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Robust Bregman Clustering
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Abstract
Using a trimming approach, we investigate a $k$-means type method based on Bregman divergences for clustering data possibly corrupted with clutter noise. The main interest of Bregman divergences is that the standard Lloyd algorithm adapts to these distortion measures, and they are well-suited for clustering data sampled according to mixture models from exponential families. We prove that there exists an optimal codebook, and that an empirically optimal codebook converges a.s. to an optimal codebook in the distortion sense. Moreover, we obtain the sub-Gaussian rate of convergence for $k$-means $\frac{1}{\sqrt{n}}$ under mild tail assumptions. Also, we derive a Lloyd-type algorithm with a trimming parameter that can be selected from data according to some heuristic, and present some experimental results.

1 Introduction
Clustering is the problem of classifying data in groups of similar points, so that the groups are as homogeneous and at the same time as well separated as possible [Duda et al., 2000]. There are no labels known in advance, so clustering is an unsupervised learning task. To perform clustering, one needs some distance-like function to serve as a proximity measure between points. A very famous clustering method is the standard $k$-means algorithm (see for instance Lloyd [1982]), based on the Euclidean distance.

Let $X_1, \ldots, X_n$ denote a sample of independent random observations with values in $\mathbb{R}^d$, with the same distribution as a generic random vector $X$ with distribution $P$. For an integer $k \geq 1$, in order to group data items $X_1, \ldots, X_n$ in meaningful classes, the $k$-means procedure minimizes the so-called empirical distortion

$$R_n(c) = \frac{1}{n} \sum_{i=1}^{n} \min_{j \in \{1, \ldots, k\}} \|X_i - c_j\|^2,$$

over all possible cluster centers or codebooks $c = (c_1, \ldots, c_k)$, with notation $[1, k]$ for $\{1, 2, \ldots, k\}$. Here, $P_n$ denotes the empirical measure associated to $X_1, \ldots, X_n$, defined by

$$P_n(A) = \frac{1}{n} \sum_{i=1}^{n} \mathbb{1}_{\{X_i \in A\}},$$

for every Borel subset $A$ of $\mathbb{R}^d$.

It has been shown by [Banerjee et al., 2005b] that the standard $k$-means clustering algorithm (see for instance Lloyd [1982]) can be generalized to general Bregman divergences. Bregman divergences are a broad class of dissimilarity measures indexed by strictly convex functions. Introduced by Bregman [1967], they are useful in a wide range of areas, among which statistical learning and data mining (Banerjee et al. [2005b], Cesa-Bianchi and Lugosi [2006]), computational geometry (Nielsen et al. [2007]), natural sciences, speech
processing and information theory [Gray et al. 1980]. Squared Euclidean, Mahalanobis, Kullback-Leibler
and $L^2$ distances are particular cases of Bregman divergences.

A Bregman divergence is not necessary a true metric, since it may be asymmetric or fail to satisfy the
triangle inequality. However, Bregman divergences fulfill an interesting projection property which generalizes
the Hilbert projection on a closed convex set, as shown in [Bregman 1967]. Moreover, [Banerjee et al. 2005b]
have established that there exists a relation between finite-dimensional Bregman divergences and exponential
families. Although they are not true metrics, Bregman divergences satisfy some properties, such as non-
negativity and separation, convexity in the first argument and linearity (see [Banerjee et al. 2005b], [Nielsen
et al. 2007]). As Bregman divergences represent a natural tool to measure proximity between observations
arising from various distributions, we use them here for clustering purpose.

The aim is to find a data-based codebook $\hat{c}_n$ such that the clustering risk $R(\hat{c}_n)$ gets close to the optimal
risk $R^*_k := \inf_c R(c)$ as the size of the data set grows.

The convergence properties of empirical distortion minimizers are now quite-well understood when the
source distribution $P$ is assumed to have a finite support [Linder 2002], [Fischer 2010], even in infinite-
dimensional cases [Biau et al. 2008], [Levrard 2015]. In real data sets, the source signal is often corrupted by
noise, violating in most cases the bounded support assumption. In practice, data are usually pre-processed
via an outlier-removal step that requires an important quantity of expertise. From a theoretical point of
view, this corruption issue might be tackled winsorizing or trimming classical estimators, or by introducing
some new and robust estimators that can adapt heavy-tailed cases. Such estimators can be based on PAC-
Bayesian or Median of Means techniques [Catoni and Giulini 2018], [Brownlees et al. 2015], [Lecué and Lerasle
2017] for instance. In a nutshell, these estimator succeed in achieving subGaussian deviation bounds under
mild tail condition such as bounded variances and expectations.

In the clustering framework, up to our knowledge, the only theoretically grounded robust procedure is to
be found in [Cuesta-Albertos et al. 1997], where a trimmed k-means heuristic is introduced. See also [García
Escudero et al. 2008] for heteroscedastic trimmed clustering. In some sense, this paper extends this trimming
approach to the general framework of clustering with Bregman divergence. Our precise contributions are
listed below.

1.1 Contribution

- We introduce and provide a robust Bregman clustering algorithm, based on the minimization of a
trimmed distortion criterion $R_h$.

- We give theoretical evidences that such a criterion is adapted to heavy-tailed cases, for instance proving
that minimizers exist whenever $P$ has a first-order moment.

- We investigate the finite-sample behavior of trimmed empirical distortion minimizers, and show that
our procedure attains state-of-the-art guarantees in terms of convergence towards the optimal. Namely,
we derive sub-Gaussian deviation bounds for the excess trimmed distortion under bounded variance
condition.

We also give numerical illustrations of the aforementioned results.

2 Clustering with trimmed Bregman divergence

2.1 Bregman divergences and distortion

A Bregman divergence is defined as follows.

Definition 1. Let $\phi$ be a strictly convex $C_1$ real-valued function defined on a convex set $\Omega \subset \mathbb{R}^d$. The
Bregman divergence $d_\phi$ is defined for all $x, y \in \Omega$ by

$$d_\phi(x, y) = \phi(x) - \phi(y) - \langle \nabla_y \phi, x - y \rangle.$$
For every codebook \( c = (c_1, c_2, \ldots, c_k) \in \Omega(k) \), we set:

\[
d_\phi(x, c) := \min_{i \in [1,k]} d_\phi(x, c_i).
\]

Observe that, since \( \phi \) is strictly convex, for all \( x, y \in \mathbb{R}^d \), \( d_\phi(x, y) \) is non-negative and equal to zero if and only if \( x = y \) (see Rockafellar [1970, Theorem 25.1]). Note that by taking \( \phi : x \mapsto \|x\|^2 \), one gets \( d_\phi(x, y) = \|x - y\|^2 \).

Let us present a few other examples.

Examples

1. Exponential loss: \( \phi : x \mapsto e^x \), from \( \mathbb{R} \) to \( \mathbb{R} \), leads to \( d_\phi(x, y) = e^x - e^y - (x - y)e^y \).

2. Logistic loss: \( \phi : x \mapsto x \ln x + (1-x) \ln (1-x) \), from \( [0,1] \) to \( \mathbb{R} \), leads to \( d_\phi(x, y) = x \ln \frac{x}{y} + (1-x) \ln \left( \frac{1-x}{1-y} \right) \).

3. Kullback-Leibler: \( \phi : x \mapsto \sum_{\ell=1}^d x_\ell \ln x_\ell \), from the \( (d-1) \)-simplex to \( \mathbb{R} \), leads to \( d_\phi(x, y) = \sum_{\ell=1}^d x_\ell \ln \frac{x_\ell}{y_\ell} \).

Let \( P \) be a distribution on \( \mathbb{R}^d \), and \( c \) a codebook. The clustering performance of \( c \) will be measured via its distortion, namely

\[
R(c) = P d_\phi(u, c),
\]

where, for any function \( f \) and measure \( Q \), \( Qf(u) \) means integration of \( f \) with respect to \( Q \). Whenever only \( \mathbb{X}_n = \{X_1, \ldots, X_n\} \) is available, we denote by \( R_n(c) \) the corresponding empirical distortion (associated with \( P_n \)). In the case where \( P \) is a mixture of distributions belonging to an exponential family, there exists a natural choice of Bregman divergence, as detailed in Section 5. Standard Bregman clustering intends to infer a minimizer of \( R \) via minimizing \( R_n \), and works well in the bounded support case (Fischer [2010]).

2.2 Trimmed optimal codebooks

As for classical mean estimation, plain \( k \)-means is sensitive to outliers. An attempt to address this issue is proposed in Cuesta-Albertos et al. [1997], Gordaliza [1991]: for a trim level \( h \in (0,1) \), both a codebook and a subset of \( P \)-mass larger than \( h \) (trimming set) are pursued. This heuristic can be generalized to our framework as follows.

