Differentially-Private Clustering of Easy Instances

Edith Cohen 1 2  Haim Kaplan 1 2  Yishay Mansour 1 2  Uri Stemmer 1 3  Eliad Tsfadia 1 2

Abstract

Clustering is a fundamental problem in data analysis. In differentially private clustering, the goal is to identify \( k \) cluster centers without disclosing information on individual data points. Despite significant research progress, the problem had so far resisted practical solutions. In this work we aim at providing simple implementable differentially private clustering algorithms that provide utility when the data is "easy," e.g., when there exists a significant separation between the clusters.

We propose a framework that allows us to apply non-private clustering algorithms to the easy instances and privately combine the results. We are able to get improved sample complexity bounds in some cases of Gaussian mixtures and \( k \)-means. We complement our theoretical analysis with an empirical evaluation on synthetic data.

1. Introduction

Differential privacy (Dwork et al., 2006b) is a mathematical definition of privacy, that aims to enable statistical analyses of databases while providing strong guarantees that individual-level information does not leak. Privacy is achieved in differentially private algorithms through randomization and the introduction of "noise" to obscure the effect of each individual, and thus differentially private algorithms can be less accurate than their non-private analogues. In most cases, this loss in accuracy is studied theoretically, using asymptotic tools. As a result, there is currently a significant gap between what is known to be possible theoretically and what can be done in practice with differential privacy. In this work we take an important step towards bridging this gap in the context of clustering related tasks.

The construction of differentially private clustering algorithms has attracted a lot of attention over the last decade, and many different algorithms have been suggested. However, to the best of our knowledge, none of these algorithms have been implemented: They are not particularly simple and suffer from large hidden constants that translate to a significant loss in utility, compared to non-private implementations.

Question 1.1. How hard is it to cluster privately with a practical implementation?

We take an important step in this direction using the following approach. Instead of directly tackling “standard” clustering tasks, such as \( k \)-means clustering, we begin by identifying a very simple clustering problem that still seems to capture many of the challenges of practical implementations (we remark that this problem is completely trivial without privacy requirements). We then design effective (private) algorithms for this simple problem. Finally, we reduce “standard” clustering tasks to this simple problem, thereby obtaining private algorithms for other tasks.

In more detail, we introduce the following problem, called the \( k \)-tuple clustering problem.

Definition 1.2 (informal, revised in Definition 3.6). An instance of the \( k \)-tuple clustering problem is a collection of \( k \)-tuples. Assuming that the input tuples can be partitioned into \( k \) “obvious clusters”, each consisting of one point of each tuple, then the goal is to report \( k \) “cluster-centers” that correctly partition the input tuples into clusters. If this assumption on the input structure does not hold, then the outcome is not restricted.

Remark 1.3.

1. By “obvious clusters” we mean clusters which are far away from each other.
2. The input tuples are unordered. This means, e.g., that the “correct” clustering might place the first point of one tuple with the fifth point of another tuple.
3. Of course, we want to solve this problem while guaranteeing differential privacy. Intuitively, this means...
that the outcome of our algorithm should not be significantly effected when arbitrarily modifying one of the input tuples.

Observe that without the privacy requirement this task is trivial: We can just take one arbitrary input tuple \((x_1, ..., x_k)\) and report it. With the privacy requirement, this task turns out to be non-trivial. It’s not that this problem cannot be solved with differential privacy. It can. It’s not even that the problem requires large amounts of data asymptotically. It does not. However, it turns out that designing an implementation with a practical privacy-utility tradeoff, that is effective on finite datasets (of reasonable size), is quite challenging.

1.1. Our algorithms for the \(k\)-tuple problem

We present two (differentially private) algorithms for the \(k\)-tuple clustering problem, which we call PrivatekAverages and PrivatekNoisyCenters. Both algorithms first privately test if indeed the input is partitioned into \(k\) obvious clusters and quit otherwise. They differ by the way they compute the centers in case this test passes. Algorithm PrivatekAverages privately averages each identified cluster. Algorithm PrivatekNoisyCenters, on the other hand, does not operate by averaging clusters. Instead, it selects one of the input \(k\)-tuples, and then adds a (relatively small) Gaussian noise to every point in this tuple. We prove that this is private if indeed there are \(k\) obvious clusters in the input. We evaluate these two algorithms empirically, and show that, while algorithm PrivatekAverages is “better in theory”, algorithm PrivatekNoisyCenters is much more practical for some interesting regimes of parameters.

We now give a simplified overview of the ideas behind our algorithms. For concreteness, we focus here on PrivatekAverages. Recall that in the \(k\)-tuple clustering problem, we are only required to produce a good output assuming the data is “nice” in the sense that the input tuples can be clustered into \(k\) “far clusters” such that every cluster contains exactly one point from every tuple. However, with differential privacy we are “forced” to produce good outputs even when this niceness assumption does not hold. This happens because if the input data is “almost nice” (in the sense that modifying a small number of tuples makes it nice) then differential privacy states that the outcome of the computation should be close to what it is when the input data is nice.

