cannot manually specify a region of interest, but rather those are fixed based on the properties of the vector field itself.

1.2.3 Line Integral Convolution (LIC)

Line integral convolution was first proposed by Cabral and Leedom [2]. This technique produces a visualization of a vector field by distorting a black and white or grey-scale

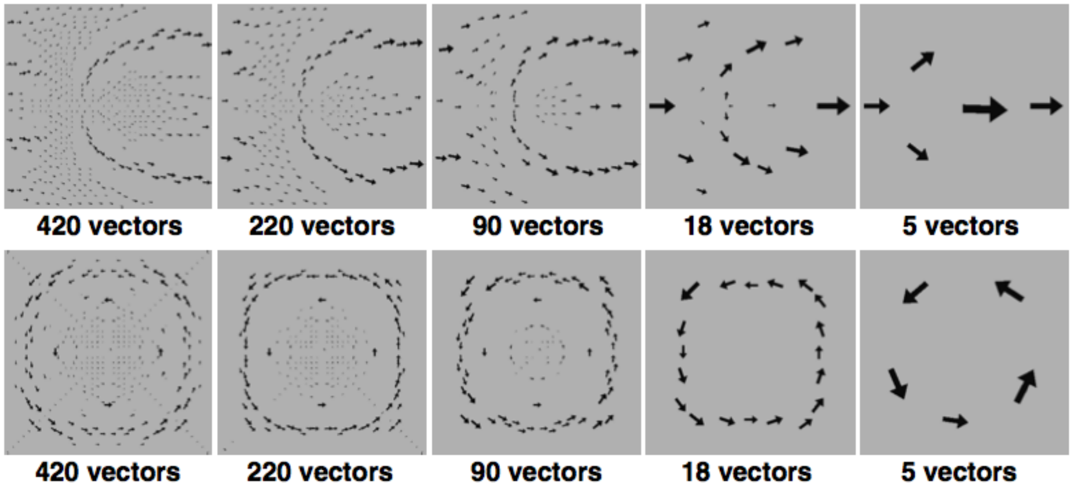


Figure 1.10: Shows two separate vector fields each rendered using a fixed number of vectors to determine the level of detail to render the vector fields at [13].

noise texture based on the values of the vector field at that point. Figure 1.11 shows a center and a turbulent vector field visualized with LIC. Due to its dependence on the resolution of the texture and the number of computations required it is considered more computationally expensive than other alternatives (glyphs and streamlines). Also, LIC does not produce any indication as to vector field direction. User studies show LIC to be one of the most inefficient visualization methods for finding the type and location of critical points [10]. LIC also requires more interpolation between data points and thus introduces more error. Because of the limitations of LIC it is impossible to determine which direction the vortex is rotating in the left image of Figure 1.11. The right image also suffers from an inability to determine direction, but also appears very cluttered.

Oriented line integral convolution (OLIC) is an attempt to add directional indications to LIC visualizations [21]. FROLIC (fast oriented line integral convolution) was later developed to optimize the performance of OLIC [20]. FROLIC uses LIC

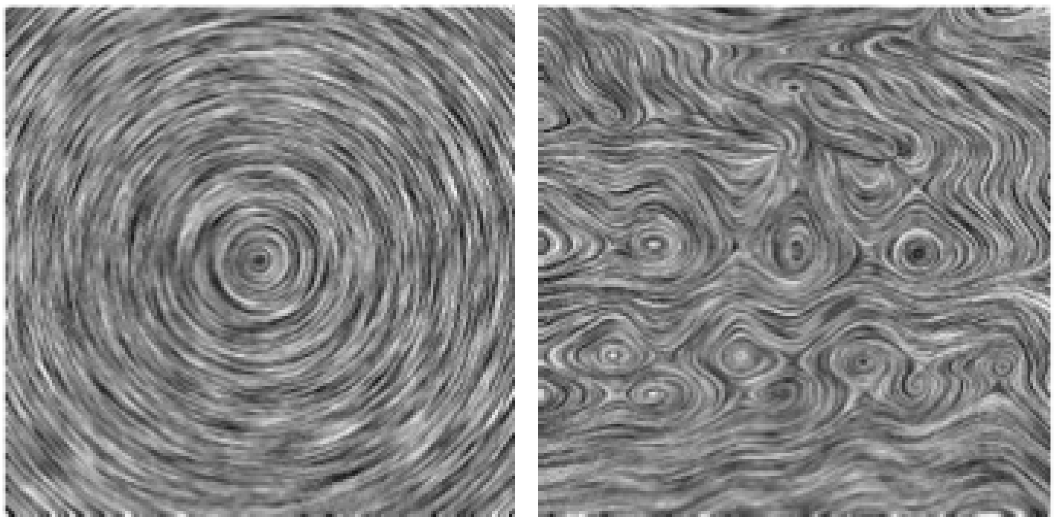


Figure 1.11: The left image shows either a center, source, or sink critical point. Due to the limitations of LIC, the orientation of the flow and whether the rotation is actually converging on the point or not is difficult to determine. The right image shows a turbulent flow visualized with LIC. The image gives a good overview of the vector field, but the details are masked by clutter [2].

on sparse textures populated with ink droplets. The variable opacity of the ink streaklines produce context to direction, while the sparse textures provide a performance boost. The results are not as cluttered as traditional LIC. Figure 1.12 shows a traditional LIC rendering on the left compared to a FROLIC rendering on the right. Notice that with LIC only there is no way of knowing the direction of rotation, while FROLIC clearly shows a clockwise rotation is present.

Another method of incorporating direction into LIC visualization was present by Shen et al. [12] which uses a principle similar to FROLIC. Colored "dye" is added to the texture which is then integrated. The main difference between this method and FROLIC is that the "dye" is not placed uniformly through the texture as droplets, but only in a few regions in large quantities. This is done to show local movement of particular features rather than overall movement of the vector field.

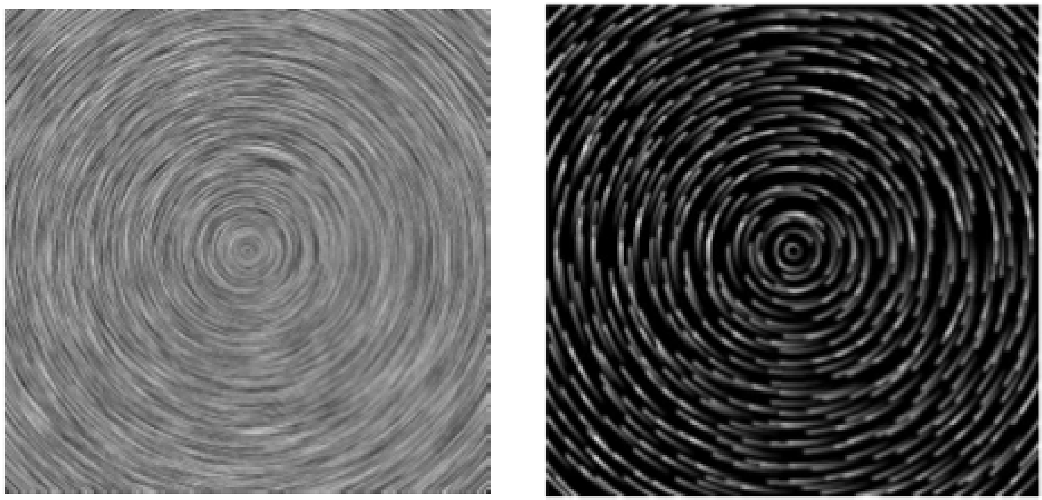


Figure 1.12: Shows the same center rendered using LIC (left) and FROLIC (right). FROLIC clearly shows the clockwise rotation that LIC alone could not show. [20]

Bordoloi et al. provide a method for GPU acceleration of LIC. By creating a clustered stream-patch quadtree and then rendering regions as blended texture mapped objects, the results produce high quality images in a fraction of the time [1]. Figure 1.13 also demonstrates how this method can be modified to produce visualizations similar to streamlines by controlling the density of the patches as well as the texture.

1.2.4 Attention Driven Visualization

The focus of attention driven rendering is to provide focus + context while avoiding potentially distracting or unimportant visual clutter. If only the focus is displayed without context, the data may be difficult to analyze or determine. If there is no focus, analyzing data may be difficult due to either lack of detail or an overwhelming clutter in the visualization. Cockburn et al. provides an overview of various focus + context models [3].

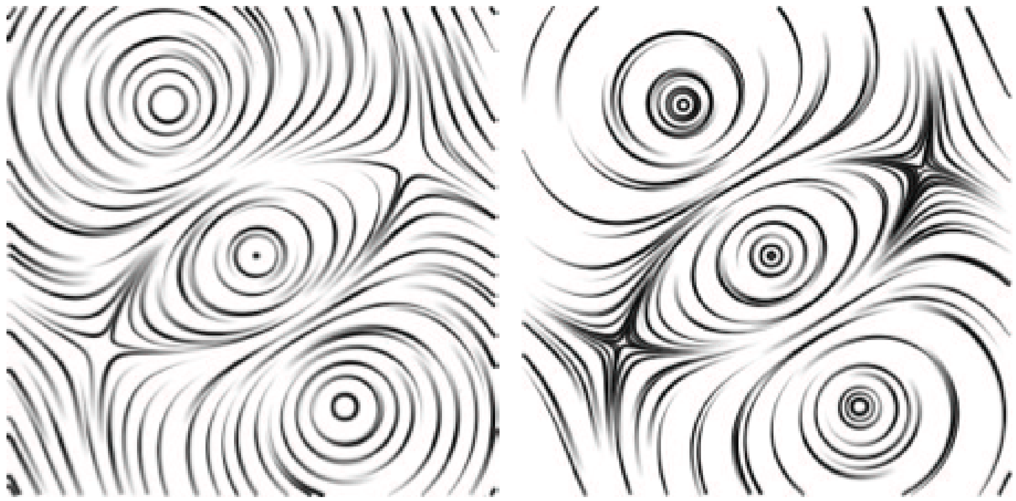


Figure 1.13: Shows how streamline visualizations can be created using a modified LIC algorithms presented by Bordoloi et al. [1].

One method of providing focus + context to a region of interest is by a zoom effect. Rather than rendering the information on the same scale (but higher detail) the region of interest is rendered on a larger scale. The problem is then how to transition between the regions of varying scale. One common method is with a *fish eye lens* effect, while another is a *zoom lens*. Fish eye effects provide a smoother transition and thus can maintain a higher level of context, but suffer from distortions which result in artifacts such as roads appearing curved when they are not as seen in Figure 1.14 (left). Zoom lenses produce harsh or broken transitions and may sometimes cause data to be occluded, but have no distortions. Figure 1.14 (right) shows how a clear closeup of some text is crisp and there are no distortions, but a large portion of nearby text has become occluded.

Other methods of attention driven visualization focus less on zoom effects and more on varying rendering styles to achieve focus + context. Cole et al. provide a method of drawing a user's attention to particular regions in a 3D scene by varying

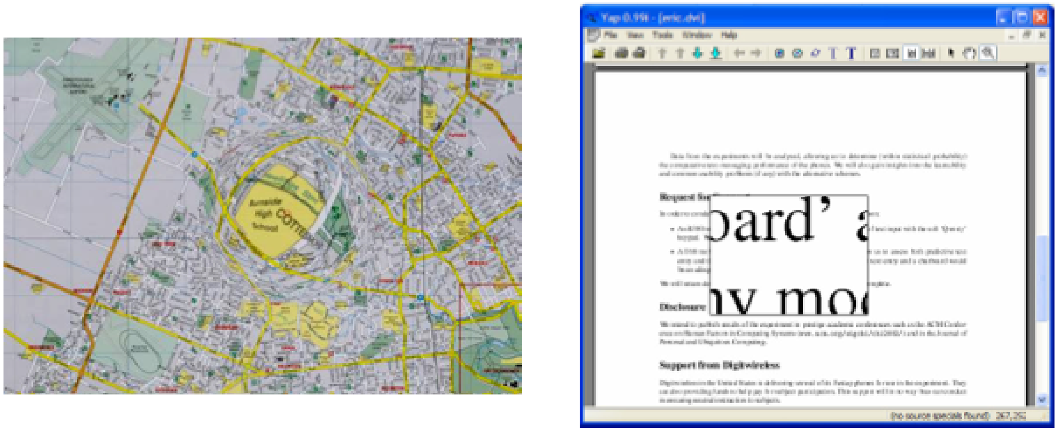


Figure 1.14: The image on the left represents a fish eye zoom effect on a map resulting in distortions in the surrounding roads. The image on the right represents a sharp zoom lens that occludes some of the nearby text. [3]

opacity, hue, blur, and other color based effects, as well as the line rendering style [4]. The authors create an illustration like scene which mimics a sketch by using item priorities and buffers. The item priority and buffers are used to diminish the number of spacing of outlines used based on the proximity to the region of focus. The authors also demonstrate the difference between focusing in the camera space, a focus plane, and on a point in 3D space. Their method produces impressive results for 3D scenes; however, the authors focus is on drawing a user's attention to a region rather than letting the user select that region in an interactive fashion. Also, their technique for line spacing actually adds computational complexity and thus there is no performance gain for rendering portions of the scene in a diminished detail. Figure 1.15 shows some examples produced by their visualization method including varying line texture, density, and width as well as varying color hue, transparency, and saturation.

Importance-driven rendering has also been shown to work in 3D with volumes [18, 17]. Viola et al. demonstrate how various importance-driven rendering techniques

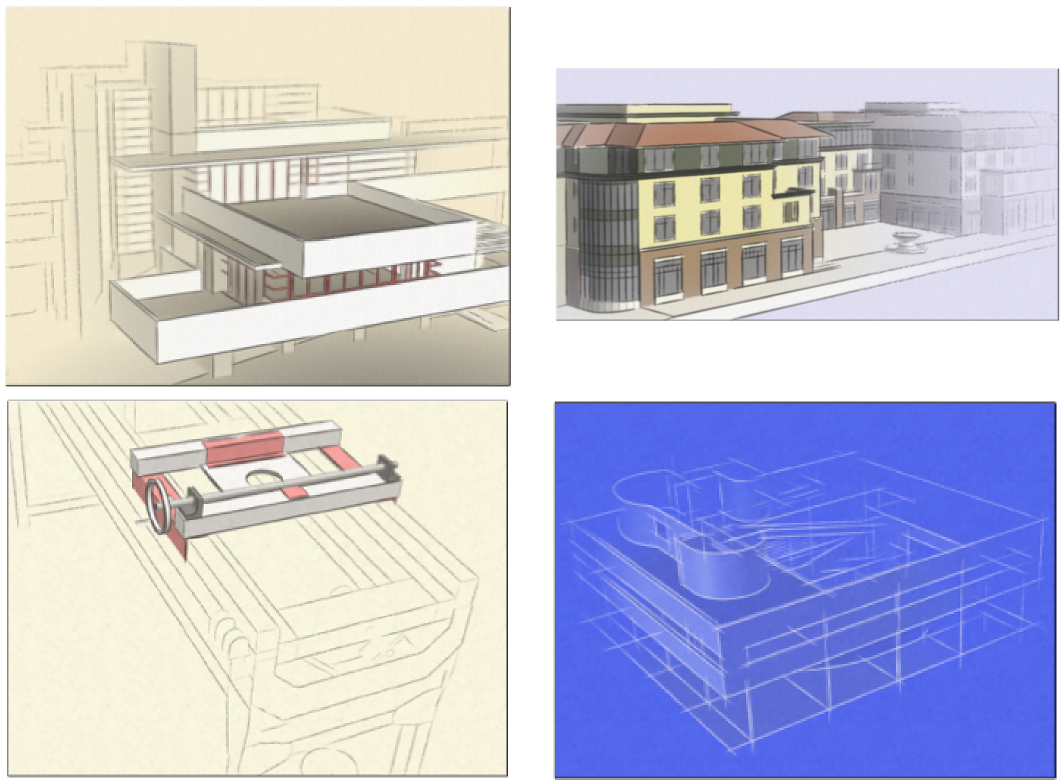


Figure 1.15: A collection of images produced by using attention driven rendering of 3D scenes. (a) Varying saturation and line density. (b) varying saturation, hue, line density, and line style (chalk like lines in low detail areas). (c) Sharp transition of color and line density used to focus on a single element rather than a region. (d) Extended line drawing to give an artistic sketch-like effect to low detail regions. [4]

can be used to solve occlusion problems when rendering volumes. The visualizations are also styled in such a way as to create textbook-like illustrations.

Wang et al. show how importance-driven visualization can be used to aid analysis of time-varying data [19]. Regions of temporal significance are analyzed and then each voxel is given an importance curve over time. These curves are clustered and then the amount of regions to focus on is limited while still ensuring temporal coherence.

