Proof: Accelerating Approximate Aggregation Queries with Expensive Predicates

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Abstract

Given a dataset $\mathcal{D}$, we are interested in computing the mean of a subset of $\mathcal{D}$ which matches a predicate. ABae leverages stratified sampling and proxy models to efficiently compute this statistic given a sampling budget N. In this document, we theoretically analyze ABae and show that the MSE of the estimate decays at rate $O(N_1^{-1} + N_2^{-1} + N_1^{1/2} N_2^{-3/2})$, where $N = K \cdot N_1 + N_2$ for some integer constant K and $K \cdot N_1$ and N_2 represent the number of samples used in Stage 1 and Stage 2 of ABae respectively. Hence, if a constant fraction of the total sample budget N is allocated to each stage, we will achieve a mean squared error of $O(N^{-1})$ which matches the rate of mean squared error of the optimal stratified sampling algorithm given a priori knowledge of the predicate positive rate and standard deviation per stratum.

Symbol	Description
$\mathcal{D}$	dataset of records
$O(x)$	predicate function
$f(x)$	statistic function
K	number of strata
S	set of K equal sized stratum formed from $\mathcal{D}$
$X_{k,i}$	subgaussian r.v. in S_k and the i'th i.i.d predicate-matching sample
p_k	predicate positive rate in stratum k
μ_k	$E[X_k]$
σ_k^2	$Var[X_k]$
$C_k^{(\mu)}$	upper bound on μ_k
$C_k^{(\sigma)}$	upper bound on σ_k
p_{all}	$\sum_i^K p_k$
w_k	p_k/p_{all}
μ_{all}	$E[X]$, also given by $\sum_{k=1}^K w_k \mu_k$
N_1	sampling budget we allocate per stratum during 1
N_2	sampling we allocate during 2 in total
N	total sampling budget $(K \cdot N_1 + N_2 = N)$
T_k	fraction of our N_2 samples we allocate to a stratum during 2
$B_k^{(1)}$	number of predicate-matching samples we get in Stage 1
$B_k^{(2)}$	number of predicate-matching samples we get in Stage 2
p_*	cutoff value used when we split cases where p_k is small and large
F_k	we say that $B_k^{(2)} \geq F_k$ with high probability

Table 1: Summary of notation.

1 Setup

Given a dataset $\mathcal{D} = \{x_1, ..., x_{|D|}\}$, a statistic $f : \mathcal{D} \to \mathbb{R}$, and a predicate $O : \mathcal{D} \to \{0, 1\}$, we want to estimate $\mathbb{E}_{x \sim \mathcal{D}}[f(x)| \ O(x) = 1] = \mu_{\text{all}}$ given a sampling budget N, which limits the number of times the predicate $O(x)$ can be computed. We measure the quality of an estimator for μ_{all} by measuring the mean squared error (MSE) or $\mathbb{E}[(\hat{\mu}_{\text{all}} - \mu_{\text{all}})^2]$.

To estimate this mean efficiently, we use stratified sampling. In stratified sampling, the data is split into K strata or disjoint subsets of the dataset. In other words, given a dataset $\mathcal{D}$, we stratify it into equal-sized strata $S_1, ..., S_K$ such that they are disjoint and span the entirety of $\mathcal{D}$. Given these strata, denote μ_k, p_k, σ_k as the per-stratum mean of records which match the predicate, the per-stratum predicate positive rate, and the per-stratum standard deviation. Then, $\mu_{\text{all}} = \sum_{k=1}^{K} \mu_k p_k / \sum_{k=1}^{K} p_k$.

We make the following assumptions on our dataset. First, we assume that the distribution of the data we sample from is subgaussian. This is so that we can obtain concentration inequalities on estimates of variables such as μ_k and σ_k. We represent the samples from a stratum by a subgaussian random variable $X_{k,i}$ where k denotes the stratum and i denotes the i'th independent and identically distributed (i.i.d.) sample. Second, we assume that $\mathbb{E}[|X_{k,i}|] \leq C_k^{(\mu)}$ and $\text{Var}[X_{k,i}] \leq C_k^{(\sigma^2)}$. Lastly, we assume that $p_{\text{all}} = \sum_{k=1}^{K} p_k \geq C^{(p_{\text{all}})}$.

Algorithm 1 Pseudocode for ABAE.

1: **function** ABAE($\mathcal{D}$, K, N_1, N_2)
2:     $S_1, ..., S_K \leftarrow \text{Stratify}(\mathcal{D}, K)$
3:     **for** each k in $[1, ..., K]$ **do**
4:         $R_k^{(1)} \leftarrow \text{Sample}(S_k, N_1)$
5:         $X_k^{(1)} \leftarrow \{f(x) \mid x \in R_k^{(1)}, \ O(x) = 1\}$
6:         $B_k^{(1)} \leftarrow |X_k|$
7:         $\hat{\mu}_k \leftarrow \sum_{i=1}^{B_k^{(1)}} X_{k,i}^{(1)} / B_k^{(1)}$ if $B_k^{(1)} > 0$ else 0
8:         $\hat{p}_k \leftarrow B_k^{(1)} / |R_k^{(1)}|$
9:         $\hat{\sigma}_k^2 \leftarrow \sum_{i=1}^{B_k^{(1)}} (X_{k,i}^{(1)} - \hat{\mu}_k)^2 / (B_k^{(1)} - 1)$ if $B_k^{(1)} > 1$ else 0
10:     **end for**
11:     **for** each k in $[1, ..., K]$ **do**
12:         $\hat{T}_k \leftarrow \sqrt{\hat{p}_k} \hat{\sigma}_k / \sum_{i=1}^{K} \sqrt{\hat{p}_i} \hat{\sigma}_i$
13:         $R_k^{(2)} \leftarrow \text{Sample}(S_k, \lceil N_2 \hat{T}_k \rceil)$
14:         $R_k^{(2)} \leftarrow R_k^{(1)} + R_k^{(2)}$ if $SampleReuse$ else $R_k^{(2)}$
15:         $X_k^{(2)} \leftarrow \{f(x) \mid x \in R_k^{(2)}, \ O(x) = 1\}$
16:         $B_k^{(2)} \leftarrow |X_k|$
17:         $\hat{p}_k \leftarrow B_k^{(2)} / |R_k^{(2)}|$ if $SampleReuse$ else $\hat{p}_k$
18:         $\hat{\mu}_k \leftarrow \sum_{i=1}^{B_k^{(2)}} X_i / B_k^{(2)}$ if $B_k^{(2)} > 0$ else 0
19:     **end for**
20:     **return** $\sum_{k=1}^{K} \hat{p}_k \hat{\mu}_k / \sum_{k=1}^{K} \hat{p}_k$
21: **end function**

For the purpose of this proof, SampleReuse is *False*. We show that SampleReuse set to *True* does not change the error of ABAE asymptotically via Corollary X. Furthermore, note that on line 13 we round up the number of allocated samples $N_2 \hat{T}_k$. This rounding ensures that our bounds hold; however, this means that we may use up to $N_2 + K$ samples. Hence, proof statements involving N are only accurate up to K samples.

2 Algorithm

Refer to Algorithm 1 for pseudocode of ABAE and Table 1 for a description of notation used throughout the document. ABAE creates the strata by splitting the dataset evenly between K strata by ordering the records by proxy score. ABAE will then perform a two-stage sampling procedure. ABAE first estimates p_k and σ_k, which are the key quantities for determining optimal allocation by sampling N_1 samples from each of the K strata. Then, ABAE will allocate the remaining samples proportional to our estimates of the optimal allocation. ABAE will return the estimate $\sum_k \hat{p}_k \hat{\mu} / \sum_k \hat{p}_k$ as the approximate answer.

3 Analysis (Optimal Stratified Sampling Allocation)

In this section, we assume that the true values of p_k and σ_k are known, and derive the optimal allocation according to knowledge of these quantities. We also assume that the sample selection process is deterministic and returns a number of draws equal to the expected number of draws which satisfy the predicate. We also derive an upper bound on the MSE based on this optimal allocation. To avoid fractional samples, we round up samples as appropriate.

Although the true p_k and σ_k are unknown in this setting, our algorithm is based on estimating them in Stage 1 and then allocating samples in Stage 2 based on those estimates. We will then later show in a future section that the estimates made in Stage 1 are tight enough with high probability to achieve matching asymptotic rates of error with respect to the optimal allocation.

