Rapid Approximate Aggregation with Distribution-Sensitive Interval Guarantees

[Technical Report]

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ABSTRACT
Aggregating data is fundamental to data analytics, data exploration, and OLAP. Approximate query processing (AQP) techniques are often used to accelerate computation of aggregates using samples, for which confidence intervals (CIs) are widely used to quantify the associated error. CIs used in practice fall into two categories: techniques that are tight but not correct, i.e., they yield tight intervals but only offer asymptotic guarantees, making them unreliable, or techniques that are correct but not tight, i.e., they offer rigorous guarantees, but are overly conservative, leading to confidence intervals that are too loose to be useful. In this paper, we develop a CI technique that is both correct and tighter than traditional approaches. Starting from conservative CIs, we identify two issues they often face: pessimistic mass allocation (PMA) and phantom outlier sensitivity (PHOS).

By developing a novel range-trimming technique for eliminating PHOS and pairing it with known CI techniques without PMA, we develop a technique for computing CIs with strong guarantees that requires fewer samples for the same width. We implement our techniques underneath a sampling-optimized in-memory column store and show how to accelerate queries involving aggregates on real and synthetic datasets with speedups of up to 124× over traditional AQP-with-guarantees and more than 1000× over exact methods.

1. INTRODUCTION
Primitives for aggregation like AVG, SUM, and COUNT are key to making sense of and drawing insights from large volumes of data, powering applications in OLAP, exploratory data analysis, and visual analytics. Accelerating their computation is therefore of great importance. Approximate Query Processing (AQP) is commonly used to accelerate computation of these aggregates by estimating them on a subset or sample of the full data. Reasoning about the error of the estimates as introduced by approximation is crucial: consumers of approximate answers—ranging from human decision makers to automated processes—rely on confidence intervals (CIs) or error bounds as the foundation for understanding the quality of the approximate answer. Therefore, many AQP techniques come with CIs to allow for more confident or informed decisions made using approximate estimates.

Error bounding, or CI computation techniques take a confidence parameter \( \delta \in [0,1] \), with the semantics that the returned intervals \([g_L, g_R]\) fail to enclose the true aggregate \( g^* \) at most \( \delta \) of the time. One can tune \( \delta \) to be as small as needed \((\delta = 10^{-15} \text{ throughout this paper})\), at the cost of requiring more samples to achieve the same interval width \(|g_R - g_L|\). Likewise, for a given \( \delta \), taking more samples typically causes the error bounding procedure to return a narrower confidence interval. Since \( \delta \) is typically small, we use the phrase “with high probability” (w.h.p.) as shorthand for “with probability greater than \( (1-\delta)^n \)”. CI computation techniques need to satisfy two goals: (i) compactness: by minimizing the interval width \( g_R - g_L \), and (ii) correctness: by ensuring that \( g^* \in [g_L, g_R] \) with high probability. However, achieving both compactness and correctness is difficult.

We outline the shortcomings of existing techniques, that either prefer compactness over correctness (asymptotic techniques), or correctness over compactness (conservative techniques), below:

**Compactness without Correctness.** Asymptotic error bounding techniques such as bootstrap CIs [25, 24, 71] or central limit theorem (CLT)-based CIs [61, 34] make assumptions about the distribution taken by the data given a “large enough” sample size. These procedures typically give CIs that are much tighter (and therefore more useful for drawing inferences about the query results), and have enjoyed numerous applications in database and visual analytics systems [56, 52, 53, 44, 28, 42], including Aqua [5], BlinkDB [7, 6], DBO [39], and online aggregation [35], and have furthermore seen a number of DBMS-specific extensions [71, 55]. However, these asymptotic techniques result in intervals that only enclose the true aggregate w.h.p. in the limit as the size of the sample grows to infinity.1 That is, these techniques are correct in the limit as the sample size approaches infinity, but they provide no real guarantees for any given finite instance, potentially leading to failures downstream. For example, consider the query in Figure 1, which determines origin airports whose departing flights are ahead-of-schedule, on average. An AQP system could use CIs to facilitate early stopping by using them to infer on which side of the \( \text{HAVING} \) threshold the various groups appear. If such a system relies on asymptotic CIs, it is prone to serious types of error, called subset error and superset error [52], whereby certain tuples may be missing, and other tuples may appear spuriously.

**Correctness without Compactness.** Recognizing the downsides of asymptotic approaches, recent work [21, 8, 40, 59, 50] has begun to adopt conservative error bounders, which leverage concentration inequalities to compute CIs. These procedures return bounds that follow probably approximately correct (PAC) [63] semantics: given \( \delta \in [0,1] \), the probability that the procedure returns lower and upper bounds \([g_L, g_R]\) around the approximate aggregate \( \hat{g} \) that fail to enclose the true aggregate \( g^* \) should be at most \( \delta \) for any sample size

1The error of CLT-based methods shrinks as \( O(1/\sqrt{m}) \), but with constants depending on unknowns such as the third absolute normalized moment, according to the Berry-Esseen theorem [13, 26].
Our contribution: We develop a simple and general error bounding technique, range trimming, that corrects PHOS without sacrificing desirable PAC semantics. At a high level, range trimming operates by making error bounders asymmetric, so that \( g_r \) depends only on the MAX value seen (and not on \( b \)), and \( g_r \) depends only on the MIN value seen, yielding tighter intervals when \( (\text{MAX} - \text{MIN}) \) is smaller than \((b - a)\). Range trimming can be used with any existing conservative range-based error bounder (i.e., an error bounder whose only assumption is that data falls in \([a, b]\)). We show how range trimming can be used to develop an error bounder for AVG (and by extension SUM) with neither PHOS nor PMA by using it alongside a bounder based on Bernstein’s inequality.

3. Minimizing sampling overhead. In order to enjoy the benefits of early termination for queries with multiple aggregates, we need to ensure that termination is not bottlenecked on any single aggregate, allowing query processing to adaptively sample from the most informative locations on physical storage while simultaneously minimizing overhead.

Our contribution: We show how to couple our approach with a sampling-optimized column store that takes without-replacement samples in a locality-aware manner, and that leverages bitmap indexes to prioritize samples that enable earlier termination in the case of GROUP BY clauses. Furthermore, although existing conservative error bounders assume knowledge of the dataset size (an unreasonable assumption when a filter of unknown selectivity is applied), we show how to circumvent this limitation by computing an upper bound on this size online.

Impact. We develop error bounding techniques that more effectively leverage distributional information of the underlying data, and that therefore often lead to tighter error bounds as compared with those yielded by typical conservative error bounders. When used in conjunction with a sampling-optimized column store for in-memory analytics, we demonstrate speedups of more than 1000× over exact techniques and up to 124× over traditional conservative approximate techniques, all without sacrificing strong correctness guarantees.

Extensibility. While our presentation focuses on confidence intervals for queries over a single table with simple AVG aggregates, we note that our techniques are more general and can be used to facilitate SUM and COUNT aggregates, queries over views formed from joins in a snowflake schema, and queries with general UDFs — we discuss these extensions in Section 4.1 and more in the appendix.

Outline. The rest of this paper is organized as follows. Section 2 discusses existing conservative error bounders and their prior usage in the DBMS literature, and develops a conceptual framework for identifying issues with these error bounders. In Section 3 we develop the theory behind our RangeTrim technique, and show how to fix issues with previous error bounders in Section 2. Section 4 addresses systems issues that appear when sampling without replacement and develops FastFrame, our sampling-optimized column store, and Section 5 empirically evaluates our techniques in the context of this system. We survey additional related work in Section 6.

2. DBMS ERROR BOUND INTEGRATION

In this section, we first describe applications of confidence intervals for facilitating query processing in a database system (§2.1). Next, we survey methods for computing error bounds with guarantees applicable to DBMS aggregates (§2.2) identify their shortcomings (§2.3) and conclude with a formal problem statement (§2.4).

2.1 DBMS CI Applications

Consider the query in Figure 1. In this query, AVG aggregates are both displayed as output in the query results, and are also used
to filter the set of tuples in the output. This reflects two major applications of confidence intervals in a DBMS setting: CIs that are explicitly used downstream, i.e., by an analyst, or CIs that are implicitly used by automated processes.

Explicit Use of Downstream CIs. When approximating aggregates in a DBMS, confidence intervals can be included in the output displayed to users. For this application, in which CIs are explicitly displayed to users, the AVG aggregates belonging to the groups output by the query in Figure 1 are augmented with confidence intervals and included in the output. This application helps users to reason about uncertainty in approximate answers and has seen prior usage in the database and visual analytics literature [35, 28].

Implicit Use of Downstream CIs. Confidence intervals have been applied toward facilitating various other kinds of downstream applications, for example in order to enable early stopping. Example applications from prior literature include high-level accuracy contracts [53, 55] (i.e., guaranteeing query results are within ε of the correct), ranking query results [40, 50], and bounding relative error [8]. In all cases, the user need not ever observe the interval: the goal is to provide early stopping while ensuring correct results. We consider these applications later in our experiments in Section 5.

Goal. In this paper, we are primarily concerned with enabling CI compactness (to reduce query latency) without sacrificing CI correctness (thereby ensuring safety), for both explicit and implicit applications of CIs. The major goal is therefore to develop CI techniques that are as tight as possible, while always enclosing the quantity in question. Throughout this section and Section 3, we will focus our discussion on CIs for AVG aggregates; we will cover SUM and COUNT aggregates in Section 4.

2.2 Computing CIs in a DBMS

We now describe methods for computing error bounds with accuracy guarantees in a database system, along with any assumptions required. Relevant notation is summarized in Table 1. We begin by defining error bounders, bounds, and confidence intervals.

| Symbols / Terms | Descriptions |
|-----------------|--------------|
| D, N, S, c, m   | Dataset, num. points in dataset (i.e. |D|), sample, num. points taken (for c) or desired (for m) in sample (i.e. |S|) |
| g f, g r        | True aggregate, estimate, error bounds |
| a, b, cσ2, cσ2 ε | Range bounds, variance, empirical variance, error probability upper bound, error |
| F, F ′, L, U    | True / empirical CDF, lower and upper bounds on true CDF |
| Lbound, Rbound  | Confidence lower (resp. upper) bounding routines parameterized on a, b, N, and other sample state(see §2.2.2) |
| SSI, PMA, PHOS  | Sample-size-independent, pessimistic mass allocation, phantom outlier sensitivity |

Table 1: Glossary of terms / notation.