1.3 Thesis Statement

As datasets become larger, the demand on data visualization also grows. Whether that demand be on increasing the amount of data displayed, the size of the screen the data is displayed on, or the level of detail it is displayed in; there exists a common problem associated with this demand. That problem is *the inefficiency of uniformly up-scaling the amount of data visualized*.

Simply showing more data on larger displays has been shown to actually decrease productivity due to overwhelming the users with data [26]. Furthermore, due to the limits of human vision, as the display size increases, less of the information around our focal point is actually observable in full detail [5].

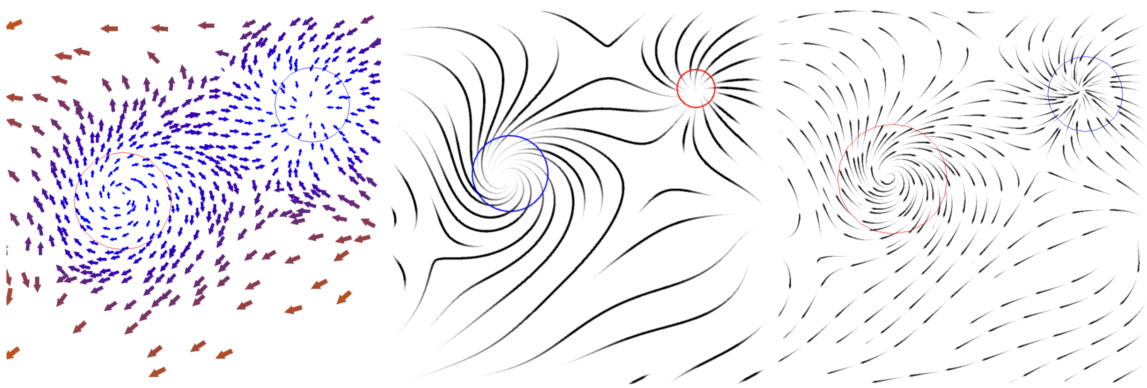
Focus+context visualization has been shown to be an efficient solution to this problem when displaying 3D models or volumes [7, 4, 25]. Furthermore, adaptive visualization driven by importance provides a way of directing the attention of the user to particular regions of interest that have been either manually or automatically determined to be significant [4, 17, 18, 19].

Current work on adaptive visualization of vector fields is limited by its ability to only perform uniform level of detail scaling for an entire scene, or by the lack of interactivity and inability to dynamically change the regions of focus [1, 8, 11].

This thesis presents methods for focus+context vector field visualizations using glyphs and streamlines. These visualizations methods allow users to interact with the data and visualization in real time and explore the data. These focus+context visualizations provide less distractions to users since unimportant data is masked, while greatly improving performance over full-detail visualizations in some cases. All of this is done without sacrificing important data and while maintaining the context of that important data.

CHAPTER 2

OVERVIEW



(a) Glyphs (b) Streamlines (c) Directed Streamlines

Figure 2.1: Visualizations produced by the methods presented in this work. From left to right are glyphs, streamlines, and streamlines modified to show direction.

The goal of this work is to reduce visual clutter without sacrificing any information the user considers important and allowing while still allowing interactivity with the visualization. To accomplish this we create visualizations with a variable level of information density. Streamlines and glyph visualizations have been chosen since the information density of these methods can be altered by changing the separation distance between streamlines or the number of glyphs used. LIC is not a focus of this work since a LIC visualization with a sparse texture appear similar to a streamline visualization (see Figure 1.13.) and unlike streamlines (which can be controlled directly while integrating) require indirect control through texture manipulation.

The user maintains control of which regions are considered important by setting *focus points*. A focus point is represented by a location, radius, and magnitude and represents a region the user considers important (see Section 3.1.1.). The user can add, delete, move, and resize multiple focus points interactively and the visualization will be updated in real-time.

The focus points are an interface presented to the user for controlling the *importance* (a normalized scalar value representing the desired information density), but are not used directly by the visualizations. The focus points are used to create the *importance field* which is a scalar field superimposed onto the vector field (see Section 3.2.). The importance field is used by the visualizations to sample the desired information density at any point in the visualization. Glyph information density is controlled by varying the number of glyphs shown (see Chapter 4.) while streamline density is controlled by varying the separation distance between streamlines (see Chapter 5.).

The simplicity of the interface for controlling focus points as well as the reduced computational cost of the sparse visualizations seems to lend well to a touch tablet platform. The visualizations of this work are implemented on both PC and Tablet platforms and user evaluations are conducted using the tablet visualizations for simpler tasks (such as critical point detection) and the PC visualizations for more advanced tasks (such as point advection).

CHAPTER 3

IMPORTANCE

Importance is a normalized scalar value representing the desired information density of the visualizations. An importance value of 1 at some point would cause that point of the visualization to have the highest information density while a value of 0 would cause it to have the lowest level of information density. The importance level is controlled by the user through focus points and stored in the importance field for the visualizations to use. The variable importance is what drives the number of glyphs or density of streamlines in the visualization and controls how the visualizations reduce visual clutter.

3.1 Focus Points

3.1.1 What is a focus point?

A *focus point* is a point in the visualization which has been given significance either through data analysis or by the user. It represents a region of interest that should be rendered in higher detail.

Focus points are composed of a point (p), weight(w), radius (r_f), and wave equation ($\mathbf{\Phi}$). Each of these values is used to evaluate the contribution a focus point gives to any point in the visualization.

Since focus points define a region of enhanced interest, they can be used to mimic a lens; however, unlike a "zoom" or "fish-eye" lens, focus points do not cause any distortion in the actual data. Instead they influence importance, which then influences the visualization density.

3.1.2 Wave equation

Each focus point is defined by a wave equation which is used to calculate the importance contributed by that focus point to all regions in the visualization. The wave equations are implemented as a 1D function with the variable being the distance (r) from the point in question to the center of the focus point (p). The importance value is highest at the center of the focus point and decays as the point moves further from the center depending on the radius and wave equation. Different wave equations will result in different decay profiles as well as slightly different performance. Figure 3.1. shows the importance fields resulting from a focus point of each wave equation type. The computational performance difference between the different wave equations was found to be negligible on the PC and thus Gaussian is chosen as the default since it produce a smooth transition of importance; however, the computational requirement was noticeable enough on the tablet platform to encourage using the linear or inverse function instead.

$$\text{Linear:} \qquad \mathbf{\Phi}(r) = \min(w - \frac{r}{r_f}, 0) \tag{3.1}$$

$$\text{Inverse:} \qquad \mathbf{\Phi}(r) = w\frac{1}{1 + \frac{r}{r_f}} \tag{3.2}$$

$$\text{Inverse Square:} \qquad \mathbf{\Phi}(r) = w\frac{1}{(1+\frac{r}{r_f})^2} \tag{3.3}$$

$$\text{Lorentzian:} \qquad \mathbf{\Phi}(r) = w\frac{r_f^2}{r_f^2 + r^2} \tag{3.4}$$

$$\text{Exponential:} \qquad \mathbf{\Phi}(r) = we^{-\frac{r}{r_f}} \tag{3.5}$$

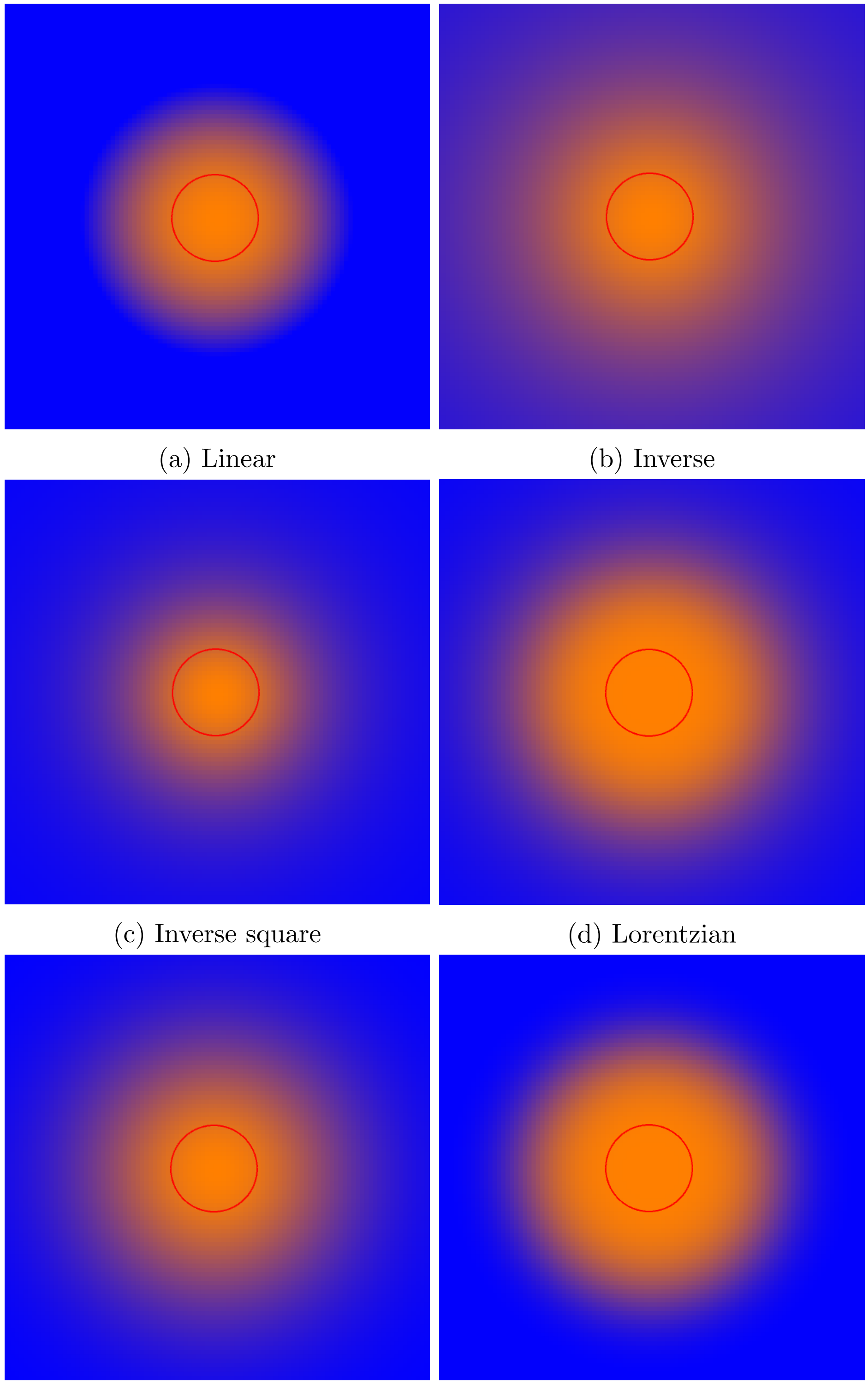
$$\text{Gaussian:} \qquad \mathbf{\Phi}(r) = we^{-(\frac{r}{r_f})^2} \tag{3.6}$$

3.1.3 Interaction

Focus points can be added by either the user or automatically by data analysis. They can be deleted or have their point (p), radius ($r - F$), or wave equation ($\mathbf{\Phi}$) changed by the user interactively during the visualization. Manipulating the focus points is how the user can interactively control the importance field during the visualization. Depending on the platform (PC or tablet), the users interact with the focus points differently.

On a PC a focus point can be created by clicking a region without a focus point. If the user clicked on a region where a focus point already exists, that focus point will be selected. Selected focus points can be deleted using the 'd' key, have their radius increased with '+' or decreased with '-', or their wave equation changed with the number keys '1' - '6'. A focus point can be moved using a click-and-drag motion.

On a tablet a focus point can be created by touching and holding a region without a focus point or deleted by touching and holding a region with a focus point. Simply touching lightly will select a focus point, while dragging will move that focus point.



(a) Linear (b) Inverse

(c) Inverse square (d) Lorentzian

(e) Exponential (f) Gaussian

Figure 3.1: Visualization of wave functions for focus points and their effects on the importance field. In all images, the importance field is represented as a color map from blue (0) to orange (1). The circle represents the radius and location of the focus point.

The pinch-and-zoom gesture is used to control the focus point radius. On the tablet, there is no way to control the wave equation of the focus point directly. Instead, a fixed type of linear or inverse is used. This is done both to keep the tablet interface simple and to avoid costly wave equations being used on a less powerful tablet device.

3.1.4 Generation from data

Focus points can be generated and placed automatically based on the data by pre-computing possible critical points using a method presented by Effenberger et al. [6] By analyzing each cell of the vector field, and determining in what way the sign of the vector field in each component (x or y) changes along the edges of the cells, possible critical points can be found. As long as the focus point's radius is larger than the size of the cell, simply determining if a cell can have one or more critical points is sufficient and placing a focus point in the center of the cell will ensure that the critical points are all contained within a focus point. No further computation to determine the number or type of critical points is needed. These checks can be optimized by creating a key for each possible configuration case and performing a lookup in a pre-computed table with flags that state if a cell holds at least one critical point or not.

Figures A.3, A.7, A.11 all show full detail visualizations with features found by this critical point detection method, while Figures A.4, A.8, A.12 all show how critical point estimation can be used to generate an initial focus point set to present to the user.

3.2 Importance Field

Importance in a visualization is controlled by the importance field. The importance field is a scalar field imposed over a vector field that is used by the visualization methods to determine which regions of the visualization require more focus than others. The importance field is normalized with a value of 0 being completely unimportant and 1 being the highest importance.

The importance field is stored as a 2D texture. This texture is populated with the superposition of all the focus points' wave equations (see Section 3.1.1) sampled at the center of each texture point. The importance field at any continuous point is then acquired by sampling this texture using bi-linear interpolation. Figure 3.2. shows the importance field resulting from two focus points.

A more accurate approach would be to sample each focus point's wave equation every time the importance field is sampled, but this would be slow since the field is constantly re-sampled and some of the wave equations can be computationally costly. This texture method is used as an optimization to improve performance by reducing the number of wave equation evaluations required.

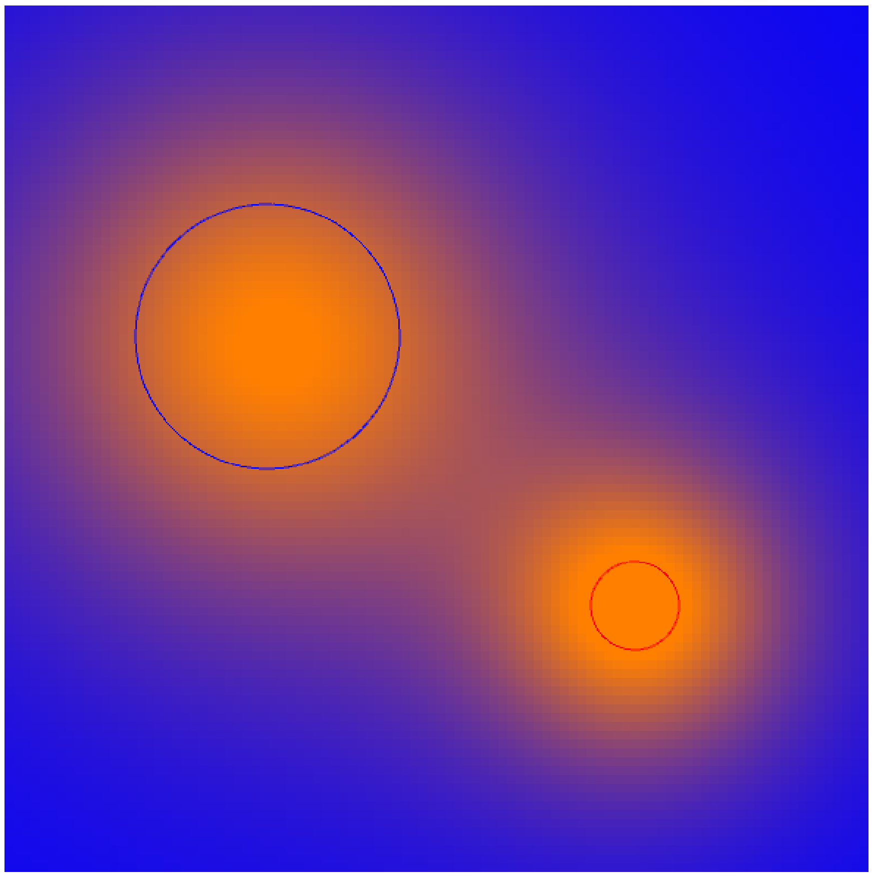


Figure 3.2: Shows the importance field resulting from multiple focus points. The importance field varies from 0 (blue) to 1 (orange). Focus points are visualized by the circles with width representing the radius of the focus. In this figure both focus points use an inverse square wave function.