So, the definition of differential privacy forces us to cope with “almost nice” datasets. Therefore, the niceness test that we start with has to be a bit clever and “soft” and succeed with some probability also for data which is “almost nice”. Then, in order to achieve good performances, we have to utilize the assumption that the data is “almost nice” when we compute the private centers. To compute these centers, Algorithm PrivatekAverages determines (non-privately) a clustering of the input tuples, and then averages (with noise) each of the clusters. The conceptual challenge here is to show that even though the clustering of the data is done non-privately, it is stable enough such that the outcome of this algorithm still preserves privacy.

1.2. Applications

The significance of algorithms PrivatekAverages and PrivatekNoisyCenters is that many clustering related tasks can be privately solved by a reduction to the \(k\)-tuple clustering problem. In this work we explore two important use-cases: (1) Privately approximating the \(k\)-means under stability assumption, and (2) Privately learning the parameters of a mixture of well-separated Gaussians.

\(k\)-Means Clustering

In \(k\)-means clustering, we are given a database \(P\) of \(n\) input points in \(\mathbb{R}^d\), and the goal is to identify a set \(C\) of \(k\) centers in \(\mathbb{R}^d\) that minimizes the sum of squared distances from each input point to its nearest center. This problem is NP-hard to solve exactly, and even NP-hard to approximate to within a multiplicative factor smaller than 1.0013 (Lee et al., 2017). The current (non-private) state-of-the-art algorithm achieves a multiplicative error of 6.357 (Ahmadian et al., 2019).

One avenue that has been very fruitful in obtaining more accurate algorithms (non-privately) is to look beyond worst-case analysis (Ostrovsky et al., 2012; Awasthi et al., 2010; 2012; Balcan et al., 2009; Bilu & Linial, 2012; Kumar & Kannan, 2010). In more details, instead of constructing algorithms which are guaranteed to produce an approximate clustering for any instance, works in this vain give stronger accuracy guarantees by focusing only on instances that adhere to certain “nice” properties (sometimes called stability assumptions or separation conditions). The above mentioned works showed that such “nice” inputs can be clustered much better than what is possible in the worst-case (i.e., without assumptions on the data).

Given the success of non-private stability-based clustering, it is not surprising that such stability assumptions were also utilized in the privacy literature, specifically by Nissim et al. (2007); Wang et al. (2015); Huang & Liu (2018); Shechner et al. (2020). While several interesting concepts arise from these four works, none of their algorithms have been implemented, their algorithms are relatively complex, and their practicability on finite datasets is not clear.

We show that the problem of stability-based clustering (with privacy) can be reduced to the \(k\)-tuple clustering problem. Instantiating this reduction with our algorithms for the \(k\)-tuple clustering problem, we obtain a simple and practical
algorithm for clustering “nice” $k$-means instances privately.

**Learning Mixtures of Gaussians.** Consider the task of privately learning the parameters of an unknown mixtures of Gaussians given i.i.d. samples from it. By now, there are various private algorithms that learn the parameters of a single Gaussian (Karwa & Vadhan, 2018; Kamath et al., 2019a; Cai et al., 2019; Bun & Steinke, 2019; Kamath et al., 2020; Biswas et al., 2020). Recently, (Kamath et al., 2019b) presented a private algorithm for learning mixtures of well-separated (and bounded) Gaussians. We remark, however, that besides the result of (Biswas et al., 2020), which is a practical algorithm for learning a single Gaussian, all the other results are primarily theoretical.

By a reduction to the $k$-tuples clustering problem, we present a simple algorithm that privately learns the parameters of a separated (and bounded) mixture of $k$ Gaussians. From a practical perspective, compared with the construction of (Kamath et al., 2019b), our algorithm is simple and implementable. From a theoretical perspective, our algorithm offers reduced sample complexity, weaker separation assumption, and modularity.

Our results for stability-based clustering and for learning mixtures of Gaussians, as well as an extended discussion on related works, are given in the supplementary material.

## 2. Preliminaries

### 2.1. Notation

In this work, a $k$-tuple $X = \{x_1, \ldots, x_k\}$ is an unordered set of $k$ vectors $x_i \in \mathbb{R}^d$. For $x \in \mathbb{R}^d$, we denote by $||x||$ the $\ell_2$ norm of $x$. For $c \in \mathbb{R}^d$ and $r > 0$, we denote $B(c, r) := \{x \in \mathbb{R}^d : ||x - c|| \leq r\}$. For a multiset $P \in (\mathbb{R}^d)^*$ we denote by $\text{Avg}(P) := \frac{1}{|P|} \sum_{x \in P} x$ the average of all points in $P$. Throughout this work, a database $D$ is a multiset. For two multisets $D = \{x_1, \ldots, x_n\}$ and $D' = \{x'_1, \ldots, x'_m\}$, we let $D \cup D'$ be the multiset $\{x_1, \ldots, x_n, x'_1, \ldots, x'_m\}$. For a multiset $D = \{x_1, \ldots, x_n\}$ and a set $S$, we let $M \cap S$ be the multiset $\{x_i\}_{i \in S}$ where $S = \{i \in [n] : x_i \in S\}$. All algorithms considered here are natural logarithms (i.e., in base $e$).