For a measure \( Q \) on \( \mathbb{R}^d \), we write \( Q \ll P \) (i.e., \( Q \) is a sub-measure of \( P \)) if \( Q(A) \leq P(A) \) for every Borel set \( A \), let \( P_h \) denote the set \( P_h = \{ \frac{1}{h} Q \mid Q \ll P, Q(\mathbb{R}^d) = h \} \), and \( P_{+h} = \cup_{s \geq h} P_s \). In analogy with Cuesta-Albertos et al. [1997] optimal trimming sets and codebooks are designed to achieve the optimal \( h \)-trimmed \( k \)-variation,

\[
V_{k,h} = \inf_{\hat{P} \in P_{+h}} \inf_{P \in \Omega^k} \hat{P} d_\phi(u, c) := \inf_{\hat{P} \in P_{+h}} \inf_{P \in \Omega^k} R(\hat{P}, c),
\]

that is the best possible \( k \)-point distortion based on a normalized sub-measure of \( P \).

If \( c \) is a fixed codebook, we denote by \( B_\phi(c, r) \) (resp \( \hat{B}_\phi(c, r) \)) the open (resp. closed) Bregman ball with radius \( r \), \( \{ x \mid d_\phi(x, c) < r \} \) (resp. \( \leq \)), and by \( r_h(c) \) the smallest radius \( r \geq 0 \) such that

\[
P(B_\phi(c, r)) \leq h \leq P(\hat{B}_\phi(c, r)).
\]

We also denote by \( r_{n,h}(c) \) the radius when the distribution is \( P_n \). Note that \( r_{n,h}(c)^2 \) is the Bregman divergence to the \( \lfloor nh \rfloor \) nearest-neighbor of \( c \) in \( \mathbb{X}_n \). Now, if \( P_h(c) \) is defined as the set of measures \( \hat{P} \) in \( P_h \) that coincides with \( P \) on \( B_\phi(c, r_h(c)) \), with support included in \( \hat{B}_\phi(c, r_h(c)) \). An easy result is
Theorem 7. 

Similarly to the Euclidean case, the clustering associated with a codebook $\mathbf{c}$ will be given by a tessellation of the ambient space. To be more precise, for $\mathbf{c} \in \Omega^{(k)}$ and $i \in [1, k]$, the Bregman-Voronoi cell associated with $c_i$ is $V_i(\mathbf{c}) = \{ x \mid \forall j \neq i, d_\phi(x, c_j) \leq d_\phi(x, c_i) \}$. Some further results on the geometry of Bregman Voronoi cells might be found in [Nielsen et al., 2007]. Since the $V_i(\mathbf{c})$’s do not form a partition, $W_i(\mathbf{c})$ will denote a subset of $V_i(\mathbf{c})$ so that $(W_1(\mathbf{c}), \ldots, W_k(\mathbf{c}))$ is a partition of $\mathbb{R}^d$ (for instance break the ties of the $V_i$’s with respect to the lexicographic rule).
Proposition 8. Let \( c \in \Omega^{(k)} \) and \( P_c \in \mathcal{P}_h(c) \). Assume that for all \( i \in [1, k] \), \( P_c(W_i(c)) > 0 \), and denote by \( m \) the codebook that consists in local means of \( P_c \), i.e. \( m_i = P_c(u^1W_i(c)(u))/P_c(W_i(c)) \). Then
\[
R_h(c) \geq R_h(m),
\]
with equality if and only if for all \( i \) in \([1, k]\), \( c_i = m_i \).

Proposition [8] emphasizes the key property that Bregman divergences are minimized by expectations (this is not the case for \( L_1 \) distance for instance), and are the only loss functions satisfying that property; see [Banerjee et al., 2005a]. Thus, a straightforward approach to minimize \( R_h \) can be based on an iterative scheme, as depicted below.

3 Description of the algorithm

The following algorithm is inspired by the trimmed version of the Lloyd’s algorithm; see Cuesta-Albertos et al. [1997], but is also a generalization of the Bregman clustering algorithm for uniform finite-supported measures; see [Banerjee et al., 2005b, Algorithm 1]. We assume that we observe \( \{X_1, \ldots, X_n\} = X_n \), and that the mass parameter \( h \) equals \( \frac{q}{n} \) for some positive integer \( q \). We also let \( C_j \) denote the subset of \([1, n]\) corresponding to the \( j \)-th cluster.

Algorithm 1. Bregman trimmed \( k \)-means

- **Input** \( \{X_1, \ldots, X_n\} = X_n \), \( q \), \( k \)
- **Initialization** Sample \( c_1, c_2, \ldots, c_k \) from \( X_n \) without replacement, \( c^{(0)} \leftarrow (c_1, \ldots, c_k) \).
- **Iterations** Repeat until stabilization of \( c^{(t)} \).
  - For \( j = 1, \ldots, k \), \( c_j^{(t)} \leftarrow W_j(c^{(t-1)}) \).
  - For \( j = 1, \ldots, k \), \( \hat{c}_j^{(t)} \leftarrow \frac{\sum_{x \in C_j^{(t)} \cap \text{NN}_Q(x)}}{|C_j^{(t)} \cap \text{NN}_Q(x)|} \).
- **Output** \( c^{(t)}, C_1^{(t)}, \ldots, C_k^{(t)} \).

As for every EM-type algorithm, initialization is a crucial point that will not be investigated in this paper. Note however that Bregman adaptations of approximate minimization methods such as \( k \)-means++ Arthur and Vassilvitskii [2007] could be an efficient way to address the initialization issue, at least in practice. An easy consequence of Proposition [8] for the empirical measure \( P_n \) associated with \( X_n \) is the following. For short we denote by \( R_{n,h} \) the trimmed distortion associated with \( P_n \).

Proposition 9. Algorithm [1] converges to a local minimum of the function \( R_{n,h} \).

It is worth mentioning that in full generality the output of Algorithm [1] is not a global minimizer of \( R_{n,h} \). However, it is likely that suitable clusterability assumptions as in Kumar and Kannan [2010], Tung and Monteleoni [2016], Levrand [2018] would lead to further guarantees on such an output.

4 Convergence of a trimmed empirical distortion minimizer

This section is devoted to investigate the convergence of a minimizer \( \hat{c}_n \) of the empirical trimmed distortion \( R_{n,h} \). Throughout this section \( \phi \) is assumed to be \( C^2 \), and \( F_0 = \text{conv}(\text{supp}(P)) \subset \Omega \). That is, the closure of the convex hull of the support of \( P \) is a subset of the interior of \( \Omega \).

We begin with a generalization of Cuesta-Albertos et al. [1997, Theorem 3.4] whenever \( P \) has a unique optimal trimmed codebook \( \hat{c}_h \).
Theorem 10. Assume that there exists a unique minimizer $c_h^n$ of $R_h$. If $P$ is continuous and satisfies $P\|u\|^p < \infty$ for some $p > 2$, then:

$$\lim_{n \to +\infty} D(c_n, c_h^n) = 0 \text{ a.e.}$$

where $D(c, c') = \min_{\sigma \in \Sigma_k} \max_{i \in [1, k]} |c_i - c'_{\sigma(i)}|$ and $\Sigma_k$ denotes the set of all permutations of $[1, k]$. Moreover,

$$\lim_{n \to +\infty} R_{n,k}(c_n) = R_h(c_h^n) \text{ a.e.}$$

Observe that slightly milder conditions are required for the trimmed distortion of $\hat{c}_n$ to converge towards the optimal at a parametric rate.

Theorem 11. Assume that $P\|u\|^p < \infty$, where $p > 2$. Then, for $n$ large enough, with probability larger than $1 - n^{-\frac{1}{2}} - 2e^{-x}$, we have

$$R_h(\hat{c}_n) - R_h(c_h^n) \leq \frac{C_P}{\sqrt{n}}(1 + \sqrt{x}).$$

Note that Theorem 11 does not require a unique trimmed optimal codebook, and only requires an order 2 moment condition for $\hat{c}_n$ to achieve a sub-Gaussian rate in terms of trimmed distortion. This condition is in line with the order 2 moment condition required in [Brownlees et al. 2015] for a robustified estimator of $c^*$ to achieve similar guarantees, as well as the finite-variance condition required in [Catoni and Giulini 2018] in a mean estimation framework. To derive results in expectation, a technical additional condition is needed.

Corollary 12. If in addition there exist $c_0 \in \hat{\Omega}$ and $\psi$ a convex function such that

$$\sup_{c \in B_\phi(c_0, t) \cap F_0} \|\nabla_c \phi\| \leq \psi(t),$$

with $P\|u\|^2 \psi^2(\frac{k\|u\|}{h}) < +\infty$, $P\|u\|^2 < +\infty$ and $P\psi^2(\frac{k\|u\|}{h}) < +\infty$, then

$$\mathbb{E}(R_h(\hat{c}_n) - R_h(c_h^n)) \leq \frac{C_P}{\sqrt{n}}.$$
For this model, the expectation of $P_{\psi,\theta}$ may be expressed as $\mu(\theta) = \nabla_\theta \psi$. We define

$$\phi(\mu) = \sup_{\theta \in \Theta} \{ \langle \mu, \theta \rangle - \psi(\theta) \}.$$

By Legendre duality, for all $\mu$ such that $\phi$ is defined, we get:

$$\phi(\mu) = \langle \theta(\mu), \mu \rangle - \psi(\theta(\mu)),$$

with $\theta(\mu) = \nabla_\mu \phi$. The density of $P_{\psi,\theta}$ with respect to $P_0$ can be rewritten using the Bregman divergence associated to $\phi$ as follows:

$$p_{\psi,\theta}(x) = \exp(-d_\phi(x, \mu) + \phi(x)).$$

In the next experiments, we use Gaussian, Poisson, Binomial and Gamma mixture distributions and the corresponding Bregman divergences. Figure 1 presents the 4 densities together with the functions $\psi$ and $\phi$, as well as the associated Bregman divergences $d_\phi$.