2.2.1 Assumptions Applicable to Data in a DBMS

In the case of AVG aggregates, all error bounding procedures require some prior knowledge about the data over which they operate—otherwise, outliers can have arbitrarily strong effects on the aggregate in question. Weaker assumptions are more general, but typically yield more conservative bounds.

In this paper, we make two assumptions about the data D over which queries operate: first, that every datapoint x ∈ D lies in some interval [a, b]; second, that datapoints can be effectively sampled without replacement from D. We now discuss these assumptions in the context of prior work and show that they can be implemented effectively within real systems.

Known Range Bounds. As in prior work [35], we assume that the database catalog maintains range bounds a and b for the MIN and MAX of each continuous column, inferred, for example, during data loading. (Note that we do not require [a, b] = [MIN, MAX], but only that [a, b] ⊆ [MIN, MAX].) These assumptions are more applicable in the context of a database as compared with stronger distributional assumptions (e.g., that the data are normal or that they obey a tighter sub-Gaussian parameter than that implied by the range bounds [64]) and can be easily maintained in the case of insertions. We refer to bounders that assume knowledge of a and b as range-based error bounders throughout this paper. Furthermore, we show in the appendix (§B) that it is possible to leverage the range assumption even in the case of aggregates involving arbitrary expressions over multiple columns by first solving an optimization problem for derived range bounds a’ and b’ that enclose the transformed data.

Sampling Without Replacement. Estimates for AVG aggregates generally converge faster for samples taken without replacement than samples taken with replacement [60, 12]. In the context of a DBMS, sampling with replacement has traditionally been considered easier than sampling without replacement, since the system does not need to “remember” the samples already taken [54, 40]. Sampling as traditionally implemented, however, also has poor locality properties, as nearly every read operation results in a cache miss. Another approach taken in prior work [58, 69, 70, 50] is to materialize samples ahead-of-time by performing a single up-front shuffle of the entire relation, so that sampling without replacement can be implemented via a scan of the data regardless of any applied filters or other transformations. Since this approach is valid for multiple queries executed during ad-hoc, exploratory workloads (in contrast with approaches that use workload assumptions to pre-materialize stratified samples [30, 7]), we design our system architecture around this approach, described in more detail in Section 4.

2.2.2 State for DBMS Error Bounds

OLAP queries must operate over many tuples, so it is desirable that aggregations and their error bounders maintain small of memory footprints as possible as new tuples are examined, although we will see in Section 2.2.3 that some bounders must maintain state which grows with the number of tuples examined. To better understand implementation details for error bounders within the context of a DBMS, we present error bounders in terms of the following interface:

1. init_state(): Initializes state needed for error bounds.
2. update_state(S, v): Given the current state S and a newly-seen value v, compute new state S’.
3. Lbound(S, a, h, N, δ): Return a confidence lower bound for a sample whose relevant statistics are captured in state S, assuming the sample came from a finite dataset D of N values in [a, b]. The probability that the sample leads to this function returning a value greater than AVG(D) is < δ.
Algorithm 1: Hoeffding-Serfling error bounder [60]

1 function init_state()  
    return \( [m: 0, \hat{g}: 0] \);

2 function update_state(S, v)  
    \( m' \leftarrow S.m + 1 \);

3 \( \hat{g}' \leftarrow S.\hat{g} + (v - S.\hat{g})/m' \);

4 return \( [m': m', \hat{g}': \hat{g}'] \);

5 function Lbound(S, \( a, b, N, \delta \)) [60]  
6 \( e \leftarrow (b - a) \cdot \sqrt{\frac{\log(\delta / N)}{N}} \);

7 return \( S.\hat{g} - e \);

8 function Rbound(S, \( a, b, N, \delta \))  
9 \( S.\hat{g} \leftarrow (a + b) - S.\hat{g} \);

10 return \( (a + b) - Lbound(S, a, b, N, \delta) \);

Algorithm 2: Empirical Bernstein-Serfling err. bounder [12]

1 function init_state()  
    return \( [m: 0, \hat{g}: 0, M_2: 0] \);

2 function update_state(S, v)  
    \( m' \leftarrow S.m + 1 \);

3 \( \hat{g}' \leftarrow S.\hat{g} + (v - S.\hat{g})/m' \);

4 \( M_2' \leftarrow S.M_2 + v^2 \);

5 return \( [m': m', \hat{g}': \hat{g}', M_2': M_2'] \);

6 function Lbound(S, \( a, b, N, \delta \)) [12]  
7 \( x \leftarrow (b - a)^2 / 2N \);

8 \( \rho \leftarrow 1 \cdot \min\{S.m \leq N/2\} - (1 - S.m/N) \cdot (1 + 1/S.m) \);

9 \( \rho \leftarrow \rho + (S.m > N/2) \cdot ((1 - S.m/N) \cdot (1 + 1/S.m)) \);

10 \( e \leftarrow \sqrt{S.M_2/S.m - S.\hat{g}^2} - \sqrt{2 \log(\delta / N)} / \sqrt{N.m} + \rho \cdot (b - a) \cdot \log(5N)/(N.m) \);

11 return \( S.\hat{g} - e \);

12 function Rbound(S, \( a, b, N, \delta \))  
13 \( S.\hat{g} \leftarrow (a + b) - S.\hat{g} \);

14 return \( (a + b) - Lbound(S, a, b, N, \delta) \);

By focusing on \( k = m \) and inverting the probability expression, we may compute a \( 1 - \delta \) lower confidence bound as

\[
\frac{1}{m} \sum_{i=1}^{m} X_i \geq (b - a) \cdot \frac{1 - \frac{1}{m} \log \frac{1}{\delta}}{2m}
\]

and likewise for an upper confidence bound (replacing \(-\) with \(+\)), so that \((1 - \frac{2}{m})\) lower and upper confidence bounds may be combined to yield a \((1 - \delta)\) confidence interval (via a union bound).

**Empirical Bernstein-Serfling-based Bounder.** A concentration inequality for sampling without replacement given in [12], the Bernstein-Serfling inequality assumes knowledge of both \((b - a)\) and \( \text{VAR}(D) = \sigma^2 = \frac{1}{N} \sum_{x \in D} (x - \text{AVG}(D))^2 \). We defer a statement of the full result to the appendix. Here we note that inverting the inequality gives error bounds as

\[
\frac{1}{m} \sum_{i=1}^{m} X_i \pm O \left( \frac{\sigma}{\sqrt{m}} + \frac{(b - a)}{m} \right)
\]

if we again ignore the sampling fraction term. Comparing these error bounds to those of Hoeffding-Serfling, which has widths of size \( O((b - a)/\sqrt{m}) \) (again ignoring the sampling fraction), we see that error bounds derived from the Bernstein-Serfling inequality can be significantly tighter when \( \sigma \) is small compared to \((b - a)\).

Knowledge of \( \text{VAR}(D) \) typically cannot be assumed in a setting where \( \text{AVG}(D) \) is unknown. Fortunately, there also exists an empirical variant of the Bernstein-Serfling inequality (also given in [12], like the non-empirical variant). The analysis for the empirical Bernstein-Serfling inequality proceeds by augmenting the analysis for the non-empirical variant with a concentration inequality relating the estimator \( \hat{\sigma}^2 = \frac{1}{m} \sum_{i=1}^{m} (x_i - \bar{X})^2 \) to \( \text{VAR}(D) \). We again deferring the full statement to the appendix. This yields \((1 - \delta)\) error bounds given by

\[
\frac{1}{m} \sum_{i=1}^{m} X_i \pm O \left( \sqrt{\frac{m}{m}} + \frac{\sigma^2}{m} \right)
\]

Note that these error bounds differ from those of the non-empirical variant only in that \( \sigma^2 \) is replaced by \( \hat{\sigma}^2 \) (modulo slightly worse constants hidden by the asymptotic notation). Although \( \hat{\sigma} \) is a random quantity, it concentrates near \( \sigma \), so that an error bound based on the empirical Bernstein-Serfling bound returns bounds of asymptotically the same width as those returned by an error bounder based on the non-empirical variant and with full access to \( \sigma^2 \), w.h.p. Algorithm 2 gives an implementation of an empirical bounder based on the non-empirical variant with a concentration inequality relating the estimator \( \hat{\sigma}^2 = \frac{1}{m} \sum_{i=1}^{m} (x_i - \bar{X})^2 \) to \( \text{VAR}(D) \).
Anderson described a way to compute distribution-free/nonparametric error bounds for the mean given i.i.d. samples taken from a distribution. Intuitively, the procedure just described for computing error bounds around the mean of a distribution given i.i.d. samples thus also works for computing error bounds around AVG(Δ) given without-replacement samples from the finite dataset Δ. It is presented in terms of our interface from Section 2.2.2 in Algorithm 3.

**Algorithm 3:** Anderson/DKW error bounder [23, 10, 51]

```python
1 function init_state() →
2     return ()
3 function update_state(S, ν) →
4     return S ∪ {ν}
5 function Lbound(S, a, b, N, δ) →
6     ε ← √ log(2/N);
7     F ← empirical CDF based on S;
8     S' = {x ∈ S: F(x) ≤ 1 − ε};
9     return ε · a + (1 − ε) · AVG(S');
10 function Rbound(S, a, b, N, δ) →
11     return (a + b) − Lbound((a + b) − S, a, b, N, δ);
```

Bernstein-Serfling-based error bounder in terms of our interface from Section 2.2.2. Note that Algorithm 2 as presented shows computation of the sample variance in terms of the second moment $M_2 = \sum_i v^2$ for the sake of exposition; a real implementation might use a more numerically stable one-pass algorithm for the variance [67, 17, 45].

**Anderson/DKW-based Bounder.** Anderson described a way to compute distribution-free/nonparametric error bounds for the mean given i.i.d. samples taken from a distribution. Intuitively, the procedure just described for computing error bounds around the mean of a distribution given i.i.d. samples thus also works for computing error bounds around AVG(Δ) given without-replacement samples from the finite dataset Δ. It is presented in terms of our interface from Section 2.2.2 in Algorithm 3.

