SDBM: Supervised Decision Boundary Maps for Machine Learning Classifiers

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Abstract: Understanding the decision boundaries of a machine learning classifier is key to gain insight on how classifiers work. Recently, a technique called Decision Boundary Map (DBM) was developed to enable the visualization of such boundaries by leveraging direct and inverse projections. However, DBM have scalability issues for creating fine-grained maps, and can generate results that are hard to interpret when the classification problem has many classes. In this paper we propose a new technique called Supervised Decision Boundary Maps (SDBM), which uses a supervised, GPU-accelerated projection technique that solves the original DBM shortcomings. We show through several experiments that SDBM generates results that are much easier to interpret when compared to DBM, is faster and easier to use, while still being generic enough to be used with any type of single-output classifier.

1 INTRODUCTION

In recent years, Machine Learning (ML) techniques have become very popular in many fields to support pattern recognition and predictive modelling. Despite their popularity, the inner workings of trained ML models are hard to explain, which can hamper their adoption where transparency and accountability of inference is required (Ribeiro et al., 2016). For Deep Learning (DL) models, explainability is an even harder concern, as such models have millions of parameters that contribute jointly to the generation of many levels of latent features (Garcia et al., 2018).

For the more specific case of ML *classifiers*, several approaches for model explanation have been proposed, using variable importance (Lundberg and Lee, 2017), locally interpretable models (Ribeiro et al., 2016), and a variety of visualization-based techniques (Rauber et al., 2017b; Rauber et al., 2017a). Garcia *et al.* (Garcia et al., 2018) recently presented a survey of visual techniques oriented towards the explanation of DL models.

A particular visual explanation technique in this set is the *Decision Boundary Map* (DBM) (Rodrigues et al., 2019). DBM extends classical multidimensional projections (Nonato and Aupetit, 2018) by filling in the gaps between projected points from a labeled dataset used to train a classifier with synthesized, classified, data points. This effectively creates a 2D dense image that shows how the classifier partitions its high-dimensional data space into per-class decision zones. DBM is, to our knowledge, the first technique that succeeds in visually depicting such classifier decision zones for any classifier. However, DBM has several limitations – it is slow, sensitive to parameter settings, and produces noisy visualizations from which it is hard to understand which are the shapes, topologies, and extents of the decision zones.

In this paper, we propose Supervised Decision Boundary Maps (SDBM), a *supervised* technique, which improves DBM in four key directions:

Quality (C1): SDBM produces decision maps that allow for a clearer, and far less noise-prone, visual separation of a higher number of decision zones from real-world, complex, datasets, than DBM;

Scalability (C2): SDBM is GPU accelerated and has a complexity linear in the number of samples and dimensions, allowing the creation of megapixel maps in

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a few seconds on commodity hardware, in contrast to the minutes needed by DBM;

Ease of Use (C3): SDBM produces good results with minimal or no parameter tuning;

Genericity (C4): SDBM can construct decision boundaries for *any* single-value classifier.

We structure this paper as follows: Section 2 discusses related work on classifier visualization. Section 3 details our SDBM method. Section 4 presents the results that support our contributions outlined above. Section 5 discusses our method. Finally, Section 6 concludes the paper.

2 BACKGROUND

We next introduce the notation used in this paper. Let $\mathbf{x} = (x^1, \ldots, x^n)$, $x^i \in \mathbb{R}, 1 \leq i \leq n$ be an n-dimensional (nD) real-valued, labeled, observation, and let $D = \{\mathbf{x}_j\}$, $1 \leq j \leq N$ be a dataset of N such samples, *e.g.*, a table with N rows (samples) and n columns (dimensions). Let $C = \{c_k\}$, $1 \leq k \leq K$ be the set of K class labels used in D. Let $\mathbf{y} = \{y_j | y_j \in C\}$, $1 \leq j \leq N$ be the class labels associated with each sample $\mathbf{x}_j$.

A classifier is a function

$$f : \mathbb{R}^n \rightarrow C, \tag{1}$$

that maps between data samples and class labels. The classifier f is typically obtained by using a training algorithm over the dataset D. Common ML algorithms are Logistic Regression (Cox, 1958), SVM (Cortes and Vapnik, 1995), Random Forests (Breiman, 2001), and Neural Networks, to name a few.

A Dimensionality Reduction (DR), or projection, technique is a function

$$P : \mathbb{R}^n \rightarrow \mathbb{R}^q, \tag{2}$$

where $q \ll n$, and typically $q = 2$. The projection $P(\mathbf{x})$ of a sample $\mathbf{x} \in \mathbb{R}^n$ is a qD point $\mathbf{p} \in \mathbb{R}^q$. Projecting a set D yields thus a qD scatterplot, which we denote next as $P(D)$. The inverse of P, denoted $P^{-1}(\mathbf{p})$, maps a qD point $\mathbf{p}$ to the high-dimensional space $\mathbb{R}^n$.