Proposition 3.1. *Let T_k represent the fraction of our sampling budget we want to allocate to stratum S_k. Suppose that p_k and σ_k are known, $\mathbb{E}[\hat{\mu}_k] = \mu_k$, and that we get $B_k = \lceil p_k T_k N_2 \rceil$ samples for all k. Then, the choice of T_k such that $T_k > 0$ and $\sum_{k=1}^{K} T_k = 1$ which minimizes the loss function $\mathcal{L}(T_1, ..., T_K) = \sum_{k=1}^{K} \frac{w_k^2 \sigma_k^2}{p_k T_k N}$ of the unbiased estimator $\hat{\mu}_{all} = \sum_{k=1}^{K} w_k \hat{\mu}_k$ is:*

$$T_k^* = \frac{\sqrt{p_k} \sigma_k}{\sum_{i=1}^{K} \sqrt{p_i} \sigma_i}. \tag{1}$$

In addition, the choice $T_k = T_k^*$ will result in the following upper bound on the MSE:

$$E^* = \mathbb{E}[(\hat{\mu}_{all} - \mu_{all})^2 | B_k = \lceil p_k T_k^* N \rceil] \leq \frac{1}{N p_{all}^2} \cdot \left(\sum_{k=1}^{K} \sqrt{p_k} \sigma_k \right)^2. \tag{2}$$

Proof. We can decompose the MSE into bias and variance. Note that the bias is zero due to the strata-specific estimates of the mean being unbiased.

$$\mathbb{E}[(\hat{\mu}_{all} - \mu_{all})^2 | B_k = \lceil p_k T_k N \rceil] = \mathbb{E}[\hat{\mu}_{all} - \mu_{all}]^2 + \text{Var}[\hat{\mu}_{all}] = \text{Var}\left[\sum_{k=1}^{K} w_k \hat{\mu}_k \right] \leq \mathcal{L}(T_1, ..., T_K) = \sum_{k=1}^{K} \frac{w_k^2 \sigma_k^2}{p_k T_k N}. \tag{3}$$

We will use Lagrange multipliers to minimize the the loss function $\mathcal{L}$ with respect to $T_1, ..., T_K$ under the constraint g which enforces that $\sum_{k=1}^{K} T_k = 1$.

$$\mathcal{L}(T_1, ..., T_K) = \sum_{k=1}^{K} \frac{w_k^2 \sigma_k^2}{p_k T_k N}, \quad g(T_1, ..., T_K) = \sum_{k=1}^{K} T_k - 1. \tag{4}$$

3

$$\frac{\partial \mathcal{L}}{\partial T_k} + \lambda \frac{\partial g}{\partial T_k} = 0 \longrightarrow \frac{w_k^2 \sigma_k^2}{p_k T_k^2 N} = \lambda \tag{5}$$

$$T_k = \frac{w_k \sigma_k}{\sqrt{p_k \lambda N}} \tag{6}$$

$$\sum_{k=1}^{K} T_k = \sum_{k=1}^{K} \frac{w_k \sigma_k}{\sqrt{p_k \lambda N}} = 1 \tag{7}$$

$$\sum_{k=1}^{K} \frac{w_k \sigma_k}{\sqrt{p_k N}} = \sqrt{\lambda} \tag{8}$$

$$\left(\sum_{i=k}^{K} \frac{w_k \sigma_k}{\sqrt{p_k N}} \right)^2 = \lambda. \tag{9}$$

Thus, the optimal choices of T_1, ..., T_K to minimize $\mathcal{L}$ under the constraint g is:

$$T_k^* = \frac{w_k \sigma_k}{\sqrt{p_k \lambda N}} \tag{10}$$

$$= \frac{w_k \sigma_k}{\sqrt{p_k N} \left(\sum_{i=1}^{K} \frac{w_i \sigma_i}{\sqrt{p_i N}} \right)} \tag{11}$$

$$= \frac{\sqrt{p_k} \sigma_k}{\sum_{i=1}^{K} \sqrt{p_i} \sigma_i}. \tag{12}$$

We will now derive an upper bound on the MSE given $T_k = T_k^*$. To deal with fractional samples, we round up $p_k T_k^* N$ or the number of draws each strata gets, which means that the bound derived below is still valid.

$$\mathbb{E}[(\hat{\mu}_{\text{all}} - \mu_{\text{all}})^2 | B_k = \lceil p_k T_k^* N \rceil] \leq \sum_{k=1}^{K} \frac{w_k^2 \sigma_k^2}{p_k T_k^* N} \tag{13}$$

$$= \sum_{k=1}^{K} \frac{w_k^2 \sigma_k^2}{p_k \frac{\sqrt{p_k} \sigma_k}{\sum_{i=1}^{K} \sqrt{p_i} \sigma_i} N} \tag{14}$$

$$= \frac{1}{p_{\text{all}}^2 N} \cdot \sum_{k=1}^{K} \frac{p_k^2 \sigma_k^2}{p_k \frac{\sqrt{p_k} \sigma_k}{\sum_{i=1}^{K} \sqrt{p_i} \sigma_i}} \tag{15}$$

$$= \frac{1}{p_{\text{all}}^2 N} \cdot \sum_{k=1}^{K} \frac{\sqrt{p_k} \sigma_k}{\frac{1}{\sum_{i=1}^{K} \sqrt{p_i} \sigma_i}} \tag{16}$$

$$= \frac{1}{p_{\text{all}}^2 N} \cdot \left(\sum_{k=1}^{K} \sqrt{p_k} \sigma_k \right)^2 \qquad \square$$

4 Analysis

Our goal is to prove that with arbitrarily small failure probability δ over Stage 1, the expectation of the mean squared error of ABAE over Stage 2 is

$$\mathbb{E}[(\hat{\mu}_{\text{all}} - \mu_{\text{all}})^2] \leq O\left(N_1^{-1}\right) + O\left(N_2^{-1}\right) + O\left(N_1^{1/2} N_2^{-3/2}\right). \tag{17}$$

Our proof strategy is outlined below.

1. Obtain high probability bounds over all the random variables in Stage 1. Namely, p_k, w_k, σ_k, $B_k^{(1)}$, and T_k.

2. Assuming the worst-case values described by these high probability bounds, we will upper bound the mean squared error of our algorithm in expectation over Stage 2.

4.1 Big-O Definition

To clarify our usage of Big-O, we will formally define it as:

$$T(...) = O(f(...)) \iff \exists\, C,\ N_0 \text{ s.t. } \forall N \geq N_0,\, 0 \leq T(...) \leq C \cdot f(...). \tag{18}$$

We use Big-O notation with respect to N_1, N_2, p_k, and δ. Hence, C and N_0 must be independent of those quantities.

4.2 Stage 1

We will obtain high probability bounds on all the random variables in Stage 1. Namely, p_k, w_k, σ_k, $B_k^{(1)}$, and T_k.

Lemma 4.1 ($\hat{p}_k$ Upper Bound). *For small $\delta > 0$, the following holds for all k simultaneously,*

$$\sqrt{\hat{p}_k} \leq \sqrt{p_k + \sqrt{\frac{2\ln(1/\delta)p_k}{N_1}}} = \sqrt{p_k}\sqrt{1 + O\left(\sqrt{\frac{\ln(1/\delta)}{p_k N_1}}\right)}. \tag{19}$$

Proof. We apply Chung and Lu [2002] reproduced as Lemma 5.1 to upper bound $\hat{p}_k$. We set $Y_i \sim Bernoulli(p_k)$ and $a_i = \frac{1}{N_1}$ for all $i \in [N_1]$. Thus, $\nu = \sum_{i=1}^{N_1} a_i^2 p_i = \frac{p_k}{N_1}$ and $Y = \sum_{i=1}^{N_1} a_i Y_i = \hat{p}_k$. Then, according to the Lemma,

$$P\left(\hat{p}_k \geq p_k + \lambda\right) \leq exp\left(\frac{-\lambda^2}{2\left(\frac{p_k}{N_1} + \frac{\lambda}{3N_1}\right)}\right). \tag{20}$$

We will set $\delta = exp\left(-\lambda^2/(2(\frac{p_k}{N_1} + \frac{\lambda}{3N_1}))\right)$ and $\lambda = \left(\sqrt{18N_1 p_k \ln(1/\delta) + \ln(1/\delta)^2} - \ln(1/\delta)\right)/(3N_1)$. Thus, with probability at least $1 - \delta$,

$$\hat{p}_k \leq p_k + \frac{\sqrt{18N_1 p_k \ln(1/\delta) + \ln(1/\delta)^2} - \ln(1/\delta)}{3N_1} \tag{21}$$

$$\leq p_k + \frac{\sqrt{18N_1 p_k \ln(1/\delta)}}{3N_1} = p_k + \sqrt{\frac{2\ln(1/\delta)p_k}{N_1}}. \tag{22}$$