<table>
<thead>
<tr>
<th>Distribution</th>
<th>$p_{\psi,\theta}(x)$</th>
<th>$\theta$</th>
<th>$\psi(\theta)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gaussian</td>
<td>$\frac{1}{\sqrt{2\pi}\sigma^2} \exp\left( \frac{-(x-a)^2}{2\sigma^2} \right)$</td>
<td>$a$</td>
<td>$\frac{\sigma^2}{2} \theta^2$</td>
</tr>
<tr>
<td>Poisson</td>
<td>$\log(\lambda) \exp(-\lambda)$</td>
<td>$\log(\lambda)$</td>
<td>$\exp(\theta)$</td>
</tr>
<tr>
<td>Binomial</td>
<td>$\frac{N!}{x!(N-x)!}q^x(1-q)^{N-x}$</td>
<td>$\log\left(\frac{q}{1-q}\right)$</td>
<td>$N \log(1 + \exp(\theta))$</td>
</tr>
<tr>
<td>Gamma</td>
<td>$\frac{x^{\alpha-1}}{\Gamma(\alpha)}$</td>
<td>$\frac{-k}{\mu}$</td>
<td>$k \log\left(-\frac{1}{\theta}\right)$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Distribution</th>
<th>$\mu$</th>
<th>$\phi(\mu)$</th>
<th>$d_\phi(x, \mu)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gaussian</td>
<td>$a$</td>
<td>$\frac{1}{\sigma^2} \mu^2$</td>
<td>$\frac{1}{2\sigma^2} (x - \mu)^2$</td>
</tr>
<tr>
<td>Poisson</td>
<td>$\lambda$</td>
<td>$\mu \log(\mu) - \mu$</td>
<td>$\log\left(\frac{x}{\mu}\right) - (x - \mu)$</td>
</tr>
<tr>
<td>Binomial</td>
<td>$Nq$</td>
<td>$\mu \log\left(\frac{\mu}{N}\right) + (N - \mu) \log\left(\frac{N - \mu}{N}\right)$</td>
<td>$\log\left(\frac{x}{\mu}\right) + (N - x) \log\left(\frac{N - x}{N - \mu}\right)$</td>
</tr>
<tr>
<td>Gamma</td>
<td>$kb$</td>
<td>$-k + k \log\left(\frac{\mu}{x}\right)$</td>
<td>$k \mu \log\left(\frac{\mu}{x}\right) + x - \mu$</td>
</tr>
</tbody>
</table>

Figure 1: Exponential family distributions and associated Bregman divergences.

5.1 Trimming parameter selection

To assess the good behavior of our procedure with respect to outliers, we propose to perform the same experiment as in [Banerjee et al. 2005b], but with a level of noise. First, we propose in this section a heuristic to select the trimming parameter $q$, that is, the number of points in the sample which are assigned to a cluster and not considered as noise. Our strategy is as follows: we let $q$ vary from 1 to the sample size $n$, plot the curve $q \mapsto \text{cost}[q]$ where $\text{cost}[q]$ denotes the optimal empirical distortion at trimming level $q$, and choose $q^*$ by seeking for a cut-point on the curve. Indeed, when the parameter $q$ gets large enough, it is likely that the procedure begins to assign outliers to clusters, which dramatically deprecates the empirical distortion.

We consider mixture models of Gaussian, Poisson, Binomial and Gamma distributions. Each of the mixtures consists in three components with equal probabilities $\frac{1}{3}$. The means are set to 10, 20 and 40. We set the standard deviation for the Gaussian densities to 5, the number of trials for the Binomial distribution to 100, and the shape parameter for the Gamma distribution to 40. Each time, 100 points are sampled from the mixture distribution and 20 outliers are added, uniformly sampled on $[0, 200]$.

We use Algorithm 1 for each of these noisy mixture distributions, using the corresponding divergence, and also make the same experiment with the Cauchy distribution, using the squared Euclidean norm, that is, the Bregman divergence associated with the Gaussian distribution.
We get $q = 110$ for the Gaussian mixture, $q = 106$ for the Poisson mixture and $q = 105$ for the Cauchy mixture. The curves for selecting $q$ are depicted in Figure 2 for Gaussian, Poisson and Cauchy mixtures. In Figure 3, we have plotted the clustering results associated to the selected parameters for these distributions.

Note that the selection of the trimming parameter works well in the Cauchy example and the associated clustering seems also good. Thus, the method can adapt to mixture models that are not necessarily from distributions in exponential families.

Figure 2: Trimming parameter $q$ selection.

Figure 3: Clustering associated to the selected parameter $q$.

5.2 Comparative performances of Bregman clustering for mixtures with noise

We build 100 120-samples with each time 100 points from the mixture distribution and 20 outliers uniformly sampled on $[0, 200]$, as in Section 5.1. Most of the time, with these amounts of points, our heuristic leads to a selection of $q$ around 103. In the next experiments, we choose $q = 103$. To assess the performance of a partitioning, we compute the normalized mutual information $NMI$, as defined in Strehl and Ghosh [2002], between the true clusters and the clusters obtained with Algorithm 1. More specifically, the points corresponding to noise are assigned to one same cluster, and we compute the renormalized mutual information between the true partition, made of the three clusters arising from the mixture and the cluster of noisy points, and the clustering obtained with the trimming procedure with parameter $q = 103$. Confidence intervals for the normalized mutual information, with level around 5 percent, centered at the mean $\text{mean}(NMI)$, and with length $2 \times 1.96 \sqrt{\frac{\text{var}(NMI)}{100}}$, are derived in Figure 4. Note that, in general, the divergences associated to the distributions provide a better clustering, although it is less marked than for data without noise, as illustrated by the Binomial mixture case.

<table>
<thead>
<tr>
<th>Model</th>
<th>$d_{\text{Gaussian}}$</th>
<th>$d_{\text{Poisson}}$</th>
<th>$d_{\text{Binomial}}$</th>
<th>$d_{\text{Gamma}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gaussian</td>
<td>0.6585 ± 0.0130</td>
<td>0.6273 ± 0.0113</td>
<td>0.6370 ± 0.0108</td>
<td>0.5926 ± 0.0119</td>
</tr>
<tr>
<td>Poisson</td>
<td>0.6582 ± 0.0134</td>
<td><strong>0.6872 ± 0.0126</strong></td>
<td>0.6790 ± 0.0146</td>
<td>0.6500 ± 0.0120</td>
</tr>
<tr>
<td>Binomial</td>
<td><strong>0.7295 ± 0.0127</strong></td>
<td>0.7271 ± 0.01381</td>
<td>0.7290 ± 0.0125</td>
<td>0.6990 ± 0.0110</td>
</tr>
<tr>
<td>Gamma</td>
<td>0.7653 ± 0.0122</td>
<td>0.8122 ± 0.0110</td>
<td>0.7912 ± 0.0118</td>
<td><strong>0.8142 ± 0.0129</strong></td>
</tr>
<tr>
<td>Cauchy</td>
<td><strong>0.7074 ± 0.0149</strong></td>
<td>0.7204 ± 0.0128</td>
<td>0.6876 ± 0.01278</td>
<td>0.6729 ± 0.0116</td>
</tr>
</tbody>
</table>

Figure 4: Normalized mutual information for noisy data, adaptive choice of $q$. 

8
We conduct the same experiment for mixtures in dimension 2, with the same parameters. More precisely, \(X_i\) is replaced by \((X_1^i, X_2^i)\) where the \(X_j^i\)'s are independent and from the same component of the original unidimensional mixture. We proceed as for dimension 1 with 100 points corresponding to signal and 20 additional points. The Bregman divergences used in the algorithm are the sum of the two coordinates of the corresponding 1-dimensional Bregman divergences. Using the same trimming parameter selection heuristic as above, we choose \(q = 110\) for the Gaussian, Poisson and Gamma cases, and \(q = 100\) for the Cauchy distribution and the Binomial case. The corresponding clustering results are depicted in Figure 5 for Gaussian, Poisson and Cauchy mixtures. In Figure 6, we computed the mutual information for the selected trimming parameter.

The heuristic for selecting the trimming set is not as effective as in dimension 1. It may come from the fact that the clutter noise is closer to the signal in dimension 2. The Bregman divergences for the Poisson, Binomial and Gamma distributions take into account the heteroscedasticity of the data, since the variance within a direction \((0, 1)\) or \((1, 0)\) depends on the mean within the direction. In the multidimensional Gaussian setting, García Escudero et al. [2008] proposed an algorithm, implemented in the R package tclust, that adapts to mixtures with different covariance matrices. It may be a future work to adapt our methods to non-Gaussian distributions with non-diagonal covariance matrices.