**Applications in Prior DB Literature.** To our knowledge, Hoeffding and Hoeffding-Serfling-based bounders are the only SSI bounders that have seen extensive use in the DB literature for computing error bounds for AVG [40, 8, 35, 31]. We are aware of one incorrect application of the empirical Bernstein-Serfling inequality [20] (incorrect because the procedure given in [20] continuously recomputes confidence (1 − δ) intervals as more samples are taken, so that the overall procedure is no longer guaranteed to fail with probability at most δ). Overall, we consider it somewhat surprising that error bounders derived from the empirical Bernstein-Serfling inequality from [12] have not seen more widespread usage, as they are nearly as simple to compute as those derived from the Hoeffding-Serfling inequality and typically yield error bounds that are much tighter.

### 2.3 Error Bounder Pathologies

As a major technical contribution of this work, we identify two problems that cause SSI error bounders to be too conservative. These pathologies, which we refer to as pessimistic mass allocation (PMA) and phantom outlier sensitivity (PHOS), are based on simple intuitions about how error bounders should behave: namely, they should return tighter bounds when observing samples with fewer extreme values, and error lower bounds (respectively error upper bounds) should only be looser due to potential large values (resp. small values) if such values are actually observed.

#### 2.3.1 Pessimistic Mass Allocation

PMA, defined as follows, captures the intuition that error bounders should be sensitive to the observed sample values:

**Definition 2** [PMA]. An error bounding procedure P exhibits pessimistic mass allocation (PMA) if there exists a dataset $\mathcal{D}$ bounded in $[a, b]$, a value $a'$ with $a < a' < b$, and a set $S \subseteq \mathcal{D}$ with values in $[a, a']$ such that, for $S' = \{x \in S : x < S\}$, P returns a confidence interval of the same width for both S and S'. P likewise exhibits PMA if there exists some $b'$ with $a < b' < b$ and an $S$ with values in $(b', b]$ such that, for $S' = \{x \in S : x > S\}$, P returns a confidence interval of the same width for both $S$ and $S'$.

A result error bounder P that has PMA if it is possible to replace the smallest (largest) elements in a sample with something larger (resp. smaller) without shrinking the width of P’s returned confidence interval. Intuitively, P is overly-pessimistic about how mass in

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**Table 2:** Summary of properties exhibited by various error bounders. $R = \text{sampling with replacement}$, $\text{NR} = \text{without}$. $\checkmark$ indicates that the non-Serfling variant also holds for NR sampling.

| Error Bounder | PMA | PHOS | Sampling | Memory |
|---------------|-----|------|----------|--------|
| Hoeffding(-Serfling) | ✓ | ✓ | R⁺ (NR) | O(1) |
| Bernstein(-Serfling) | ✓ | ✓ | R⁺ (NR) | O(1) |
| Anderson/DKW | ✓ | ✓ | R, NR | O(m) |

been proved by Massart [51], so it appears that Anderson computed $\alpha$ and $\beta$ using a lookup table.

Although Lemma 3 as stated applies for sampling with replacement from an infinite population, please see Appendix C for a proof that DKW still holds when $X_1, \ldots, X_m$ are drawn without replacement from a finite population of size $N$, for any $N > 0$, stated as the following theorem:

**Theorem 1.** For any $N > 0$, the DKW inequality applies for sampling without replacement from a finite dataset of size $N$.

The procedure just described for computing error bounds around the mean of a distribution given i.i.d. samples thus also works for computing error bounds around AVG(Δ) given without-replacement samples from the finite dataset Δ. It is presented in terms of our interface from Section 2.2.2 in Algorithm 3.
the underlying distribution from which it is sampling is allocated, despite contrary evidence observed in the sample.

2.3.2 Phantom Outlier Sensitivity

PHOS captures the intuition that unobserved extreme values should not affect both lower and upper error bounds:

**Definition 3 [PHOS].** An error bounding procedure $P$ exhibits phantom outlier sensitivity (PHOS) if, for data falling in $[a, b]$, $P$’s returned confidence lower bound $g_\ell$ depends on the value of $b$, and similarly if the $g_r$ returned by $P$ depends on $a$.

To understand PHOS intuitively, consider the case of computing a confidence lower bound. Given a sample $S$, the worse $P$ “believes” $S$ could be shifted (on average) toward larger values as compared to $D$, the smaller of a confidence lower bound it should return. In what ways could $S$ be shifted toward higher values? One possibility is if small elements are underrepresented in $S$. The other possibility, and the one we are interested in, is if large elements are overrepresented in $S$. For this reason, a confidence lower bound should only be affected by datapoints near the upper range bound $b$ if it actually observes them, and the appearance of $b$ in the computation of a confidence lower bound is a potential source of unnecessary conservativeness.

2.3.3 Examples of PMA and PHOS in Error Bounders

In this section, we give examples of PMA and PHOS in Error Bounders. Table 2 summarizes pathologies exhibited by various SSI error bounders.

**Hoefding-based.** Hoefding-based error bounders suffer from both PMA and PHOS. They have PMA since their returned CIs have widths depending only on the range of the data, $(b - a)$, and the number of samples. As such, replacing values in the sample with larger or smaller values does not affect the width of the returned error bounds. Such bounders also have PHOS since they have symmetric error, with both ends of the confidence interval depending on both range bounds $a$ and $b$.

**Bernstein-based.** Bernstein-based error bounders do not suffer from PMA. To see this, notice that increasing the smallest values in some sample will also reduce the sample variance, affecting the width of the returned confidence interval, and likewise for decreasing the largest values in the sample. These bounds do, however, suffer from PHOS. Like Hoefding-based bounders, they return confidence intervals with symmetric error, so that each end of the confidence interval is affected by both ends of the data range $a$ and $b$.

We will see in our experiments that these bounds can yield significant speedups as compared with Hoefding-based bounds, when used to facilitate early termination of approximate queries.

**Anderson/DKW-based.** Anderson/DKW-based error bounders are interesting in that they suffer from PMA, but not PHOS. Consider the $\epsilon$ mass unaccounted for when computing a confidence lower bound using an Anderson/DKW-based bounder. As shown in Figure 3, it all goes toward to lower range bound, $a$, which is sufficient for PMA. On the other hand, where does it come from? It comes from the $\epsilon$-fraction largest observed points. This does not depend at all on the value of the upper range bound $b$, indicating that the confidence lower bound does not suffer from PHOS. Symmetric statements hold for the confidence upper bound, of course.

2.4 Problem Statement

We are now ready to give a formal problem statement.

**Problem 1.** Design an SSI error bounder that, given a without-replacement sample from any $D$ with elements from $[a, b] \subseteq \mathbb{R}$, suffers from neither PMA nor PHOS when computing $(1 - \delta)$ error bounds for AVG$(D)$, for any $0 < \delta < 1$.

Our solution to Problem 1 is given in Section 3 and relies on a technique we call range trimming in order to systematically eliminate PHOS from any range-based error bounder.

Although the solution as presented in Section 3 additionally assumes knowledge of the size of $D$, Section 4 shows how our real-world implementation circumvents this limitation.

3. FIXING BOUNDER PATHOLOGIES

Excepting an error bounder based on DKW, all of the error bounders surveyed suffer from PHOS. This is because all the other error bounders are based on concentration inequalities with symmetric error — that is, they cannot compute bounds of the form $\hat{g} \pm \epsilon$, where the same $\epsilon$ is both added and subtracted to the sample average $\hat{g}$ in order to compute bounds. Next, we describe how to use a process we call range trimming to convert any symmetric, ranged-based error bounder to an asymmetric one without PHOS.

3.1 Decoupling Lower and Upper Bounds

From our discussion in Section 2.3, we see that there do exist error bounders with either PMA or PHOS, but not both. We first argue that error bounders without PHOS must be asymmetric; that is, they cannot compute bounds of the form $\hat{g} \pm \epsilon$, where the same $\epsilon$ is both added and subtracted to the sample average $\hat{g}$ in order to compute bounds. As such, we describe how to use a process we call range trimming to convert any symmetric, ranged-based error bounder to an asymmetric one without PHOS.

3.2 Range Trimming

Our approach to deriving an error bounder with neither PMA nor PHOS is to start with a symmetric bounder without PMA (such as that of Algorithm 2) and “asymmetrize” it so that Lbound becomes independent of $b$, and Rbound becomes independent of $a$, thereby eliminating PHOS. The result, given in Algorithm 4, wraps any existing range-based error bounder.
3.3 Proof of Correctness

In this section, we prove correctness of Algorithm 4 (that is, that it returns intervals that fail to enclose $\text{AVG}(D)$ with probability less than $\delta$). For the sake of simplicity, our analysis assumes that $D$ contains no duplicate values, although we show how to remove this assumption at the end of this section. To begin, we first prove a crucial lemma about the sampling distribution of $S - \{\text{max} S\}$, given that $S$ was sampled uniformly without-replacement from $D$.

**Lemma 4.** Given a dataset $D$ of $N$ unique real values in $[a, b]$ and a uniform without-replacement sample $S$ of $m$ values from $D$, if we denote $b' = \text{max} S$, the set $S - \{b'\}$ takes the distribution of a uniform without-replacement sample from $D_{<b'} = D \cap (a, b')$, for any applicable value of $b' \in D$.