### 2.2. Indistinguishability and Differential Privacy

**Definition 2.1** (Neighboring databases). Let $D = \{x_1, \ldots, x_n\}$ and $D' = \{x'_1, \ldots, x'_n\}$ be two databases over a domain $X$. We say that $D$ and $D'$ are **neighboring** if there is exactly one index $i \in [n]$ with $x_i \neq x'_i$.

**Definition 2.2** ($(\varepsilon, \delta)$-indistinguishable). Two random variable $X, X'$ over a domain $X$ are called $(\varepsilon, \delta)$-indistinguishable, iff for any event $T \subseteq X$, it holds that $\Pr[X \in T] \leq e^\varepsilon \cdot \Pr[X' \in T] + \delta$. If $\delta = 0$, we say that $X$ and $X'$ are $\varepsilon$-indistinguishable.

**Definition 2.3** ($(\varepsilon, \delta)$-differential privacy (Dwork et al., 2006b)). An algorithm $A$ is called $(\varepsilon, \delta)$-differentially private, if for any two neighboring databases $D, D'$ it holds that $\mathcal{A}(D)$ and $\mathcal{A}(D')$ are $(\varepsilon, \delta)$-indistinguishable. If $\delta = 0$ (i.e., pure privacy), we say that $A$ is $\varepsilon$-differentially private.

**Lemma 2.4** ((Bun & Steinke, 2016)). Two random variable $X, X'$ over a domain $X$ are $(\varepsilon, \delta)$-indistinguishable, iff there exist events $E, E' \subseteq X$ with $\Pr[X \in E], \Pr[X' \in E'] \geq 1 - \delta$ such that $X|_E$ and $X'|_{E'}$ are $\varepsilon$-indistinguishable.

### 2.2.1. The Laplace Mechanism

**Definition 2.5** (Sensitivity). We say that a function $f : U^n \rightarrow \mathbb{R}$ has sensitivity $\lambda$, if for all neighboring databases $S, S'$ it holds that $|f(S) - f(S')| \leq \lambda$.

**Theorem 2.6** (The Laplace Mechanism (Dwork et al., 2006b)). Let $\varepsilon > 0$, and assume $f : U^n \rightarrow \mathbb{R}$ has sensitivity $\lambda$. Then the mechanism that on input $S \subseteq U^n$ outputs $f(S) + \text{Lap}(\lambda/\varepsilon)$ is $\varepsilon$-differentially private.

### 2.2.2. The Gaussian Mechanism

**Definition 2.7** ($\ell_2$-sensitivity). We say that a function $f : U^n \rightarrow \mathbb{R}^d$ has $\ell_2$-sensitivity $\lambda$ if for all neighboring databases $S, S'$ it holds that $|f(S) - f(S')| \leq \lambda$.

**Theorem 2.8** (The Gaussian Mechanism (Dwork et al., 2006a)). Let $\varepsilon, \delta \in (0, 1)$, and assume $f : U^n \rightarrow \mathbb{R}^d$ has $\ell_2$-sensitivity $\lambda$. Let $\sigma \geq \frac{\lambda}{\varepsilon} \sqrt{2 \log(1.25/\delta)}$. Then the mechanism that on input $S \subseteq U^n$ outputs $f(S) + (N(0, \sigma^2))^d$ is $(\varepsilon, \delta)$-differentially private.

### 2.2.3. Estimating the Average of Points

The Gaussian mechanism (Theorem 2.8) allows for privately estimating the average of points in $B(0, \Lambda) \subseteq \mathbb{R}^d$ within $\ell_2$ error of $\approx \frac{\Lambda \sqrt{d}}{\varepsilon n}$. In some cases, we could relax the dependency on $\Lambda$. For example, using the following proposition.

**Proposition 2.9** (Estimating the Average of Bounded Points in $\mathbb{R}^d$). Let $\varepsilon \in (0, 1)$, $d, \Lambda > 0$ and let $r_{\min} \in [0, \Lambda]$. There exists an efficient $(\varepsilon, \delta)$-differentially private algorithm that takes an $n$-size database $S$ of points inside the ball $B(0, \Lambda)$ in $\mathbb{R}^d$ and satisfy the following utility guarantee: Let $r > 0$ be the minimal radius of a $d$-dimensional ball that contains all points in $S$. Then with probability $1 - \beta$, the algorithm outputs $\hat{\mu} \in \mathbb{R}^d$ such that

$$||\hat{\mu} - \text{Avg}(S)|| \leq \tilde{O} \left( \max \{r, r_{\min}\} \frac{d \log(\frac{\varepsilon}{\delta}) \log \left( \frac{\Lambda}{r_{\min}} \right)}{\varepsilon n} \right),$$

where the $\tilde{O}$ hides a $\sqrt{\log(d/\beta)}$ factor. The algorithm runs in time $\tilde{O}(dn)$ (ignoring logarithmic factors).

Proposition 2.9 can be seen as a simplified variant of (Nissim...
et al., 2016)’s private average algorithm. The main difference is that (Nissim et al., 2016) first uses the Johnson Lindenstrauss (JL) transform (Johnson & Lindenstrauss, 1984) to randomly embed the input points in \( \mathbb{R}^d \) for \( d \approx \log n \), and then estimates the average of the points in each axis of \( \mathbb{R}^d \). As a result, they manage to save a factor of \( \sqrt{d} \) upon Proposition 2.9 (at the cost of paying a factor of \( \log(n) \) instead). However, for simplifying the construction and the implementation, we chose to omit the JL transform step, and we directly estimate the average along each axis of \( \mathbb{R}^d \). For completeness, we present the full details of Proposition 2.9 in the supplementary material.

