

# Research Statement and Agenda

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Organizations are struggling to keep up with their rapidly increasing volumes of data and demanding scalable systems so their analysts can rapidly iterate through analyses. Such wide-spread adoption also means that database (DBMS) users cannot be expected to broadly or deeply understand data management techniques. Instead, they will be domain experts that want simple ways to process their data without worrying about scalability and management limitations. To be useful for this new class of users, new systems must simplify and address performance bottlenecks at every step in the analysis pipeline — from loading raw data [7], improving core query performance [3, 8, 11, 4, 2], supporting new forms of data and new domains [9, 5, 6, 1], summarizing and debugging query results [12, 13], and scaling up visualizations [10].

My goal is to build scalable and useful data management systems for real people. This is reflected in my research approach, which emphasizes building end-to-end systems. I have tackled performance challenges ranging from low-level core database query performance optimization to speeding up high-level data cleaning and result debugging tasks. Such a comprehensive view is necessary in order to identify and address the most significant bottlenecks across the entire system.

## Research Projects

My thesis explores practical fine-grained provenance techniques for large-scale data analysis applications so that data scientists can easily understand and debug their results. In contrast to systems that track the files and scripts used in a workflow, my work tracks input and output data at the *record* granularity. This is particularly important in exploratory settings where data scientists run a complex sequence of transformations that reformat, clean, rescale, aggregate and combine the input data. When the analyst identifies trends or outlier results — often the most interesting parts of the dataset! — it is crucial to understand exactly how those results were computed.

Tracking such provenance information is expensive, as most statistical summaries commonly depend on a large number of input records. Although prior work developed closed-form methods to compute provenance for common SQL operators, they either did not support custom operators, or provided APIs that incur impractical amounts of storage and query overhead. Moreover, provenance results can easily inundate the analyst with non-informative inputs (e.g., the sum over an entire table would return every record) and methods to reduce the provenance to a meaningful subset have not been explored. For these reasons, provenance systems are not used in practice and are regarded by practitioners as academic systems, not useful tools.

To address these limitations, I developed research systems to explore the three key dimensions that must be tackled to make provenance usage practical — result simplification, overhead, and latency. Scorpion [12] is an outlier explanation framework that summarizes the most influential inputs that generated an aggregate outlier. Subzero [13] is a DBMS that reduces provenance overhead by tuning the storage behavior based on user-specified runtime and storage constraints. Smoke [10] is a provenance system for interactive scenarios that can execute provenance queries with low-latency.

## Scorpion: Using Provenance to Explain Outliers

When confronted with outlier results, we naturally ask "why?". Consider a simple analytic query that computes a hospital's total expenses by disease and shows that lung cancer cases disproportionately account for millions of dollars. Do these patients require expensive treatments, or is the cause correlated with another factor? While a provenance system can automatically identify the lung cancer patients, an

analyst must still *manually* partition that data along various combinations of dimensions (e.g., treatment, age), re-run the query on each subset, and hope a combination points to the cause. This ad-hoc process becomes untenable in the presence of multiple outliers, or high dimensionality.

Scorpion is an interactive system that uses and filters provenance results to answer "why" questions in the context of SQL aggregation queries. Users simply select outlier and normal results through a novel interface and the system constructs predicates that most influenced the outliers. Our work formalized a notion of predicate influence in terms of sensitivity analysis, provided a framework to search for influential predicates, and identified aggregation operator properties that help reduce search times by orders of magnitude as compared to a naive exhaustive algorithm. Our Harvard Medical School collaborator spent six months manually analyzing the lung cancer problem described above. Scorpion can identify the two doctors who over-treated their patients and are responsible for a significant amount of the costs within a few minutes of visual interaction and computation.

### **SubZero: A Low Overhead Provenance System**

Scientific applications such as the Large Synoptic Survey Telescope (LSST) are difficult domains for existing provenance systems because they 1) demand pixel level provenance (e.g., "what pixels generated this star?") for debugging and result validation, 2) are high throughput systems (LSST processes 2GB/sec each night), and 3) can only incur a fixed amount of storage and runtime overhead (LSST budgets  $\leq 20\%$  of storage for provenance and must process each image in 15 seconds). Many operators are vectorized, so even generating provenance information can slow operators by orders of magnitude. Custom "black box" operators are common, so the provenance system must provide an efficient APIs to extract the operator's provenance information.

I built SubZero [13], a provenance-enabled workflow system that separates *how* provenance is stored from decisions of *what* provenance to generate. We developed APIs that differentiate operators by the amount of provenance they need to store (constant, linear, or polynomial with the output dataset size). This allows operators to incur the cost of provenance generation and storage in proportion to its complexity. When SubZero executes a provenance query, it can use previously stored provenance or dynamically generate it by re-running previous operators. This lets the optimizer make policy decisions that trade off provenance query performance and the overhead of achieving such query performance. In our experiments, the combination of efficient encoding schemes and dynamic optimization reduced storage overhead by up to  $70\times$  and query costs from a hundred seconds to fractions of a second. This is a huge leap towards making provenance systems feasible for high-throughput applications.

### **Smoke: Low Latency Provenance for Interactive Visualizations**

Smoke is a system that allows data visualization authors to declaratively express visualization interactions as simple provenance queries and automatically optimizes the query execution to maintain low latency. Increasingly, people are publishing data as interactive visualizations. Although tools to create static visualizations and animations are prevalent, there are few tools that help create rich interactions — many authors manually implement and optimize interactions such as brushing and linking <sup>1</sup>.