![Gaussian](image1)

![Poisson](image2)

![Cauchy](image3)

Figure 5: Clustering associated to the selected parameter \(q\) (dimension 2).

<table>
<thead>
<tr>
<th>Model</th>
<th>(d_{\text{Gaussian}})</th>
<th>(d_{\text{Poisson}})</th>
<th>(d_{\text{Binomial}})</th>
<th>(d_{\text{Gamma}})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gaussian</td>
<td><strong>0.6543 ± 0.0107</strong></td>
<td>0.6356 ± 0.0094</td>
<td>0.6426 ± 0.0106</td>
<td>0.5732 ± 0.0017</td>
</tr>
<tr>
<td>Poisson</td>
<td>0.7237 ± 0.0095</td>
<td><strong>0.7450 ± 0.0091</strong></td>
<td>0.7432 ± 0.0085</td>
<td>0.7109 ± 0.0085</td>
</tr>
<tr>
<td>Binomial</td>
<td>0.7650 ± 0.0116</td>
<td>0.7592 ± 0.0102</td>
<td><strong>0.7728 ± 0.0102</strong></td>
<td>0.7073 ± 0.0083</td>
</tr>
<tr>
<td>Gamma</td>
<td>0.7800 ± 0.0073</td>
<td>0.8167 ± 0.0047</td>
<td>0.8038 ± 0.0059</td>
<td><strong>0.8349 ± 0.0043</strong></td>
</tr>
<tr>
<td>Cauchy</td>
<td><strong>0.6667 ± 0.0115</strong></td>
<td>0.6375 ± 0.0102</td>
<td>0.6400 ± 0.0119</td>
<td>0.6409 ± 0.0103</td>
</tr>
</tbody>
</table>

Figure 6: Normalized mutual information for noisy data (dimension 2), adaptive choice of \(q\).

6 Proofs for Section 2.1

6.1 Intermediate results

The proof of Theorem 7, Theorem 10 and Theorem 11 make extensive use of the following technical lemmas. The first of them is a global upper bound on the radii \(r_s(c)\), when \(c\) is in a compact subset of \(\Omega\).

**Lemma 13.** Assume that \(\phi\) is \(C^2\) and \(F_0 = \text{conv}(\text{supp}(P)) \subset \hat{\Omega}\). Then, for every \(h \in (0, 1)\) and \(K > 0\), there exists \(r^+ < \infty\) such that

\[
\sup_{c \in F_0 \cap B(0, K), s \leq h} r_s(c) \leq r^+.
\]

As a consequence, if \(c\) is a codebook with a codepoint \(c_{j_0} \in F_0\) satisfying \(\|c_{j_0}\| \leq K\) and \(s \leq h\),

\[
r_s(c) \leq r^+.
\]
Proof of Lemma 13. Let $K_+$ be such that $P(B(0, K_+)) > h$. Thus, if $c \in B(0, K)$, $P(B(c, K + K_+)) > h$. Since $B(c, K + K_+) \subset B(0, 2K + K_+)$, and $\phi$ is $C^2$, according to the mean value theorem, there exists $C_+$ such that,

$$
\forall x, y \in B(c, K + K_+) \cap F_0, d_\phi(x, y) \leq C_+ \|x - y\|.
$$

Therefore, for every $c \in B(0, K)$, $P\left(B _\phi \left(c, \sqrt{C_+ (2K + K_+)} \right) \right) > h$. Hence

$${r_s(c) \leq r_h(c) \leq C_+ \sqrt{2K + K_+} = r^+}.
$$

At last, if $c$ is such that $c_{j_0} \in B(0, K) \cap F_0$, then $B_\phi(c_{j_0}, r_h(c_{j_0}) < B_\phi(c, r_h(c_{j_0}))$. Therefore $P(B_\phi(c, r_h(c_{j_0})) > s$, hence $r_s(c) \leq r^+$. □

Next, the following Lemma makes connections between the difference of Bregman divergences and distance between codebooks.

**Lemma 14.** Assume that $F_0 \subset \hat{\Omega}$ and $\phi$ is $C^2$ on $\hat{\Omega}$. Then, for every $K > 0$, there exists $C_K > 0$ such that for every $c$ and $c'$ in $\overline{B}(0, K) \cap F_0$, and $x \in \hat{\Omega}$,

$$
|d_\phi(x, c) - d_\phi(x, c')| \leq C_K D(c, c') (1 + \|x\|),
$$

where we recall that $D(c, c') = \min_{\sigma \in \Sigma} \max_{j \in [1, K]} |c_j - c'_{\sigma(j)}|$ with $\Sigma$ the set of all permutations of $[1, K]$.

**Proof of Lemma 14.** The set $F_0 \cap \overline{B}(0, K)$ is a convex compact subset of $\hat{\Omega}$. Let $x \in \mathbb{R}^d$ and $c, c' \in F_0 \cap \overline{B}(0, K)$. Since $\phi$ and $x \mapsto \nabla \phi(x)$ are $C^1$, the mean value theorem yields that

$$
|d_\phi(x, c_j) - d_\phi(x, c'_j)| \leq |\phi(c'_j) - \phi(c_j)| + \left| \left\langle x, \nabla c_j' \phi - \nabla c_j \phi \right\rangle \right| + \left| \left\langle \nabla c_j' \phi, c_j' \right\rangle - \left\langle \nabla c_j \phi, c_j \right\rangle \right|
$$

for some constant $C_K$. Thus,

$$
|d_\phi(x, c) - d_\phi(x, c')| \leq C_K (1 + \|x\|) \max_j \|c_j - c'_j\|
$$

and

$$
|d_\phi(x, c) - d_\phi(x, c')| \leq C_K (1 + \|x\|) D(c, c').
$$

□

We will also need a continuity result on the function $(s, c) \mapsto R_s(c)$, stated as the following Lemma.

**Lemma 15.** Assume that $F_0 \subset \hat{\Omega}$, $P\|u\| < \infty$ and $\phi$ is $C^2$ on $\hat{\Omega}$. Then the map $(s, c) \mapsto R_s(c)$ is continuous. Moreover, for every $h \in (0, 1)$, $\epsilon > 0$ and $K > 0$, there is $s < h$ such that

$$
\sup_{c \in (F_0 \cap \overline{B}(0, K))^{(k)}} R_h(c) - R_s(c) \leq \epsilon.
$$

**Proof of Lemma 15.** According to Lemma 2 and Lemma 14, for every $h \in (0, 1),

$$
R_h(c) - R_h(c') \leq h (P_{c', h}d_\phi(u, c) - P_{c', h}d_\phi(u, c'))
$$

$$
\leq h P_{c', h} \|d_\phi(u, c) - d_\phi(u, c')\|
$$

$$
\leq C_K D(c, c')(1 + P\|u\|),
$$

for some $C_K > 0$. As a consequence, $|R_h(c) - R_h(c')| \to 0$ when $D(c, c') \to 0$. Now, note that for every $s < h,

$$
R_h(c) - R_s(c) = Pd_\phi(u, c) (1_{B_\phi(c, r_h(c))}(u) - 1_{B_\phi(c, r_s(c))})(u)
$$

$$
\leq r_h(c)(h - s)
$$

Moreover, according to Lemma 13, $\sup_{c \in (F_0 \cap \overline{B}(0, K))^{(k)}} r_h(c) \leq r^+$ for some $r^+ < \infty$, hence the result. □
6.2 Proof of Lemma 2
For \( u \in [0,1] \), let \( F_c^{-1}(u) = r_u^2(c) \) denote the \( u \)-quantile of the random variable \( d_\phi(X,c) \) for \( X \sim P \). That is, 
\[
F_c^{-1}(u) = \inf \{ r \geq 0 \mid P(B_\phi(c,r)) > u \}.
\]

If \( \tilde{F}_c^{-1}(u) \) denotes the \( u \)-quantile of \( d_\phi(\tilde{X},c) \), for \( \tilde{X} \sim P \in \mathcal{P}_h(c) \), it holds \( \tilde{F}_c^{-1}(u) = F_c^{-1}(hu) \). Let \( U \) be a uniform random variable on \([0,1]\), then \( \tilde{F}_c^{-1}(U) \) and \( d_\phi(\tilde{X},c) \) have the same distribution. Thus, we may write:
\[
R(\tilde{P},c) = \mathbb{E}_X d_\phi(\tilde{X},c) = \int_0^1 F_c^{-1}(hu)du.
\]
Let \( \tilde{P} \in \mathcal{P}_h(P) \) be a Borel probability measure on \( \Omega \) such that \( h\tilde{P} \) is a sub-measure of \( P \), and let \( \tilde{F}_c^{-1}(u) \) denote the \( u \)-quantile of \( d_\phi(\tilde{X},c) \) for \( \tilde{X} \sim \tilde{P} \). Since \( P(B_\phi(c,r)) \geq h\tilde{P}(B_\phi(c,r)) \), it holds that \( \tilde{F}_c^{-1}(u) \geq F_c^{-1}(hu) \). Thus, we may write:
\[
R(\tilde{P},c) = \int_0^1 \tilde{F}_c^{-1}(u)du \geq R(\tilde{P},c).
\]
Note that equality holds if and only if \( \tilde{F}_c^{-1}(u) = \tilde{F}_c^{-1}(u) \) for almost all \( u \in [0,1] \), that is \( \tilde{P} \in \mathcal{P}_h(c) \).