**Proof.** Because $S$ is drawn uniformly without-replacement from $D$, any particular instance satisfies

$$\mathbb{P}_D \{ S = s \} = \left( \frac{|D|}{m} \right)^{-1} \mathbb{I} \{ s \subseteq D \} = \left( \frac{N}{m} \right)^{-1} \mathbb{I} \{ s \subseteq D \}$$

where we use the notation $\mathbb{P}_D \{ S = s \}$ to denote the probability that $s$ was drawn uniformly without-replacement from $D$, and $\mathbb{I} \{ \cdot \}$ denotes the indicator function. We need to show that, for any $b' \in D$,

$$\mathbb{P}_D \{ S = s \} \mathbb{I} \{ \text{max} S = b' \} = \mathbb{P}_{D_{<b'}} \{ S = s - \{b'\} \} \mathbb{I} \{ \text{max}(s) = b' \}$$

First, letting $s'$ be any set such that $|s'| = m - 1$, we have that

$$\mathbb{P}_{D_{<b'}} \{ S = s' \} = \left( \frac{|D_{<b'}|}{m-1} \right)^{-1} \mathbb{I} \{ s' \subseteq D_{<b'} \}$$

Next, consider $\mathbb{P}_D \{ S = s \} \mathbb{I} \{ \text{max} S = b' \}$. Bayes’ rule gives that

$$\mathbb{P}_D \{ S = s \} \mathbb{I} \{ \text{max} S = b' \} = \frac{\mathbb{P}_D \{ S = s \} \mathbb{I} \{ \text{max}(s) = b' \}}{\mathbb{P}_D \{ \text{max} S = b' \}}$$

We have $\mathbb{P}_D \{ S = s \} \mathbb{I} \{ \text{max} S = b' \} = \mathbb{P}_D \{ S = s \} \mathbb{I} \{ \text{max}(s) = b' \}$, which is a known quantity, so the key is to compute the denominator $\mathbb{P}_D \{ \text{max} S = b' \}$. Using the assumption that $D$ contains unique elements, we may proceed by analogy with binary strings. The rank of $b'$ within $D$ (starting from the smallest element) is $1 + |D_{<b'}|$, so we need to compute the number of binary strings of length $N$ containing $m$ 1’s and $(N - m)$ 0’s such that position 1 is at $D_{<b'}$, and the remaining $(m - 1)$ 1’s are all at positions less than 1 + $|D_{<b'}|$. This is precisely the same as the number of binary strings of length $|D_{<b'}|$ with $(m - 1)$ 1’s and $(|D_{<b'}| - m + 1)$ 0’s. Putting everything together,

$$\mathbb{P}_D \{ S = s \} \mathbb{I} \{ \text{max} S = b' \} = \frac{\mathbb{P}_D \{ S = s \} \mathbb{I} \{ \text{max}(s) = b' \}}{\mathbb{P}_D \{ \text{max} S = b' \}}$$

which is precisely what we wanted to show. □

**Wrinkle in Lemma 4 and Fix.** The proof of Lemma 4 assumes unique values; we show here how to remove this assumption without loss of generality. The uniqueness assumption as used is necessary...
only to ensure that elements of \( D \) are totally ordered under some relation \( \prec \) (with \( \prec \) \( \equiv \) \( \leq \) in the proof). To fix, we can simply augment every \( v \in \mathcal{D} \) with an additional unique label (where the set of labels are totally ordered) such that item \( v \) becomes \( v' \equiv (v, v_i) \). Then, define \( \prec \) as a relation such that \( v' \prec w' \) if \( v \prec w \) or \( v = w \) and \( v_i < w_i \). In this way, any \( v', w' \in \mathcal{D} \) satisfy exactly one of \( v' \prec w' \) or \( w' \prec v' \), and the proof of Lemma 4 goes through, replacing \( \mathcal{D} \) with \( \mathcal{D}' \) and \( \prec \) with \( \prec' \) where appropriate.

We next give a symmetric statement for \( S - \{ \min S \} \) and \( \mathcal{D}_{\min \mathcal{S}} \) as the below corollary:

**Corollary 1.** Given a dataset \( \mathcal{D} \) of \( N \) unique real values in \( [a, b] \) and a uniform without-replacement sample \( S \) of \( m \) values from \( \mathcal{D} \) such that \( \min S = a' \), the set \( S - \{ a' \} \) is a uniform without-replacement sample from \( \mathcal{D}_{a'} = \mathcal{D} \cap (a', b] \), for any applicable value of \( a' \in \mathcal{D} \).

**Monotonicity Property and Correctness Proof.** Before proving the main result, we briefly describe the dataset size monotonicity property obeyed by all bounders in this paper. This fact will be used in the main correctness proof. When \( N \) is unknown, an upper bound on \( N \) suffices, because bounders in this paper all satisfy the monotonicity property and symmetrically for \( m \).

We are now ready to prove correctness of Algorithm 4.

**Theorem 2.** Given SSI range-based bounders \( \text{Lbound} \) and \( \text{Rbound} \) for computing lower (resp. upper) confidence bounds and a dataset \( \mathcal{D} \) of \( N \) unique values known to all fall in the interval \( [a, b] \subseteq \mathbb{R} \), Algorithm 4 returns a \((1 - \delta)\) confidence interval for \( \text{AVG}(\mathcal{D}) \).

**Proof.** Algorithm 4 proceeds by drawing \( S \) uniformly and without replacement from \( \mathcal{D} \) and computing \( a' = \min S, b' = \max S, S_r, \) and \( S_l \), where the latter two quantities capture relevant statistics from the sample \( S - \{ b' \} \) and \( S - \{ a' \} \), respectively, so we treat \( S_r \) and \( S_l \) as if \( S_r = S - \{ b' \} \) and \( S_l = S - \{ a' \} \). By Lemma 4, we have that \( S_r \) is a uniform sample of \( m - 1 \) values drawn without replacement from \( D_{b'} \), and likewise by Corollary 1 \( S_l \) is a uniform sample of \( m - 1 \) values drawn without replacement from \( D_{a'} \). Because \( \text{Lbound} \) and \( \text{Rbound} \) are assumed to be SSI, range-based error bounders, we have that

\[
\mathbb{P}
\left[
\text{Lbound}
\left(S_r, a, b, N - 1, \frac{\delta}{2}\right) > \text{AVG}(\mathcal{D})
\right]
\leq
\mathbb{P}
\left[
\text{Lbound}
\left(S_r, a, b', \mathcal{D}_{b'}, \frac{\delta}{2}\right) > \text{AVG}(\mathcal{D})
\right]
\leq
\mathbb{P}
\left[
\text{Lbound}
\left(S_l, a, b', \mathcal{D}_{a'}, \frac{\delta}{2}\right) > \text{AVG}(\mathcal{D}_{a'})
\right]
\leq
\mathbb{P}
\left[
\text{Rbound}
\left(S_l, a, b', \mathcal{D}_{a'}, \frac{\delta}{2}\right) < \text{AVG}(\mathcal{D}_{a'})
\right]
\leq
\mathbb{P}
\left[
\text{Rbound}
\left(S_r, a, b, \mathcal{D}, N - 1, \frac{\delta}{2}\right) < \text{AVG}(\mathcal{D})
\right]
\leq
\mathbb{P}
\left[
\text{Rbound}
\left(S_r, a, b', \mathcal{D}_{b'}, \frac{\delta}{2}\right) < \text{AVG}(\mathcal{D}_{b'})
\right]
\leq
\mathbb{P}
\left[
\text{Rbound}
\left(S_l, a, b', \mathcal{D}_{a'}, \frac{\delta}{2}\right) < \text{AVG}(\mathcal{D}_{a'})
\right]
\]

and symmetrically for \( \text{Rbound}(S_r, a', b, N - 1, \frac{\delta}{2}) \), but with \( > \) replaced with \( \leq \) in the probability expression above, and replacing \( D_{b'} \) with \( D_{a'} \). (1) \( \rightarrow \) (2) follows from the dataset size monotonicity property of \( \text{Lbound} \) (§2.2.2), applicable since \( N - 1 \geq |D_{b'}| \), and (2) \( \rightarrow \) (3) follows since \( \text{AVG}(\mathcal{D}_{b'}) \leq \text{AVG}(\mathcal{D}) \), as the former is clipped above \( b' \) (and similarly for \( \text{Rbound} \) since \( \text{AVG}(\mathcal{D}_{a'}) \geq \text{AVG}(\mathcal{D}) \)). Union bounding over the cases for each of \( \text{Lbound} \) and \( \text{Rbound} \), the probability that Algorithm 4 returns an interval that does not enclose \( \text{AVG}(\mathcal{D}) \) is at most \( \delta \).

4. **SYSTEM CONSIDERATIONS**

In this section, we address a number of implementation issues that become pertinent when applying techniques of previous sections in a real system. Although the techniques presented in this section are auxiliary to our primary contribution and can be used with any CI approach, they are developed with SSI error bounders and strong probabilistic guarantees in mind. First, we describe how to augment the techniques of Section 3, which apply for a fixed sample size taken without replacement from a finite dataset of known size, with locality-aware scan-based without-replacement sampling that need not know \( N \), and we further describe how to use this layout to facilitate SUM and COUNT aggregations (§4.1). Next, we describe an optional stopping routine that does not require a sample size to be specified up-front (§4.2). Finally, we describe an active scanning architectural optimization that prioritizes samples that facilitate early termination (§4.3), all without losing guarantees proved in Section 3.

These system details are implemented within the context of FastFrame, which is our general relational column store for approximate report generation with guarantees. FastFrame uses the error bounders from Section 3 and pairs them with a practical architecture for without-replacement sampling. FastFrame uses block-based bitmaps over categorical attributes (similar to [50]) for efficient processing of queries with predicates or groups. Furthermore, for continuous attributes, FastFrame stores the minimum and maximum values in a catalog, to be used as the range bounds \( a \) and \( b \) for the desired range-based error bounder.

4.1 **Scan-Based Sampling for DB Aggregates**

We now describe how FastFrame implements without-replacement sampling in a locality-aware manner by scanning over pre-shuffled data, and furthermore how this approach can be used to compute CIs for COUNT and SUM. The up-front shuffling cost need only be paid once in order to facilitate many queries, although care must be taken to set the error probability \( \delta \) small enough when running multiple queries to avoid losing error bounder guarantees. The high-level idea behind this implementation of without-replacement sampling is not new and has been used in prior work for approximate query processing [58, 69, 70, 50] and other analytics [27]. We begin by introducing scrambles and aggregate views:

**Definition 4** [Scramble]. A scramble is an ordered copy of a relational table that has been permuted randomly, allowing for scan-based without-replacement sampling.

Scanning a continuous column in a scramble is equivalent to sampling without replacement. In fact, scanning any subset of data in a continuous column in a scramble (assuming the subset is chosen without knowledge of the order of data) is also equivalent to sampling without replacement, so that scanning a scramble can be used to sample without replacement for any aggregate appearing in a query containing arbitrary filters or GROUP BY clauses. We call such subsets aggregate views:

**Definition 5** [Aggregate View]. An aggregate view for some aggregate \( A \) appearing in a query (possibly belonging to a group induced by a GROUP BY clause) is the set of values in a scramble that contribute toward the computation of \( A \).

Note that \( \delta \) must be divided by the number of aggregate views in a query (or an upper bound) to preserve error guarantees.