CHAPTER 4

GLYPHS

Glyphs are chosen because they offer the most control over information density. By varying the number of glyphs placed in a particular region, the information density can be either increased or decreased. Glyphs are also computationally inexpensive compared to other visualization methods and often give a clearer indication of direction than streamline based methods.

4.1 Glyph Pool

The *glyph pool* is a high-density collection of potential glyphs created before the visualization. Each glyph in the glyph pool has its position chosen and fixed before the visualization. During visualization glyphs are chosen from the pool based on the importance field and rendered. A higher importance results in more glyphs being chosen from the pool and thus a higher density. A lower importance results in fewer glyphs being chosen from the pool and thus a lower density.

A glyph pool is chosen for two reasons. The first is for efficiency (to avoid unnecessary addition and deletion of glyphs during visualization). The second is to maintain temporal coherence. By fixing the positions of all potential glyphs before visualization, temporal disruption is limited to glyphs fading in and out rather than moving around.

The choice of whether a glyph from the pool should be rendered is made using the glyph's *importance threshold*. The importance threshold is the minimum importance that must be present at the glyph's position for that glyph to be rendered. By varying the importance threshold of the glyphs appropriately, a higher importance will result in more glyphs being rendered since there are more glyphs with a low enough importance threshold.

Three methods for choosing the placement and importance thresholds are discussed. Each attempting to address the shortcomings of the method before it.

- Random Glyphs
- Grid-Based Glyphs
- Mipmap Glyphs

4.2 Random Glyphs

The first method for glyphs involves randomly selecting the positions and importance values. The desired result is to create a uniform distribution of glyphs throughout the visualization. The problem with this method is that some glyphs may be placed too close together and result in the glyphs occluding one another.

Attempts to resolve these occlusion problems included attempting to get a more uniform distribution of glyphs by further jittering the glyph positions after generation, but this did not appear to have a significant impact and made little difference visually.

Even with an ideal uniform distribution of glyphs and with occlusion avoided; another problem with this method exists. The set of all glyphs may have a uniform spatial distribution, but the subset of all *visible* glyphs can still have pockets of unintended density.

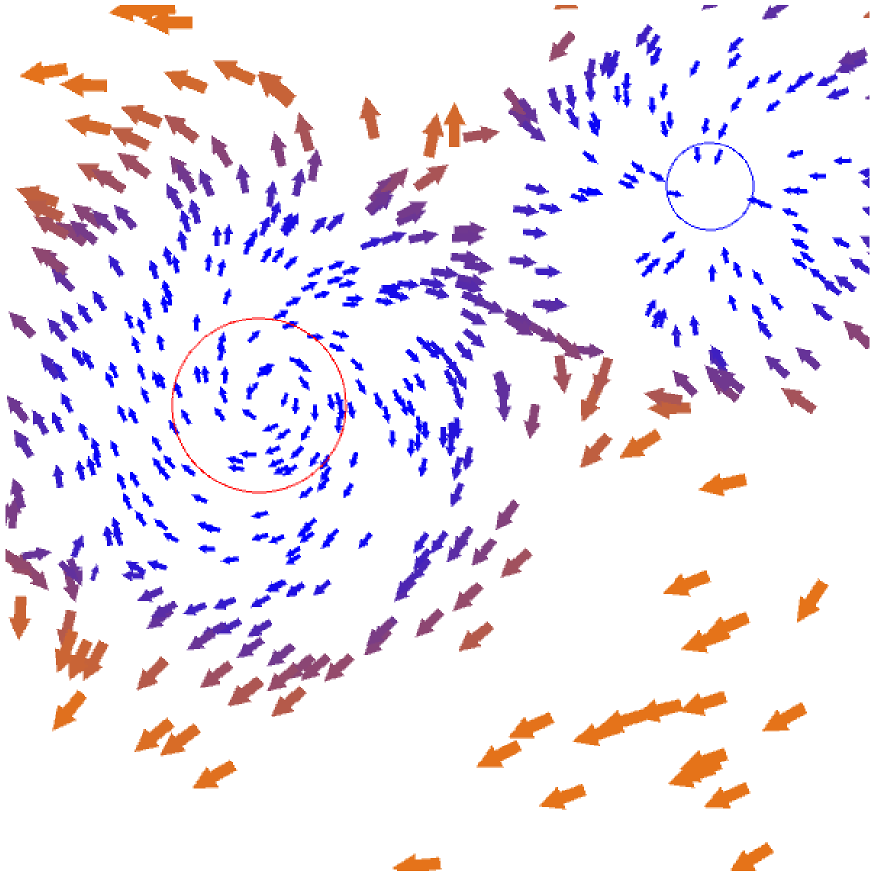


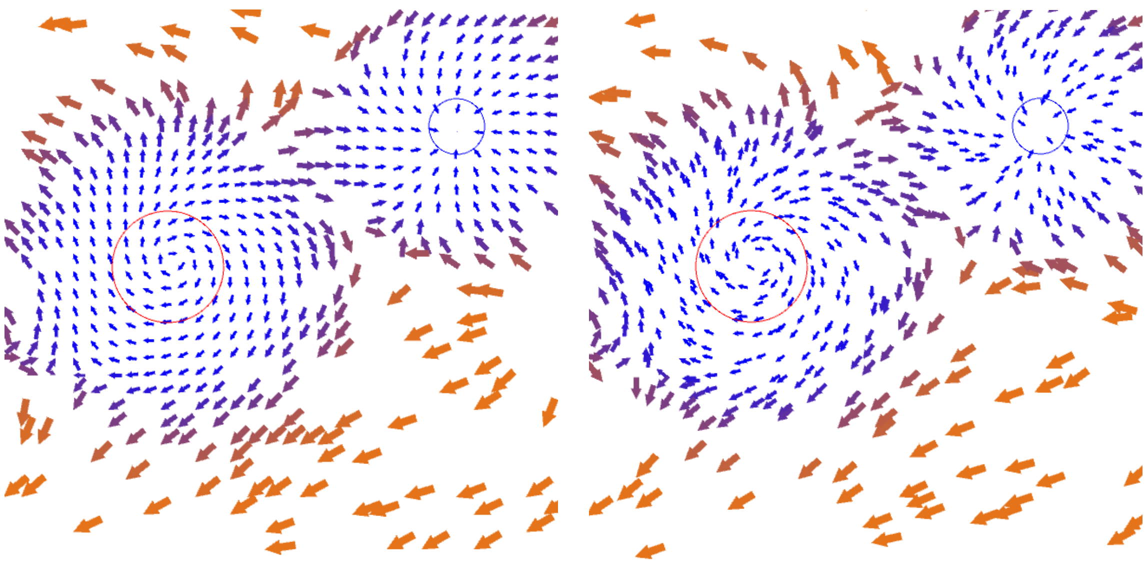
Figure 4.1: Shows a vector field visualization using randomly placed glyphs. Note how some glyphs overlap. Also note that there are small regions of higher density that are far away from the focus point.

Figure 4.1. shows a visualization using random glyphs. Note how some glyphs are occluding one another. This figure also shows small regions of high density even in regions which should clearly be low density since they are far from the focus point.

4.3 Grid-Based Glyphs

The next method attempts to avoid occlusion by placing the glyphs on a uniform or jittered grid and choosing the importance thresholds randomly. Glyphs placed on a grid will not occlude one another provided that nearby glyphs are not scaled too much and the jittering is small.

This method of glyph placement prevents occlusion, but since the importance threshold is still randomized it is possible for small pockets of high or low density to appear. Figure 4.2. shows these pockets still exist even when using a uniform or jittered grid to place the glyphs.



(a) Uniform 32x32 grid (b) Jittered 32x32 grid

Figure 4.2: Shows the results of placing glyphs on a uniform and jittered grid while choosing importance threshold randomly. Notice that occlusion is suppressed, but pockets of uneven density still exist.

4.4 Mipmap Glyphs

The reason pockets of high density appear in low importance regions is because two or more glyphs near each other are all assigned low importance thresholds. This causes a small region of increased density. The reason pockets of low density appear is that too many glyphs in a small region are all assigned high importance thresholds.

Randomly choosing the importance threshold may result in a uniform distribution of importance threshold values, but it is also essential that these importance values be uniformly distributed in space.

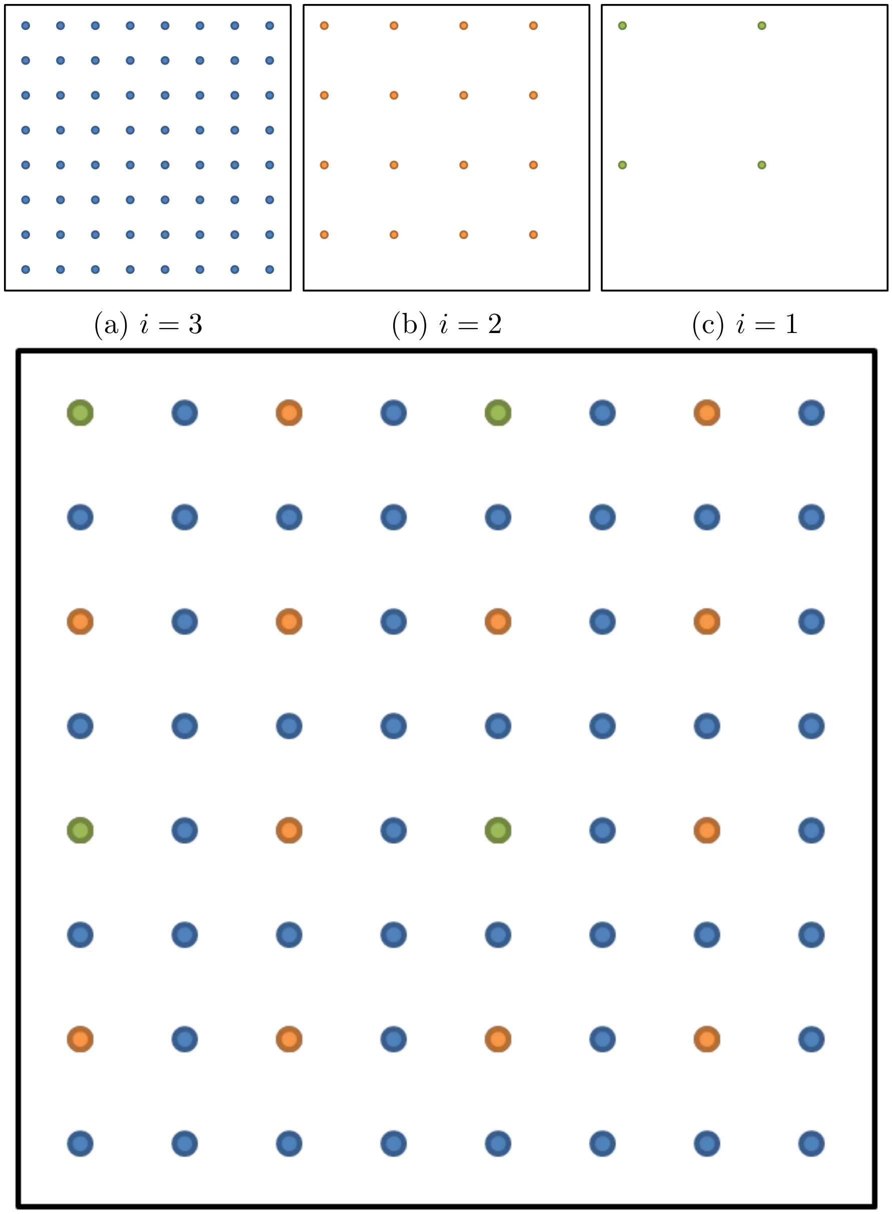
To avoid these pockets of high or low density and create a uniform spacial distribution of importance thresholds, the importance threshold is calculated using a mipmap approach. For a grid of dimension $2^n \times 2^n$, n sub-grids of decreasing dimension are generated. For each value i from 1 to n a grid of size $2^i \times 2^i$ is generated and each element is assigned a random value between $\frac{i-1}{n}$ and $\frac{i}{n}$. These sub-grids represent multiple levels-of-detail with each sub-grid having importance threshold values randomly chosen around a value proportional to the number of elements in the sub-grid. For example a $2^3 \times 2^3$ sub-grid will have higher importance threshold values than a $2^2 \times 2^2$ sub-grid.

The final threshold value for each glyph is selected by sampling all valid sub-grids and choosing the lowest threshold value among them. A sub-grid i is considered valid for some index (u, v) if and only if $u \mod 2^{n-i} = 0$ and $v \mod 2^{n-i} = 0$. Figure 4.3 shows an example of a 8x8 grid and its sub-grids being used to chose importance thresholds.

This mipmap approach ensures that no two neighbouring glyphs both have low importance values and thus avoids pockets of high density. It also ensures that there exists at least one glyph with a low importance threshold in each region thereby avoiding pockets of low density.

Figure 4.4. shows uniform and jittered grid glyph placement using the mipmap approach to assign importance thresholds. Notice there are no longer localized regions of higher density and occlusion is mostly avoided.

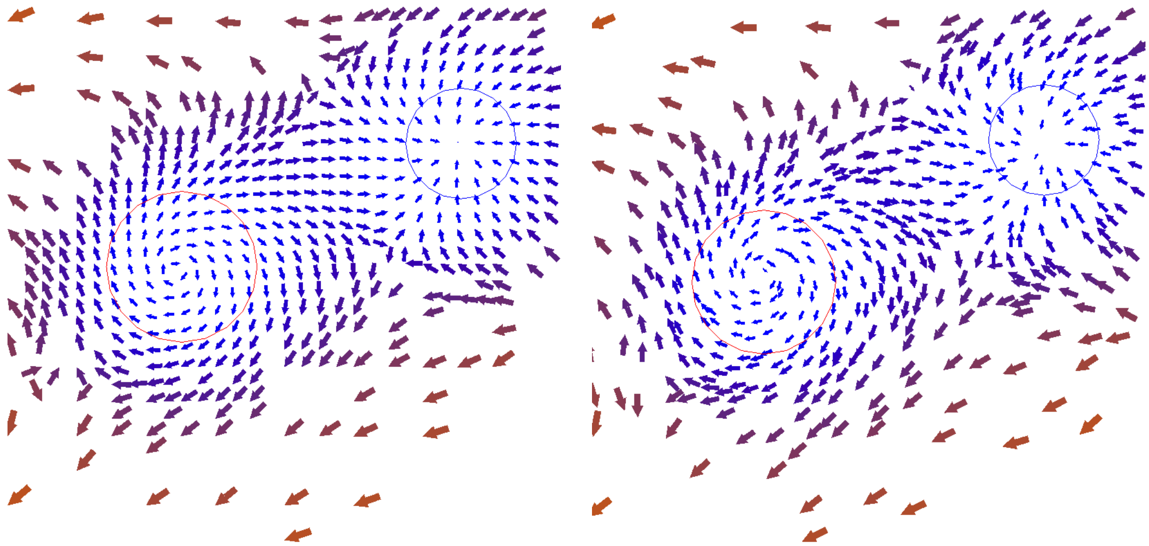
The reason that each element in a sub-grid is assigned a random number within



(a) $i = 3$ (b) $i = 2$ (c) $i = 1$

(d) $n = 3$

Figure 4.3: The sub-grids for a $2^3 \times 2^3$ grid are shown above and the final sampled grid is shown below. Importance thresholds are shown with blue being the highest, then orange, and green being the lowest.



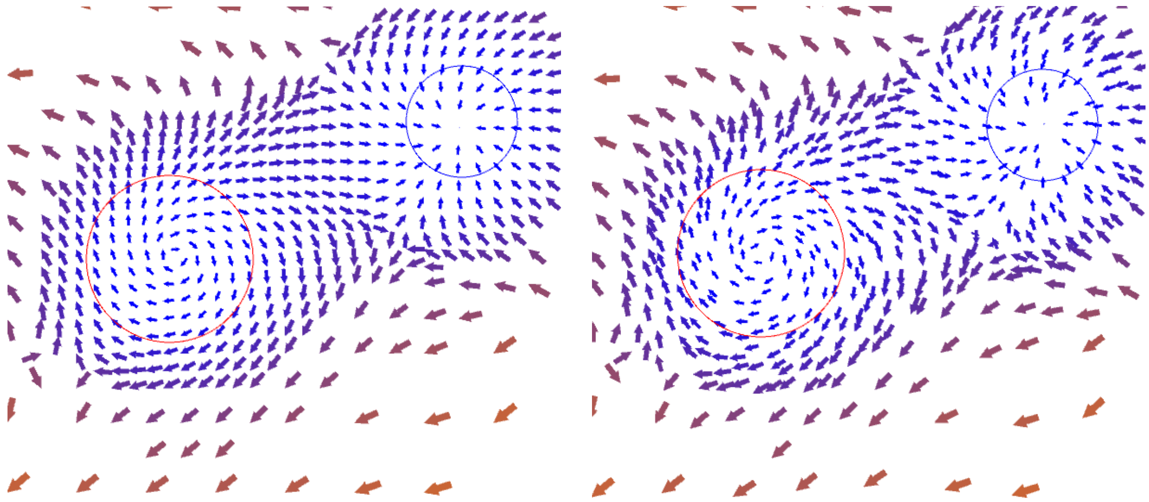
(a) Uniform 32x32 grid. (b) Jittered 32x32 grid.