2.2.4. Sub-Sampling

**Lemma 2.10** ((Beimel et al., 2010; Kasiviswanathan et al., 2011)). Let \( A \) be an \((\varepsilon', \delta')\)-differentially private algorithm operating on databases of size \( m \). Fix \( \varepsilon \leq 1 \), and denote \( n = \frac{m}{\varepsilon} (3 + \exp(\varepsilon')) \). Construct an algorithm \( B \) that on an input database \( D = \{z_i\}_{i=1}^{n} \), uniformly at random selects a subset \( T \subseteq \{1\ldots n\} \) of size \( m \), and executes \( A \) on the multiset \( D_T = \{z_i\}_{i \in T} \). Then \( B \) is \((\varepsilon, \delta)\)-differentially private, where \( \delta = \frac{n}{4m} \cdot \delta' \).

### 3. k-Tuples Clustering

We first introduce a new property of a collection of (unordered) \( k \)-tuples \( \{x_1, \ldots, x_k\} \in (\mathbb{R}^d)^k \), which we call partitioned by \( \Delta \)-far balls.

**Definition 3.1** (\( \Delta \)-far balls). A set of \( k \) balls \( B = \{B_i = B(c_i, r_i)\}_{i=1}^{k} \) over \( \mathbb{R}^d \) is called \( \Delta \)-far balls, if for every \( i \in [k] \) it holds that \( \|c_i - c_j\| \geq \Delta \cdot \max\{r_i, r_j\} \) (i.e., the balls are relatively far from each other).

**Definition 3.2** (partitioned by \( \Delta \)-far balls). A tuple \( X \in (\mathbb{R}^d)^k \) is partitioned by a given set of \( k \)-\( \Delta \)-far balls \( B = \{B_1, \ldots, B_k\} \), if for every \( i \in [k] \) it holds that \( |X \cap B_i| = 1 \). A multiset of \( k \)-tuples \( T \in ((\mathbb{R}^d)^k)^* \) is partitioned by \( B \), if all \( X \in T \) are partitioned by \( B \). We say that \( T \) is partitioned by \( \Delta \)-far balls if such a set \( B \) of \( k \)-\( \Delta \)-far balls exists.

In some cases we want to use a notion of almost partitioned property of a database of \( k \)-tuples \( T \). This is defined below using the additional parameter \( \ell \).

**Definition 3.3** (\( \ell \)-nearly partitioned by \( \Delta \)-far balls). A multiset \( T \in ((\mathbb{R}^d)^k)^* \) is \( \ell \)-nearly partitioned by a given set of \( \Delta \)-far balls \( B = \{B_1, \ldots, B_k\} \), if there are at most \( \ell \) tuples in \( T \) that are not partitioned by \( B \). We say that \( T \) is \( \ell \)-nearly partitioned by \( \Delta \)-far balls if such a set of \( \Delta \)-far balls \( B = \{B_1, \ldots, B_k\} \) exists.

For a database of \( k \)-tuples \( T \in ((\mathbb{R}^d)^k)^* \), we let \( \text{Points}(T) \) be the collection of all the points in all the \( k \)-tuples in \( T \).

**Definition 3.4** (The points in a collection of \( k \)-tuples). For \( T = \{(x_{i,j})_{i=1}^{k}, \ldots, (x_{n,j})_{j=1}^{k}\} \in ((\mathbb{R}^d)^k)^n \), we define \( \text{Points}(T) = \{x_{i,j}|i \in [n], j \in [k] \in (\mathbb{R}^d)^kn \} \).

We next define \( \text{Partition}(T) \) of a database \( T \in ((\mathbb{R}^d)^k)^* \) which is partitioned by \( \Delta \)-far balls for \( \Delta > 2 \).

**Definition 3.5** (\( \text{Partition}(T) \)). Given a multiset \( T \in ((\mathbb{R}^d)^k)^* \) which is partitioned by \( \Delta \)-far balls for \( \Delta > 2 \), we define the \( \text{Partition of} \ T \), which we denote by \( \text{Partition}(T) = \{P_1, \ldots, P_k\} \), by fixing an (arbitrary) \( k \)-tuple \( X = \{x_1, \ldots, x_k\} \in T \) and setting \( P_i = \{x \in \text{Points}(T) | i = \arg \min_{j \in [k]} \|x - x_j\|\} \).

In the supplementary material we prove that \( \text{Partition}(T) \) is uniquely defined.

We now define the \( k \)-tuple clustering problem.

**Definition 3.6** (\( k \)-tuple clustering). The input to the problem is a database \( T \in ((\mathbb{R}^d)^k)^* \) and a parameter \( \Delta > 2 \). The goal is to output a \( k \)-tuple \( Y = \{y_1, \ldots, y_k\} \in (\mathbb{R}^d)^k \) such that the following holds: If \( T \) is partitioned by \( \Delta \)-far balls, then for every \( i \in [k] \), there exists a cluster in \( \text{Partition}(T) \) (call it \( P_i \)) such that \( P_i = \{x \in \text{Points}(T) | i = \arg \min_{j \in [k]} \|x - x_j\|\} \).