**Computing CIs for COUNT.** Ensuring that data in a scramble are permuted randomly makes it easy to compute bounds on the selectivities of aggregate views, and by extension on the COUNT of tuples in each aggregate view, using existing techniques [32, 33]. One can conceptually assign each row of a scramble a 1 if it belongs to the aggregate view of interest, and a 0 otherwise. The AVG of this
“derived” view (over the whole scramble) is exactly the selectivity of the aggregate view, and we can use a Hoeffding-Serfling-based bounder to compute a CI for the selectivity (using range bounds of $a = 0$ and $b = 1$). Multiplying these bounds by the total number of rows in the scramble then yields a CI for the COUNT of rows that participate in the aggregate view.

In more detail, for a scramble with $\mathbb{R}$ rows, $N$ of which are in the sample view $V$ for a query $Q$, the number of rows seen that belong to $V$, $m_v$, after scanning $r$ rows of the scramble is a hypergeometric random variable [15] whose mean is the selectivity $\sigma_v$ of $V$ multiplied by $r$, $\sigma_v \cdot r$. One could use bounds specifically tailored to the hypergeometric distribution (or even perform an exact computation) to compute an upper bound on $\sigma_v$ that holds w.h.p., but in this work we use a simple strategy that uses Hoeffding-Serfling to bound $\sigma_v$, stated as follows.

**Lemma 5.** The probability that a scan of a scramble of size $R$ that has processed $r$ rows so far sees fewer than $(\sigma_v - e) \cdot r$ or more than $(\sigma_v + e) \cdot r$ rows belonging to $V$ is at most $\delta$, for $e = \sqrt{\frac{\log(2/\delta)}{2r}} \cdot (1 - \frac{r - 1}{R})$.

**Proof.** Follows immediately from application of the Hoeffding-Serfling inequality [60].

Lemma 5 implies that, for a scan that has seen $m_v$ rows so far belonging to $V$, $\sigma_v$ is within $\sigma_v \pm e = \frac{m_v}{r} \pm \sqrt{\frac{\log(2/\delta)}{2r}} \cdot \left(1 - \frac{r - 1}{R}\right)$ w.h.p. This in turn implies that $N$, the number of tuples belonging to $V$, is within $[N^+, N^-] = [(\sigma_v - e) \cdot R, (\sigma_v + e) \cdot R]$, w.h.p.

**Combining Lemma 5 with error bounders.** For error bounders Lbound and Rbound of the form described in Section 3 that require the data range bounds $a$ and $b$ as well as the data size $N$, a $(1 - \delta)$ confidence interval is computed as $[L\text{bound}(S, a, b, N, \delta/2), R\text{bound}(S, a, b, N, \delta/2)]$.

The following theorem describes how to use Lemma 5 to compute $(1 - \delta)$ error bounds when $N$ is unknown.

**Theorem 3.** Consider a query $Q$ operating over some size-$R$ scramble with corresponding sample view $V$. Suppose a scan the scramble that has processed $k$ rows so far has seen $m_v$ rows belonging to $V$ (from which $S$ is computed). Letting

$$N^+ = \frac{m_v}{r} + \sqrt{\frac{\log(1/(1 - a) \cdot \delta)}{2r}} \cdot \left(1 - \frac{r - 1}{R}\right),$$

then the interval $[L\text{bound}(S, a, b, N^+, a \cdot \delta/2), R\text{bound}(S, a, b, N^+, a \cdot \delta/2)]$ is a $(1 - \delta)$ confidence interval for the mean of $V$, for any $a \in (0, 1)$.

**Proof.** Conditioning over whether $N \leq N^+$ or $N > N^+$, the probability that the aforementioned interval $[L, R]$ fails to contain the desired mean $\mu$ is

$$\Pr(\mu \notin [L, R] \mid N > N^+) \cdot \Pr(N > N^+),$$

$$+\Pr(\mu \notin [L, R] \mid N \leq N^+) \cdot \Pr(N \leq N^+),$$

$$\leq \Pr(N > N^+) + \Pr(\mu \notin [L, R] \mid N \leq N^+).$$

By Lemma 5, the first probability is at most $(1 - \alpha) \cdot \delta$, and Lbound and Rbound are such that the probability of the second term is at most $\alpha \cdot \delta$. The sum of these equals $\delta$, implying that the interval is a valid $(1 - \delta)$ confidence interval, completing the proof.

Throughout Section 5, we fix $\alpha = 0.99$, giving most of the weight to the confidence interval computation, corresponding to a looser upper bound for $N$.

**Computing CIs for SUM.** Now that we have established how to compute CIs for AVG and COUNT, we briefly describe how to combine these two techniques to compute CIs for SUM. Given a $(1 - \frac{\delta}{2})$ confidence interval for COUNT as $[\hat{c}_\ell, \hat{c}_r]$ and a $(1 - \frac{\delta}{2})$ confidence interval for SUM as $[\hat{g}_\ell, \hat{g}_r]$, union bounding gives $[\hat{c}_\ell, \hat{g}_\ell, \hat{c}_r, \hat{g}_r]$ as a $(1 - \delta)$ confidence interval for SUM.

### 4.2 Optional Stopping

The techniques discussed in Section 3 describe how to compute high-probability bounds on error given statistics computed from a particular sample of $m$ datapoints. Fixing a sample size ahead of time is oftentimes impractical, since it is usually unknown how many samples are needed to ensure CIs that are “just tight enough” to facilitate downstream applications on the part of the user or the system. For example, one approach (e.g. taken by VerdictDB [55]) is to first compute error bounds around an approximate aggregate, and then run an exact query if these bounds are too loose.

Another approach, which we take in this paper, is to continue taking samples until a bound on the error is provably small enough. For this approach, care must be taken to avoid losing guarantees offered by range-based error bounders, since the tighter of two $(1 - \delta)$ confidence intervals for a particular aggregate is itself not necessarily a $(1 - \delta)$ confidence interval.

Various techniques have been developed for computing sequentially valid confidence intervals as new samples are taken [65, 72, 40, 48, 47, 46]. In addition to techniques for sequential estimation [65] for sequences of i.i.d. random variables from a known family of distributions, various concentration results applicable to AVG which make no distributional assumptions have likewise been derived [72, 40]. Unfortunately, these existing results are derived from variants of Hoeffding’s inequality, and therefore suffer from PMA. For the sake of simplicity, we use a much simpler meta-algorithm that can be used in conjunction with any range-based error bounder, including those that leverage our RangeTrim technique, given in Algorithm 5. Although Algorithm 5 requires more samples than the aforementioned techniques when used in conjunction with Hoeffding- or Hoeffding-Serfling-based error bounders, we consider the tradeoff worthwhile due to its generality and simplicity and leave better sequential error bounders to future work.

---

**Algorithm 5: The OptStop meta-algorithm**

**Input:** Dataset $D$ of $N$ values in $[a, b]$, error probability $\delta$

**Output:** Error bounds that fail to enclose $AVG(D)$ with probability $< \delta$

```
1 $S \leftarrow$ init_state();
2 for $k = 1$ to $\infty$
3    for $i = 1$ to $B$ do
4       $v \leftarrow$ sample_without_replacement($D$);
5       $S \leftarrow$ update_state($S$, $v$);
6    end
7 if should_stop([max_{j \in k} (L_j), min_{j \in k} (R_j)]) then
8    break;
9 end
10 return [max_k (L_k), min_k (R_k)]
```

---
Analysis of Algorithm 5. Algorithm 5 proceeds in “rounds”, with each iteration of the outer loop on line 2 forming a round. During each round, $B$ without-replacement samples are taken and used to incrementally update the state of any range-based error bounder that implements our interface from Section 2.2.2. At the end of each round, confidence intervals are recomputed, with the input error probability $\delta'$ decayed “enough” to ensure that the probability of error across all rounds is at most $\delta$. If the stopping condition on line 10 is met, then the algorithm terminates; otherwise, it proceeds to the next round, decaying $\delta'$ appropriately to control the overall error probability.

We now give a proof of correctness of Algorithm 5.

Theorem 4. With probability at least $(1 - \delta)$, the $\{L_k\}$ and $\{R_k\}$ computed by Algorithm 5 satisfy $\text{AVG}(\mathcal{X}) \in [L_k, R_k]$ for every $k$ in the outer loop. In particular, $\text{AVG}(\mathcal{X}) \in [\max_{k \geq 1} L_k, \min_{k \geq 1} R_k]$ with probability at least $(1 - \delta)$.

Proof. Denote the $\delta'$ used at iteration $k$ with $\delta_k$. Union bounding over rounds, the probability of a mistake is at most

$$\sum_{k \geq 1} \delta_k = \frac{6}{\pi^2} \sum_{k \geq 1} \delta = \frac{6}{\pi^2} \frac{\pi^2}{6} \delta = \delta$$

using the identity $\sum_{k \geq 1} \frac{1}{k^2} = \frac{\pi^2}{6}$, completing the proof. $\square$

FastFrame performs I/O at the level of blocks, so instead of computing bounds every $B$ samples as described in the pseudocode of Algorithm 5, we compute bounds after every $B$ block read. In our experiments (Section 5), we set $B = 40000$. We leave development of alternative approaches to future work.

Stopping Conditions for Algorithm 5. Correctness of Algorithm 5 is independent of whether the error bounder uses our RangeTrim technique (please see Appendix A in the appendix for an implementation of our RangeTrim technique in terms of the interface from Section 2.2.2), and it is furthermore independent of stopping condition. We consider several stopping conditions used in our system implementation:

(Desired Samples Taken): This condition is met as long as fewer than the desired $m$ samples have been taken that contribute to that group’s aggregate.

(Sufficient Relative Accuracy): Same as the previous, but a group is active as long as its confidence bounds exceed $\epsilon$.

(Sufficient Absolute Accuracy): We consider a group active as long as its upper confidence bound $\hat{g} - \hat{r}$ is greater than or equal to $\epsilon$.

(Threshold Side Determined): A group is active as long as the threshold side has not been determined; i.e., $\hat{g} - \hat{r} \geq \epsilon$.