5

With probability at least $1 - \delta$,

$$\sqrt{\hat{p}_k} \leq \sqrt{p_k + \sqrt{\frac{2\ln(1/\delta)p_k}{N_1}}} \leq \sqrt{p_k} \cdot \sqrt{1 + \sqrt{\frac{2\ln(1/\delta)}{p_k N_1}}} = \sqrt{p_k}\sqrt{1 + O\left(\sqrt{\frac{\ln(1/\delta)}{p_k N_1}}\right)}. \qquad (23)$$

We union bound across all strata $S_1, ..., S_k$. As a result, the bound above holds for all k simultaneously with probability at least $1 - K\delta$. $\qquad \square$

Lemma 4.2 ($\hat{p}_k$ Lower Bound). *For small $\delta > 0$, the following holds for all k simultaneously,*

$$\sqrt{\hat{p}_k} \geq \sqrt{p_k - \sqrt{\frac{2\ln(1/\delta)p_k}{N_1}}} = \sqrt{p_k}\sqrt{1 - O\left(\sqrt{\frac{\ln(1/\delta)}{p_k N_1}}\right)}. \qquad (24)$$

Proof. We apply Chung and Lu [2002] reproduced as Lemma 5.1 to lower bound $\hat{p}_k$. We set $X_i \sim Bernoulli(p_k)$ and $a_i = \frac{1}{N_1}$ for all $i \in [N_1]$. Thus, $\nu = \sum_{i=1}^{N_1} a_i^2 p_i = \frac{p_k}{N_1}$ and $X = \sum_{i=1}^{N_1} a_i X_i = \hat{p}_k$. Then, according to the Lemma:

$$P\left(\hat{p}_k < p_k - \lambda\right) \leq exp\left(\frac{-\lambda^2}{2(\frac{p}{N_1})}\right). \qquad (25)$$

We will set $\delta = exp\left(\frac{-\lambda^2}{2(\frac{p}{N_1})}\right)$ and $\lambda = \frac{\sqrt{p}}{\sqrt{N_1}} \cdot \sqrt{2\ln(1/\delta)}$. Hence, with probability at least $1 - \delta$ (where δ is probability of failure):

$$\hat{p}_k \geq p_k - \frac{\sqrt{p_k}}{\sqrt{N_1}} \cdot \sqrt{2\ln(1/\delta)} = p_k - \sqrt{\frac{2\ln(1/\delta)p_k}{N_1}}. \qquad (26)$$

In other words, with probability at least $1 - \delta$,

$$\sqrt{\hat{p}_k} \geq \sqrt{p_k - \sqrt{\frac{2\ln(1/\delta)p_k}{N_1}}} \geq \sqrt{p_k}\sqrt{1 - \sqrt{\frac{2\ln(1/\delta)}{p_k N_1}}} \qquad (27)$$

$$= \sqrt{p_k}\sqrt{1 - O\left(\sqrt{\frac{\ln(1/\delta)}{p_k N_1}}\right)}. \qquad (28)$$

We then apply the union bound, so the above holds for all k simultaneously with probability at least $1 - K\delta$. $\qquad \square$

Lemma 4.3 ($\hat{w}_k$ Upper and Lower Bounds). *For small $\delta > 0$, the bounds of Lemma 4.1 and Lemma 4.2 hold and*

$$w_k - O\left(\frac{\ln(1/\delta)\sqrt{p_k}}{\sqrt{N_1}}\right) \leq \frac{p_k - \sqrt{\frac{2\ln(1/\delta)p_k}{N_1}}}{p_{all} + \sum_{k=1}^{K}\sqrt{\frac{2\ln(1/\delta)p_k}{N_1}}} \leq \hat{w}_k \leq \frac{p_k + \sqrt{\frac{2\ln(1/\delta)p_k}{N_1}}}{p_{all} - \sum_{k=1}^{K}\sqrt{\frac{2\ln(1/\delta)p_k}{N_1}}} \leq w_k + O\left(\frac{\ln(1/\delta)\sqrt{p_k}}{\sqrt{N_1}}\right).$$

$$\qquad (29)$$

Proof. Recall that $\hat{w}_k = \hat{p}_k/\hat{p}_{\text{all}}$, where $\hat{p}_{\text{all}} = \sum_{k=1}^K \hat{p}_k$. (29) holds on the event that the bounds of Lemma 4.1 and Lemma 4.2 hold for all k simultaneously, which occurs with probability at least $1 - 2K\delta$ according to the union bound. For the remainder of the proof of this Lemma, we condition on this event and prove (29). Specifically, the condition is that for each k,

$$p_k - \sqrt{\frac{2\ln(1/\delta)p_k}{N_1}} \le \hat{p}_k \le p_k + \sqrt{\frac{2\ln(1/\delta)p_k}{N_1}}. \tag{30}$$

Hence, by summing these inequalities across k, we have that with probability at least $1 - 2K\delta$,

$$p_{\text{all}} - \sum_{k=1}^K \sqrt{\frac{2\ln(1/\delta)p_k}{N_1}} \le \hat{p}_{\text{all}} \le p_{\text{all}} + \sum_{k=1}^K \sqrt{\frac{2\ln(1/\delta)p_k}{N_1}}. \tag{31}$$

We will now maximize or minimize the numerator and denominator appropriately in $\hat{w}_k = \hat{p}_k/\hat{p}_{\text{all}}$.

$$\frac{p_k - \sqrt{\frac{2\ln(1/\delta)p_k}{N_1}}}{p_{\text{all}} + \sum_{k=1}^K \sqrt{\frac{2\ln(1/\delta)p_k}{N_1}}} \le \hat{w}_k \le \frac{p_k + \sqrt{\frac{2\ln(1/\delta)p_k}{N_1}}}{p_{\text{all}} - \sum_{k=1}^K \sqrt{\frac{2\ln(1/\delta)p_k}{N_1}}}. \tag{32}$$

We will now simplify this bound with Big O. Note that $p_{\text{all}} \ge C^{(p_{\text{all}})}$.

$$\hat{w}_k \le \frac{p_k + \sqrt{\frac{2\ln(1/\delta)p_k}{N_1}}}{p_{\text{all}} - \sum_{k=1}^K \sqrt{\frac{2\ln(1/\delta)p_k}{N_1}}} \tag{33}$$

$$= \frac{\frac{1}{p_{\text{all}}}}{\frac{1}{p_{\text{all}}}} \cdot \frac{p_k}{p_{\text{all}} - \sum_{k=1}^K \sqrt{\frac{2\ln(1/\delta)p_k}{N_1}}} + \frac{\frac{1}{p_{\text{all}}}}{\frac{1}{p_{\text{all}}}} \cdot \frac{\sqrt{\frac{2\ln(1/\delta)p_k}{N_1}}}{p_{\text{all}} - \sum_{k=1}^K \sqrt{\frac{2\ln(1/\delta)p_k}{N_1}}} \tag{34}$$

$$= \frac{w_k}{1 - \sum_{k=1}^K \sqrt{\frac{2\ln(1/\delta)p_k}{p_{\text{all}}^2 N_1}}} + \frac{\sqrt{\frac{2\ln(1/\delta)p_k}{p_{\text{all}}^2 N_1}}}{1 - \sum_{k=1}^K \sqrt{\frac{2\ln(1/\delta)p_k}{p_{\text{all}}^2 N_1}}} \tag{35}$$

$$\le \left(w_k + \sqrt{\frac{2\ln(1/\delta)p_k}{p_{\text{all}}^2 N_1}}\right) \cdot \left(1 + \sum_{k=1}^K \sqrt{\frac{2\ln(1/\delta)p_k}{p_{\text{all}}^2 N_1}}\right). \tag{36}$$

$$\le \left(w_k + \sqrt{\frac{2\ln(1/\delta)p_k}{p_{\text{all}}^2 N_1}}\right) \cdot \left(1 + O\left(\sqrt{\frac{\ln(1/\delta)}{N_1}}\right)\right) \tag{37}$$

$$\le w_k + \sqrt{\frac{2\ln(1/\delta)p_k}{p_{\text{all}}^2 N_1}} + O\left(\frac{p_k\sqrt{\ln(1/\delta)}}{\sqrt{N_1}}\right) + O\left(\frac{\ln(1/\delta)\sqrt{p_k}}{N_1}\right) \tag{38}$$

$$\le w_k + O\left(\frac{\sqrt{\ln(1/\delta)p_k}}{\sqrt{N_1}}\right) + O\left(\frac{p_k\sqrt{\ln(1/\delta)}}{\sqrt{N_1}}\right) + O\left(\frac{\ln(1/\delta)\sqrt{p_k}}{N_1}\right) \tag{39}$$

$$\le w_k + O\left(\frac{\ln(1/\delta)\sqrt{p_k}}{\sqrt{N_1}}\right). \tag{40}$$

7

We repeat these steps for the lower bound. Thus,

$$w_k - O\left(\frac{\ln(1/\delta)\sqrt{p_k}}{\sqrt{N_1}}\right) \leq \hat{w}_k \leq w_k + O\left(\frac{\ln(1/\delta)\sqrt{p_k}}{\sqrt{N_1}}\right). \tag{41}$$