Namely, in the \( k \)-tuple clustering problem, the goal is to output a \( k \)-tuple \( Y \) that partitions \( T \) correctly. We remark that for applications, we are also interested in the quality of the solution. Namely, how small is the distance between \( y_i \) and \( P_i \), compared to the other clusters in \( \text{Partition}(T) \). We also remark that without privacy, the problem is trivial, since any \( k \)-tuple \( X \in T \) is a good solution by definition.

4. Our Algorithms

In this section we present two \((\varepsilon, \delta)\)-differentially private algorithms for the \( k \)-tuple clustering problem: PrivateAverages and PrivatekNoisyCenters. Algorithm PrivateAverages attempts to solve the problem by determining the clusters in \( \text{Partition}(T) \) and then privately estimating the average of each cluster using the algorithm from Proposition 2.9. Algorithm PrivatekNoisyCenters, on the other hand, does not operate by averaging clusters. Instead, it first selects one of the input tuples \( X \in T \) (in a special way), and then adds a (relatively small) Gaussian noise to this tuple.\(^2\)

Both algorithms share the same first step, which is to call Algorithm PrivateTestPartition (Figure 2), that privately decides whether \( T \) is \( \ell \)-nearly partitioned by \( \Delta \)-far balls or not (for small \( \ell \)). If so, the algorithm determines (non-\(^2\)We remind that all the tuples in this work are unordered, and indeed the privacy analysis of our algorithms relies on it (i.e., the domain of outputs that we consider is all the unordered \( k \)-tuples, and \((\varepsilon, \delta)\)-indistinguishability holds for each subset of this domain).
All of the missing proofs are given in the supplementary material.

4.1. Algorithm PrivateTestPartition

Algorithm PrivateTestPartition is described in Figure 2. Its main component is Algorithm PrivateTestCloseTuples (Figure 1), which inputs two multisets of \( k \)-tuples \( T_1 \) and \( T_2 \) and privately checks whether the tuples in \( T_1 \) are close to the tuples in \( T_2 \). In the supplementary material, we prove that the value of \( \text{Status} \) in PrivateTestCloseTuples preserves \( \varepsilon_1 \)-DP w.r.t. \( T_1 \), and preserves \( \varepsilon_2 \)-DP w.r.t. \( T_2 \).

Figure 1: Algorithm PrivateTestCloseTuples for privately checking if \( \Delta \)-far balls around each \( k \)-tuples in \( T_1 \) partitions the tuples in \( T_2 \).

In the following, we specify our choices of \( m \) and \( \varepsilon_1 \) (functions of \( n, \varepsilon, \delta, \beta \)) that are used by PrivateTestPartition.

**Definition 4.1.** Let \( m = m(n, \varepsilon, \delta, \beta) \) be the smallest integer that satisfies \( m > \frac{1}{\varepsilon_1} \cdot \left( 2 \log(1/\delta) + \log(1/\beta) \right) \), where \( \varepsilon_1 = \log \left( \frac{m}{2m - 3} \right) \).

The dependence between \( m \) and \( \varepsilon_1 \) for Algorithm PrivateTestPartition is due to the choice of \( T_1 \) as an \( m \)-size random sample of \( T \). A smaller \( m \) allows for a larger value of \( \varepsilon_1 \) for the same overall privacy, by a sub-sampling argument (e.g., Lemma 2.10). We note that for \( n \gg 1/\varepsilon \) and \( \beta, \delta \geq \frac{1}{\text{poly}(n)} \), we have \( \varepsilon_1 = \Theta(\log n) \), which yields that \( m = O(1) \). For smaller values of \( \delta \), we obtain that \( m = O \left( \frac{\log(1/\delta)}{\log n} \right) \).

Algorithm PrivateTestPartition

**Input:** A multiset \( T \in ((\mathbb{R}^d)^k)^n \), privacy parameters \( \varepsilon, \delta \in (0, 1] \), confidence parameter \( \beta \in (0, 1] \), and separation parameter \( \Delta > 6 \).

1. Let \( m \) and \( \varepsilon_1 \) be the values from Definition 4.1 w.r.t. \( n, \varepsilon, \delta, \beta \), and let \( \varepsilon_2 = \varepsilon/2 \).
2. Let \( T_1 \) be a uniform sample of \( m \) \( k \)-tuples from \( T \) (without replacement), and let \( T_2 = T \).
3. Output \((\text{Status}, B)\) = PrivateTestCloseTuples\((T_1, T_2, \varepsilon_1, \varepsilon_2, \beta, \Delta)\).
PrivateTestPartition(\(T, \varepsilon, \delta, \beta\)), and let \((\text{Status}, B)\) be the outcome of the execution. Let \(S\) be the event that \(\text{Status} = \text{"Success"}\), and let \(E \subseteq S\) be the event that \(T\) is \(\ell\)-nearly partitioned by \(B\), where \(\ell = \ell(n, \varepsilon, \delta, \beta)\) is the value from Definition 4.4. Then the following holds: If \(\Pr[S] \geq \delta\), then \(\Pr[E \mid S] \geq 1 - \delta\).