(Top- or Bottom-K Separated): The activeness condition for this stopping condition is the most complicated out of any we consider. First, consider the sorting the aggregates for all the groups in increasing order. A group among the top-$K$ is active if its lower confidence bound $g_r$ crosses the midpoint of the aggregate value for the smallest of the top-$K$ and the largest of the bottom $N - K$. Likewise, a group among the bottom $N - K$ is active if its upper confidence bound $g_l$ crosses this midpoint. Analogous statements hold if we consider the separation between the bottom-$K$ and the top $N - K$ as the stopping condition, but with the aggregates sorted in decreasing order.

(Groups Ordered Correctly): A group is active if its interval $[g_l, g_r]$ intersects the interval of any other group.

Asyn Lookahead. We furthermore accelerate active scanning with an asynchronous lookahead technique from prior work [50], which we briefly describe here. Active scanning with lookahead uses block-based bitmap indexes to efficiently check whether a block contains tuples for any active group. Instead of synchronously checking whether a given block contains tuples for active groups by iterating over each active group and querying the index, a separate lookahead thread iterates over a batch of 1024 blocks and marks blocks for processing or skipping, for each group. By iterating over an entire batch of 1024 blocks for a given active group, bitmaps for the group tend to be in cache more often, making the index lookup operation more efficient. We refer the reader to [50] for more details. In our experiments in Section 5, we set the block size to 25 rows, so a batch of 1024 blocks contains a total of 25600 rows.

5. EMPIRICAL STUDY
Additionally, several queries are parametrized, in order to reveal the accompanying stopping conditions are summarized in Table 4.

Table 4: Summary of stopping conditions used for queries provided in Figure 5. Template variable arguments shown in blue.

| Query | Stop When | Parameters Varied |
|-------|-----------|-------------------|
| F-q1  | \( \max \{ g_r - \bar{g}_r, \bar{g}_r - g_r \} < \varepsilon \) | Saiport (Figure 6(a)), \( \varepsilon \) (Figure 7(a)) |
| F-q2  | Sfresh \( \theta \) \( \{ g_r, \bar{g}_r \} \) | Sfresh (Figure 7(b)) |
| F-q3  | bottom-2 separated | \( \min \text{dep}_\text{time} \) (Figure 8) |
| F-q4  | 10 \( \notin \{ g_r, \bar{g}_r \} \) | N/A |
| F-q5  | 0 \( \notin \{ g_r, \bar{g}_r \} \) | N/A |
| F-q6  | top-5 separated | N/A |
| F-q7  | groups ordered | N/A |
| F-q8  | top-1 separated | N/A |
| F-q9  | top-1 separated | N/A |

Table 3: Descriptions of Flights Dataset

| Dataset | Size | #Tuples | #Attributes | Replications |
|---------|------|---------|-------------|--------------|
| Flights | 32 GB | 606 million | 5 | 5x |

5.1 Flights Dataset and Queries

We evaluate various error bounding techniques on the publicly available Flights dataset [1], extracting attributes for origin airport, airline, departure delay, departure time, and day of week. The details for this dataset are summarized in Table 3. The replication value indicates how many times the dataset was replicated to create a larger dataset and ensure sufficient scale for our experiments. We eliminated rows with “N/A” or erroneous values for any column appearing in one or more of our queries.

Queries and Query Templates. We evaluate our techniques on a diverse set of queries that include various filters and GROUP BY clauses and exercise all the stopping conditions described in Section 4.2 (except conditions 0 and \( \Theta \), which gives similar behavior to condition \( \theta \)). The queries themselves are given in Figure 5, and the accompanying stopping conditions are summarized in Table 4. Additionally, several queries are parametrized, in order to reveal interesting data-dependent behavior by varying corresponding parameters. Any query parameters varied are also summarized in Table 4, with parameters shown in blue.

5.2 Experimental Setup

The core of our experiments consists of two ablation studies, intended to evaluate the impact of both our error bounder innovations and that of our architectural innovations. In particular, we evaluate various error bounders with and without our RangeTrim technique developed in Section 3, and for the best error bounder (Bernstein+RT), we furthermore evaluate the impact of leaving out features of our active scanning sampling strategy described in Section 4.

We set \( \delta = 10^{-15} \) for all queries, as we expect users of with-guarantees AQP to desire results that are correct in an *effectively deterministic* manner. Union bounding over the number of queries run, the upper bound on the error probability will still be sufficiently small to guarantee correctness of all queries, for any practical number of queries encountered.

Approaches. We used the following strategies to bound error when running queries in Figure 5:

- **Error Bounders.**
  - Bernstein. Same as the previous, but without RangeTrim. Bernstein and Bernstein+RT are included to evaluate the impact of an error bounder without PMA.
  - Bernstein+RT. This uses the empirical Bernstein-Serfling error bounder described in Section 2.3, coupled with our RangeTrim technique described in Section 3, which eliminates PHOS.
  - Hoeffding+RT. This uses the Hoeffding-Serfling error bounder described in Section 2.3, coupled with our RangeTrim technique described in Section 3, which eliminates PHOS from Hoeffding (but does not fix PMA).
  - Exact. This strawman approach eschews approximation and runs queries exactly, to serve as a simple baseline.

We furthermore used the following strategies for sampling when running queries in Figure 5:

**Sampling Strategies.**
- **ActivePeek.** This uses the active scanning technique to prioritize groups that are preventing satisfaction of various stopping conditions, along with cache-efficient queries to bitmaps with lookahead (see Section 4.3 for details).
- **ActiveSync.** This uses active scanning, but processes each block synchronously when deciding whether to read it, incurring high overhead since queries to bitmaps typically result in cache misses.
- **Scan.** This strategy does not leverage bitmaps in order to decide whether to read a block for active scanning (but may leverage bitmaps for evaluation of whether a block contains tuples that satisfy a fixed predicate, such as the one appearing in F-q1). Without any predicate, this approach simply processes all blocks in the scramble sequentially. Note that the Exact baseline described previously always uses Scan, as only approximate approaches can prune groups.

Environment. Experiments were run on single Intel Xeon E5-2630 node with 125 GiB of RAM and with 8 physical cores (16 logical) each running at 2.40 GHz, although we restrict our experiments to a single thread (excepting the ActivePeek sampling strategy, which uses one extra thread), noting that our techniques can be easily parallelized. The Level 1, Level 2, and Level 3 CPU cache sizes are, respectively: 512 KiB, 2048 KiB, and 20480 KiB. We ran Linux with kernel version 2.6.32. We report results for data stored in-memory, since the cost of main memory has decreased to the point that many interactive workloads can be performed entirely in-core. Each approximate query was started from a random position in the shuffled data. We found wall clock time to be stable for all approaches, and report times as the average of 3 runs for all methods.

5.3 Metrics

We gather several metrics in order to test two hypotheses: one, that our error bounding strategies in conjunction with our sampling strategies lead to speedups over simpler baselines; and two, that they do so without sacrificing correctness of query results.

Correctness of Query Results. The most important metric is the fraction of queries run that returned correct results. Across all methods, all queries, and all parameter settings, results either matched the ground truth determined from an Exact evaluation, or were within error tolerance in the case of F-q1 and F-q7. This is expected, given that we are considering SSI error bounders with strong probabilistic guarantees in this paper, coupled with the fact that our RangeTrim technique and system architecture do not compromise these guarantees. As such, we expect fewer than \( \delta = 10^{-15} \) fraction of queries to yield incorrect results, which rounds down to a cool 0.
In this section, we present results of our empirical study.

5.4.1 Impact of Error Bounder Used

| # F-q1: avg delay for airport | SELECT AVG(DepDelay) FROM flights WHERE Origin = $airport |
|-------------------------------|----------------------------------------------------------|
| # F-q2: avg delay above $sresh | SELECT Airline FROM flights GROUP BY Airline ORDER BY AVG(DepDelay) = $sresh |
| # F-q3: avg delay for $airport | SELECT Origin FROM flights GROUP BY Origin HAVING AVG(DepDelay) $airport |
| # F-q4: avg delay for $airport | SELECT DayOfWeek FROM flights GROUP BY DayOfWeek HAVING AVG(DepDelay) $airport |
| # F-q5: avg delay for $airport | SELECT Airline FROM flights GROUP BY Airline HAVING AVG(DepDelay) $airport |

Figure 5: SQL and semantics for Flaggars queries. Template parameters are shown in $blue.$

![Figure 6: Effect of query selectivity on wall time and blocks fetched, for selectivity determined by varying the origin airport used to filter F-q1(ε = .5). Note that Bernstein shows inverse time for clarity.](image)

**Estimate Error.** For a given requested error bound ε supplied to applicable queries, we measure the actual error. The observed error should always fall within the requested error bound.

**Wall-Clock Time.** Our primary metric evaluates the end-to-end time required for various error bounders and various sampling strategies (where the Exact baseline is included as a “sampling strategy”), across all the queries considered.

**Number of Blocks Fetched.** We also measure the number of blocks fetched from main memory into CPU cache when using various approaches. This is mainly due to the fact that error bounders incur additional CPU overhead and therefore wall-clock time, with Bernstein and Bernstein+RT incurring the highest overhead, so measuring blocks fetched for these approaches removes this confounding variable by decoupling performance from CPU attributes.

### 5.4 Results

In this section, we present results of our empirical study.

**Summary.** Using the Bernstein+RT error bounder resulted in enormous speedups (more than 1000× over Exact and up to 124× over Hoeffding), and additionally was almost always on par or better than Bernstein (2× faster under certain conditions).