$\square$

Lemma 4.4 ($B_k^{(1)}$ Lower Bound). *For small $\delta > 0$, the following is true for all k,*

$$B_k^{(1)} \geq p_k N_1 - \sqrt{2\ln(1/\delta)p_k N_1}. \tag{42}$$

Proof. We apply Tarjan [2009] reproduced as Lemma 5.2 to lower bound $B_k^{(1)}$. Note that $B_k^{(1)} \sim Binomial(N_1, p_k)$ and that equivalently $B_k^{(1)} = \sum_{i=1}^{N_1} Y_i$ where $Y_i \sim Bernoulli(p_k)$. Hence,

$$P\left(B_k^{(1)} \leq (1-\epsilon)(p_k N_1)\right) \leq exp\left(\frac{-\epsilon^2 p_k N_1}{2}\right). \tag{43}$$

We set $\delta = exp\left(\frac{-\epsilon^2 p_k N_1}{2}\right)$ and $\epsilon = \sqrt{\frac{2\ln(1/\delta)}{p_k N_1}}$. Thus, with probability at least $1 - \delta$:

$$B_k^{(1)} \geq p_k N_1 - \sqrt{2\ln(1/\delta)p_k N_1}. \tag{44}$$

We then union bound across all k. As a result, with probability at least $1 - K\delta$, (44) holds for all k simultaneously. $\square$

Lemma 4.5 (σ_k Upper and Lower Bound for $B_k^{(1)} \geq 2$). *For small $\delta > 0$, the following holds for all k such that $B_k^{(1)} \geq 2$.*

$$\sigma_k \cdot \sqrt{1 - O\left(\sqrt{\frac{\ln(1/\delta)}{p_k N_1}}\right)} \leq \hat{\sigma}_k \leq \sigma_k \cdot \sqrt{1 + O\left(\sqrt{\frac{\ln(1/\delta)}{p_k N_1}}\right)}. \tag{45}$$

Proof. To obtain a concentration inequality on $\hat{\sigma}_k$, we will apply bounded differences on the unbiased sample variance estimator for $B_k^{(1)} > 2$, which is:

$$\hat{\sigma}_k^2 = \frac{1}{B_k^{(1)} - 1} \sum_{i=1}^{B_k^{(1)}} (X_{k,i} - \hat{\mu}_k)^2. \tag{46}$$

Note that the unbiased sampled variance is a U-Statistic U_n that arises from taking $g(X_{k,i}, X_{k,j}) = \frac{1}{2}(X_{k,i} - X_{k,j})^2$ (Ferguson [2005] reproduced as Lemma 5.3). For bounded U-Statistics, we can apply bounded differences to obtain a concentration bound (Rinaldo [2018] reproduced as Lemma 5.4). Namely, where $g(X_{k,i}, X_{k,j}) \leq b$,

$$P(|U_n - \mathbb{E}[U_n]| \geq t) \leq 2\exp(-\frac{nt^2}{8b^2}). \tag{47}$$

We use this concentration inequality with $n = B_k^{(1)}$ and $g(X_{k,i}, X_{k,j}) \leq b = C_k^{(\mu^2)}$. Hence,

$$P(|\hat{\sigma}_k^2 - \sigma_k^2| \geq t) \leq 2\exp(-\frac{B_k^{(1)} t^2}{8C_k^{(\mu^4)}}). \tag{48}$$

8

We then set $2\delta = 2\exp(-\frac{B_k^{(1)}t^2}{8C_k^{(\mu^4)}})$ and $t = \sqrt{8\ln(1/\delta)C_k^{(\mu^4)}/B_k^{(1)}}$. Thus, with probability at least $1 - 2\delta$,

$$\sigma_k^2 - \sqrt{\frac{8\ln(1/\delta)C_k^{(\mu^4)}}{B_k^{(1)}}} \leq \hat{\sigma_k}^2 \leq \sigma_k^2 + \sqrt{\frac{8\ln(1/\delta)C_k^{(\mu^4)}}{B_k^{(1)}}}. \tag{49}$$

Using Lemma 4.4, we have $B_k^{(1)} \geq p_k N_1 - \sqrt{2\ln(1/\delta)p_k N_1}$ with probability at least $1 - K\delta$.

$$\sigma_k^2 - \sqrt{\frac{8\ln(1/\delta)C_k^{(\mu^4)}}{p_k N_1 - \sqrt{2\ln(1/\delta)p_k N_1}}} \leq \hat{\sigma_k}^2 \leq \sigma_k^2 + \sqrt{\frac{8\ln(1/\delta)C_k^{(\mu^4)}}{p_k N_1 - \sqrt{2\ln(1/\delta)p_k N_1}}} \tag{50}$$

$$\sigma_k^2 - \sqrt{\frac{8\ln(1/\delta)C_k^{(\mu^4)}}{p_k N_1\left(1 - \sqrt{\frac{2\ln(1/\delta)}{p_k N_1}}\right)}} \leq \hat{\sigma_k}^2 \leq \sigma_k^2 + \sqrt{\frac{8\ln(1/\delta)C_k^{(\mu^4)}}{p_k N_1\left(1 - \sqrt{\frac{2\ln(1/\delta)}{p_k N_1}}\right)}} \tag{51}$$

$$\sigma_k^2 - \sqrt{\frac{8\ln(1/\delta)C_k^{(\mu^4)}}{p_k N_1}\cdot\left(1 + \sqrt{\frac{2\ln(1/\delta)}{p_k N_1}}\right)} \leq \hat{\sigma_k}^2 \leq \sigma_k^2 + \sqrt{\frac{8\ln(1/\delta)C_k^{(\mu^4)}}{p_k N_1}\cdot\left(1 + \sqrt{\frac{2\ln(1/\delta)}{p_k N_1}}\right)} \tag{52}$$

$$\sigma_k^2 - \sqrt{\frac{8\ln(1/\delta)C_k^{(\mu^4)}}{p_k N_1} + \frac{8\sqrt{2}\ln(1/\delta)^{3/2}}{p_k^{3/2}N_1^{3/2}}} \leq \hat{\sigma_k}^2 \leq \sigma_k^2 + \sqrt{\frac{8\ln(1/\delta)C_k^{(\mu^4)}}{p_k N_1} + \frac{8\sqrt{2}\ln(1/\delta)^{3/2}}{p_k^{3/2}N_1^{3/2}}} \tag{53}$$

$$\sigma_k^2 - \sqrt{O\left(\frac{1}{p_k N_1}\right)} \leq \hat{\sigma_k}^2 \leq \sigma_k^2 + \sqrt{O\left(\frac{1}{p_k N_1}\right)} \tag{54}$$

$$\sqrt{\sigma_k^2 - \sqrt{O\left(\frac{1}{p_k N_1}\right)}} \leq \hat{\sigma_k} \leq \sqrt{\sigma_k^2 + \sqrt{O\left(\frac{1}{p_k N_1}\right)}} \tag{55}$$

$$\sigma_k \cdot \sqrt{1 - O\left(\frac{1}{\sqrt{p_k N_1}}\right)} \leq \hat{\sigma_k} \leq \sigma_k \cdot \sqrt{1 + O\left(\frac{1}{\sqrt{p_k N_1}}\right)}. \tag{56}$$

We union bound across the strata and intersection bound our application of Lemma 4, and get that the above holds with probability at least $(1 - 2K\delta)(1 - K\delta) = 1 - 3K\delta + 2K^2\delta^2 \geq 1 - 3K\delta$. We impose the condition that $\sigma_k \neq 0$ on this derivation because we divide by σ_k in (55). However, if $\sigma_k = 0$, then $\hat{\sigma}_k = \sigma_k$, so the bound still holds. $\qquad\square$

Lemma 4.6 ($\sqrt{p_k}\sigma_k$ Upper Bound for $B_k^{(1)} < 2$). *For $B_k^{(1)} < 2$, the following holds for all k:*

$$\sqrt{\hat{p}_k}\hat{\sigma}_k \leq \sqrt{p_k}\sigma_k + O\left(\frac{1}{\sqrt{N_1}}\right). \tag{57}$$