Recall that Algorithm PrivateTestPartition has two outputs: \(A\) and \(B\). From Claim 4.3, the bit \(\text{Status}\) preserves privacy. The set of balls \(B\), however, does not. Still, in the following sections we use Algorithm PrivateTestPartition as a subroutine in our two main algorithms PrivateAverages and PrivateNoisyCenters. To argue about the privacy properties of these algorithms, we rely on the following key property of algorithm PrivateTestPartition.

**Claim 4.6.** Let \(A^*\) be an algorithm that gets as input a multiset \(T \in (\mathbb{R}^d)^n\) and a set of balls \(B = \{B_1, \ldots, B_k\}\), and let \(\ell = \ell(n, \varepsilon/2, \delta/4, \beta/2)\) be the value from Definition 4.4. Assume that \(A^*\) has the property that for any neighboring multisets \(T, T'\) and any sets of \(\Delta\)-far balls \(B, B'\) that \(\ell\)-nearly partitions \(T\) and \(T'\) (respectively), it holds that \(A^*(T, B)\) and \(A^*(T', B')\) are \((\varepsilon^*, \delta^*)\)-indistinguishable. Let \(A\) be the algorithm that on input \(T\), does the following steps: (1) Compute \((\text{Status}, B) = \text{PrivateTestPartition}(T, \varepsilon/2, \delta/4, \beta/2, \Delta)\), and (2) If \(\text{Status} = \text{"Failure"}\), output \(\perp\) and abort. Then \(A\) is \((\varepsilon^* + \varepsilon, \delta^* + \delta)\)-differentially private.

**Proof Sketch.** Consider two executions over two neighboring databases. If the probability of success is smaller than \(\delta\) in the two executions, then the outputs are \((0, \delta)\)-indistinguishable by Lemma 2.4. Otherwise, Claim 4.5 tells us that when the tests succeed, then w.h.p. the sets of \(\Delta\)-far balls \(\ell\)-nearly partitions the databases in both executions. Hence, the proof holds by the assumption on \(A^*\). \(\square\)

**Remark 4.7.** Note that PrivateTestPartition runs in time \(O(md\log n) = \tilde{O}(dk^2 n)\) since for each iteration \(T \in T_i\) in PrivateTestCloseTuples, Step 1a takes \(O(dk^2)\) time, and Step 1b takes \(O(dk^2 n)\) times.

### 4.2. Algorithm PrivateAverages

In this section we describe and state the properties of Algorithm PrivateAverages (Figure 3). The properties are given in the following theorems.

**Theorem 4.8** (Utility of PrivateAverages). Let \(d, k, \Lambda > 0\), \(r_{\min} \in [0, \Lambda]\), \(\varepsilon, \delta, \beta \in (0, 1]\), and let \(T \in (\mathbb{B}(0, \Lambda)^k)^n \subseteq ((\mathbb{R}^d)^k)^n\). Assume that \(T\) is partitioned by \(\Delta\)-far balls for \(\Delta = 16\), let \(\{P_1, \ldots, P_k\} = \text{Partition}(T)\) (according to Definition 3.5), let \(r_i\) be the radius of the ball that contains \(P_i\). Then w.p. \(1 - \beta\), algorithm PrivateAverages on inputs \(T, r_{\min}, \varepsilon, \delta, k\), outputs \(k\)

\[
\hat{a}_i - a_i \leq \tilde{O}\left(\frac{dk \log(\frac{\epsilon}{\delta}) \log\left(\frac{\Lambda}{r_{\min}}\right)}{\varepsilon n}\right),
\]

where \(a_i = \text{Avg}(P_i)\) and \(\ell = \ell(n, \varepsilon/2, \delta/4, \beta/2) + 2\) (where \(\ell\) is the function from Definition 4.4), algorithm PrivateAverages\((\cdot, \varepsilon, \delta, \beta, r_{\min}\) is \((\varepsilon, \delta)\)-differentially private for databases \(T \in (\mathbb{B}(0, \Lambda)^k)^n \subseteq ((\mathbb{R}^d)^k)^n\).

**Proof Sketch.** Consider two independent executions over neighboring databases \(T\) and \(T'\), and let \(B\) and \(B'\) be the balls from Step 1, respectively. By Claim 4.6, if we treat Step 3 to 6 as algorithm \(A^*\) of the claim, then it is enough to prove indistinguishability only in the case that \(T\) and \(T'\) are \(\ell\)-nearly partitioned by \(B\) and \(B'\), respectively. In this case, since \(T\) and \(T'\) are neighboring and \(n \geq 2l + 2\), there exists at least one \(k\)-tuples that is partitioned by both \(B\) and \(B'\),

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**Figure 3:** Algorithm PrivateAverages for privately estimating the \(k\) averages.
yielding that each ball \( B_i \) in \( B \) intersects a single ball in \( B' \)
call it \( B'_i \) w.l.o.g.). Since \( B \) and \( B' \) are sets of \( \Delta \)-far balls for
large enough \( \Delta \) (\( \Delta = 7 \), as defined in the algorithm,
is sufficient), then each area \( B_i \cup B'_i \) is “far away” from
each \( B_j \cup B'_j \) for \( j \neq i \). This yields that the partition into
\( \{ Q_1, \ldots, Q_k \} \) in Step 3 of both executions, agree on all the
points that belong to \( B_i \cup B'_i \) for some \( i \). Therefore, this
partition disagree on at most \( k(\ell + 1) \) points, which are the
points of the (at most) \( \ell + 1 \) tuples that are not partitioned by
\( B \) or \( B' \). Hence, the privacy now holds by Proposition 2.9
with group privacy of size \( k(\ell + 1) \).