Figure 4.4: Shows uniform and jittered grids using mipmap importance thresholds.

some range is so the transition between LODs is smoother. If each sub-grid was filled with a constant value proportional to its depth, then artifacts are visible when transitioning between the LODs as seen in Figure 4.5.

4.5 Shape and Size

Glyphs are rendered as simple arrows pointing in the direction of the vector field at the position of the glyph. In general glyph widths and lengths can be scaled according to any attribute of the vector field. The method chosen is to render glyph length based on the magnitude of the vector and also scale the glyph inversely with importance. Glyphs will be smaller in high density regions to avoid overlapping glyphs and larger in less dense regions to indicate that the glyph represents an approximation for a larger region. Glyph color is also scaled with importance to visually confirm regions of higher importance, but can also be scaled with any other vector attribute.



(a) Uniform 32x32 grid.

(b) Jittered 32x32 grid.

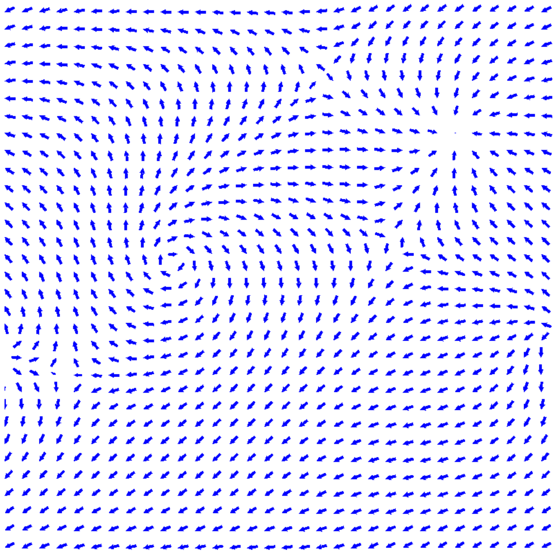
Figure 4.5: Shows uniform and jittered grids mipmap importance thresholds, but without random variation within a level. Notice how the boundary between level transitions is much more defined.

4.6 Temporal Coherence

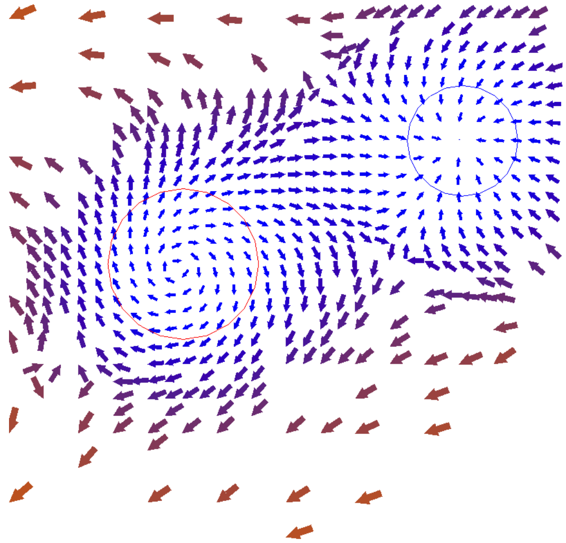
As stated before, the glyph pool helps maintain temporal coherence by fixing glyph positions and avoiding glyph movement during visualization. To further improve temporal coherence when interacting with glyph based visualizations glyphs are gradually faded in and out of the scene by modulating the opacity and width of the glyphs. This provides a smooth transition and minimizes any popping artifacts caused when glyphs quickly toggle visibility when changing the importance field.

4.7 Performance

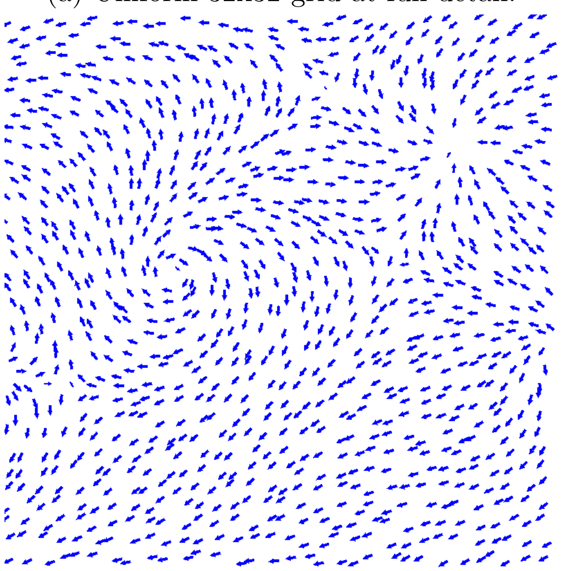
Table 4.1. shows glyph visualization performance results for the data shown in Figure 4.6. Testing was performed on an Apple MacBook with a 2.3 GHz Intel i7, with 4 GB



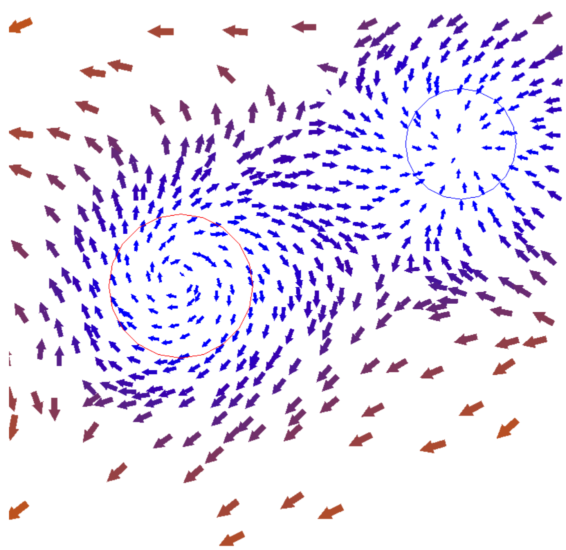
(a) Uniform 32x32 grid at full detail.



(b) Uniform 32x32 grid with focus+context.



(c) Jittered 32x32 grid at full detail.



(d) Jittered 32x32 grid with focus+context.

Figure 4.6: Shows both full detail and focus+context visualization using jittered and uniform grid placement with mipmap importance thresholds.

Glyph Distribution	Full Detail (fps)	Focus+Context (fps)
Uniform 32x32 Grid	325	320
Jittered 32x32 Grid	313	311

Table 4.1: Shows performance of glyph visualizations for uniform grid, jittered grid, and random distributions.

RAM and a NVidia GeForce 650M (1GB) GPU. Based on these results, performance does not vary by a significant amount regardless of what glyph visualization technique is used.

CHAPTER 5

STREAMLINES

Unlike glyphs, streamlines excel at showing connected flow between regions in the vector field. They require more computation but have been shown to be more useful in advecting particles and locating critical points [10].

5.1 Seed Point Selection

5.1.1 Image Guided

Turk et al. and Jobard et al. both present specialized methods for placing streamlines at a uniform density [9, 15], but these methods present temporal coherence issues when changing the density. Jobard's method of seed point generation lead to bad temporal coherence because the next seed point is based on the previous streamline. If one streamline changes, the positions of all the streamlines may change. Figure 5.6. shows overlapping visualizations with slightly different focus point positions. The visualization using the method presented by Jobard et al. results in many changes and thus has poor temporal coherence.

5.1.2 Randomized Seed Pool

We use a large randomized seed pool when choosing seed points. A large number of candidate seed points are generated with a uniform distribution and high density.

Each seed point is used to generated a streamline. If there is no valid streamline available (because there is already a streamline within d of this seed point or because the streamline would be too short), the seed point is skipped. This process continues for all seed points. The more seed points that are chosen, the more likely that a seed point will be closer to an 'ideal' or 'optimized' seed point. The density of the visualization is also bound by the density of seed points. If the minimum separation distance d_{min} is small, then the number of seed points in the pool must be high or that distance cannot be achieved. Figure 5.1. shows an example where all seed points in the pool are in blue and all valid seed points that have generated a streamline in red.

5.2 Controlling Density

5.2.1 Separation Distance

Streamline density is controlled by maintaining a separation distance d between streamlines. This separation distance is calculated by Equation 5.1. and used to determine if a seed point is valid and when to terminate integration of a streamline.

$$d(x, y) = d_{max} - \mathbf{I}(x, y)(d_{max} - d_{min}) \tag{5.1}$$

Computing the actual distance between a streamline point and all other streamlines was performed by using a grid based method similar to that taken by Jobard et al. [9]. The visualization space is divided into a uniform grid with each cell equal to some value between d_{min} and d_{max}. Each cell of this grid contains a list of points from other streamlines that lie within that cell. A point query only needs to test against all other points in the same cell and nearby cells; however, unlike Jobard's method,

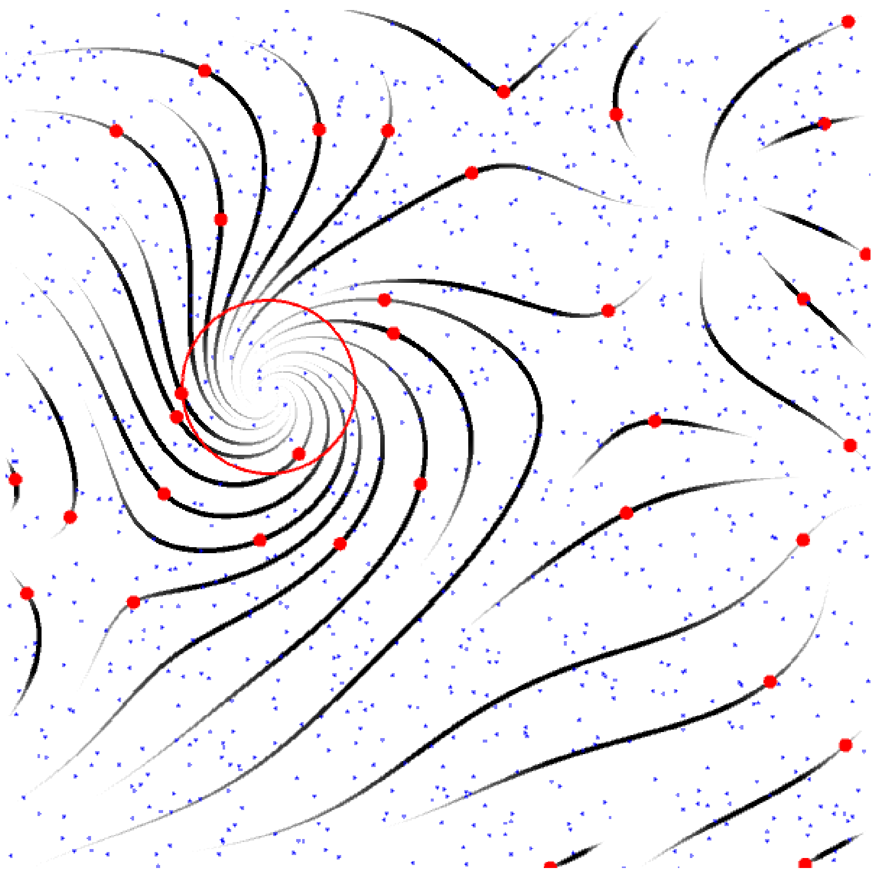
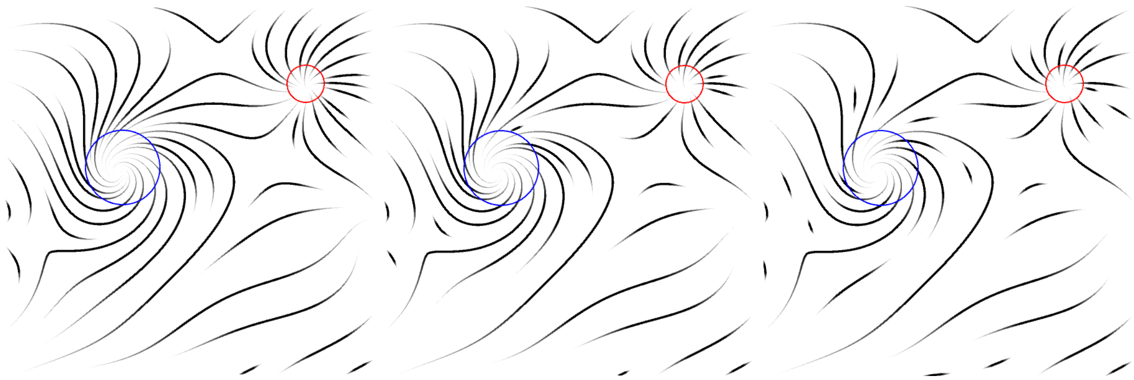


Figure 5.1: Shows seed point pool used in streamline visualization. Seed points that generate valid streamlines are shown in red, while ignored seed points are shown in blue.



(a) $d_{test} = 0.6$ (b) $d_{test} = 0.8$ (c) $d_{test} = 0.99$

Figure 5.2: Shows streamline visualizations with varying d_{test}. Notice how streamlines appear short and choppy with high d_{test}. For all images d_{min}=0.01 and d_{max}=0.08.

all nearby cells within the search distance must be checked since the density is not uniform over the entire image. Although the number of cells checked each time is not a constant value; it is still bound by an upper limit since the maximum distance between two streamlines is also bound.

5.2.2 Integration Method

Integration of streamlines is performed using the midpoint method for the tablet and the 2nd order Runge-Kutta method for the desktop. The midpoint method is used instead of Runge-Kutta on the tablet to reduce computational load on the weaker system. Streamlines are integrated forward and then backwards from each seed point using a step size of d_s. Integration stops if the next point would be out of bounds of the image, if the next point results in a self-intersecting streamline, or if the next point is found to be within d_{test} of another streamline. This separation test threshold d_{test} is used both to avoid creating short streamlines and to allow streamlines to converge closer to each other after they are created. The effects of varying d_{test} can be seen in Figure 5.2.

5.3 Visual Effect

Streamlines are rendered as triangles instead of lines to allow for tapering and width variation along the streamline. Since the streamlines are oriented along one path, a single triangle strip can be used to render the streamline by starting at one end and alternating points between the left and right side of the streamline until reaching the other end. By using a triangle strip instead of several triangles, sending duplicate points to the GPU can be avoided.

This optimization can be taken a step further. If two "collapsed" triangles are added such that the end points are equal to the end of one streamline and the beginning of another, all the streamlines in the entire visualization can be rendered as a single triangle strip (with the connecting triangles having 0 area and being invisible). This optimization allows sending all the streamline data to the GPU at once rather than in packets.

5.3.1 Splines

Before streamlines are rendered, the original streamline may be further interpolated using a hermite spline. This spline interpolation is skipped on the tablet for performance reasons. A lookup table is computed for the hermite spline coefficients and a fast interpolation can be performed. The vector field is used to compute the tangents of each point along the streamline during the spline computation.

5.3.2 Thickness

Maximum streamline thickness is controlled by the t_s parameter. Streamlines can be tapered by allowing the thickness to vary from 0 to t_s and back to t_s along the

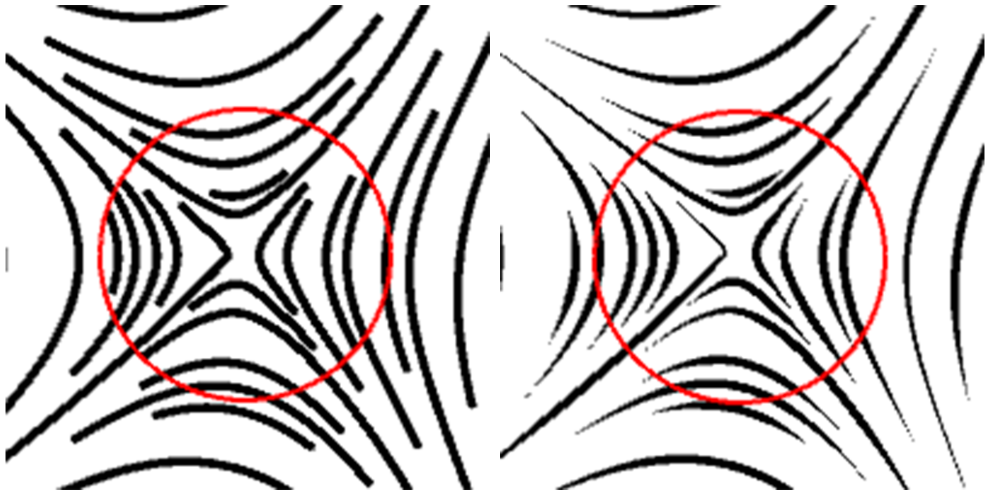


Figure 5.3: Demonstrates potential occlusions that occur near the ends of streamlines if no tapering occurs. The image on the left has no tapering enabled, while the image on the right has tapering.

length of the streamline. This tapering effect gives the streamlines a brush-like effect while also reducing streamline occlusion near the ends of streamlines where multiple streamlines terminate. Figure 5.3. demonstrates this by showing a visualization with and without tapering.