Proof. In the cases where $B_k^{(1)} < 2$, we will upper bound $\sqrt{\hat{p}_k}\hat{\sigma}_k$ directly instead of combining our concentration inequalities for $\sqrt{\hat{p}_k}$ and $\hat{\sigma}_k$ separately.

$$\sqrt{\hat{p}_k}\hat{\sigma}_k \leq \sqrt{\frac{2}{N_1}}\hat{\sigma}_k \leq \sqrt{p_k}\sigma_k + \sqrt{\frac{2}{N_1}}C_k^{(\sigma)} \leq \sqrt{p_k}\sigma_k + O\left(\frac{1}{\sqrt{N_1}}\right). \tag{58}$$

$\qquad\square$

Lemma 4.7 (T_k Lower Bound). *For small $\delta > 0$, the following is true simultaneously for all k where $p_k > p_* = \frac{2(\sqrt{\ln(1/\delta)}+1)}{N_1}$,*

$$\hat{T}_k \geq T_k\left(1 - O\left(\sqrt{\frac{\ln(1/\delta)}{p_k N_1}}\right)\right). \tag{59}$$

Proof. Our goal is to lower bound $\hat{T}_k = \frac{\sqrt{\hat{p}_k}\hat{\sigma}_k}{\sum_{i=1}^K \sqrt{\hat{p}_i}\hat{\sigma}_i}$. To accomplish this, we will upper bound the denominator and lower bound the numerator. To lower bound the numerator, we will apply our concentration inequalities for $\sqrt{\hat{p}_k}$ and $\hat{\sigma}_k$ from Lemma 4.2 and Lemma 4.5. We only lower bound for k where $B_k^{(1)} \geq 2$. Through our high probability lower bound on $B_k^{(1)}$, we know that for $B_k^{(1)} \geq 2$ to be true we can assume $p_k > \frac{2(\sqrt{\ln(1/\delta)}+1)}{N_1}$. We denote $p_* = \frac{2(\sqrt{\ln(1/\delta)}+1)}{N_1}$. This allows us to satisfy the conditions of Lemma 4.5.

$$\sqrt{\hat{p}_k}\sigma_k \geq \sqrt{p_k}\sigma_k\sqrt{1 - O\left(\sqrt{\frac{\ln(1/\delta)}{p_k N_1}}\right)}\sqrt{1 - O\left(\sqrt{\frac{\ln(1/\delta)}{p_k N_1}}\right)} \tag{60}$$

$$\geq \sqrt{p_k}\sigma_k\left(1 - O\left(\sqrt{\frac{\ln(1/\delta)}{p_k N_1}}\right)\right) \geq \sqrt{p_k}\sigma_k - O\left(\sqrt{\frac{\ln(1/\delta)}{N_1}}\right). \tag{61}$$

To maximize the denominator, we also apply Lemma 4.1 and split the cases where $p_k > p_*$ and where $p_k \leq p_*$.

$$\sum_{i=1}^K \sqrt{\hat{p}_i}\hat{\sigma}_i \leq \sum_{p_k>p_*}^K \sqrt{p_i}\sigma_i\sqrt{1 + O\left(\sqrt{\frac{\ln(1/\delta)}{p_i N_1}}\right)}\sqrt{1 + O\left(\sqrt{\frac{\ln(1/\delta)}{p_i N_1}}\right)} + \sum_{p_k>p_*}^K \sqrt{p_i}\sigma_i + O\left(\frac{1}{\sqrt{N_1}}\right) \tag{62}$$

$$\leq \sum_{p_k<p_*}^K \sqrt{p_i}\sigma_i\left(1 + O\left(\sqrt{\frac{\ln(1/\delta)}{p_i N_1}}\right)\right) + \sum_{p_k\leq p_*}^K \sqrt{p_i}\sigma_i + O\left(\frac{1}{\sqrt{N_1}}\right) \tag{63}$$

$$\leq \sum_{i=1}^K \sqrt{p_i}\sigma_i + O\left(\sqrt{\frac{\ln(1/\delta)}{N_1}}\right). \tag{64}$$

Thus, for $p_k > p_* = \frac{2(\sqrt{\ln(1/\delta)}+1)}{N_1}$,

$$\hat{T}_k = \frac{\sqrt{\hat{p}_k}\hat{\sigma}_k}{\sum_{i=1}^K \sqrt{\hat{p}_i}\hat{\sigma}_i} \geq \frac{\sqrt{p_k}\sigma_k - O\left(\sqrt{\frac{\ln(1/\delta)}{N_1}}\right)}{\sum_{i=1}^K \sqrt{p_i}\sigma_i + O\left(\sqrt{\frac{\ln(1/\delta)}{N_1}}\right)} = \frac{\frac{1}{\sum_{i=1}^K \sqrt{p_i}\sigma_i}}{\frac{1}{\sum_{i=1}^K \sqrt{p_i}\sigma_i}} \cdot \frac{\sqrt{p_k}\sigma_k - O\left(\sqrt{\frac{\ln(1/\delta)}{N_1}}\right)}{\sum_{i=1}^K \sqrt{p_i}\sigma_i + O\left(\sqrt{\frac{\ln(1/\delta)}{N_1}}\right)} \tag{65}$$

$$\geq \frac{T_k - O\left(\sqrt{\frac{\ln(1/\delta)}{N_1}}\right)}{1 + O\left(\sqrt{\frac{\ln(1/\delta)}{N_1}}\right)} \geq \left(T_k - O\left(\sqrt{\frac{\ln(1/\delta)}{N_1}}\right)\right)\left(1 - O\left(\sqrt{\frac{\ln(1/\delta)}{N_1}}\right)\right) \tag{66}$$

$$\geq T_k - O\left(\sqrt{\frac{\ln(1/\delta)}{N_1}}\right) - O\left(\sqrt{\frac{p_k\ln(1/\delta)}{N_1}}\right) + O\left(\frac{\ln(1/\delta)}{N_1}\right) \tag{67}$$

$$\geq T_k - O\left(\sqrt{\frac{\ln(1/\delta)}{N_1}}\right) \geq T_k\left(1 - O\left(\sqrt{\frac{\ln(1/\delta)}{p_k N_1}}\right)\right) \qquad \square$$

Through the union bound on Lemma 4.1, Lemma 4.2, Lemma 4.5, (73) occurs with probability at least $1 - 5K\delta$.

4.3 Stage 2

Recall that we use high probability bounds over Stage 1 and take the expectation over Stage 2. In this section, we derive bounds on quantities in Stage 2 that will help us upper bound the mean squared error of our algorithm.

Lemma 4.8 ($B_k^{(2)}$ Lower Bound). *If Lemma 4.7 holds, the following is true for all k where $p_k > p_* = \frac{2(\sqrt{\ln(1/\delta)}+1)}{N_1}$ with probability at least $1 - \gamma$,*

$$B_k^{(2)} \geq p_k T_k N_2 \left(1 - O\left(\sqrt{\frac{1}{p_k N_1}}\right) - O\left(\sqrt{\frac{\ln(1/\gamma)}{N_2 p_k^{3/2}}}\right)\right). \tag{68}$$

Proof. Recall that $B_k^{(2)} \sim Binomial(N_2 \hat{T}_k, p_k)$. Thus, using Tarjan [2009] reproduced as Lemma 5.2, we have that:

$$P\left(B_k^{(2)} \leq (1 - \epsilon)\left(p_k \hat{T}_k N_2\right)\right) \leq exp\left(\frac{-\epsilon^2 p_k \hat{T}_k N_2}{2}\right). \tag{69}$$

We set $\delta = exp\left(\frac{-\epsilon^2 p_k \hat{T}_k N_2}{2}\right)$ and $\epsilon = \sqrt{\frac{2\ln(1/\delta)}{p_k \hat{T}_k N_2}}$. Thus, we have that with probability $1 - 6K\delta$:

$$B_k^{(2)} \geq p_k \hat{T}_k N_2 \left(1 - \sqrt{\frac{2\ln(1/\delta)}{p_k \hat{T}_k N_2}}\right) \geq p_k \hat{T}_k N_2 - \sqrt{2\ln(1/\delta) p_k \hat{T}_k N_2} \geq p_k \hat{T}_k N_2 \left(1 - \sqrt{\frac{2\ln(1/\delta)}{p_k \hat{T}_k N_2}}\right). \tag{70}$$