6.3 Proof of Lemma 4
Set \( 0 < h < h' < 1 \), and recall that \( F_c^{-1}(u) = r_u^2(c) \) denote the \( u \)-quantile of the random variable \( d_\phi(X,c) \) for \( X \sim P \) and \( u \in [0,1] \). Since \( F_c^{-1} \) is non-decreasing, we may write
\[
\frac{R_h(c)}{h} = \int_0^1 F_c^{-1}(hu)du \leq \int_0^1 F_c^{-1}(h'u)du = \frac{R_{h'}(c)}{h'}.
\]
Equality holds if and only if \( F_c^{-1}(hu) = F_c^{-1}(h'u) \) for almost all \( u \in [0,1] \). Since \( F_c^{-1} \) is non-decreasing and right-continuous, \( F_c^{-1}(hu) = F_c^{-1}(h'u) \) entails \( F_c^{-1}(l) = F_c^{-1}(0) \), for all \( l < h' \), or, in other words, \( r_l^2(c) = r_0^2(c) \). From (2), it follows that \( P(B_\phi(c,r_{h'}(c))) = 0 \). Conversely, equality holds when \( P(B_\phi(c,r_{h'}(c))) = 0 \).

6.4 Proof of Theorem 7
In the following, we will use the more concise notation \( R_{k,h}^* \) for the optimal risk \( hV_{k,h} = \inf_{c\in\Omega^{(k)}} R_h(c) \). For \( s \in [0,1] \), let \( T_s : \Omega^{(k)} \to \Omega^{(k)} \) denote the operator that maps a codebook \( c \) onto its local means, that is
\[
T_s(c)_j = \frac{P_c u_1 W_j(c)(u)}{P_{c,s}(W_j(c))},
\]
with \( P_{c,s} \in \mathcal{P}_s(c) \) and adopting the convention that \( T(c)_j = 0 \) whenever \( P_c(W_j(c)) = 0 \). The intuition behind the proof of Theorem 7 is that optimal codebooks can be found as iterations of \( T \), and that \( T \) is a bounded operator whenever each Voronoi cell has enough weight. This idea is summarized by the following Lemma, that encompasses Theorem 7.
Lemma 16. For every $k \geq 2$, if $R_{k-1,h} - R_{k,h} > 0$, then
\[
\alpha := \min_{j=2,\ldots,k} R_{j-1,h}^* - R_{j,h}^* > 0.
\]
Moreover there exists $0 < h^- < h < h^+ < 1$ and $C_{h^-,h^+}$ such that, for every $j \in [2,k]$ and $s \in [h^-,h^+]$,
- $R_{j-1,h}^* - R_{j,h}^* \geq \frac{\alpha}{2}$.
- For every $\frac{\alpha}{4}$-minimizer $c_{j,s}^*$ of $R_{j,s}^*$, sup$_{p \in [1,j]} \|T_s(c_{j,s}^*)p\| \leq C_{h^-,h^+}$.
- There is a minimizer $c_{j,s}^*$ of $R_{j,s}^*$ such that $\forall p \in [1,j]$, $\|c_{j,s,p}^*\| \leq C_{h^-,h^+}$.

Proof of Lemma 16. First note that if there exists $j \leq k$ such that $R_{j-1,h}^* - R_{j,h}^* = 0$, then there exists a set $A$ with $P(A) \geq h$ such that $P_A$ is supported on $j-1$ points. Thus, $R_{j-1,h}^* = R_{j,h}^* = 0$. As a consequence, when $R_{k-1,h}^* - R_{k,h}^* > 0$, $\alpha$ is positive.

Note also that the third point follows from the second point. Indeed, for every sequence $c_{k,s}^*$ of $\frac{\alpha}{4}$ minimizers of $R_{k,s}^*$, for every $i \in [1,k]$, $\|T_s(c_{k,s}^*)i\| \leq C_{h^-,h^+}$. Since $(B(0,C_{h^-,h^+}) \cap F_0)$ is a compact set, the limit in $(B(0,C_{h^-,h^+}) \cap F_0)$ of any converging subsequence of $(T_s(c_{k,s}^*))_n$ is a minimizer of $R_{k,s}^*$.

Now assume that $R_{k-1,h}^* - R_{k,h}^* > 0$. In order to prove the other points, we proceed recursively. Assume that $k = 2$. Since, for $s > 0$ and any 1-point codebooks $c$, $\|T_s(c)\| \leq P\|u\|/s$, optimal 1-point codebooks can be found in $B(0,C_1) \cap F_0$. From a compactness argument there exists an optimal 1-point codebook $c_{1,s}^*$ satisfying $\|c_{1,s}^*\| \leq P\|u\|/s$.

Denote by $c_{1,h^-}^*$ a minimizer of $R_{1,h^-}^*$, and $c_{2,h}^*$ an $\frac{\alpha}{8}$ minimizer of $R_{2,h}^*$. According to Lemma 15 for a fixed $c$, $s \mapsto R_s(c)$ is continuous, thus we may choose $h^-$ such that $R_{h^-}(c_{2,h}^*) \leq R_h(c_{2,h}^*) + \frac{\alpha}{8}$. Then,
\[
R_{2,h^+}^* \leq R_{h^+}(c_{2,h}^*) \\
\leq R_h(c_{2,h}^*) + \frac{\alpha}{8} \\
\leq R_{2,h}^* + \frac{\alpha}{4}.
\]

On the other hand, set $h_1 = \frac{h}{2}$. Then sup$_{s \geq h_1} \|c_{1,s}^*\| \leq P\|u\|/h_1 = C_{h_1}$. According to Lemma 15 there exists $h > h_2 \geq h_1$ such that sup$_{s \leq C_{h_1}} (R_{h_1}(c) - R_{h_2}(c)) \leq \frac{\alpha}{4}$. For such an $h_2$, we may write
\[
R_{1,h_2}^* = R_{h_2}(c_{1,h_2}^*) \\
\geq R_h(c_{1,h_2}^*) - \frac{\alpha}{4} \\
\geq R_{1,h}^* - \frac{\alpha}{4}.
\]

Since $R_{k,h}^* - R_{k-1,h}^* \geq \alpha$, it comes that $R_{1,h_2}^* - R_{2,h^+}^* \geq \frac{\alpha}{2}$.

Now, if $c$ is an $\alpha/4$-minimizer of $R_{1,s}^*$, for $s \geq h - (h - h_2)/2 := h^-$, its Bregman-Voronoi cells restricted to the s-trimming set, $V_{s,a}$, have weight not smaller than $h - h^-$. Indeed, suppose that $P(V_{1,s}) < h - h^-$. Then
\[
R_{1,h_2}^* \geq R_s(c) - \frac{\alpha}{4} \\
\geq Pd_{\phi}(u,c_{1,h_2}^*)1_{V_{s,a}}(u) - \frac{\alpha}{4} \\
\geq R_{1,h}^* - \frac{\alpha}{4} \\
\geq R_{1,h_2}^* - \frac{\alpha}{4},
\]
hence the contradiction. Choosing \( s \geq h^- \) entails that \( \| T_s(c_j^+, s)_p \| \leq \frac{P\|u\|}{h-h^+} \), this gives the result for \( k = 2 \).

Assume that the proposition is true for index \( k-1 \), we will prove that it is also true for index \( k \). Set \( \alpha = \min_{j \in [2,k]} R_{\phi}^* - R_{\phi}^{+, h} > 0 \). Set \( h^- \) and \( h^+ \) the elements \( h^- \) and \( h^+ \) associated with step \( k-1 \). Set \( c_{k-1,h^-}^* \) a minimizer of \( R_{\phi}^{k-1, h^-} \) and \( c_{k,h}^* \) an \( \frac{\alpha}{8} \)-minimiser of \( R_{\phi}^{k,h} \). According to Lemma 15, there exists \( h < h^+ < h^{++} \) such that \( R_{\phi}^*(c_{k,h}^*) \leq R_{\phi}(c_{k,h}^*) + \frac{\alpha}{8} \). Thus \( R_{\phi}^{k-1,h^-} \leq R_{\phi}^{k-1,h^-} + \frac{\alpha}{8} \).

