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How can we theoretically measure the performance of density-based clustering algorithms?

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Categories and Subject Descriptors

Measurement [**Metrics**]: Performance—we define the “percolation rate” to measure the performance of density-based clustering algorithms; Theory [**Methodologies**]: Analytical modeling techniques and model validation—*Analysis of the mathematical phenomenon behind these algorithms: the percolation*

Keywords

density-based clustering, percolation, geometric graphs, Nearest Neighbors density estimator

1. INTRODUCTION

Many of clustering algorithms for a point cloud $\mathcal{X}_n \subset \mathbb{R}^d$ in the Euclidean space are based on density estimates [1]. In fact, the density function f of point generation contains the relevant information. It is quite natural to try to extract what HARTIGAN called ‘high-density clusters’ [2].

One elegant solution to do this task consists in constructing a graph whose nodes are the points of the cloud and whose edges connect nearby points. We want the connected components of this graph to reflect the *high-density clusters*.

Some very classical algorithms such as (*Robust*) *Single-Linkage* [3] or (H)DBSCAN [4, 5] work in this way. It is particularly helpful because its connected components correspond exactly to the *high-density clusters* of the estimator $\hat{f}_{1\text{-Nearest Neighbor}}$.

An example of the Single-Linkage will show us the mathematical phenomenon at the heart of these algorithms: the *percolation* [6, 7].

We define and measure the *percolation rate* to evaluate the performance of such algorithms.

By way of example, we look at the Robust Single-Linkage algorithm and calculate its percolation rate. This will show theoretically why it is actually preferable to use K -Nearest Neighbours rather than 1-NN. However, convergence in K towards a perfect estimator is very slow, so this analysis explains why in practice $K = 10$ is often a good trade-off.

2. MATHEMATICAL MODEL

Let $\mathcal{X}_n := \{x_1, \dots, x_n\}$ be a cloud of n points all plotted IID according to a probability measure with density $f : \mathbb{R}^d \rightarrow \mathbb{R}_+$. With the very intuitive idea that the different

classes of the point cloud are represented by the “peaks” of the density function f , HARTIGAN [2] defines the high-density clusters of level r as the different connected components of the level set $L_r := \{x \in \mathbb{R}^d : f(x) \geq r\}$.

By varying the level r , we can obtain an *hierarchical clustering* representable by a tree, the *dendrogram*.

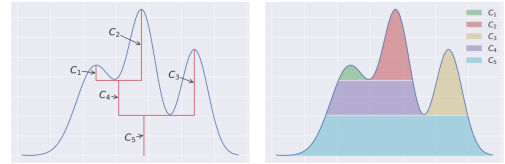


Figure 1: Hierarchical clustering obtained via density level sets. © Images taken from [5].

3. SINGLE-LINKAGE AND PERCOLATION

The *Single-Linkage* algorithm constructs a hierarchical clustering as follows: It starts with the trivial initial clustering (n points for n clusters) $\mathcal{C}_0 = \{C_1^0, \dots, C_n^0\}$ with $C_i^0 = \{x_i\}$. At each step, we merge the two clusters that are closest for the distance: $d_{Clust}(C, C') = \min_{x \in C, y \in C'} \|x - y\|$.

At step t , the resulting clustering $\mathcal{C}_t = \{C_1^t, C_2^t, \dots, C_{n-t}^t\}$ corresponds to the connected components of a geometric graph $\mathcal{G}(\mathcal{X}_n, r_t)$ built on \mathcal{X}_n [7]. Therefore, Single-Linkage performs *persistent analysis* on geometric graphs $\mathcal{G}(\mathcal{X}_n, r)$. Furthermore, the connected components of $\mathcal{G}(\mathcal{X}_n, r)$ match exactly with the high-density clusters of the 1-Nearest Neighbor density estimator $\hat{f}_{1\text{-NN}}$.

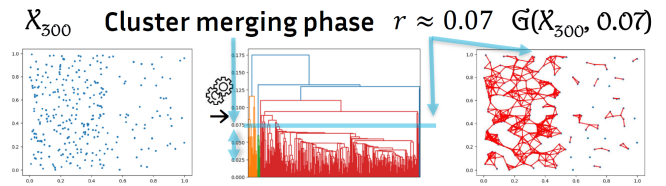


Figure 2: From left to right: 1) \mathcal{X}_{300} 2) Dendrogram of Single-Linkage 3) Geometric graph $\mathcal{G}(\mathcal{X}_{300}, 0.07)$.

See Fig. 2 for an illustration. The density is constant on each half-rectangle (left and right), and is larger on left-hand side. We observe on the dendrogram the first percolation phase (on left). Suddenly, for $r \lesssim 0.07$, plenty of clusters merge. The associated geometric graph $\mathcal{G}(\mathcal{X}_{300}, 0.07)$ has a giant component almost corresponding to the left high-

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density cluster. This sudden appearance of a giant connected component is called *percolation* [6, 7].