**Remark 4.10 (Run time of PrivatekAverages).** Step 1 of
PrivatekAverages takes \( O(dk^2 n) \) time (see Remark 4.7).
By Proposition 2.9, the \( k \) executions of Step 5 take time
\( \sum_{i=1}^{k} O(|T_i|) = O(dkn) \). Overall, the running time of
PrivatekAverages is \( O(dk^2 n) \).

### 4.2.1. Reducing the dependency in \( d \)

Algorithm PrivatekAverages estimates the average of each
cluster \( T_i \) with radius \( r_i \) up to an additive error of \( \tilde{O}(d/k, r_i) \)
(ignoring \( \text{poly}(\ell, 1/\varepsilon) \) and \( \text{polylog}(n, \delta, \beta, \Delta, 1/r_{\text{min}}) \)
factors). Yet, we can easily reduce the \( d \) into \( \sqrt{d} \) by replacing
in Step 5 the average algorithm of Proposition 2.9 by the
average algorithm of (Nissim et al., 2016) (see Section 2.2.3).

### 4.3. Algorithm PrivatekNoisyCenters

In this section we describe and state the properties of Algo-
rithm PrivatekNoisyCenters (Figure 4).

The properties of PrivatekNoisyCenters are given in the
following theorems.

**Theorem 4.11 (Utility of PrivatekNoisyCenters).** Let
\( d, k > 0, \varepsilon, \beta, \delta \in (0, 1) \) with \( \delta < \beta \), let \( T \in (\mathbb{R}^d)^n \),
and assume that \( T \) is partitioned by \((2\Delta + 2)\)-far balls,
for \( \Delta = \sqrt{\frac{4\log(k/\delta)}{\varepsilon}} \cdot \frac{\log(k/\beta)}{\varepsilon} \).
Then when executing PrivatekNoisyCenters\( (T, \varepsilon, \delta, \beta, \Delta) \), with probability
1 - \( \beta \), the output \( \hat{C} = \{ \hat{c}_1, \ldots, \hat{c}_k \} \) satisfy for every \( i \) and
\( j \neq i \) that \( \| \hat{c}_i - c_i \| < \| \hat{c}_i - c_j \| \).

We remark that the \( k \) factor in the \( \Delta \) in Theorem 4.11, comes
from applying basic composition over the \( k \) noisy centers \( \hat{C} \).
This however can be reduced to \( \tilde{O}(\sqrt{k}) \) factor by applying
advanced composition (Dwork et al., 2010).

**Theorem 4.12 (Privacy of PrivatekNoisyCenters).** Let
\( d, k > 0, \varepsilon, \beta \in (0, 1], \delta \in (0, 1/2], \Delta > 6 \).
Then for any integer \( n \geq 2 \cdot \ell(n, \varepsilon/2, \delta/4, \beta/2) + 2 \)
(\( \ell \) is the function from Definition 4.4),
PrivatekNoisyCenters\( (\varepsilon, \beta, \delta, \Delta) \) is \((\varepsilon + \delta/4, \delta)\)-
differentially private for databases \( T \in (\mathbb{R}^d)^n \).

**Proof sketch.** Consider two independent executions over
neighboring databases \( T \) and \( T' \), and let \( B \) and \( B' \) be the
balls from Step 1, respectively. Similarly to the proof sketch
of Theorem 4.9 (privacy of PrivatekAverages), it is enough
to prove indistinguishability only in the case that \( T \) and \( T' \)
are \( \ell \)-nearly partitioned by \( B \) and \( B' \), where in this case,
each ball \( B_i \) in \( B \) intersects a single ball in \( B' \) (call it \( B_i' \)
w.l.o.g.). Since \( B \) and \( B' \) are \( \Delta \)-far balls, this yields that
the centers of \( B \) and \( B' \) are relatively close, i.e., \( \| c_i - c_i' \| \)
is bounded by (approximately) \( \frac{\Delta}{4} \cdot \min_{j \neq i} \| c_i - c_j \| \approx \frac{\Delta}{4} \cdot \min_{j \neq i} \| c_i' - c_j' \| \).
Therefore, we deduce by the properties of the Gaussian mechanism
that the outputs are indistinguishable.

**Remark 4.13 (Run time of PrivatekNoisyCenters).** Step 1
of PrivatekNoisyCenters takes \( O(dk^2 n) \) time (see Remark 4.7).
The for-loop in Step 4 only takes \( O(dkn) \) time. Overall, the running time of
PrivatekNoisyCenters is \( O(dk^2 n) \).