On the other hand, Lemma 15 provides \( h > h^+ > h^- \) such that

\[
\sup_{c \in \mathcal{B}(0,C_{h^+,h^+}) \cap F_\phi(k)} (R_{\phi}(c) - R_{\phi}(c_{k-1,h^-})) \leq \frac{\alpha}{4}
\]

Then, according to step \( k-1 \), since \( \| (c_{k-1,h^-}^*)_j \| \leq C_{h^+,h^+} \) for \( j = 1, \ldots, k \), we may write

\[
R_{\phi}^{k-1,h^+} = R_{\phi}(c_{k-1,h^+}) \geq R_{\phi}^{k-1,h^-} - \frac{\alpha}{4}.
\]

As a consequence, since \( R_{\phi}^{k-1,h^-} - R_{\phi}^{k,h^-} \geq \alpha \), we have \( R_{\phi}^{k-1,h^+} - R_{\phi}^{k,h^-} \geq \frac{\alpha}{2} \). Now, let \( c \) be a \( \frac{\alpha}{4} \)-minimizer of \( R_{\phi}^{k,s} \), for \( s \geq h^- = \frac{h^+ + h^-}{2} \), and assume that \( P(V_{\phi,s}) < h - h^- \). Then

\[
R_{\phi}^{k,h^+} \geq R_{\phi}(c) - \frac{\alpha}{4}
\]

\[
\geq P \sum_{j=2}^{k} d_\phi(u, c_j) \mathbb{I}_{V_{\phi,s}}(u) - \frac{\alpha}{4}
\]

\[
\geq R_{\phi}^{k-1,h^-} - \frac{\alpha}{4}
\]

\[
\geq R_{\phi}^{k-1,h^+} - \frac{\alpha}{4},
\]

this is a contradiction. Thus, for such a choice of \( h^- \) and \( h^- \leq s \leq h^+ \), \( P(V_{\phi,s}) \geq h - h^- \), which entails \( \| (T_u(c))_p \| \leq P\|u\|/(h-h^-) \), for every \( p \in [1,k] \).

\[\hfill\Box\]

7 Proofs for Section 4

7.1 Intermediate results

Theorem 10 and 11 require some additional probabilistic results that are gathered in this subsection. We begin with standard deviation bounds.

**Lemma 17.** Let \( C \) denote the class of Bregman balls \( B_\phi(x,r) = \{ y \in \mathbb{R}^d \mid \sqrt{d_\phi(y,x)} < r \} \), \( x \in \mathbb{R}^d \), \( r \geq 0 \). Then

\[
d_{VC}(C) < d + 1,
\]

where \( d_{VC} \) denotes the Vapnik-Chervonenkis dimension.

**Proof of Lemma 17.** Let \( S = \{ x_1, \ldots, x_{d+2} \} \) be shattered by \( C \). And let \( A_1, A_2 \) be a partition of \( S \). Then we may write

\[
A_1 = S \cap B_\phi(c_1, r_1) \cap B_\phi(c_2, r_2)^c
\]

\[
A_2 = S \cap B_\phi(c_2, r_2) \cap B_\phi(c_1, r_1)^c,
\]

for \( c_1, c_2 \in \mathbb{R}^d \) and \( r_1, r_2 \geq 0 \). Straightforward computation shows that, for any \( x \in A_1 \),

\[
\ell_{1,2}(x) < 0,
\]

where \( \ell_{1,2}(x) = \phi(c_2) - \phi(c_1) + \langle x, \nabla c_2 \phi - \nabla c_1 \phi \rangle + \langle \nabla c_1 \phi, c_1 \rangle - \langle \nabla c_2 \phi, c_2 \rangle - r_1^2 + r_2^2 \). Similarly we have that, for any \( x \in A_2 \) \( \ell_{1,2}(x) > 0 \). Thus \( S \) is shattered by affine hyperplanes (whose VC-dimension is \( d + 1 \)), hence the contradiction. \[\hfill\Box\]
Proposition 18. With probability larger than $1 - e^{-x}$, we have, for $k \geq 2$,
\[
\sup_{c \in (\mathbb{R}^d)^k, r \geq 0} \left| (P - P_n) \mathbb{I}_{B_{\phi}(c, r)} \right| \leq C \sqrt{(d+1) \log(k)} \sqrt{\frac{2k}{n}} + \sqrt{\frac{2x}{n}},
\]
where $C$ denotes a universal constant. Moreover, if $r^+$ and $K$ are fixed, and $P\|x\|^2 \leq M_2^2 < \infty$, we have, with probability larger than $1 - e^{-x}$,
\[
\sup_{c \in B(0,K)^k \cap F_0, r \leq r^+} \left| (P - P_n) d_{\phi}(., c) \mathbb{I}_{B_{\phi}(c, r)} \right| \leq C_{K,r^+, M_2} r^+ \sqrt{\frac{k d}{n}} + r^+ \sqrt{\frac{2x}{n}},
\]
where we recall that $\text{conv}(\text{supp}(P)) = F_0 \subset \Omega$.

Proof of Proposition 18. Let $c \in \mathbb{R}^k$, since $B_{\phi}(c, r) = \bigcup_{j=1}^k B_{\phi}(c_j, r)$, according to [van der Vaart and Wellner 2009, Theorem 1.1], we may write
\[
d_{VC} \left( \{B_{\phi}(c, r) | c \in (\mathbb{R}^d)^k, r \geq 0 \} \right) \leq c_1 (d + 1) \log(c_2 k),
\]
where $c_1$ and $c_2$ are universal constant. Thus, applying [Boucheron et al. 2005, Theorem 3.4] gives (3).

The second inequality (4) is more involved. Denote by $Z$ its left-hand side. A bounded difference inequality (see, e.g., Boucheron et al. 2013, Theorem 6.2) yields
\[
P \left( Z \geq \mathbb{E}Z + r^+ \sqrt{\frac{2x}{n}} \right) \leq e^{-x}.
\]
It remains to bound
\[
\mathbb{E}Z \leq 2\mathbb{E}_X \mathbb{E}_\sigma \frac{1}{n} \sup_{c \in B(0,K)^k \cap F_0, r \leq r^+} \sum_{i=1}^n \sigma_i d_{\phi}(X_i, c) \mathbb{I}_{B_{\phi}(c, r)}(X_i),
\]
according to the symmetrization principle (see, e.g., Boucheron et al. 2013, Lemma 11.4), where for short $\mathbb{E}_Y$ denotes expectation with respect to the random variable $Y$. Consider $X_1, \ldots, X_n$ as fixed, and denote, for any set of real-valued functions $\mathcal{F}$, by $\mathcal{N}(\mathcal{F}, \varepsilon, L_2(P_n))$ its $\varepsilon$ covering number with respect to the $L_2(P_n)$ norm. In order to apply Dudley’s entropy integral, we will make use of the following result.

Theorem 19. [Mendelson and Vershynin 2003, Theorem 1] If $\mathcal{F}$ is a set of functions taking values in $[-1, 1]$. Then, for all $S$ and $\varepsilon \leq 1$
\[
\mathcal{N}(\mathcal{F}, \varepsilon, L_2(S)) \leq \left( \frac{2}{\varepsilon} \right)^{k_{\mathcal{VC}}(\mathcal{F})},
\]
where $k$ denotes a universal constant and with a slight abuse of notation $d_{\mathcal{VC}}(\mathcal{F})$ denotes the pseudo-dimension of $\mathcal{F}$.

Now let $\Gamma_0$ denote the set of functions $\left\{ \frac{d_{\phi}(., c) \mathbb{I}_{B_{\phi}(c, r)}}{r^+} \right\}$, with $c \in B(0,K)^k, r \leq r^+$. It is immediate that
\[
\mathcal{N}(\Gamma_0, \varepsilon, L_2(P_n)) \leq \mathcal{N}(\Gamma_1, \varepsilon/2, L_2(P_n)) \times \mathcal{N}(\Gamma_2, \varepsilon/2, L_2(P_n)),
\]
where $\Gamma_1 = \left\{ \frac{d_{\phi}(., c)}{r^+} \right\}$ and $\Gamma_2 = \{ \mathbb{I}_{B_{\phi}(c, r)} \}$. On one hand, we have
\[
\mathcal{N}(\Gamma_2, u, L_2(P_n)) = \mathcal{N}(1 - \Gamma_2, u, L_2(P_n))
\leq \mathcal{N} \left( \left\{ \mathbb{I}_{B_{\phi}(c, r^+)} \mid c, r \right\}, u, L_2(P_n) \right)
\leq \mathcal{N} \left( \left\{ \mathbb{I}_{B_{\phi}(c, r)} \mid c \in \mathbb{R}^d, r \geq 0 \right\}, u/k, L_2(P_n) \right)^k
\leq \left( \frac{2k}{u} \right)^{k(d+1)}.
\]
according to Theorem 19.