4. PERCOLATION RATE

HARTIGAN [2] showed that the Single-Linkage algorithm is a consistent estimator of high-density clusters in dimension $d = 1$, but only *fractionally* consistent in dimension $d \geq 2$.

How can we measure this recoverable ‘fraction’? This led us to define a *percolation rate* in [8]. Percolation is a ‘fast’ phenomenon. Once it appears for a critical radius r_c , the proportion $p_\infty(r)$ of points within the giant component grows quickly to 1. From a certain radius r_{\min} , the giant component contains $\varepsilon \leftarrow 5\%$ of the point and becomes detectable. For another larger radius $r_{\max} > r_{\min}$, the giant component encompass almost all the points (a proportion $1 - \varepsilon$): the cluster is recovered. Namely, let $r_{\min} := p_\infty^{-1}(\varepsilon)$ and $r_{\max} := p_\infty^{-1}(1 - \varepsilon)$. The quantity of interest – we call the *percolation rate* v – is:

$$v := \frac{r_{\min}}{r_{\max}}.$$

Note that $v \leq 1$. This percolation rate depends on the

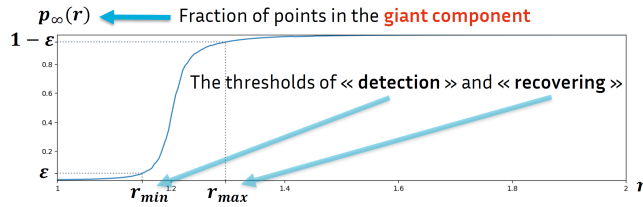


Figure 3: Estim. of $p_\infty(r)$ in \mathbb{R}^2 on random geometric graphs [7]. $\varepsilon \leftarrow 0.05 \implies r_{\min} = 1.15, r_{\max} = 1.30$.

kind of objects one ‘percolates’ and the associated notion of ‘connected components’. For example, in order to increase v , it would be a good idea to consider *hypergraphs* rather than classical graphs [9]. A percolation rate $v = 1$ is synonymous of an almost perfect clustering.

5. PERCOLATION RATE OF DISCRETIZED ROBUST SINGLE-LINKAGE

To gain in robustness, a *robust* version of the Single-Linkage was proposed [3], inspired by the consistency of the K -NN density estimator [10].

The main difference is that in the K -Robust version, a point $x \in \mathcal{X}_n$ must have at least $K - 1$ other points in his r -neighbourhood to appear in the geometric graph.

Let us consider the grid \mathbb{Z}^d rather than \mathbb{R}^d . A cell $s \in \mathbb{Z}^d$ – a *site* in the jargon of percolation – is activated ($=$ open) once it contains K points of an homogeneous Poisson point process $\mathcal{X} \subset \mathbb{R}^d$. Then, we look at the *clusters* formed by

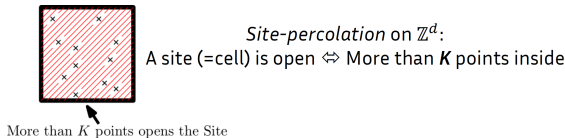


Figure 4: Discretization of the Robust Single-Linkage (RSL) on \mathbb{Z}^d : we look at *site-percolation*.

the open sites: this is the *discretized* Robust Single-Linkage.

On the grid \mathbb{Z}^d , we are now able to compute the exact percolation rate v^K of the K -discretized Robust Single-Linkage. In fact, the probability of a site to be open is $p = \mathbb{P}[\mathcal{P} \geq K]$ where $\mathcal{P} \sim \text{Poisson}(\lambda)$, λ being the intensity of the Poisson point process. We define as previously λ_{\min}^K and λ_{\max}^K and

$$v^K := \frac{\lambda_{\min}^K}{\lambda_{\max}^K}.$$

THEOREM. *Discretized RSL is asymptotically almost instantaneous: $v^K = 1 - O\left(\frac{1}{\sqrt{K}}\right)$. The constant for $\frac{1}{\sqrt{K}}$ depends on ε and the dimension d .*

Since v^K increases slowly towards 1 (in $1/\sqrt{K}$), it is easy to understand why the choice of $K \leftarrow 10$ is often a good trade-off in practice.

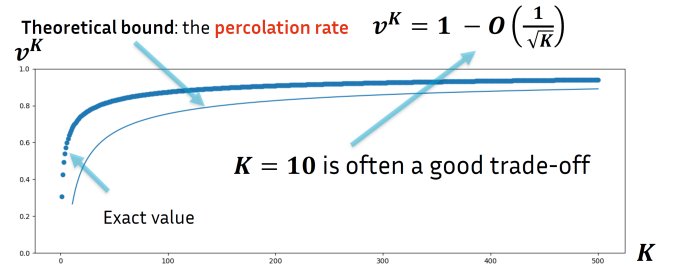


Figure 5: Theoretical bound and exact value of the discretized RSL percolation rate in dimension $d = 2$.

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