Smoke establishes the parallel between common forms of visual interaction and data provenance by modeling visualizations as workflows from raw data to visual elements and visual interactions as provenance queries. This allows visualizations to leverage performance optimizations in the provenance system and scale interactions to larger datasets. I am currently building Smoke, which uses two key insights to execute provenance queries at interactive ( $\leq 100\text{ms}$ ) speeds. First, when designing a publishable visualization, the author can specify the exact set of provenance queries that the system will need to run, which can be used to optimize its storage representation. In contrast, existing systems are designed for ad-hoc queries so cannot compare the benefits of different optimizations. Second, many interactions do not need all of the source data specified by a provenance query, and only need a sample of the data, their identifiers, or a summary statistic. Smoke uses materialization and approximation techniques to execute these restricted queries much faster.

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<sup>1</sup>A common form of brushing and linking is when a user selects (brushes) a set of points in one view, and the corresponding (linked) objects in other views are also selected

## Research Agenda

I am interested to continue building useful and usable data management systems. A fascinating area is exploring the intersection between data management, visualization, and interaction. In particular, I am extending my thesis to explain a larger class of outliers and to develop a provenance benchmark. In addition, I am going to investigate how visualization and database systems can be co-optimized in an integrated system.

### Practical Provenance

Scorpion was a first step in showing that provenance can explain aggregation query results by properly filtering and prioritizing the provenance information. However, we are still far from using provenance in a general manner to debug and understand our analysis results. The following are some immediate directions to continue this exploration:

#### *"Why" Explanations for More Complex Operators*

Although Scorpion is a general framework, we have only developed optimizations for simple aggregation operators such as MEAN and STDDEV. Extending efficient support to more complex aggregation operators (e.g., linear regression) will require finding additional operator properties that can be leveraged. Additionally, supporting other output types such as data constraint violations (e.g., identifying records that violate a constraint such as "Canada is not a U.S. state") is valuable for data cleaning and integration. I plan on pursuing both of these directions.

#### *Understanding Provenance Usage*

Although the Open Provenance Challenge provides a benchmark to evaluate inter-operability between provenance systems, there are currently no performance-oriented provenance benchmarks. Furthermore, there does not exist a corpus of provenance queries that are used in practice. Without such benchmarks, it is difficult to evaluate different provenance systems and make consistent progress as a field. I plan to release Smoke, which is built into a full-featured visualization system, and gather usage information about how the visualization and provenance systems are used. This will be the first study on how fine-grained provenance is used in the wild, and the results will be used to develop new provenance interfaces and a fine-grained provenance benchmark.

### A Scalable Visual Analytics System

A key difficulty in scaling interactive visual analytics to large datasets is maintaining interactive (sub-100 millisecond) latencies. This is necessary so analysts can quickly try many different analyses. Current approaches decouple the visualization and data management systems via a SQL query interface — each interaction translates to a SQL query and each query takes seconds or minutes to run. The visualization layer compensates for the high latency by either optimizing for a specific type of visualization (e.g., interactive heat maps), or caching a subset of the data and reimplementing query executors in the client.

I want to develop an integrated exploratory data analysis system where users interact and specify at the visualization level and the query processing system takes advantage of the visualization semantics and human perceptual limitations to execute the analyses with low latency. Such a system has the potential to scale without giving up functionality nor interactivity and to enable valuable exploratory features such as accurate analysis recommendations. The following are several immediate research opportunities.

#### *Perceptually-accurate Approximation*

An integrated system can reduce query latencies by approximating results while still minimizing user perceived errors by understanding the granularities of the visual encodings (e.g., color, x-position, radius). For example, human perception of color has very low resolution as compared to position, so queries that generate heat-maps can afford greater approximation error than those that compute bar charts. Similarly, the output resolution is a visual variable that bounds the differences that the user can detect. The system can quickly generate an initial result by computing an approximation that preserves the most perceivable features in the visualization (e.g., an upward trend in a line chart). I plan to explore how these perceptual properties can inform query processing optimizations such as sampling, approximation and filtering.

### *Speculation and Pipelining*

Interaction latency can be further reduced by taking advantage of interaction-level semantics. Each visualization allows a limited number of interactions, which constrains the scope of possible queries. In addition, many interactions (e.g., clicking on the border of a selection box to resize it) are triggered by user motions that can take several seconds. This is an ideal environment to speculatively execute queries and pipeline the execution with the time the user takes to express the queries. The key challenges are developing a language to declaratively specify and detect interactions, mapping them to optimization hints, and taking advantage of the hints.

### *Parallel Analysis*

Analysts commonly test hypotheses on a subset of the data, then apply the analysis to the full dataset. For example, an analyst exploring a large taxi ridership dataset may pick the rides during a single week and location to rapidly iterate upon, and later expand the analysis to the full dataset or all other weeks and locations. The system can automatically replicate the analysis on different samples (e.g., the previous week, or a different location) to test result robustness or to identify similar trends. This requires solving data layout challenges to efficiently parallelize the analysis, finding query sharing opportunities to re-use computed results, and developing pruning techniques to avoid fully analyzing unpromising datasets.

### *Contextual Recommendations*

Recommending relevant data, visualizations and analyses is an important tool in exploratory data analysis. Prior recommendation algorithms are typically implemented at the database layer and only have access to the data and the historical SQL queries. Higher level cues, such as the analyst's exploration history and visualization-specific features (e.g., distributional differences in a boxplot vs trends in a line plot) can substantially improve the recommendation quality. I would like to explore how features across multiple semantic levels — raw data, query result, visualization, image — can be combined and leveraged. The techniques for tackling *Parallel Analysis* will be equally applicable for quickly generating recommendations.

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