We lower bound the number of draws $\hat{T}_k N_2$ by conditioning on Lemma 4.7 which says that $\hat{T}_k \geq T_k\left(1 - O\left(\sqrt{\frac{\ln(1/\delta)}{p_k N_1}}\right)\right)$. Thus, with probability at least $1 - \gamma$,

$$\geq p_k T_k N_2 \left(1 - O\left(\sqrt{\frac{\ln(1/\delta)}{p_k N_1}}\right)\right)\left(1 - \sqrt{\frac{2\ln(1/\delta)}{p_k T_k N_2 \left(1 - O\left(\sqrt{\frac{\ln(1/\delta)}{p_k N_1}}\right)\right)}}\right) \tag{71}$$

$$\geq p_k T_k N_2 \left(1 - O\left(\sqrt{\frac{\ln(1/\delta)}{p_k N_1}}\right) - \sqrt{\frac{2\ln(1/\delta)}{p_k T_k N_2 \left(1 - O\left(\frac{\ln(1/\delta)}{\sqrt{p_k N_1}}\right)\right)}}\right) \tag{72}$$

$$\geq p_k T_k N_2 \left(1 - O\left(\sqrt{\frac{\ln(1/\delta)}{p_k N_1}}\right) - \sqrt{\frac{2\ln(1/\delta)}{p_k T_k N_2} \cdot \left(1 + O\left(\frac{\ln(1/\delta)}{\sqrt{p_k N_1}}\right)\right)}\right) \tag{73}$$

$$\geq p_k T_k N_2 \left(1 - O\left(\sqrt{\frac{\ln(1/\delta)}{p_k N_1}}\right) - \sqrt{\frac{2\ln(1/\delta)}{p_k T_k N_2} + O\left(\frac{\ln(1/\delta)\ln(1/\gamma)}{N_2 p_k^2 \sqrt{N_1}}\right)}\right) \tag{74}$$

$$\geq p_k T_k N_2 \left(1 - O\left(\sqrt{\frac{1}{p_k N_1}}\right) - O\left(\sqrt{\frac{\ln(1/\gamma)}{N_2 p_k^{3/2}}}\right)\right) \qquad \square$$

We use the fact that $p_k > p_* = 1/N_1$.

Lemma 4.9 ($w_k^2 P(B_k^{(2)} = 0)$ Upper Bound). *If Lemma 4.7 holds for $p_k > p_*$ and if $N_2 = \omega(N_1^{3/4})$,*

$$p_k^x P(B_k^{(2)} = 0) \leq O\left(\frac{1}{N_1^{x/2}}\right) + O\left(\frac{\sqrt{N_1}}{N_2^2}\right). \tag{75}$$

Proof.

$$p_k^x P(B_k^{(2)} = 0) = p_k(1 - p_k)^{\lceil \hat{T}_k N_2 \rceil} \leq p_k(1 - p_k)^{\hat{T}_k N_2}. \tag{76}$$

If $p_k \leq p_* = \frac{2(\sqrt{\ln(1/\delta)}+1)}{N_1}$, ,

$$p_k^x (1 - p_k)^{\hat{T}_k N_2} \leq O\left(\frac{1}{N_1^{x/2}}\right). \tag{77}$$

Else if $p_k > p_*$, which satisfies the conditions of Lemma 4.7,

$$p_k^x (1 - p_k)^{\hat{T}_k N_2} \leq (1 - p_k)^{T_k N_2 \left(1 - O\left(\frac{1}{\sqrt{p_k N_1}}\right)\right)} \tag{78}$$

$$\leq (1 - p_k)^{N_2 \left(O(\sqrt{p_k}) - O\left(\frac{1}{\sqrt{N_1}}\right)\right)} \tag{79}$$

$$\leq (1 - p_k)^{O\left(\frac{N_2}{N_1^{1/4}}\right)}. \tag{80}$$

We assume that $N_2 = \omega(N_1^{3/4})$ which means that (80) is decreasing exponentially. Hence, we can say that $(1 - p_k)^{O\left(\frac{N_2}{N_1^{1/4}}\right)} = O\left(\frac{\sqrt{N_1}}{N_2^2}\right)$.

$$p_k^x P(B_k^{(2)} = 0) \leq O\left(\frac{1}{N_1^{x/2}}\right) + O\left(\frac{\sqrt{N_1}}{N_2^2}\right) \qquad \square$$

4.4 Final Result

Theorem 1. *For small $\delta > 0$ over Stage 1 (Lemma 4.1, Lemma 4.2, Lemma 4.3, Lemma 4.4, Lemma 4.5, Lemma 4.6, and Lemma 4.7) and if $N_2 = \omega(N_1^{3/4})$, the expectation of the mean squared error of* ABAE *over Stage 2 is*

$$\mathbb{E}[(\hat{\mu}_{all} - \mu_{all})^2] \leq O\left(N_1^{-1}\right) + O\left(N_2^{-1}\right) + O\left(N_1^{1/2} N_2^{-3/2}\right). \tag{81}$$

Proof. By Lemma 4.1, Lemma 4.2, Lemma 4.3, Lemma 4.4, Lemma 4.5, Lemma 4.6, and Lemma 4.7, we have that for small $\delta > 0$:

$$\sqrt{p_k}\sqrt{1 - O\left(\sqrt{\frac{\ln(1/\delta)}{p_k N_1}}\right)} \leq \sqrt{\hat{p}_k} \leq \sqrt{p_k}\sqrt{1 + O\left(\sqrt{\frac{\ln(1/\delta)}{p_k N_1}}\right)}. \tag{82}$$

$$w_k - O\left(\frac{\ln(1/\delta)\sqrt{p_k}}{\sqrt{N_1}}\right) \leq \hat{w}_k \leq w_k + O\left(\frac{\ln(1/\delta)\sqrt{p_k}}{\sqrt{N_1}}\right) \tag{83}$$

$$B_k^{(1)} \geq p_k N_1 - \sqrt{2\ln(1/\delta) p_k N_1}. \tag{84}$$

12

$$\sigma_k \cdot \sqrt{1 - O\left(\sqrt{\frac{\ln(1/\delta)}{p_k N_1}}\right)} \le \hat{\sigma}_k \le \sigma_k \cdot \sqrt{1 + O\left(\sqrt{\frac{\ln(1/\delta)}{p_k N_1}}\right)}. \tag{85}$$

$$\hat{T}_k \ge T_k \left(1 - O\left(\sqrt{\frac{\ln(1/\delta)}{p_k N_1}}\right)\right). \tag{86}$$

Let $\mathcal{E}$ be the event that all these inequalities are satisfied. For the remainder of the proof, we condition on $\mathcal{E}$ and take the expectation over the randomness in Stage 2. We now begin to decompose the mean squared error.

$$\mathbb{E}[(\hat{\mu}_{\text{all}} - \mu_{\text{all}})^2] = \mathbb{E}\left[(\sum_{k=1}^{K} \hat{w}_k \hat{\mu}_k - w_k \mu_k)^2\right]. \tag{87}$$

We know that $\mathbb{E}[\hat{\mu}_k] = P(B_k^{(2)} > 0) \cdot \mu_k$. As a result, $\mathbb{E}[\hat{\mu}_k] + \mu_k P(B_k^{(2)} = 0) = \mu_k$. Hence,

$$= \mathbb{E}\left[\left(\sum_{k=1}^{K} \hat{w}_k(\hat{\mu}_k - \mathbb{E}[\hat{\mu}_k]) + (\hat{w}_k - w_k)\mathbb{E}[\hat{\mu}_k] - w_k \mu_k P(B_k = 0)\right)^2\right] \tag{88}$$

We now use that $\mathbb{E}[(A+B)^2] = \mathbb{E}[A^2 + 2AB + B^2]$, so if $\mathbb{E}[A] = 0$ then $\mathbb{E}[(A+B)^2] = \mathbb{E}[A^2] + \mathbb{E}[B^2]$. We set $A = \hat{w}_k(\hat{\mu}_k - \mathbb{E}[\hat{\mu}_k])$ and $B = (\hat{w}_k - w_k)\mathbb{E}[\hat{\mu}_k] - w_k \mu_k P(B_k = 0)$. Note that $\mathbb{E}[A] = 0$. Thus,

$$= \mathbb{E}\left[(\sum_{k=1}^{K} \hat{w}_k(\hat{\mu}_k - \mathbb{E}[\hat{\mu}_k]))^2\right] + \mathbb{E}\left[(\sum_{k=1}^{K} (\hat{w}_k - w_k)\mathbb{E}[\hat{\mu}_k] - w_k \mu_k P(B_k = 0))^2\right] \tag{89}$$

$$\le \sum_{k=1}^{K} \hat{w}_k^2 \text{Var}(\hat{\mu}_k) + \left[\max_k C_k^{\mu_k^2}\right] \mathbb{E}\left[\left(\sum_{k=1}^{K} w_k P(B_k^{(2)} = 0) + (\hat{w}_k - w_k)\right)^2\right]. \tag{90}$$