Now turn to $\Gamma_1$. According to Lemma 14, we may write
\[
N(\Gamma_1, u, L_2(P_n)) \leq N \left( \frac{d \phi(\cdot, c)}{r^+} \left| c \in (F_0 \cap B(0, K))^k \right\} , u, L_2(P_n) \right)
\leq N \left( B(0, K)^k, \frac{r^+ u}{C_K (1 + \|x\|_{L_2(P_n)})}, d_H \right).
\]

Since $N(B(0, 1), u, \|\| \| \leq \left( \frac{3}{n} \right)^d$, it follows that
\[
N(\Gamma_1, u, L_2(P_n)) \leq \left( \frac{3K C_K (1 + \|x\|_{L_2(P_n)})}{r^+ u} \right)^{kd},
\]
hence
\[
N(\Gamma_0, \varepsilon, L_2(P_n)) \leq \left( \frac{6KC_K (1 + \|x\|_{L_2(P_n)})}{r^+ \varepsilon} \right)^{kd} \times \left( \frac{4k}{\varepsilon} \right)^{(d+1)}.
\]

Using Dudley’s entropy integral (see, e.g., Boucheron et al. 2013 Corollary 13.2) yields, for $k \geq 2$,
\[
E_X E_\sigma E_{\hat{\sigma}} \frac{1}{n} \sup_{c \in B(0, K)^k \cap F_0, r \leq r^+} \sum_{i=1}^{n} \sigma_i \frac{d \phi(X_i, c)}{r^+} \mathbb{1}_{B_\sigma(c, r)}(X_i)
\leq C \frac{\varepsilon}{n} \sqrt{k d \log \left( \frac{C_K (1 + \|x\|_{L_2(P_n)})}{r^+} \right) + \kappa(d+1) \log(4k)}
\]

Thus, applying Jensen’s inequality leads to
\[
E_X E_\sigma E_{\hat{\sigma}} \frac{1}{n} \sup_{c \in B(0, K)^k \cap F_0, r \leq r^+} \sum_{i=1}^{n} \sigma_i \frac{d \phi(X_i, c)}{r^+} \mathbb{1}_{B_\sigma(c, r)}(X_i) \leq r^+ C_{K, r^+, M_2} \sqrt{\frac{kd}{n}}
\]
and to (4). \qed

To prove Theorem 10, a more involved version of Markov’s inequality is needed, stated below.

**Lemma 20.** If $P\|u\|^p < \infty$ for some $p \geq 2$, then, there exists some positive constant $C$ such that with probability larger than $1 - n^{-\frac{p}{2}}$,
\[
P_n\|u\| \leq C.
\]

**Proof.** According to the Markov inequality, we may write
\[
\mathbb{P} (P_n\|u\| - P\|u\| \geq \varepsilon) \leq \frac{E \left[ \frac{1}{n} \sum_{i=1}^{n} \|X_i\| - P\|u\| \right]^p}{\varepsilon^p}.
\]
That leads to
\[
\mathbb{P} (P_n\|u\| - P\|u\| \geq \varepsilon) \leq \frac{E \left[ \sum_{i=1}^{n} \|X_i\| - P\|u\| \right]^p}{n^p \varepsilon^p}.
\]
From the Marcinkiewicz-Zygmund inequality applied to the real-valued centred random variables $Y_i = \|X_i\| - P_n\|u\| \geq \varepsilon$
Proof of Proposition 21. Assume that $P\|u\|^p < +\infty$ for some $p \geq 2$. Let $h^-$ and $h^+$ denote the quantities such that $\min_{j=2, \ldots, k} R_{j-1}^+ - R_{j}^- \geq \frac{\eta}{2}$ with $h^- < h < h^+$, as in Lemma 16. Denote by $\eta = \frac{h^+ - h^-}{k - 1}$. Then there exists $C_P$ such that, for $n$ large enough, with probability larger than $1 - n^{-\frac{\eta}{2}}$, we have, for all $j = 2, \ldots, k$, and $i = 1, \ldots, j$,

$$\sup_{h^-(k-j) \leq s \leq h} \|\hat{c}_{j,s,i}\| \leq C_P,$$

where $\hat{c}_{j,s}$ denotes a $j$-codepoint empirical risk minimizer with trimming level $s$.

Proof of Proposition 22. We let $C_P$ denote a constant to be fixed later. Similarly to the proof of Theorem 7, we denote by $\hat{T}_s$ the operator that maps $\hat{c}$ to the empirical means of its Bregman-Voronoi cells. Let $h^-$ and $h^+$ be as in Lemma 16. Then, according to Proposition 18 for $n$ large enough we have that,

$$\sup_{c \in (R^d)_0, r \geq 0} \|P - P_n\|B_\phi(c, r) \leq \min \left( \frac{\eta}{2}, h^+ - h^- \right).$$

with probability larger than $1 - \frac{1}{8n^2}$. On this probability event, from Lemma 13 and the fact that $s \mapsto r_s(c)$ is non-decreasing, we deduce that for some $r^+ > 0$,

$$\sup_{c \in B(0, C_P) \cap \Phi_0, s \leq h^+} \sup_{r \leq r^+} r_{n,s}(c) \vee r_s(c) \leq r^+.$$

Since $P\|u\|^p < +\infty$, Lemma 20 yields that $P_n\|u\| \leq C_1$, for $C_1$ large enough, with probability larger than $1 - \frac{1}{8n^2}$. Besides, choosing $x = \log(8n^2)$ in Proposition 18 we also have, with probability larger than $1 - \frac{1}{8n^2}$,

$$\sup_{c \in (B(0, C_P) \cap \Phi_0)^k, r \leq r^+} \|P - P_n\|d_\phi(u, c)\mathbb{I}_{B_s(c, r)}(u) \leq \alpha_n,$$

where $\alpha_n = O(\sqrt{\log(n)/n})$. We then work on the global probability event on which all these deviation inequalities are satisfied, that have probability larger than $1 - \frac{1}{n^2}$, and proceed recursively on $j$.

For $j = 1$ and $s \geq h^-$, according to Proposition 8, $\hat{T}_s(\hat{c}_{1,s}) = \hat{c}_{1,s}$, hence

$$\|\hat{c}_{1,s}\| \leq \frac{P_n\|u\|}{h^-} \leq C_P.$$
Now assume that the statement of Proposition 21 holds up to order $j - 1$. We choose $C_p = \frac{C_1}{h} + C_{h^{-}}, \frac{C_2}{h} + C_{p}'$, where $C_{p}'$ corresponds to the constant $C_p$ for the step $j - 1$ and $C_{h^{-}}$ is given by Lemma 16. Let $\hat{c}_{j,s}$ be a $j$-points empirically optimal codebook with trimming level $s \geq h - (k - j)\eta$, and assume that there exists one cell (say $V_1$) such that $P_n(V_1(\hat{c}_{j,s}) \cap B_{\phi}(\hat{c}_{j,s}, r_{n,s}(\hat{c}_{j,s})) \leq \frac{\eta}{2}$. On the one hand, we may write

$$R_s(\hat{c}_{j,s}) \leq \hat{R}_s(\hat{c}_{j,s})^* + \leq P_n d_\phi(u, c_{j,h}^*) \mathbb{I}_{B_\phi(c_{j,h}^*, r_{h,h}^*)}(u) \leq R_{j,h}^* + \alpha_n,$$

where $c_{j,h}^*$ is a $R_{j,h}^*$ minimizer provided by Theorem 7.

On the other hand, letting $h' = h - (k - j + \frac{1}{2})\eta \geq h^{-}$, we have

$$R_s(\hat{c}_{j,s}) \geq \sum_{p=2}^j P_n d_\phi(u, \hat{c}_{j,s,p}) \mathbb{I}_{V_p(\hat{c}_{j,s}) \cap B_\phi(\hat{c}_{j,s}, r_{n,s}(\hat{c}_{j,s}))}(u) \geq R_{j-1,h'} - \alpha_n,$$

according to the recursion assumption and (6). Thus,

$$R_s(\hat{c}_{j,s}) \geq R_{j-1,h'}^* - \alpha_n,$$

which is impossible for $\alpha_n < \frac{\eta}{4}$. Thus, for every $p \in [1, j]$,

$$P_n(V_p(\hat{c}_{j,s}) \cap B_{\phi}(\hat{c}_{j,s}, r_{n,s}(\hat{c}_{j,s})) \geq \frac{\eta}{2}.$$

According to Proposition 8 equality $\hat{T}(\hat{c}_{j,s}) = \hat{c}_{j,s}$ holds and entails

$$\|\hat{c}_{j,s,p}\| \leq \frac{P_n\|u\|}{h - (k - j)\eta} \leq \frac{P_n\|u\|}{h^{-}} \leq C_p.$$

7.2 Proof of Theorem 10

Before proving Theorem 10, first note that since $\phi$ is strictly convex and continuous, $\psi : x \mapsto \phi(x) - \langle x, a \rangle + b$ is also strictly convex and continuous, for every $a$ and $b$, thus $\psi^{-1}(0)$ is a closed set. This proves that $\mathbb{I}_{\psi^{-1}(0)}$ is measurable. Moreover, since $\psi$ is strictly convex, there are at most two points of $\psi^{-1}(0)$ in any line containing the point 0. Thus, the Lebesgue measure of $\psi^{-1}(0)$ is 0. Since $P$ is absolutely continuous with respect to the Lebesgue measure, it follows that boundaries of Bregman balls have $P$-mass equal to 0.