We evaluate Hoeffding+RT and Bernstein+RT error bounders, along with Hoeffding and Bernstein (to ablate our RangeTrim technique) and an Exact query processor (to ablate any benefits due to approximation) against all the queries in Figure 5, with the resulting time measurements summarized in Table 5. We can make a number of interesting observations. First of all, note that all error bounders incur additional overhead — in the case of F-q5 where techniques like Hoeffding and Hoeffding+RT needed to process all the data in order to terminate (due to PMA), they actually...
Table 5: Summary of average query speedups and latencies for various error bounders.

| Query | Exact (s) | Hoeffding (s) | Bernstein (s) | Bernstein+RT (s) |
|-------|-----------|----------------|----------------|------------------|
| F-q1  | 4.20      | 1.11 (0.76)    | 1.20 (1.69)    |                   |
| F-q4  | 10.11     | 1.14 (40.74)   | 1.40 (33.76)   | 5.35 (8.81)      |
| F-q6  | 16.15     | 1.24 (3.32)    | 1.36 (3.03)    |                   |
| F-q7  | 24.11     | 1.14 (9.68)    | 1.13 (9.80)    |                   |
| F-q8  | 34.15     | 1.40 (33.76)   | 1.34 (34.31)   | 134.84 (3.02)    |

Table 6: Summary of query speedups and latencies for various sampling strategies, restricted to GROUP BY queries that take more than 500ms for Scan with Bernstein+RT.

| Query | Avg Speedup over Exact (raw time in (s)) |
|-------|-----------------------------------------|
| F-q3  | 2.04 Scan (s) 1.13× (1.76) 2.00× (1.69) |
| F-q4  | 4.15 Scan (s) 1.11× (40.74) 3.43× (13.18) |
| F-q6  | 11.05 Scan (s) 1.14× (9.68) 1.13× (9.80) |
| F-q8  | 47.12 Scan (s) 1.40× (33.76) 5.35× (8.81) |
| F-q3(10:50pm) | F-q3(10:50pm) | F-q3(10:50pm) |

Table 5: Summary of average query speedups and latencies for various error bounders.

5.4.2 Impact of Sampling Strategy Used

**Summary.** Using ActiveSync sampling was almost always better than Exact, and using Bernstein, which does not suffer from PMA, yielded significant benefits over Exact, Hoeffding, and Hoeffding+RT across all queries. In cases where Hoeffding and Hoeffding+RT showed improvements over Exact, Bernstein amplified these improvements (F-q1, F-q2).

Using RangeTrim in conjunction with both Hoeffding and Bernstein typically led to similar performance, with a few queries exhibiting clearly superior performance (F-q3, F-q6, and F-q3). These queries have the following in common: they all have sparse groups with low selectivity (either because of the large number of groups in the case of F-q5 and F-q3, or because of the restrictive filter in the case of F-q5), and they are all “easy” to approximate, in that none of the groups require too many samples in order to achieve the relevant stopping condition. (F-q3 also has many groups, but some of them require many samples due to a large number of airports with average delay near the max.) This is an ideal condition for Bernstein+RT to show benefit: sparse groups will bottleneck the query, but RangeTrim will achieve termination faster since these sparse groups tend to have fewer outliers than do non-sparse groups. For such bottlenecking sparse groups, the range bounds for the DepDelay column are over-conservative and dominate the sampling complexity. In this case, Bernstein, which has PHOS, will require twice as many samples for such groups — and since these groups are the bottleneck, it will require roughly twice as much time, an intuition reflected in Table 5.

5.4.3 Impact of Data and Query Characteristics

**Summary.** Wall clock time decreases as the fraction of tuples passing F-q1’s filter increases, while blocks fetched first increases, then decreases. RangeTrim gives the most benefit for filters of intermediate selectivity.

Different Origin attribute values used for filtering F-q1 have different selectivities. By varying the filter attribute value, we reveal interesting behavior impacted by the selectivity of the filter. (We consider selectivity as a number and not a quality, so that larger proportions of tuples satisfy predicates with higher selectivity.) For all four error bounding techniques considered, wall time and blocks fetched are plotted versus query selectivity in Figure 6. Bernstein and Bernstein+RT are plotted separately from Hoeffding and Hoeffding+RT for presentation.

As selectivity increases, wall-clock time decreases, as one might expect, with the benefits of RangeTrim being more obvious for Hoeffding than for Bernstein. The performance gap between techniques with and without RangeTrim generally decreases with increasing selectivity — perhaps because filters with higher selectivity tend to have range bounds that are not as conservative when compared with the a priori range bounds known to hold for the entire column.

Interestingly, as selectivity increases, the number of blocks fetched first increases, then decreases. This is likely because the sparsest filters require examining all the data before terminating, obviating early stopping benefits. After a certain point, however, early termination kicks in, happening more quickly as fewer tuples are filtered.

**Summary.** For different upper bounds on relative error, the actual relative error in the query result is always within the requested error, for all error bounders applied to F-q1. The achieved relative error drops to 0 more quickly for the more conservative bounders Hoeffding and Hoeffding+RT as the requested error is decreased.

By varying the requested maximum relative error $\epsilon$ for query F-q1, we reveal its impact on the relative error achieved for various error bounders, shown in Figure 7(a). The main takeaways are that, for however, the improvement was mediocre across the board, while the active scanning with lookahead achieved significantly better performance for F-q5 and F-q8. It is no coincidence that these are the same queries for which Scan performance using approximation is similar to Exact performance. This indicates that there were a few sparse groups preventing termination when Scan is used, which is the very case for which the greatest benefit can be derived from (an efficient implementation of) block skipping.

---

| Query | Avg Speedup over Exact (raw time in (s)) |
|-------|-----------------------------------------|
| F-q3  | 2.04 Scan (s) 1.13× (1.76) 2.00× (1.69) |
| F-q4  | 4.15 Scan (s) 1.11× (40.74) 3.43× (13.18) |
| F-q6  | 11.05 Scan (s) 1.14× (9.68) 1.13× (9.80) |
| F-q8  | 47.12 Scan (s) 1.40× (33.76) 5.35× (8.81) |
all error bounders, the achieved relative error generally decreases as the requested error bound decreases, with Hoeffding-based bounders dropping more quickly, as they are more conservative due to PMA.

**HAVING threshold for stopping condition $\theta$.**

**Summary.** HAVING thresholds that are closer to group aggregates require more samples in order to achieve stopping condition $\theta$, and Hoeffding-based error bounders in particular are more sensitive than Bernstein-based error bounders for the same threshold.

By varying the HAVING threshold used to filter groups / airlines post-aggregate in $F$-q2 and measuring its effect on the number of blocks fetched for a particular query, we reveal interesting data-dependent behavior impacted by the true aggregates for each airline, depicted in Figure 7(b). This figure also plots the group aggregates using a horizontal bar chart sharing the same x-axis as the HAVING threshold, revealing that it is “harder” to determine which side of the HAVING threshold a given group is if its aggregate is close to the threshold. Indeed, from Figure 7(b), we see that the initial thresholds near 0 are very easy for all groups, allowing for very fast termination. The first spike in number of blocks fetched occurs between 6 and 7, corresponding to the aggregate for airline NW. At and after this point, we see spikes in blocks fetched for both Hoeffding-based and Bernstein-based error bounders whenever the threshold approaches one or more airline aggregate values, although we note that Bernstein-based error bounders appear to be more robust, requiring the threshold to be much closer before they are adversely affected as compared to Hoeffding-based bounders.

**Minimum Departure Time for $F$-q3.**

**Summary.** As the minimum departure time is increased, the spread of average delay between airlines increases, making it easier to separate the two airlines with the minimum average delays and achieve stopping condition $\theta$ earlier. At the same time, termination becomes bottlenecked on sparse airlines, increasing the gap between similar bounders with and without RangeTrim.

By varying the minimum departure time $\min_{dep\_time}$ in F-q3, we reveal its impact on the number of blocks fetched for various error bounders, shown in Figure 8. This plot exhibits two interesting data-dependent behaviors worth unpacking. First, as the $\min_{dep\_time}$ increases, the variance in average delay between different airlines increases, perhaps because some airlines tend to have flights that are delayed more for later flights as compared with other airlines. This makes it easier to achieve stopping condition $\theta$, since the average delays become more spread out with increasing minimum departure time, so we observe a decreasing trend in the number of blocks fetched. At the same time, as $\min_{dep\_time}$ increases, the selectivity of the various groups decreases. Since all the groups are sparser, the groups for which stopping condition $\theta$ is bottlenecked are also sparser. Since we have an “easy” query (due to the higher variance between groups) for which sparse groups are bottlenecking termination, we tend to see a bigger performance gap between bounders with and without our RangeTrim technique.

### 6. RELATED WORK

In this section, we survey related literature and highlight similarities and differences with this work.

**Approximate Query Processing (AQP).** We survey the AQP literature along two dimensions: first, online versus offline; second, approaches with strong versus asymptotic guarantees.

**Online versus Offline AQP.** Online sampling-based AQP schemes select samples as queries are issued, contrasted with offline schemes which compute strata ahead of time. Although our approach does perform a shuffle offline, it is nevertheless closer to online schemes, as it uses the scramble to compute samples on the fly as in [50, 27, 58, 69, 70]. Online schemes can use index structures like bitmaps to materialize relevant samples on-the-fly [35, 40, 59, 50], or obey an accuracy constraint for computing predefined aggregates without indices [37, 38]. Offline schemes, on the other hand, materialize samples ahead-of-time [21, 7, 6, 30] based off workload assumptions, sometimes tuning the computed strata as new workload information is available [7, 30].

While we implement our error bounders without PMA or PHOS in the context of a system for online AQP, our core algorithmic techniques are orthogonal to the exact approach, and could be paired with either online or offline schemes.

**Sample-size-independent versus Asymptotic Guarantees.** Most of the AQP systems from prior work have traditionally leveraged asymptotic error bounders [7, 6, 5, 55], though some have mentioned allowing either approach as an option [35]. Other approaches have leveraged deterministic [57, 32] or concentration-based error bounding techniques [21, 8, 50, 59, 40] under range-based or other very mild assumptions. In some cases, novel asymptotic error bounding techniques have been developed [55, 71, 32] to be used in conjunction with existing systems. Our approach is analogous to these, but instead of basing our techniques on asymptotic methods, we develop error bounding techniques with guarantees independent of sample size, starting from existing concentration-based methods and systematically ameliorating various pathologies.

**Access Patterns for Informative Samples.** A number of techniques have been developed to optimize access to relevant data for analytical queries. Sampling-based approaches [40, 54, 19, 18, 43, 69, 50, 11, 33, 30, 21] attempt to retrieve tuples that will shrink approximation error as quickly as possible. Index structures such as bitmaps [40, 50] or inverted indexes [21] have been employed to facilitate this, or to simply accelerate exact analytical queries by quickly retrieving relevant tuples [68, 16, 41]. We make use of the sampling engine developed in [50], which leverages bitmaps and active scanning to adaptively prioritize different groups in the data while a query is running. While our RangeTrim technique is technically orthogonal to whatever data access method is employed, it demonstrates the most gains over existing error bounding techniques when few samples are needed to terminate. Active scanning is particularly useful for skipping to data needed to terminate when they are sparse.