We will now separately upper bound the two terms in this expression. For the first term, notice that

$$\text{Var}[\hat{\mu}_k] = \mathbb{E}[\hat{\mu}_k^2] - \mathbb{E}[\hat{\mu}_k]^2 \tag{91}$$

$$= P(B_k^{(2)} > 0)(\mathbb{E}[\frac{\sigma_k^2}{B_k^{(2)}}|B_k^{(2)} > 0] + \mu_k^2) - P(B_k^{(2)} > 0)^2 \mu_k^2 \tag{92}$$

$$= P(B_k^{(2)} > 0)\mathbb{E}[\frac{\sigma_k^2}{B_k^{(2)}}|B_k^{(2)} > 0] + P(B_k^{(2)} > 0)(1 - P(B_k^{(2)} > 0))\mu_k^2 \tag{93}$$

$$= P(B_k^{(2)} > 0)\mathbb{E}[\frac{\sigma_k^2}{B_k^{(2)}}|B_k^{(2)} > 0] + P(B_k^{(2)} > 0)P(B_k^{(2)} = 0)\mu_k^2 \tag{94}$$

$$\le \mathbb{E}[\frac{\sigma_k^2}{B_k^{(2)}}|B_k^{(2)} > 0] + P(B_k^{(2)} = 0)\mu_k^2 \tag{95}$$

$$\sum_{k=1}^{K} \hat{w}_k^2 \text{Var}[\hat{\mu}_k] \le \sum_{k=1}^{K} \hat{w}_k^2 \left(\mathbb{E}[\frac{\sigma_k^2}{B_k^{(2)}}|B_k^{(2)} > 0] + P(B_k^{(2)} = 0)\mu_k^2\right) \tag{96}$$

$$\le \sum_{k=1}^{K} \left(O\left(p_k^2\right) + O\left(\frac{p_k^{3/2}}{\sqrt{N_1}}\right)\right)\left(\mathbb{E}[\frac{\sigma_k^2}{B_k^{(2)}}|B_k^{(2)} > 0] + P(B_k^{(2)} = 0)\mu_k^2\right) \tag{97}$$

$$\le \sum_{k=1}^{K} \left(O\left(p_k^2\right) + O\left(\frac{p_k^{3/2}}{\sqrt{N_1}}\right)\right)\left(\mathbb{E}[\frac{\sigma_k^2}{B_k^{(2)}}|B_k^{(2)} > 0] + P(B_k^{(2)} = 0)\mu_k^2\right) \tag{98}$$

We split the cases where p_k is small and p_k is large via $p_* = \frac{2(\sqrt{\ln(1/\delta)}+1)}{N_1}$. This value of p_* is chosen as according to the conditions of Lemma 4.7.

$$\leq \sum_{p_k > p_*}^{K} \left(O\left(p_k^2\right) + O\left(\frac{p_k^{3/2}}{\sqrt{N_1}}\right) \right) \left(\mathbb{E}[\frac{\sigma_k^2}{B_k^{(2)}}|B_k^{(2)} > 0] + P(B_k^{(2)} = 0)\mu_k^2 \right) + \sum_{p_k \leq p_*}^{K} O\left(\frac{1}{N_1^2}\right) \tag{99}$$

Note that $p_k^2 P(B_k^{(2)} = 0) \leq O\left(\frac{1}{N_1}\right) + O\left(\frac{\sqrt{N_1}}{N_2^2}\right)$ according to Lemma 4.9.

$$\leq \sum_{p_k > p_*}^{K} \left(O\left(p_k^2\right) + O\left(\frac{p_k^{3/2}}{\sqrt{N_1}}\right) \right) \mathbb{E}[\frac{\sigma_k^2}{B_k^{(2)}}|B_k^{(2)} > 0] + O\left(\frac{1}{N_1}\right) + O\left(\frac{\sqrt{N_1}}{N_2^2}\right) \tag{100}$$

We will now apply Lemma 4.8 to upper bound $\mathbb{E}[\frac{\sigma_k^2}{B_k^{(2)}}|B_k^{(2)} > 0]$. Namely, we will split the expectation into two cases, one where $B_k^{(2)} \geq F_k$ and another where $B_k < F_k$. Specifically, we apply it such that $B_k^{(2)} \geq F_k = p_k T_k N_2 \left(1 - O\left(\sqrt{\frac{1}{p_k N_1}}\right) - O\left(\sqrt{\frac{\ln(1/\gamma)}{N_2 p_k^{3/2}}}\right) \right)$ with failure probability $\gamma = \frac{1}{e^{\sqrt{N_1}}} \leq O\left(\frac{1}{N_1}\right)$.

$$\leq \sum_{p_k > p_*}^{K} \left(O\left(p_k^2\right) + O\left(\frac{p_k^{3/2}}{\sqrt{N_1}}\right) \right) \left(\mathbb{E}[\frac{\sigma_k^2}{B_k^{(2)}}|B_k^{(2)} > 0] \right) + O\left(\frac{1}{N_1}\right) + O\left(\frac{\sqrt{N_1}}{N_2^2}\right) \tag{101}$$

$$\leq \sum_{p_k > p_*}^{K} \left(O\left(p_k^2\right) + O\left(\frac{p_k^{3/2}}{\sqrt{N_1}}\right) \right) \left(P(B_k^{(2)} > F_k)\mathbb{E}[\frac{\sigma_k^2}{B_k^{(2)}}|B_k^{(2)} > F_k] + O\left(\frac{1}{N_1}\right) C_k^{\sigma^2} \right) + O\left(\frac{1}{N_1}\right) + O\left(\frac{\sqrt{N_1}}{N_2^2}\right) \tag{102}$$

$$\leq \sum_{p_k > p_*}^{K} \left(O\left(p_k^2\right) + O\left(\frac{p_k^{3/2}}{\sqrt{N_1}}\right) \right) \left(\mathbb{E}[\frac{\sigma_k^2}{B_k^{(2)}}|B_k^{(2)} > F_k] + O\left(\frac{1}{N_1}\right) C_k^{\sigma^2} \right) + O\left(\frac{1}{N_1}\right) + O\left(\frac{\sqrt{N_1}}{N_2^2}\right) \tag{103}$$

$$\leq \sum_{p_k > p_*}^{K} \left(O\left(p_k^2\right) + O\left(\frac{p_k^{3/2}}{\sqrt{N_1}}\right) \right) \mathbb{E}[\frac{\sigma_k^2}{B_k^{(2)}}|B_k^{(2)} > F_k] + O\left(\frac{1}{N_1}\right) + O\left(\frac{\sqrt{N_1}}{N_2^2}\right) \tag{104}$$

$$\leq \sum_{p_k > p_*}^{K} \left(O\left(p_k^2\right) + O\left(\frac{p_k^{3/2}}{\sqrt{N_1}}\right) \right) \frac{\sigma_k^2}{p_k T_k N_2 \left(1 - O\left(\sqrt{\frac{1}{p_k N_1}}\right) - O\left(\sqrt{\frac{\ln(1/\gamma)}{N_2 p_k^{3/2}}}\right) \right)} + O\left(\frac{1}{N_1}\right) + O\left(\frac{\sqrt{N_1}}{N_2^2}\right) \tag{105}$$

$$\leq \sum_{p_k > p_*}^{K} \left(O\left(\frac{\sqrt{p_k}}{N_2}\right) + O\left(\frac{1}{N_2\sqrt{N_1}}\right) \right) \left(1 + O\left(\sqrt{\frac{1}{p_k N_1}}\right) + O\left(\sqrt{\frac{\ln(1/\gamma)}{N_2 p_k^{3/2}}}\right) \right) + O\left(\frac{1}{N_1}\right) + O\left(\frac{\sqrt{N_1}}{N_2^2}\right) \tag{106}$$

$$\leq \sum_{p_k > p_*}^{K} \left(O\left(\frac{\sqrt{p_k}}{N_2}\right) + O\left(\frac{1}{N_2\sqrt{N_1}}\right) \right) \left(1 + O\left(\sqrt{\frac{1}{p_k N_1}}\right) + O\left(\sqrt{\frac{\ln(1/\gamma)}{N_2 p_k^{3/2}}}\right) \right) + O\left(\frac{1}{N_1}\right) + O\left(\frac{\sqrt{N_1}}{N_2^2}\right) \tag{107}$$

$$\leq \sum_{p_k > p_*}^{K} O\left(\frac{1}{N_2} + \frac{1}{N_2\sqrt{N_1}} + \frac{\sqrt{N_1}}{N_2\sqrt{N_2}}\right) + O\left(\frac{1}{N_2\sqrt{N_1}}\right) \left(1 + O\left(\sqrt{\frac{1}{p_k N_1}}\right) + O\left(\sqrt{\frac{\ln(1/\gamma)}{N_2 p_k^{3/2}}}\right) \right) + O\left(\frac{1}{N_1}\right) + O\left(\frac{\sqrt{N_1}}{N_2^2}\right) \tag{108}$$

$$\leq \sum_{p_k > p_*}^{K} O\left(\frac{1}{N_2} + \frac{\sqrt{N_1}}{N_2\sqrt{N_2}}\right) + O\left(\frac{1}{N_2\sqrt{N_1}} + \frac{1}{N_2\sqrt{N_1}} + \frac{\sqrt{N_1}}{N_2\sqrt{N_2}}\right) + O\left(\frac{1}{N_1}\right) + O\left(\frac{\sqrt{N_1}}{N_2^2}\right) \tag{109}$$

$$\leq O\left(\frac{1}{N_1}\right) + O\left(\frac{1}{N_2}\right) + O\left(\frac{\sqrt{N_1}}{N_2\sqrt{N_2}}\right) \tag{110}$$