5.3.3 Opacity

Opacity can also be controlled and varied along the length of a streamline at the same rate as thickness. Varying opacity helps avoid aliasing that occurs when rendering very small triangles near the end of streamlines. Figure 5.4. demonstrates these artifacts and how opacity modulation removes them.

5.3.4 Indicating Direction

Streamlines normally lack the ability to indicate direction. To create directed streamlines, opacity and thickness can be modulated by using a biased saw-tooth function.

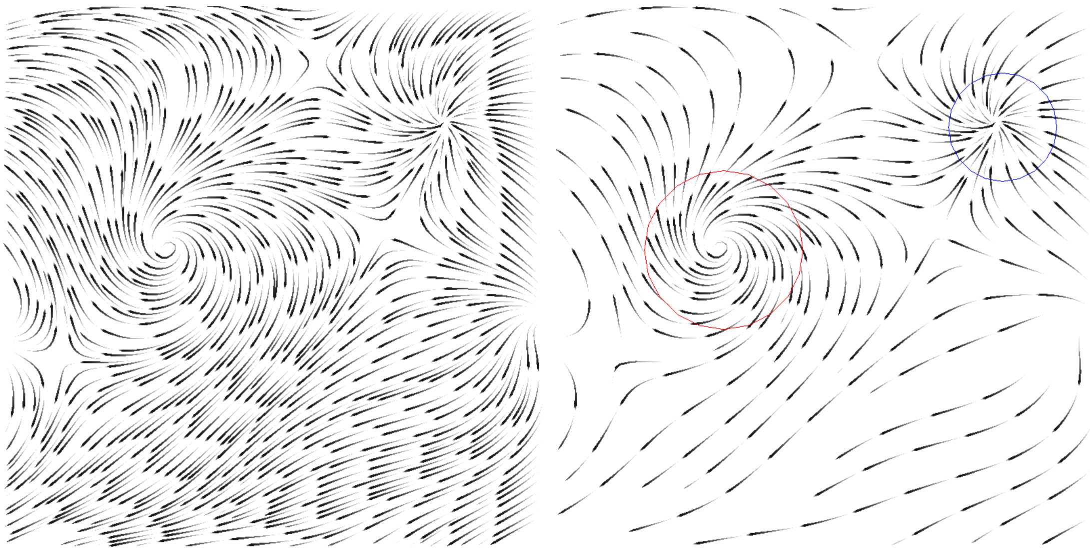
Figure 5.4: Demonstrates artifacts caused by tapering. The image on the left has only tapering enabled. The image on the right has tapering and opacity modulation enabled to smooth out the aliasing.

This makes the streamline appear as a series of streaks similar to brush strokes that allows the user to see the direction the streamline is traveling in. Figure 5.5. shows streamlines with modulated opacity and used to indicate direction.

5.4 Temporal Coherence

5.4.1 Choosing Seed Points

Image guided streamline placement works well for static images or visualizations with uniform density, but leads to small changes in density propagating larger changes in streamline positions. This can been seed in Figure 5.6. The figure shows an image guided streamline method presented by Jobard et al [9] being used to choose seed points compared to the random seed pool method. Each image is a composite of two images with a focus point moved by some small amount. Notice how the image guide method causes changes in streamlines far from the focus point, while the seed pool



(a) Full detail. (b) Focus+Context.

Figure 5.5: Shows streamlines with thickness and opacity modulated with a sawtooth function along the streamline to indicate direction.

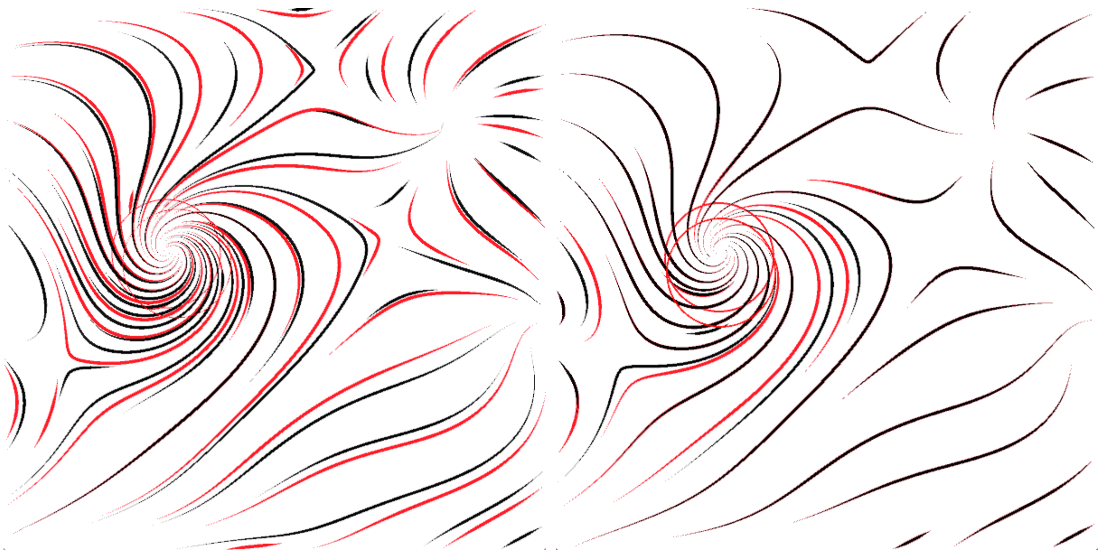
method contains the changes to streamlines near the focus point.

5.4.2 Animation

To increase temporal coherence when a user is interacting and changing the importance field, streamlines visibility toggling is animated. Streamline maximum thickness t_s of a streamline will slowly grow from 0 to its default value when a streamline becomes visible and shrink to 0 when a streamline is no longer visible. This help avoid "popping" artifacts when streamlines quickly toggle visibility.

5.5 Performance

Because no computational power is wasted integrating streamlines in regions of low interest, computational performance is much higher for this focus+context method than the full detail method. Figure 5.7. shows comparisons of focus+context and full



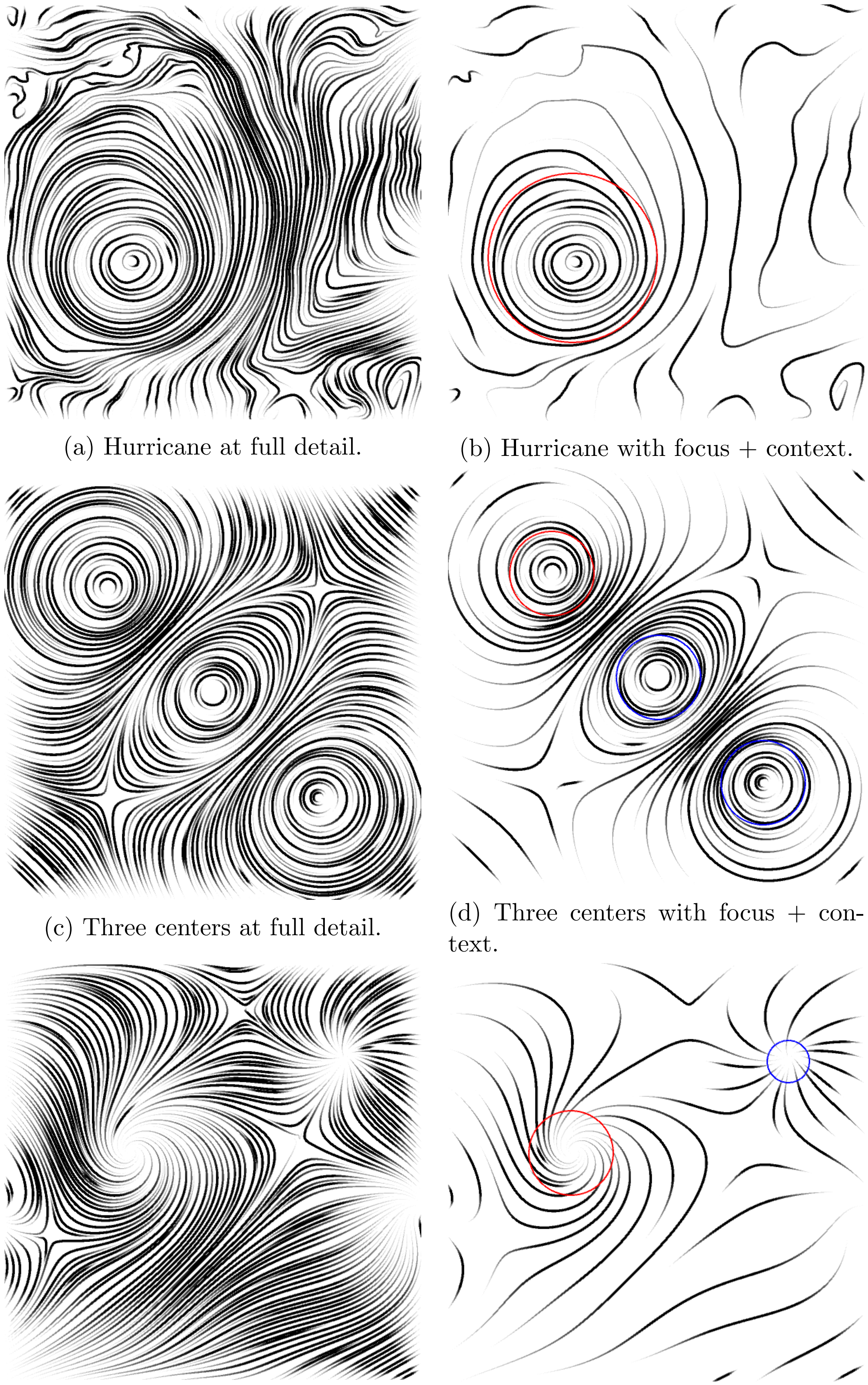
(a) Image guided (b) Random seed pool

Figure 5.6: Shows overlapping visualizations with slightly different focus point positions. The image on the left shows how the technique presented by Jobard et al. results in almost every streamline changing [9], while the image on the right shows that almost all streamlines further from the focus point remain constant when using the random seed pool method.

Dataset	Full Detail (fps)	Focus + Context (fps)
Hurricane	38	129
Three Centers	44	112
Random	41	182

Table 5.1: Results for datasets shown in Figure 5.7.

detail visualizations of various datasets. Note that for these images, the maximum detail is the same between both images in each set, but in the focus + context images, only a small portion of the image near the focus points are rendered at this density. Table 5.1 shows the performance for each of these datasets and indicates as much as a 4.4x improvement in fps for the focus+context methods discussed in this work. Testing was performed on an Apple MacBook with a 2.3 GHz Intel i7, with 4 GB RAM and a NVidia GeForce 650M (1GB) GPU.



(a) Hurricane at full detail.

(b) Hurricane with focus + context.

(c) Three centers at full detail.

(d) Three centers with focus + context.

(e) Random field at full detail.

(f) Random field with focus + context.

Figure 5.7: For all images d_{min}=0.01, d_{max}=0.08, d_{test}=0.6, d_s=0.01, and maximum streamline thickness is 0.03.

CHAPTER 6

EVALUATION

User evaluations were conducted on the Android platform for basic tasks (critical point detection) and the PC platform for advanced tasks (particle advection). This chapter details the tasks the users were requested to perform as well as their results.

6.1 Parameters

6.1.1 Tasks

Users were presented with a visualization and asked to perform one or more of the following tasks.

Feature Counting

The user is asked to count the number of features in a visualization. This is the total number of features, and not necessarily the number of unique features. The user is presented with 5 multiple choice numbers and must select the correct one.

Identify Feature Type

The location of a particular feature is specified to the user through the testing program visually and the user must identify the type of the feature from the following 6 choices:

Saddle, Center, Attracting Node, Repelling Node, Attracting Spiral, and Repelling Spiral.

Point Advection

The user is presented with a point a in the visualization and must select a point b such that a will be at point b after some time has passed assuming that a is influenced in direction by the vector field in the visualization. The users were allowed to change their answer as many times as they needed before confirming their answer. Error is measured by finding the distance from their answer to the nearest point on the path integrated along the initial point. This error metric avoids inconsistencies arising from different users advecting the particle further down the path.

6.1.2 Platform

For the feature counting and feature identification tasks users were given a tablet with the visualizations and a java application which presented the questions on a desktop or laptop. The reason that separate devices were used was because the tablet screen was too small to fit both the questions and visualization on and because it was easier to collect and retrieve the users data from the desktop than the tablet.

User demographics including age and tablet proficiency were collected before testing.

Each participant was presented with 12 visualizations and asked to perform one or both of the related tasks. The order of these visualizations was random, but the order of the questions within each visualizations was constant. The test would indicate which application to open and the user was required to open that application on the tablet.

Each question was timed and the users were presented with a place to make comments about the visualization after the questions were finished and before moving on.

After the users were done with the first two tasks, they were presented with 8 of the visualization they had previously seen on the laptop/desktop and asked to perform the point advection task.

6.1.3 Data

The vector fields used in each visualization were generated by simulating an electric field generated by placing 2-5 randomly charged points at random positions on the screen. These data-sets were generated before hand and stored for each test. Half of the visualizations are full detail while the other half are focus+context visualizations. Interaction was disabled for full detail since it would not affect the visualization in any way, while the standard interaction methods discussed were enabled in the focus+context based visualizations. Appendix A.1. details all the datasets used and what tasks were performed for each.

6.1.4 Participants

Seventeen users participated with 2 female participants and 15 male participants and ages ranging from 18 to 48 and over. All users considered themselves proficient in touch-based technology and general tablet experience.

6.2 Results

6.2.1 Glyphs

The following four visualizations were used during glyph evaluation:

- G1 - Full-detail glyphs
- G2 - Focus+Context glyphs
- G3 - Full-detail glyphs with initial guess
- G4 - Focus+Context glyphs with initial focus points

Counting Features

Figure 6.1 shows the user evaluation results for counting features using glyph based visualizations. Analysis shows a p-value of 0.76 for the times and 0.11 for the scores. These results indicate that even though users are expected to interact with the focus+context visualizations they took only slightly longer on average and were still able to maintain a score higher than the default full detail visualization.

Identify Features

Figure 6.2 shows the user evaluation results for identifying features using glyph based visualizations. The p-value for times is 0.82 and the p-value for scores is 0.65. These results indicate the users were able to perform feature identification just as effectively with the focus+context glyph visualizations as they were with full detail visualizations.

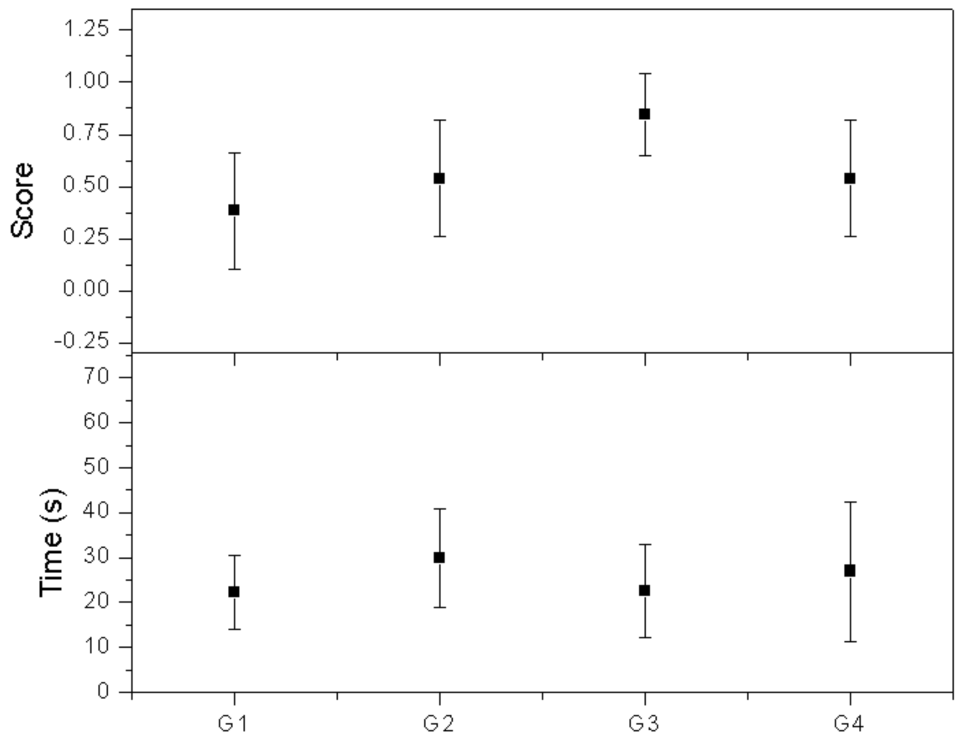


Figure 6.1: User evaluation results for counting the number of features present using glyph based visualizations. The top graph shows the score (proportion correct) the bottom shows the times. The 95% confidence intervals are also shown.