Another access strategy worth mentioning explicitly comes from [18] and leverages an outlier index. Outlier indexing [18] works by computing approximate aggregates derived by combining an estimate from the main table and an exact aggregate from the so-called “outlier index”, which stores all the rows with outlier values. The benefit of the outlier index is that it shrinks the range of the data from which samples are taken, allowing for faster convergence of approximate answers. One could think of the outlier index as an offline analogy of our own RangeTrim technique. Outlier indexing has some additional limitations that RangeTrim does not have; namely, it cannot be used to facilitate queries with aggregates involving arbitrary expressions, since such expressions can drastically change the set of outlying values. That said, for simple aggregates the two approaches are orthogonal, and could be leveraged together.

Priority sampling [22, 9, 62] is also particularly useful for coping with outliers. If the attribute being aggregated has values $\{w_i\}$, priority sampling computes $\{\alpha_i\}$ (where $\alpha_i \sim \text{Unif}(0,1)$) and estimates $\sum_i w_i \alpha_i$ using the subset of the $\{w_i\}$ with the $k$ largest priorities, where the priority for the $i$th tuple is given by $w_i/\alpha_i$. While priority sampling applies in the presence of arbitrary filters and can furthermore be modified to allow for computation of AVG aggregates in addition to SUM, it has the drawback that the attribute
or expression being aggregated must be known ahead of time (to say nothing of arbitrary expressions), so that the tuples can be sorted in descending order of priority, a limitation our techniques do not have.

**Statistical Estimators and Confidence Intervals.** The well-known error bounders in statistics and probability leverage asymptotic techniques [61, 24, 25, 34], while those that give strong guarantees independent of sample size beyond Hoeffding’s and Serfling’s seminal work [36, 60] are relatively more obscure [29, 10]. We surveyed these in Section 2 when we discussed the empirical Bernstein-Serfling error bounder developed by Bardenet et al. [12], which we adapt for use in a database setting with our RangeTrim technique.

### 7. CONCLUSION AND FUTURE WORK

We categorized existing conservative error bounders in terms of two pathologies, PMA and PHOS, and developed a technique, RangeTrim, for eliminating PHOS from any range-based error bounder. We showed the advantage of using the empirical Bernstein-Serfling bounder in the context of a real system we are developing, FastFrame, that accelerates approximate queries significantly over a Hoeffding-Serfling-based error bounder, which suffers from PMA. We furthermore showed that augmenting this error bounder with our RangeTrim technique leads to an additional $2\times$ in the best case, without ever hurting performance in the worst case. By implementing our distribution-aware techniques in the context of FastFrame, which is aware of practical considerations such as locality, optional stopping, and block skipping in order to prioritize groups that require more samples in order to facilitate early termination, we demonstrate significant speedups (more than $1000\times$ over exact processing and up to $124\times$ over traditional techniques based on Hoeffding) without losing guarantees. This suggests a viable path toward practical with-guarantees AQP for workload-agnostic analytics; future work could include, for example, the development of an optimizer that intelligently determines when to leverage traditional data layouts and index structures for exact query processing and when to leverage a scramble for approximate results with exact quality.

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APPENDIX

A. RangeTrim Bounder Pseudocode

Algorithm 6: RangeTrim error bounder

```
function init_state()
  return {
    S[0]: inner.init_state(),
    a': undefined,
    b': undefined
  }
end

function update_state(S, v)
  if a', b' are undefined then
    S' ← S;
    S[0] ← S;
    a' ← v;
    b' ← v;
  else
    S[0] ← inner.update_state(S, min(v, b'));
    S[0] ← inner.update_state(S, max(v, a'));
    a' ← min(a', v);
    b' ← max(b', v);
  end
  return {S[0]: S[0], S[1]: S', a': a'', b': b''};
end

function Lbound(S, a, b, N, δ)
  return inner.Lbound(S[S[0], a, S[b'], N − 1, δ);
end

function Rbound(S, a, b, N, δ)
  return inner.Rbound(S[S[0], S[b'], b, N − 1, δ);
```

We give an implementation of our RangeTrim technique in terms of the interface from Section 2.2.2 in Algorithm 6.

B. Handling Arbitrary Expressions

In this paper, we assumed that column c_i was known to lie in some range [a_i, b_i]. We then showed how to feed these bounds into our RangeTrim procedure to compute conservative CIs for, e.g., \(\text{AVG}(c_i)\). In general, however, we may want to compute an aggregate involving an arbitrary expression in terms of several columns. That is, we may want to compute CIs for, e.g., \(\text{AVG}(f(c_1, \ldots, c_n))\). We now show how to do so for a large class of \(f\) by optimizing over such \(f\) (while using the individual bounds \([a_i, b_i]\) for each column as constraints) in order to compute derived range bounds of the form

\[
\inf_{c_1, \ldots, c_n} \sup_{c_1, \ldots, c_n} f(c_1, \ldots, c_n)
\]

Applicable Expressions. To compute a derived lower range bound, we need to be able to either solve or compute a lower bound for the following optimization problem:

\[
\min_{c_1, \ldots, c_n} f(c_1, \ldots, c_n)
\]

s.t. \(a_i \leq c_i \leq b_i, \; \forall 1 \leq i \leq n\)

The case for the derived upper range bound is analogous, but with \(f\) replaced by \(-f\). We show how to compute both lower and upper derived bounds under two kinds of conditions: (i) the monotonicity condition; i.e., \(f\) is monotone in each \(c_i\), and (ii) the convexity condition; i.e., either \(f\) or \(-f\) is convex. This handles a large number of expressions in practice.

1. Expressions Monotone in each Column. If \(f\) is monotone in each column \(c_i\), one simply needs to check whether \(a_i\) or \(b_i\) gives the smaller (resp. larger) value when computing the lower (resp. upper) bound, and evaluate \(f\) on the boundaries for each of these cases.

2. Convex or Concave Expressions. Without loss of generality, we now consider the case of convex \(f\). A large body of existing work focuses on minimizing a convex function subject to convex constraints; please see Boyd et al. [14] for relevant background. In our case, the constraints are all linear (and are sometimes referred to as “box” constraints), and most kinds of convex functions in practice can be optimized efficiently with off-the-shelf software under such constraints, so we do not go into detail here.

Maximizing a \(f\) under box constraints is more difficult. Since \(f\) is convex, the maximum (and therefore the derived upper range bound we seek) will occur at some boundary points; i.e., if \(a_i \leq c_i \leq b_i\), we know that the maximum will occur at one of \(c_i = a_i\) or \(c_i = b_i\). If we have \(n\) columns involved in the expression \(f\), however, we will require evaluating \(f\) on all \(2^n\) combinations of boundary points for the constraints. Fortunately, database aggregates over expressions typically do not involve more than 2 or 3 columns, and any \(n \leq 20\) or so can be handled without trouble.

Example 1. Suppose the user issues a query to compute \(\text{AVG}(2c_1 + 3c_2 - 1)^2\) involving columns \(c_1\) and \(c_2\), where we have range bounds \(c_1 \in [-3, 1]\) and \(c_2 \in [-3, 3]\). The minimum of \((2c_1 + 3c_2 - 1)^2\) subject to these constraints is simply 0, and can be found via quadratic programming. The maximum can be obtained by checking the boundaries \((-3, -1), (-3, 3), (1 - 1),\) and \((1, 3)\), and we see that it occurs at \((1, 3)\), for which \((2 \cdot 1 + 3 \cdot 3 - 1)^2 = 100\); thus, the derived range bounds will be \([0, 100]\).

C. Proof of Theorem 1

In Section 2.2.3, we claimed that the DKW inequality holds for sampling without replacement from a finite population; we now sketch the proof.

Theorem 1. For any \(N > 0\), the DKW inequality applies for sampling without replacement from a finite dataset of size \(N\).

Proof. Sketch: following the original paper from Wald and Wolowitz on confidence limits for CDFs [66], it suffices to consider the CDF for mass distributed uniformly at each integer \(1, 2, \ldots, N\). For each without-replacement sample size \(m\) and each deviation \(\epsilon\), we would like to be able to claim that

\[
P\left(\sup |F_N - \hat{F}_{N,m}| \geq \epsilon\right) < P\left(\sup |F_{N'} - \hat{F}_{N',m}| \geq \epsilon\right)
\]

for every \(N' > N\) — that is, in some sense, the CDF becomes monotonically “harder” to estimate as we increase the dataset size. Unfortunately, this turns out not to be the case, but in fact the claim follows if we merely prove the weaker condition that

\[
P\left(\sup |F_N - \hat{F}_{N,m}| \geq \epsilon\right) < P\left(\sup |F_{N'} - \hat{F}_{N',m}| \geq \epsilon\right)
\]

for infinitely many \(N' > N\), implying that, as \(N' \to \infty\), the resulting probability to which \(P\left(\sup |F_{N'} - \hat{F}_{N',m}| \geq \epsilon\right)\) converges (necessarily bounded by the probability computed in the DKW inequality) is an upper bound for the corresponding probability at every finite \(N'\), from which the claim would follow.

We show this via construction: namely, we show that, for every \(N, m,\) and \(\epsilon\),

\[
P\left(\sup |F_{N} - \hat{F}_{N,m}| \geq \epsilon\right) < P\left(\sup |F_{2N} - \hat{F}_{2N,m}| \geq \epsilon\right)
\]

That is, the CDF becomes monotonically harder to estimate each time we double the dataset size. To show this, we consider two cases. Case 1: if point \(2i - 1\) is sampled, then point \(2i\) is not sampled, and vice versa for every \(i = 1, \ldots, N\). Conditioned on
this event, the probability that \( \sup |F_{2N} - \hat{F}_{2N,m}| \geq \varepsilon \) at least the (unconditioned) probability that \( \sup |F_N - \hat{F}_{N,m}| \geq \varepsilon \), since samples at odd indices can only increase the deviation, and samples at even indices cannot decrease it. Case 2: there is at least one \( i \) for which points at both indices \( 2i - 1 \) and \( 2i \) are sampled. Each such point is conceptually similar to reducing \( m \) by 1 in the original dataset of size \( N \), but randomly weighting one of the samples by 2 instead of 1. It can be shown that each time this is done, the probability that \( \sup |F_N - \hat{F}_{N,m}| \geq \varepsilon \) increases. \( \square \)