We will now upper bound the second term in the expression on (90).

$$\mathbb{E}\left[(\sum_{k=1}^{K}(\hat{w}_k - w_k)\mathbb{E}[\hat{\mu}_k] - w_k\mu_k P(B_k = 0))^2\right] \leq \left[\max_k C_k^{\mu_k^2}\right]\mathbb{E}\left[\left(\sum_{k=1}^{K} w_k P(B_k^{(2)} = 0) + (\hat{w}_k - w_k)\right)^2\right] \tag{111}$$

$$\leq \left[\max_k C_k^{\mu_k^2}\right]\mathbb{E}\left[\left(O\left(\frac{\sqrt{N_1}}{N_2}\right) + O\left(\frac{1}{\sqrt{N_1}}\right)\right)^2\right] \tag{112}$$

$$\leq O\left(\frac{1}{N_1}\right) + O\left(\frac{1}{N_2}\right) \tag{113}$$

Thus, by combining (110) and (113), we finally have that

$$\mathbb{E}[(\hat{\mu}_{\text{all}} - \mu_{\text{all}})^2|\mathcal{E}] = \mathbb{E}\left[(\sum_{k=1}^{K}\hat{w}_k\hat{\mu}_k - w_k\mu_k)^2\right] \tag{114}$$

$$= \sum_{k=1}^{K}\hat{w}_k^2\text{Var}(\hat{\mu}_k) + \left[\max_k C_k^{\mu_k^2}\right]\mathbb{E}\left[\left(\sum_{k=1}^{K} w_k P(B_k^{(2)} = 0) + (\hat{w}_k - w_k)\right)^2\right] \tag{115}$$

$$\leq \left[O\left(\frac{1}{N_1}\right) + O\left(\frac{1}{N_2}\right) + O\left(\frac{\sqrt{N_1}}{N_2\sqrt{N_2}}\right)\right] + \left[O\left(\frac{1}{N_1}\right) + O\left(\frac{1}{N_2}\right)\right] \tag{116}$$

$$\leq O\left(N_1^{-1}\right) + O\left(N_2^{-1}\right) + O\left(N_1^{1/2}N_2^{-3/2}\right) \qquad \square$$

4.5   Sample Reuse

Note that our algorithm shown in Algorithm 1 involves a parameter *SampleReuse*, which decides whether we reuse samples from Stage 1 in Stage 2 and vice-versa. In our analysis, we assumed that *SampleReuse* was false. However, we show that *SampleReuse* strictly reduces the error of ABAE.

Corollary 4.1. *If SampleReuse is true, ABAE still achieves the the following upper bound on the the mean squared error for small $\delta > 0$ over Stage 1 and expectation over Stage 2,*

$$\mathbb{E}[(\hat{\mu}_{all} - \mu_{all})^2] \leq O\left(N_1^{-1}\right) + O\left(N_2^{-1}\right) + O\left(N_1^{1/2}N_2^{-3/2}\right). \tag{117}$$

Proof. The high probability bounds we have on $\hat{p}_k$, $\hat{w}_k$, $B_k^{(1)}$, $\hat{\sigma}_k$, $\hat{T}_k$ still hold with sample reuse, so the rates presented in Theorem 1 still hold. Furthermore, note that the estimate $\hat{\mu}_k$ is actually a stochastic sum where the number of summands are dependent on Stage 1. As a result, the samples from Stage 1 and Stage 2 are actually identical and independently distributed, so we can reuse samples when estimating $\hat{\mu}_k$. Although not reflected in the bounds presented for $\hat{p}_k$, $\hat{w}_k$, and $\hat{\mu}_k$, the error is further reduced by better estimates produced by sample reuse in practice. $\square$

4.6   Edge Cases

We address the following edge cases in our algorithm and analysis.

1. If the variance in a stratum is estimated to be zero, this will result in $\hat{T}_k = 0$. In this scenario, we can simply use a simple sample from Stage 1 to represent the constant μ_k.

2. If the predicate positive rate or the variance in every stratum is estimated to be zero, this will result in $\hat{T}_k = 0$ for all k. In this scenario, we set $T_k = 1/K$ for each k.

3. ...

5 Appendix

Lemma 5.1 (Chung and Lu [2002]). *Let $X_1, ..., X_n$ be independent random variables with:*

$$P(X_i = 1) = p_i, \ P(X_i = 0) = 1 - p_i \tag{118}$$

For $X = \sum_{i=1}^{n} a_i X_i$, we have $\mathbb{E}[X] = \sum_{i=1}^{n} a_i p_i$ and we have define $\nu = \sum_{i=1}^{n} a_i^2 p_i$. Then we have:

$$P(x < \mathbb{E}[X] - \lambda) \leq e^{-\lambda^2/2\nu} \tag{119}$$

$$P(X > \mathbb{E}[X] + \lambda) \leq e^{-\frac{\lambda^2}{2(\nu + a\lambda/3)}} \tag{120}$$

where $a = max\{a_1, ..., a_n\}$

Lemma 5.2 (Tarjan [2009]). *Let $X_1, ..., X_n$ be independent random variables. They do not need to be from the same distribution. Assume that $0 \leq X_i \leq 1$ for each i. LEt $X = X_1 + ... + X_n$. Write $\mu = \mathbb{E}[X] = \mathbb{E}[X_1] + ... + \mathbb{E}[X_n]$. Then, for any $\epsilon \geq 0$,*

$$P(X \geq (1 + e)\mu) \leq exp\left(-\frac{-\epsilon^2}{2 + e}\mu\right) \tag{121}$$

$$P(X \leq (1 - e)\mu) \leq exp\left(-\frac{-\epsilon^2}{2}\mu\right) \tag{122}$$

Lemma 5.3 (Ferguson [2005]). *Let $X_1, ..., X_n$ be i.i.d. For a U-statistic of order 2 in the form $U_n = \frac{1}{\binom{n}{2}} \sum_{i<j} g(X_i, X_j)$, if $g(X_i, X_j) = \frac{1}{2}(X_i - X_j)^2$,*

$$\mathbb{E}[U_n] = Var[X] \tag{123}$$

Lemma 5.4 (Rinaldo [2018]). *Let $X_1, ..., X_n$ be i.i.d. For a U-statistic of order 2 in the form $U_n = \frac{1}{\binom{n}{2}} \sum_{i<j} g(X_i, X_j)$ with an upper bound $g(X_i, X_j) \leq b$,*

$$P(|U_n - \mathbb{E}[U_n]| \geq t) \leq 2\exp(-\frac{nt^2}{8b^2}) \tag{124}$$

References

Fan Chung and Linyuan Lu. Connected components in random graphs with given expected degree sequences. *Annals of combinatorics*, 6(2):125–145, 2002.

Thomas Ferguson. U-statistics notes for statistics 200c, spring 2005. `http://www.stat.cmu.edu/~arinaldo/Teaching/36710/F18/Scribed_Lectures/Sep24.pdf`, 2005. [Online; accessed 11-Feb-2021].

Alessandro Rinaldo. 36-710: Advanced statistical theory lecture 7: September 24. `http://www.stat.cmu.edu/~arinaldo/Teaching/36710/F18/Scribed_Lectures/Sep24.pdf`, 2018. [Online; accessed 11-Feb-2021].

Robert Tarjan. 15-359: Probability and computing lecture 10: More chernoff bounds, sampling, and the chernoff + union bound method. `http://aiweb.techfak.uni-bielefeld.de/content/bworld-robot-control-software/`, 2009. [Online; accessed 11-Feb-2021].