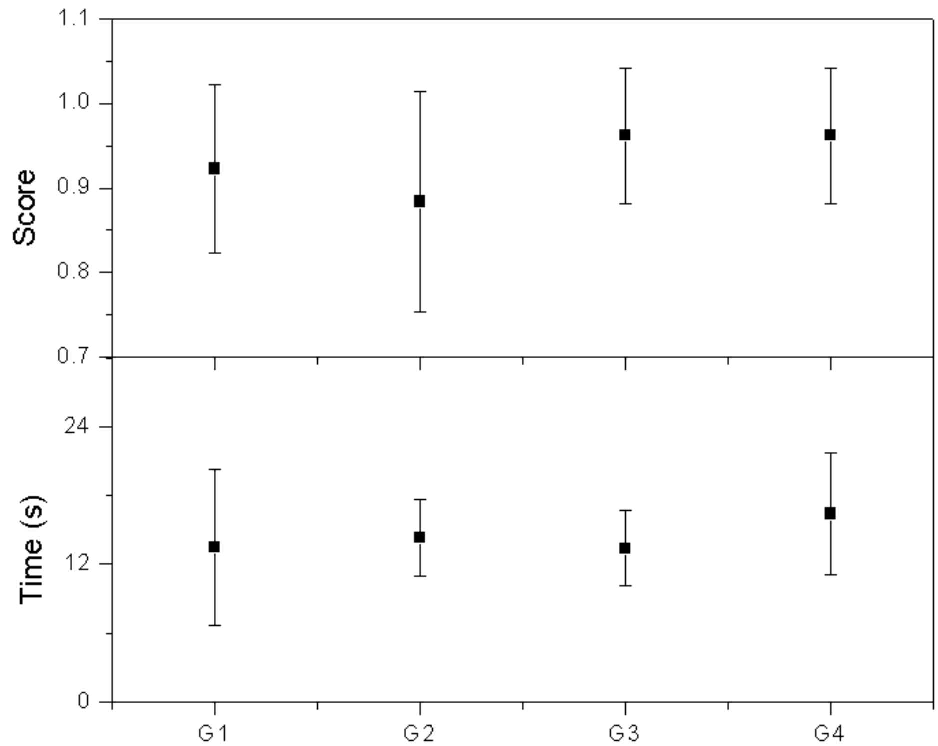


Figure 6.2: User evaluation results for identifying the type of features using glyph based visualizations. The top graph shows the score (proportion correct) and the bottom shows the times. The 95% confidence intervals are also shown.

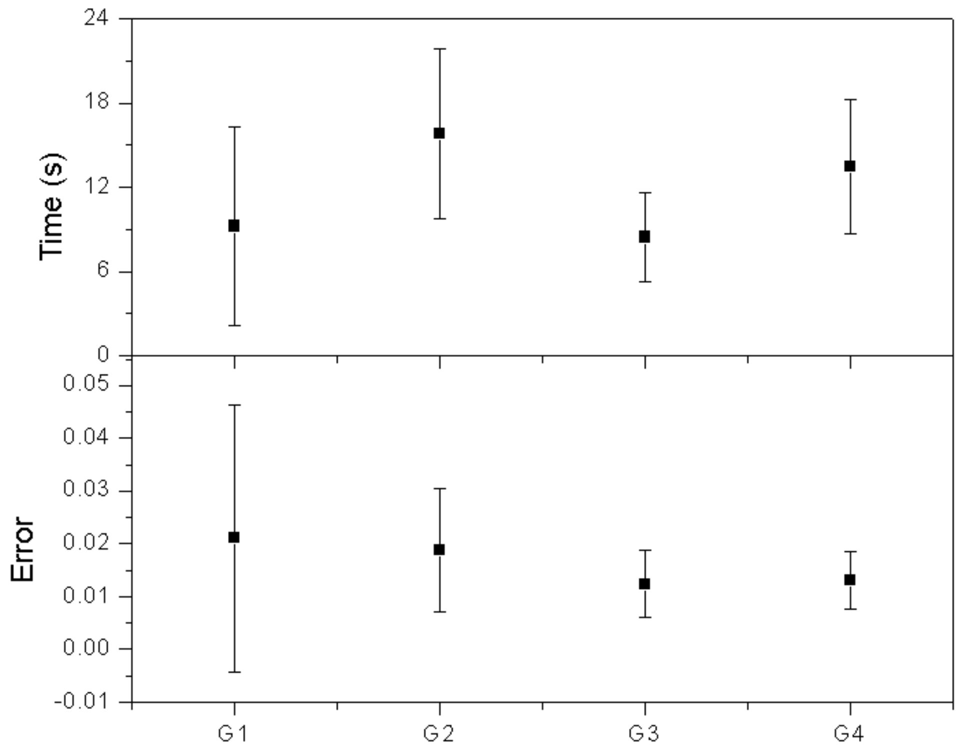


Figure 6.3: User evaluation results for advecting a particle using glyph based visualizations. The bottom graph shows the average error (measured as the distance from the selected point to the nearest point on the streamline) and the top shows the times. The 95% confidence intervals are also shown.

Advection

Figure 6.3 shows the user evaluation results for advecting a particle using glyph based visualizations. The p-value for the errors is 0.8 and the p-value of time was 0.1. Users took longer for the focus+context visualizations as expected due to the time required for interaction. The distribution of error for the default full detail glyph visualization was much higher than any other glyph visualization. These results indicate that the users were able to perform particle advection more effectively when a focus point was initially chosen for them (G4).

6.2.2 Streamlines

The following four visualizations were used during streamline evaluation:

- S1 - Full-detail simple streamlines
- S2 - Focus+Context simple streamlines
- S3 - Full-detail simple streamlines with initial guess
- S4 - Focus+Context simple streamlines with initial focus points

Counting Features

Figure 6.4 shows the user evaluations results for counting features using streamline visualizations. The p-vale of times was 0.99 and the p-value for scores was 0.028.

Users took the same time to perform this task for all visualizations and were able to achieve better results when initial focus points were selected for them.

6.2.3 Directed Streamlines

The following four visualizations were used during directed streamline evaluation:

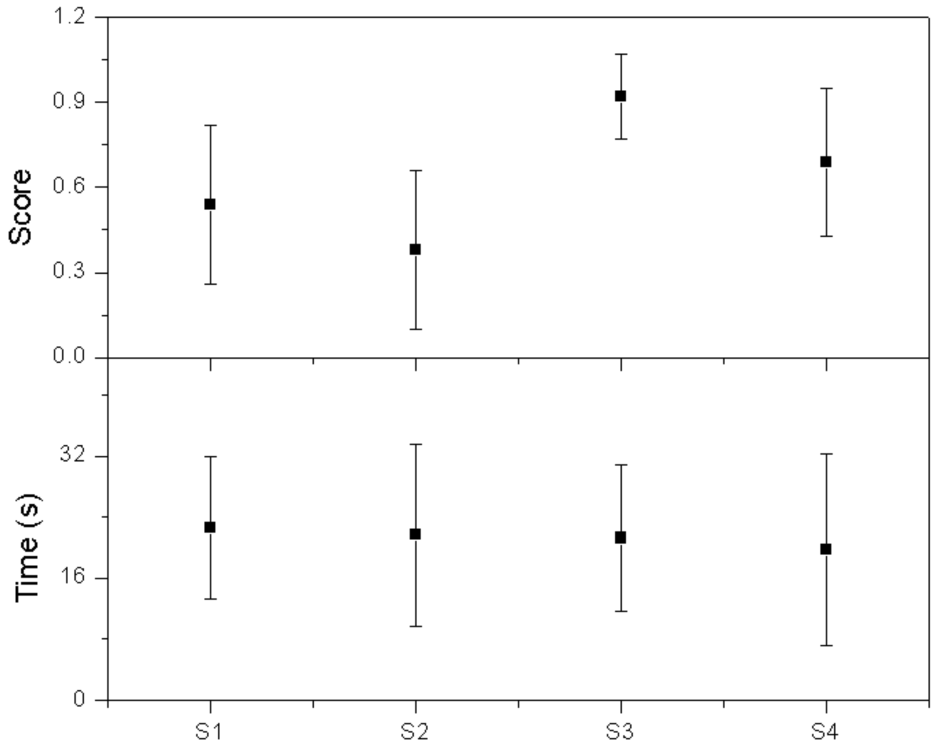


Figure 6.4: User evaluation results for counting the number of features using streamline visualizations. The top graph shows the score (proportion correct) and the bottom shows the times. The 95% confidence intervals are also shown.

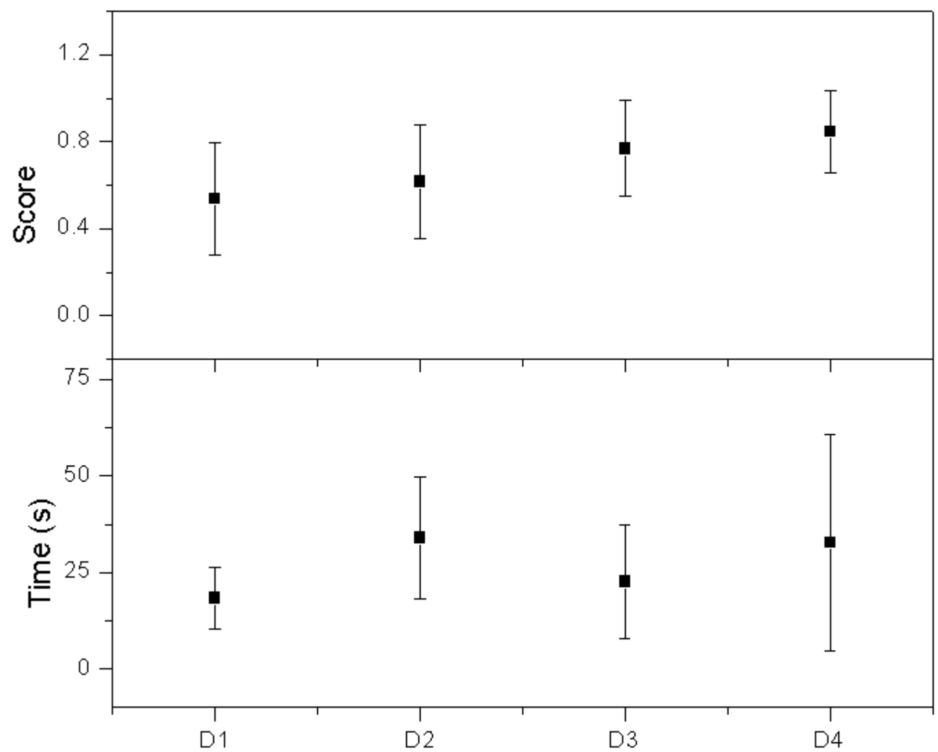


Figure 6.5: User evaluation results for counting the number of features using directed streamline visualizations. The top graph shows the score (proportion correct) and the bottom shows the times. The 95% confidence intervals are also shown.

- D1 - Full-detail directed streamlines
- D2 - Focus+Context directed streamlines
- D3 - Full-detail directed streamlines with initial guess
- D4 - Focus+Context directed streamlines with initial focus points

Counting Features

Figure 6.5. shows the user evaluations results for counting features using directed streamline visualizations. The timings have a p-value of 0.62 and the p-value for the

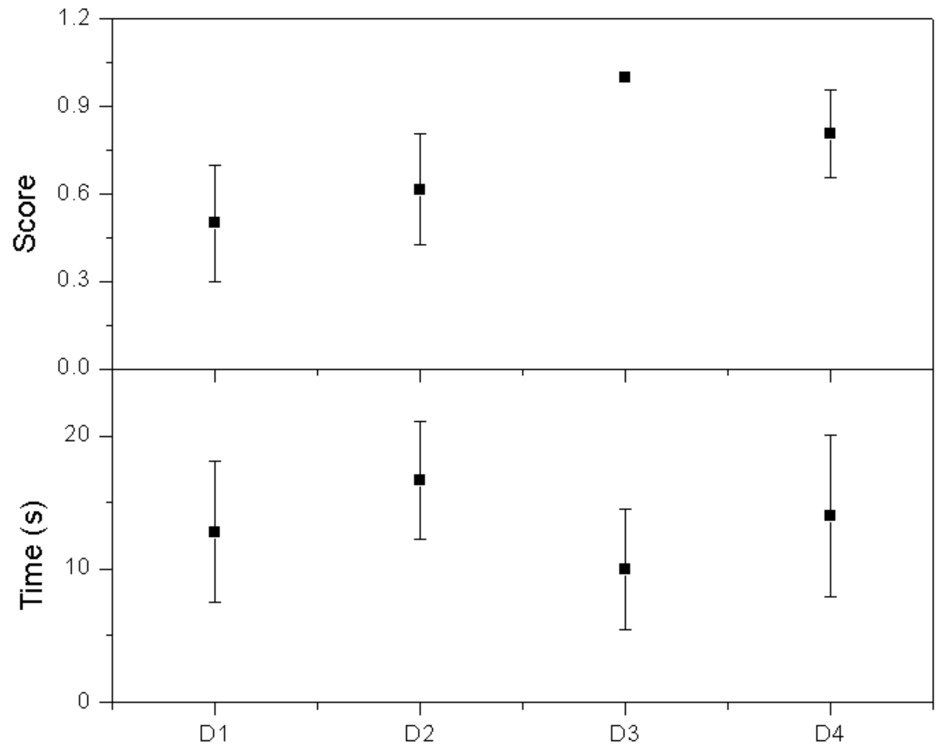


Figure 6.6: User evaluation results for identifying features using directed streamline visualizations. The top graph shows the score (proportion correct) and the bottom graph shows the times. The 95% confidence intervals are also shown.

scores is 0.32.

Users took slightly longer for focus+context visualizations, but scored higher with the focus+context visualizations than the full detail counterparts.

Identify Features

Figure 6.6 shows the user evaluations results for identifying features using directed streamline visualizations. The timings have a p-value of 0.35 and the scores have a p-value of 0.0001.

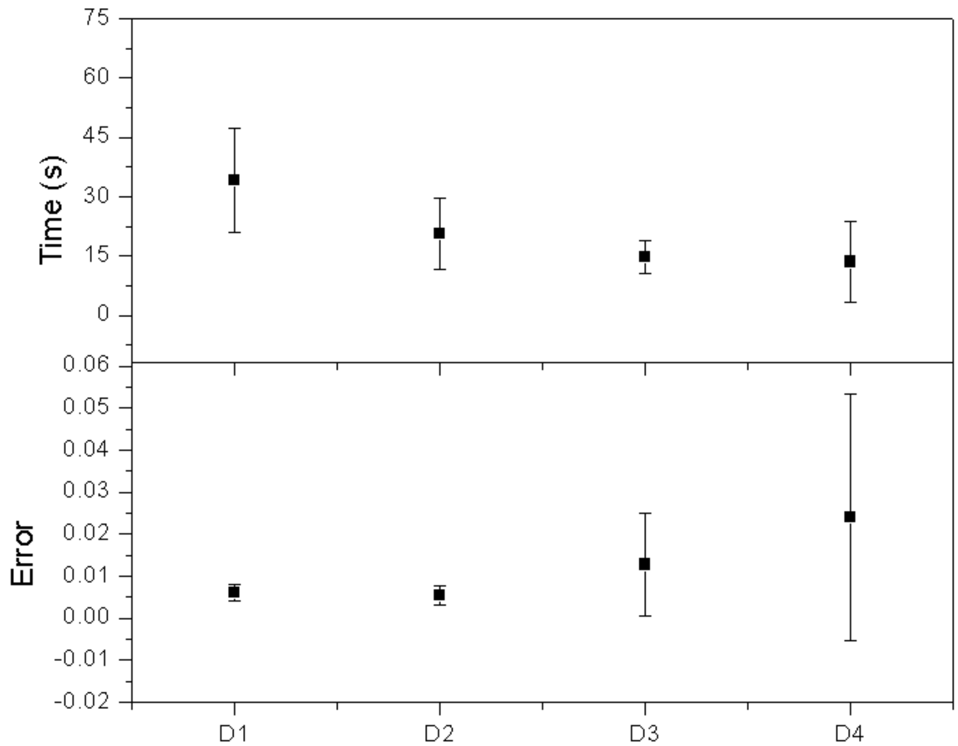


Figure 6.7: User evaluation results for advecting a point using directed streamline visualizations. The top graph shows the time and the bottom shows the error (as a distance from the selected point to the nearest point on the streamline). The 95% confidence intervals are also shown.