### 5. Empirical Results

We implemented in Python our two main algo-
rithms for \( k \)-tuple clustering: PrivatekAverages and
PrivatekNoisyCenters. We compared the two
algorithms in terms of the sample complexity that
is needed to privately separate the samples from a
given mixture of Gaussians. Namely, how many \( k \)-
tuples we need to sample such that, when executing
We perform three tests, where in each test we considered a \( \Delta = 4 \)-core Intel i7 CPU with 2.8GHz, and with 16GB RAM. (Figure 6) we examined the case \( d \)

The graphs show the main bottleneck of Algorithm (Figure 7) we could avoid the dependency of \( \text{PrivatekAverages} \) the supplementary material for more details). However, since we do not improve even when the assumed separation \( R \) is very large. The cause of this large constant is the group privacy of size \( O(k\ell) \) that we do in

Step 5, where recall that \( \ell = O\left(\frac{\log^2(1/\delta)}{\varepsilon \log n}\right) \) (Definition 4.4). While in theory this \( \ell \) is relatively small, with our choice of parameters we get \( \ell \approx 1000 \). This means that we need to execute the private average algorithm with \( \tilde{\varepsilon} \approx \frac{\varepsilon}{10000} \).

In Test1 (Figure 5) we examined the sample complexity in the case \( d = 1, k = 2 \), for \( R \in \{2^5, 2^6, \ldots, 2^9\} \). In Test2 (Figure 6) we examined the case \( d = 4, R = 512 \cdot k \), for \( k \in \{2, 4, 6, 8\} \). In Test3 (Figure 7) we examined the case \( k = 2, R = 256\sqrt{d} \), for \( d \in \{4, 8, 12, 16\} \). In all the experiments we used privacy parameters \( \varepsilon = 1 \) and \( \delta = e^{-28} \), and used \( \beta = 0.05 \). In all the tests of PrivateNoisyCenters, we chose \( \Delta = \frac{12}{\varepsilon} \cdot k \log(k/\delta) \sqrt{\log(k/\beta)} \), the number of \( k \)-tuples that we generated was exactly 3781 (the minimal value that is required for privacy), but the number of samples per \( k \)-tuple varied from test to test. In the tests of PrivateAverages, we chose \( \Lambda = 2^{10} \cdot k \sqrt{d} \) and \( r_{\min} = 0.1 \), we generated each \( k \)-tuple using \( \approx 15 \cdot k \) samples, but the number of \( k \)-tuples varied from test to test.3 All the experiments were tested in a MacBook Pro Laptop with 4-core Intel i7 CPU with 2.8GHz, and with 16GB RAM.

The graphs show the main bottleneck of Algorithm PrivatekAverages in practice. It requires only \( O_{\varepsilon, \delta}(kd) \) tuples (or \( O_{\varepsilon, \delta}(k\sqrt{d}) \) for large values of \( d \)) in order to succeed, but the hidden constant is \( \approx 500,000 \) for our choice of \( \varepsilon \) and \( \delta \), and this does not improve even when the assumed separation \( R \) is very large. The cause of this large constant is the group privacy of size \( O(k\ell) \) that we do in

3We remark that in different settings, such as node, edge or weight-differential privacy, there exist some available implementations (e.g., (Pinot et al., 2018)).

Figure 5: The case \( d = 1 \) and \( k = 2 \), for varies \( R \).

Figure 6: The case \( d = 4 \) and \( R = 512 \cdot k \), for varies \( k \).

Figure 7: The case \( k = 2 \), \( R = 256\sqrt{d} \), for varies \( d \).
\[ \sigma \approx \frac{\Lambda}{\varepsilon} \sqrt{\log(1/\delta)} \gg 1 \] for some \( \Lambda > R \), meaning that the resulting mixture consists of very close Gaussians. We applied GaussianMixture from the package sklearn.mixture to learn this mixture, but it failed even when we used 100,000 samples, as this method is not intended for learning such close Gaussians. We remark that there are other non-private methods that are designed to learn any mixture of Gaussians (even very weakly separated ones) using enough samples (e.g., (Suresh et al., 2014)). The sample complexity and running time of these methods, however, are much worse than ours even asymptotically (e.g., the running time of (Suresh et al., 2014) is exponential in \( k \)), and moreover, we are not aware of any implementation we could use.\(^5\)

6. Conclusion

We developed an approach to bridge the gap between the theory and practice of differentially private clustering methods. For future, we hope to further optimize the “constants” in the \( k \)-tuple clustering algorithms, making the approach practical for instances with lower separation. Tangentially, the inherent limitations of private versus non-private clustering suggest exploring different rigorous notions of privacy in the context of clustering.

Acknowledgements

Edith Cohen is supported by Israel Science Foundation grant no. 1595-19.

Haim Kaplan is supported by Israel Science Foundation grant no. 1595-19, and the Blavatnik Family Foundation.

Yishay Mansour has received funding from the European Research Council (ERC) under the European Union’s Horizon 2020 research and innovation program (grant agreement No. 882396), by the Israel Science Foundation (grant number 993/17) and the Yandex Initiative for Machine Learning at Tel Aviv University.

Uri Stemmer is partially supported by the Israel Science Foundation (grant 1871/19) and by the Cyber Security Research Center at Ben-Gurion University of the Negev.

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