The proof of Theorem 10 is based on the following lemma:

Lemma 22. Let $(P_n)_{n \in \mathbb{N}}$ be a sequence of probabilities that converges weakly to a distribution $P$. Assume that $\text{supp}(P_n) \subset \text{supp}(P) \subset \mathbb{R}^d$, $F_0 = \text{conv}(\text{supp}(P)) \subset \bar{\Omega}$ and $\phi$ is $C_2$ on $\bar{\Omega}$. Then, for every $h \in (0, 1)$ and $K > 0$, there exists $K_+ > 0$ such that for every $c \in \Omega^{(k)}$ satisfying $|c_i| \leq K$ for some $i \in [1, k]$ and every $n \in \mathbb{N}$,

$$r_{n,h}(c) \leq r_+ = \sqrt{4(2K + K_+) \frac{\sup_{c \in F_0 \cap \bar{B}(0, 2K + K_+)} \|\nabla \phi\|}}.$$

Proof of Lemma 22. Set $c \in \bar{B}(0, K) \cap F_0$. Since $P_n$ converges weakly to $P$, according to the Prokhorov theorem, $(P_n)_{n}$ is tight. Thus, there is $K_+ > 0$ such that $P_n(B(0, K_+)) > h$ for all $n \in \mathbb{N}$ and $P(B(0, K_+)) >
It comes that \( P_n(B(c, K + K_+)) > h \). Moreover, for every \( x, y \) in \( F_0 \cap \overline{B}(0, 2K + K_+) \), the mean value theorem yields
\[
d_{\phi}(x, y) \leq 2 \sup_{c \in F_0 \cap \overline{B}(0, 2K + K_+)} \| \nabla_c \phi \| \| x - y \| \\
\leq 4(K + K_+)C_+ = (r^+)^2,
\]
for \( C_+ = \sup_{c \in F_0 \cap \overline{B}(0, 2K + K_+)} \| \nabla_c \phi \| \) that is finite since \( F_0 \cap \overline{B}(0, 2K + K_+) \) is compact. Thus, it follows that
\[
B(c, K + K_+) \subset B_{\phi}(c, r_+).
\]
As a consequence, \( P_n(B_{\phi}(c, r_+)) > h \) and \( P_n(B_{\phi}(c, r_+)) > h \) if \( c \in c \) and \( r_{n, \phi, h}(c) \leq r_+ \).

The proof of Theorem 10 is an adaptation of the proof of Theorem 3.4 in Cuesta-Albertos et al. 1997. Let \((X_n)_{n \in \mathbb{N}}\) be a sequence of independent random variables from \( P \). We can define \( P_n = \frac{1}{n} \sum_{i=1}^{n} \delta_{X_i} \) the empirical distribution associated with the \( n \) first realisations. Note that \( P_n \) is random, and \( P_n \) converges weakly to \( P \) a.s.

According to Proposition 21 provided that \( P[\| u \|^p < \infty] \), for some \( p \geq 2 \), there exists \( C_P > 0 \) such that for some \( N \in \mathbb{N} \), \( \sum_{n \geq N} P[\max_{i \in [1, k]} \| \hat{c}_{n,i} \| > C_P] < \infty \). Thus, according to the Borel-Cantelli Lemma, a.s. for \( n \) large enough, for every \( i \in [1, k] \), \( |\hat{c}_{n,i}| \leq C_P \).

Now \( C_P > 0 \) and \( N \in \mathbb{N} \) such that \( \forall n \geq N, \forall i \in [1, k], \| \hat{c}_{n,i} \| \leq C_P \). As aforementioned, this occurs with probability 1.

According to the Skorokhod’s representation theorem in the Polish space \( \mathbb{R}^d \), it is possible to construct a measured space \((\Omega, \mathcal{F}, \tilde{P})\) and a sequence of random variables \((X_n)_{n \in \mathbb{N}}\) and a random variable \( X \) on \((\Omega, \mathcal{F}, \tilde{P})\) such that \( X_n \sim P_n, X \sim P \) and \( X_n \) converges to \( X \) \( \tilde{P} \)-a.s.

Denote by \( c^* \) the unique minimiser of \( c \mapsto V_{\phi, h}(c) \), \( r'_{n} = r_{n, \phi, h}(c^*) \) and \( \tau'_n \) a \([0, 1]\)-valued measurable function such that \( hP_{n, c^*, h} = P_{n, \tau'_{n}} \), that is, such that \( P_{n, \tau'_{n}}(u) = h \) and
\[
\mathbb{1}_{B_{\phi}(c^*, r'_{n})} \leq \tau'_{n} \leq \mathbb{1}_{B_{\phi}(c^*, r'_{n})}.
\]

According to Lemma 22 with \( K = |c^*_i| \) for instance, it comes \( r'_{n} \leq r^+ \), for some finite \( r^+ \). Thus, up to a subsequence, we may assume that \( r'_{n} \rightarrow r' \) for some \( r' \leq r_+ \).

Moreover,
\[
|d_{\phi}(X_n, c^*) - d_{\phi}(X, c^*)| \leq |\phi(X_n) - \phi(X)| + \max_{j \in [1, k]} \| \nabla_{c_j} \phi \| \| X_n - X \| \rightarrow 0,
\]
when \( n \rightarrow \infty \). As a consequence, \( \tau'_{n}(X_n) \rightarrow \mathbb{1}_{B_{\phi}(c^*, r'_{n})}(X) \) \( \tilde{P} \)-a.e. The dominate convergence theorem yields \( h = P_n \tau'_{n}(u) \rightarrow P(B_{\phi}(c^*, r'_{n})) \). Thus, \( \mathbb{1}_{B_{\phi}(c^*, r'_{n})} = \tau_0 \) \( P \)-a.e where \( \tau_0 \) denotes the trimming set associated with \( c^* \) and \( P \). Moreover, since \( \tau'_n(X_n)d_{\phi}(X_n, c^*) \) is bounded by \( r_+ \) and converges to \( \tau_0(X)d_{\phi}(X, c^*) \) a.e., the dominated convergence theorem entails
\[
R_{n, h}(\hat{c}_n) \leq R_{n, h}(c^*) \leq \mathbb{E} \left[ \tau'_{n}(X_n)d_{\phi}(X_n, c^*) \right] \rightarrow \mathbb{E} \left[ \tau_0(X)d_{\phi}(X, c^*) \right].
\]
Thus, up to a subsequence,
\[
\limsup_{n \rightarrow \infty} R_{n, h}(\hat{c}_n) \leq R_{k, h}^*.
\]

Since, for \( n \geq N \) and every \( i \in [1, k] \), \( |\hat{c}_{n,i}| \leq C_P \), we have \( \hat{c}_{n,i} \rightarrow c_i \) for some \( c_i \in F_0 \cap \overline{B}(0, C_P) \), up to a subsequence. Set \( c = (c_1, c_2, \ldots, c_k) \). Again, according to Lemma 22 with \( K = C_P \), it comes that up to a subsequence, \( r_{n, h}(\hat{c}_n) \rightarrow r \) for some \( r \geq 0 \). As a consequence, from [8], Lemma 14 and the continuity of \( P \),
\[
\lim_{n \rightarrow \infty} \tau_n(X_n) = \mathbb{1}_{B_{\phi}(c, r)}(X) a.e.
\]
According to the dominated convergence theorem, we have \( h = P(B_{\phi}(c, r)) = P_n(\tau_n(u)) \).
Again, the dominated convergence theorem entails that up to a subsequence,

$$\liminf_{n \to \infty} R_{n,h}(\hat{c}_n) \geq \int 1_{B_\phi(c,r)}(u)d\phi(u) \geq R^*_k, h.$$  

As a consequence, \( \lim_{n \to \infty} R_{n,h}(\hat{c}_n) = R^*_k, h \) and \( c = c^* \). Since every subsequence of \( (\hat{c}_n)_{n \in \mathbb{N}} \) has a converging subsequence to \( c^* \), the sequence \( (\hat{c}_n)_{n \in \mathbb{N}} \) converges to \( c^* \).

### 7.3 Proof of Theorem \[11\]

We assume that all the probability events described in the proof of Proposition \[21\] hold. This occurs with probability larger than \( 1 - n^{-\frac{r}{2}} \). On this probability event, recall that for all \( j \|\hat{c}_{n,j}\| \leq C_P \), \( \sup_{c \in (F_0 \cap B((0,C_P))^{(k)})} r_{n,h}(c) \vee r'_h(c) \leq r^+ \). Next we further assume that the deviation bounds of Proposition \[18\] hold, with parameter \( C_P \) and \( r_+ \), to define a global probability event with mass larger than \( 1 - n^{-\frac{r}{2}} - 2e^{-x} \). On this event, we have

$$R_h(\hat{c}_n) - R^*_k, h = Pd_\phi(u, \hat{c}_n)1_{B_\phi(\hat{c}_{n,r_h}(\hat{c}_n))}(u) - R^*_k, h$$

$$\leq Pd_\phi(u, \hat{c}_n)1_{B_\phi(\hat{c}_{n,r_h}(\hat{c}_n))}(u) - Pd_\phi(u, c^*)1_{B_\phi(c^*, r_{n,h}(c^*))}(u)$$

$$+ Pd_\phi(u, c^*)(1_{B_\phi(c^*, r_{n,h}(c^*))}(u) - 1_{B_\phi(c^*, r_{n,h}(c^*))}(u))$$

$$\leq 2 \sup_{c \in (F_0 \cap B((0,C_P))^{(k)})} \|P - P_n\|d_\phi(u,c)1_{B_\phi(c,r)}(u)$$

$$+ 2r^+ \sup_{c \in (\Omega^{(h)})} \|P - P_n\|B_\phi(c,r)$$

$$\leq \frac{C_P}{\sqrt{n}} (1 + \sqrt{x}),$$

for some constant \( C_P \).

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