Users took longer to identify features in focus+context visualizations, but performed better with both focus+context visualizations than the default full detail visualization. Interestingly, all users correctly identified all features in D3. This is the only visualization/task in which all users scored 100%.

Advection

Figure 6.7 shows the user evaluations results for advecting a point using directed streamline visualizations. The p-value of error was 0.35 and the p-value for time was

0.018.

Users were able to perform the advection task faster when the focus points were initially selected for them, but the error average and distribution was much higher.

CHAPTER 7

CONCLUSIONS

As datasets become larger, uniformly up-scaling the visualization at full-detail becomes less efficient. Focus+context visualizations present the user with the detail necessary to solve problems and analyze data without wasting resources on less-important regions.

7.1 Results

7.1.1 Glyphs

A focus+context glyph visualization technique has been presented that runs at the same framerate as a full detail glyph visualization (See Section 4.7.). User evaluations show high p-values indicating there is little difference in performance between the full detail and focus+context visualizations and thus the users are able to perform common analysis tasks with the same proficiency in both cases (See Section 6.2.1.).

7.1.2 Streamlines

Focus+context streamline visualizations with and without direction indication were also presented. These visualizations showed a large improvement in performance (See Section 5.5.) over their full detail counterparts while maintaining the ability to be effective when performing common analysis tasks (See Section 6.2.2. and 6.2.3).

7.2 Discussion

This work presented an importance driven framework for focus+context vector visualizations (particularly applied to glyph and streamline visualizations). This importance driven framework focused on demonstrating the ability to allow users to explore the data through manual interaction, but the reverse is also possible.

Suppose the user wants to generate a visualization where the goal is to find regions flowing in a particular direction or that have a particular gradient. By using these values to generate the importance field, focus+context visualizations emphasising the values the user deems important are immediately apparent.

7.3 Future Work

These visualization techniques show great promise for use in displaying large datasets. Not only does the streamline visualization technique show improvement in performance, but also the ability to load lower resolution versions of a dataset into memory. A data structure could be made to break a dataset into tiles containing multiple levels of resolution for each section of a dataset. When the importance field is higher in a particular region, a higher resolution tile will be loaded for that region, resulting in faster processing and lower memory usage.

Another application is on large scale displays. The focus points could be extended to allow eye-tracking systems to control them to allow hands free interaction with the data. These eye-tracking techniques could show promise in controlling the visualizations on large scale displays such as display walls or projectors.

If eye-tracking is not available another option is to use a portable tablet with a scaled down version of the dataset. A large scale display would show a higher resolution and larger scale focus+context visualization with the focus points controlled by the user on a tablet with touch gestures.

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APPENDIX A

APPENDIX

A.1 User Evaluation Datasets

G1 - Full Detail Glyphs

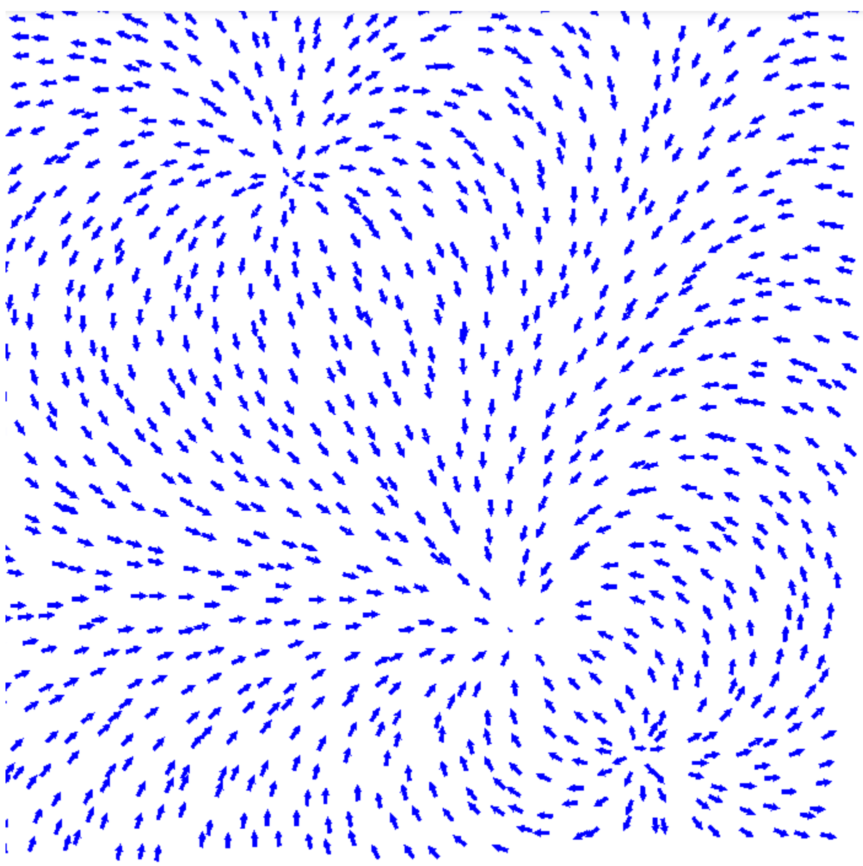

Figure A.1: Full detail glyph visualization.

The user is presented with a full detail glyph visualization and asked the following questions:

- Identify the number of features present (3)
- Identify the feature in the middle (Attracting Focus)
- Identify the feature at the top(Repelling Focus)
- Estimate where a particle will move after some small amount of time has passed

G2 - Focus+Context Glyphs

Figure A.2: Focus+context glyph visualization with no initial focus points.

The user is presented with a focus+context glyph visualization with no initial focus points and asked the following questions:

- Identify the number of features present (5)
- Identify the feature at the top (Repelling Focus)
- Identify the feature in the middle towards the bottom(Saddle)
- Estimate where a particle will move after some small amount of time has passed

This dataset expects users to create focus points in order to answer the questions since the initial dataset is so sparse without focus points.

G3 - Full Detail Glyphs

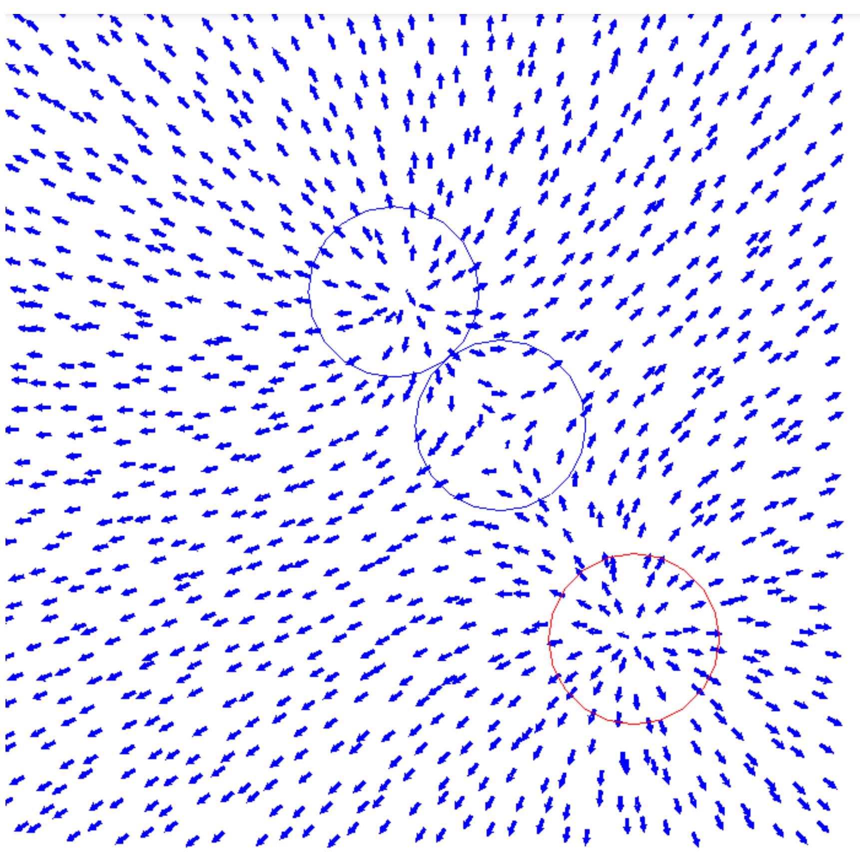

Figure A.3: Full detail glyph visualization with focus point guesses shown.

The user is presented with a full detail glyph visualization with feature location estimates shown and asked the following questions:

- Identify the number of features present (3)
- Identify the feature at the bottom (Repelling Focus)
- Identify the feature in the middle(Saddle)
- Estimate where a particle will move after some small amount of time has passed

G4 - Focus+Context Glyphs

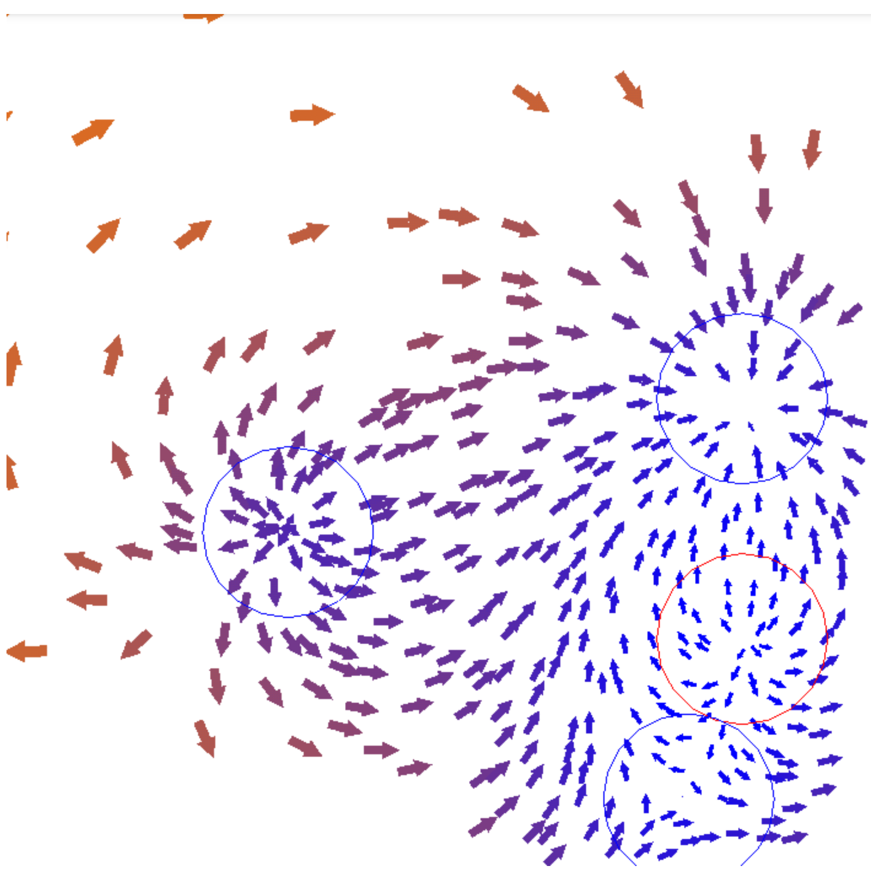

Figure A.4: Focus+context glyph visualization with initial focus points given.

The user is presented with a focus+context glyph visualization with initial focus points selected:

- Identify the number of features present (4)
- Identify the feature on the left (Repelling Focus)
- Identify the feature on the right in the middle (Repelling Focus)
- Estimate where a particle will move after some small amount of time has passed

D1 - Full Detail Directed Streamlines

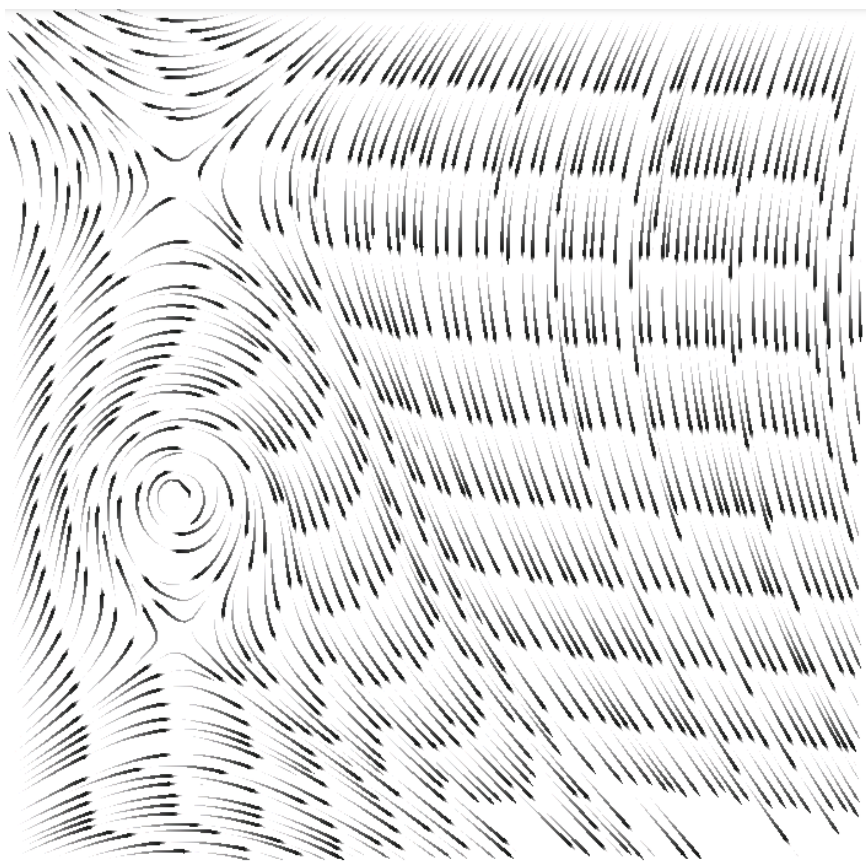

Figure A.5: Directed streamlines at full detail with no focus+context.

The user is presented with a directed streamline visualization at full detail with no interaction and asked the following questions:

- Identify the number of features present (3)
- Identify the feature at the top (Saddle)
- Identify the feature in the middle (Attracting Focus)
- Estimate where a particle will move after some small amount of time has passed

D2 - Focus+Context Directed Streamlines

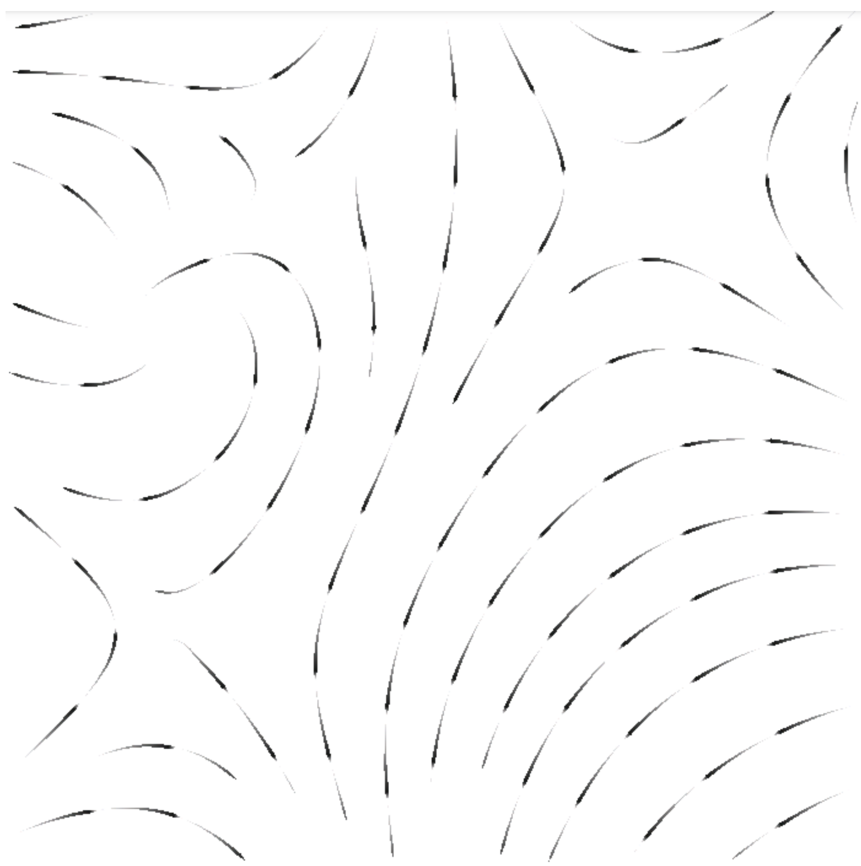

Figure A.6: Directed streamlines with focus+context interaction enabled, but no focus points initially created.

The user is presented with a directed streamline visualization with focus+context interaction enabled and asked the following questions:

- Identify the number of features present (4)

- Identify the feature at the bottom (Saddle)
- Identify the feature at the top-left(Repelling Focus)
- Estimate where a particle will move after some small amount of time has passed

D3 - Full Detail Directed Streamlines

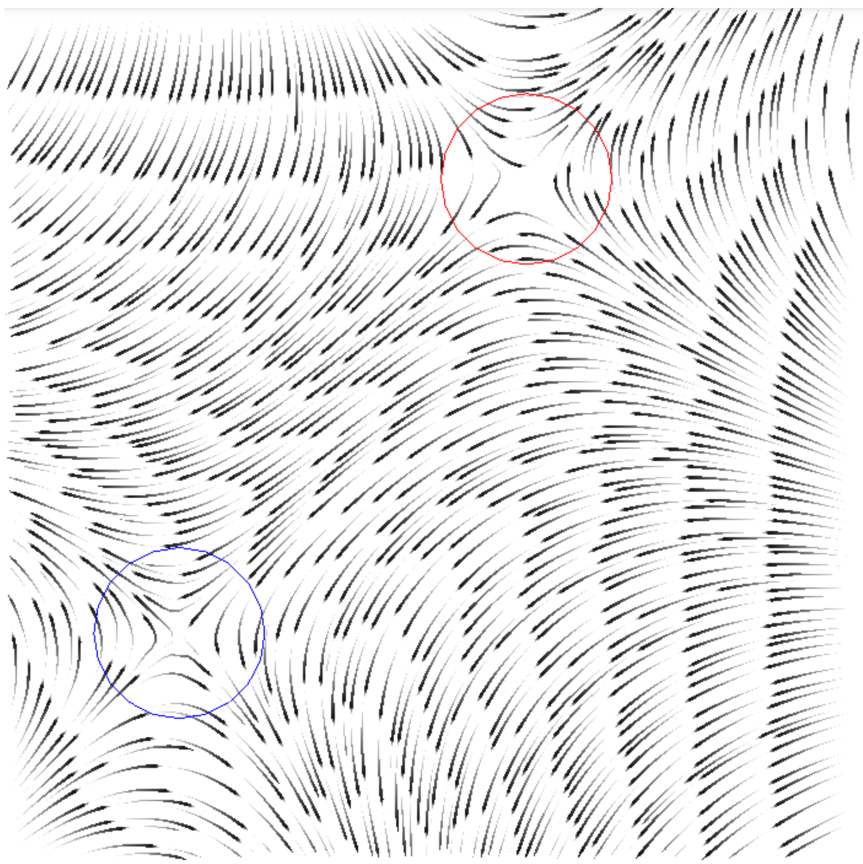

Figure A.7: Directed streamlines at full detail with initial focus points chosen.

The user is presented with a directed streamline visualization at full detail with no interaction allowed and with feature guesses highlighted and asked the following questions:

- Identify the number of features present (2)
- Identify the feature on the top (Saddle)

- Identify the feature on the bottom(Saddle)
- Estimate where a particle will move after some small amount of time has passed

D4 - Focus+Context Directed Streamlines

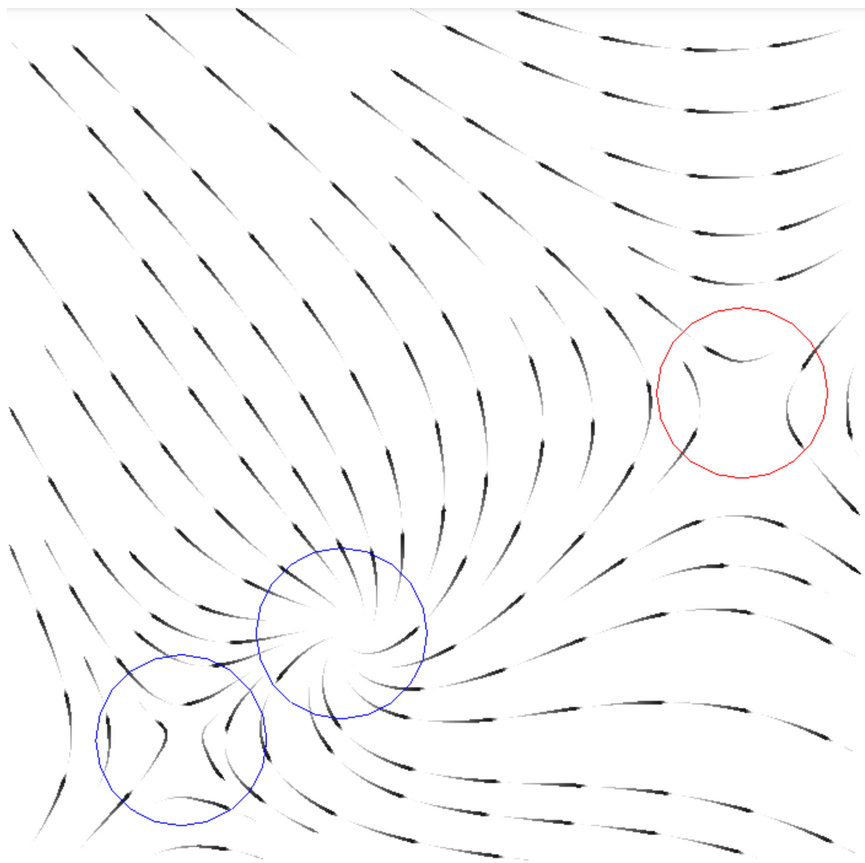

Figure A.8: Focus+Context directed streamlines with focus points initially created near possible features.

The user is presented with a focus+context directed streamline visualization with focus points initially created near possible features and asked the following questions:

- Identify the number of features present (3)
- Identify the feature in the middle (Repelling Focus)
- Identify the feature on the right(Saddle)

- Estimate where a particle will move after some small amount of time has passed

S1 - Full Detail Streamlines

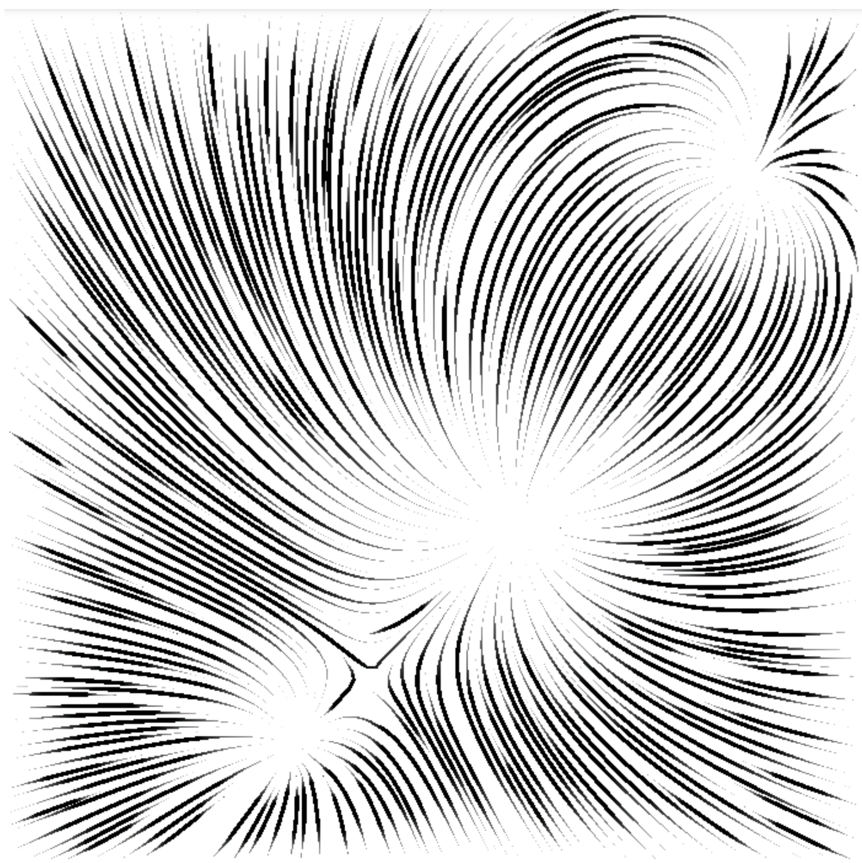

Figure A.9: Full detail streamlines.

The user is presented with a full detail streamline visualization and asked the following questions:

- Identify the number of features present (3)

S2 - Focus+Context Streamlines

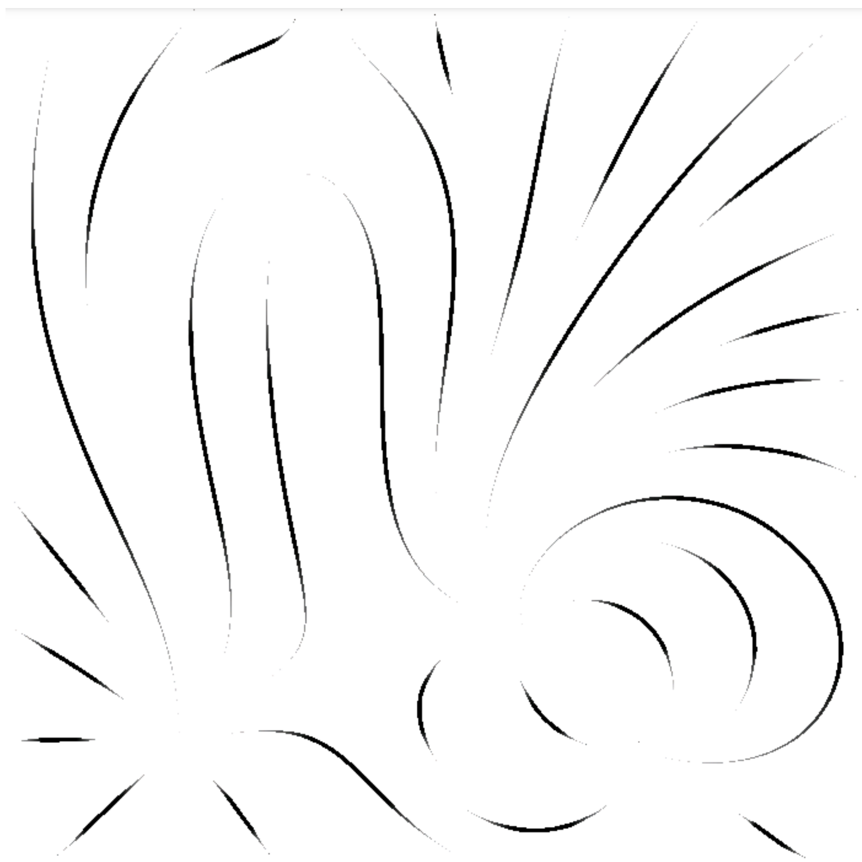

Figure A.10: Focus+context streamlines with no initial focus points.

The user is presented with a focus+context visualization with no initial focus points and asked the following questions:

- Identify the number of features present (6)

S3 - Full Detail Streamlines

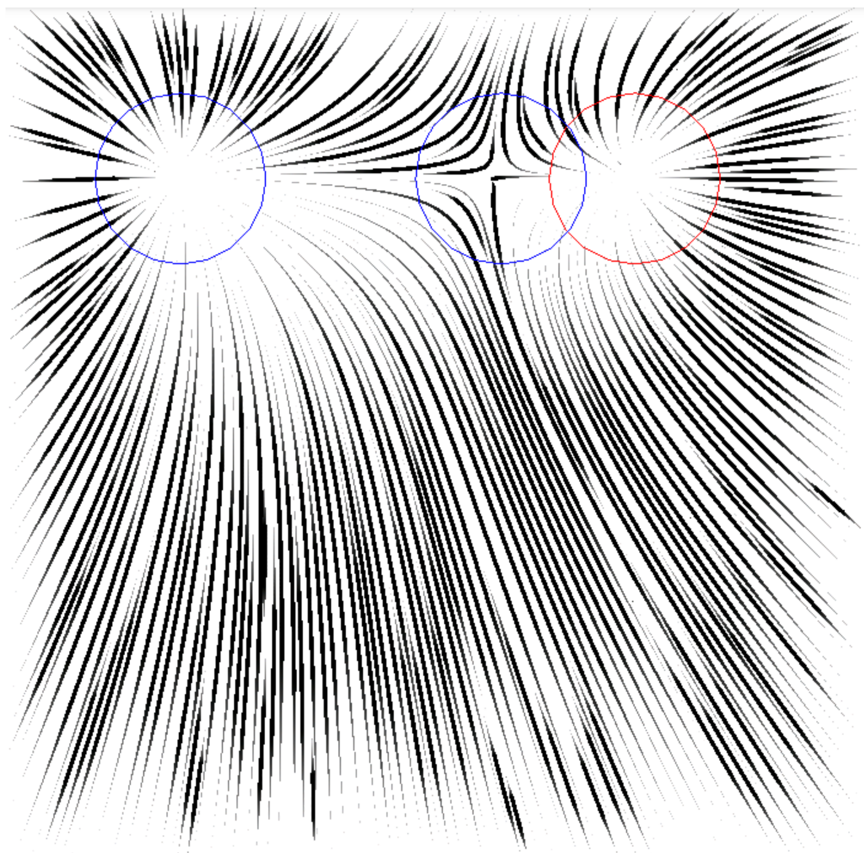

Figure A.11: Full detail streamlines with feature estimates shown.

The user is presented with a full detail streamline visualization with feature estimates shown and asked the following questions:

- Identify the number of features present (3)

S4 - Focus+Context Streamlines

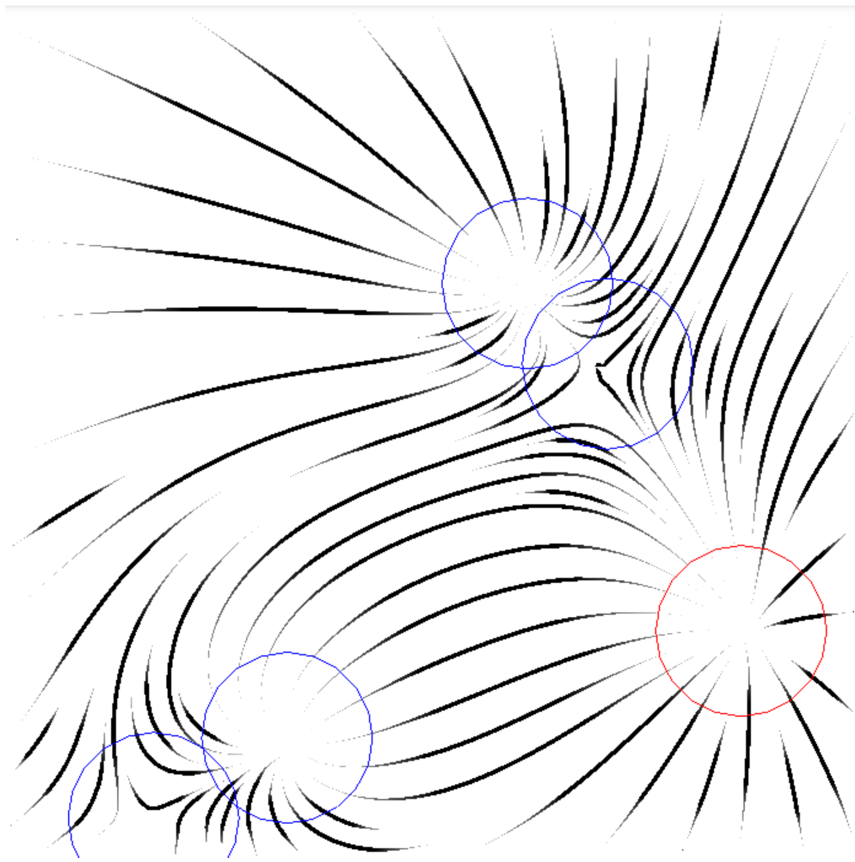

Figure A.12: Focus+context streamlines with initial focus points given.

The user is presented with a focus+context streamline visualization with initial focus points created and asked the following questions:

- Identify the number of features present (5)