Decision Boundary Maps: Given a classifier f, a Decision Boundary Map (DBM) is a 2D image that shows a representation of how f partitions the $\mathbb{R}^n$ data space into decision zones. A *decision zone* is a set of 2D points $\mathbf{p}$ for which $f(P^{-1}(\mathbf{p})) = \{c_k | c_k \in C\}$ – that is, map high-dimensional points which are classified by f to the same class c_k. Class labels c_k are color-coded in the decision maps. Decision zones are separated by *decision boundaries*, which are pixels $\mathbf{p}$ whose labels (colors) differ from those of at least one 8-neighbor pixel in the DBM. The DBM shows, among other things, how the high-dimensional space is effectively partitioned by f into decision zones, how large these zones are, how they are adjacent to each other, and how smooth the decision boundaries between classes are (Rodrigues et al., 2019). This gives insights on whether the classifier f has overfitted the training data, and how well separated the data is, *i.e.*, how difficult is the task of partitioning the high-dimensional space to obtain good classification accuracy. DBMs are a step forward atop of the key observation in Rauber *et al.* (Rauber et al., 2017b), which showed how multidimensional projections aid deciding whether a high-dimensional dataset is easily classifiable or not. Simply put, DBMs support the same task but provide more information by ‘filling in’ the white gaps between the points of a 2D scatterplot $P(D)$ by extrapolating the classifier f.

The DBM technique, as introduced by Rodrigues *et al.* (Rodrigues et al., 2019), relies heavily on direct and inverse projections, to create the mappings P and P^{-1}. The direct mapping is used to create a 2D scatterplot $P(D)$ from the dataset D. The inverse mapping P^{-1} creates synthetic nD data points from all pixels $\mathbf{p}$ in the 2D bounding box of $P(D)$. These points $P^{-1}(\mathbf{p})$ are then classified by f, and colored by the assigned class labels $f(P^{-1}(\mathbf{p}))$. While this approach is conceptually sound, it has two main issues: (1) The inverse projection technique P^{-1} used, iLAMP (Amorim et al., 2012), scales poorly to the hundreds of thousands of points a dense pixel map has. This was addressed in (Rodrigues et al., 2019) by subsampling the 2D projection space into cells larger than one pixel, sampling a few 2D pixels from each cell, and next deciding the label (and thus color) of each cell by majority voting on the classification of the inverse-projections of these samples. This subsampling creates artifacts which are visible in the highly jagged boundaries of the decision zones. (2) Since the direct projections P used are unsupervised, outliers in the data D can generate ‘islands’ of pixels having a different label (and thus color) than their neighbors. This creates spurious decision zones and decision boundaries which next make the resulting DBMs hard to analyze by the user, in particular when the problem has several classes.

Dimensionality Reduction: Both the original DBM technique and our improved version SDBM rely heavily on Dimensionality Reduction (DR) techniques. Many DR techniques have been proposed over the years, as reviewed in various surveys (Hoffman and Grinstein, 2002; Maaten and Postma, 2009; Engel et al., 2012; Sorzano et al., 2014; Liu et al., 2015;

Cunningham and Ghahramani, 2015; Xie et al., 2017; Nonato and Aupetit, 2018; Espadoto et al., 2019a). Below we describe a few representative ones, referring to the aforementioned surveys for a more thorough discussion.

Principal Component Analysis (Jolliffe, 1986) (PCA) is one of the most popular DR techniques for many decades, being easy to use, easy to interpret, and scalable. However, PCA does not perform well for data of high intrinsic dimensionality, and is thus not the best option for data visualization tasks.

The Manifold Learning family of methods contains techniques such as MDS (Torgerson, 1958), Isomap (Tenenbaum et al., 2000), and LLE (Roweis and Saul, 2000), which aim to capture nonlinear data structure by mapping the high-dimensional manifold on which data is located to 2D. These methods generally yield better results than PCA for visualization tasks, but do not scale well computationally, and also yield poor results when the intrinsic data dimensionality is higher than two.

The SNE (Stochastic Neighborhood Embedding) family of methods, of which the most popular member is t-SNE (Maaten and Hinton, 2008), are very good for visual tasks due to the visual cluster segregation they produce. Yet, they can be hard to tune (Wattenberg, 2016), and typically have no out-of-sample capability. Several refinements of t-SNE improve speed, such as tree-accelerated t-SNE (Maaten, 2014), hierarchical SNE (Pezzotti et al., 2016), and approximated t-SNE (Pezzotti et al., 2017), and various GPU accelerations of t-SNE (Pezzotti et al., 2020; Chan et al., 2018). Uniform Manifold Approximation and Projection (UMAP) (McInnes and Healy, 2018), while not part of the SNE family, generates projections with comparable quality to t-SNE, but much faster, and with out-of-sample capability.

All above projection techniques work in an *unsupervised* fashion, by using information on distances between data points in D to compute the projection $P(D)$. Recently, (Espadoto et al., 2020) proposed Neural Network Projection (NNP) to learn the projection $P(D)$, computed by any user-selected technique P, from a small subset $D' \subset D$, using a deep learning regressor. While slightly less accurate than the original P, this technique is computationally linear in the size and dimensionality of D, has out-of-sample capability, is stable, and it simple to implement and parameter-free. The same idea was used by NNInv (Espadoto et al., 2019b) to learn the inverse mapping P^{-1}. These approaches were next extended by Self-Supervised Network Projection (SSNP) (Espadoto et al., 2021), which can be used either in a *self-supervised* fashion, by computing pseudo-labels by a generic clustering algorithm on D, or in a *supervised* fashion (similar to NNP), using ground-truth labels $\mathbf{y}$ coming with D. SSNP's supervised mode is key to the creation of our proposed SDBM for the following reasons:

- SSNP provides good cluster separation by partitioning the data space D as a classifier would do, which is closely related to the original goal of DBM;
- SSNP provides both the direct and inverse mappings (P and P^{-1}) needed by DBM to generate synthetic data points;
- SSNP is GPU-accelerated, which makes SDBM one to two magnitude orders faster than DBM.

3 METHOD

We next describe our proposed SDBM technique and how it is different from its predecessor, DBM (see also Fig. 1 for step-by step details of the SDBM pipeline):

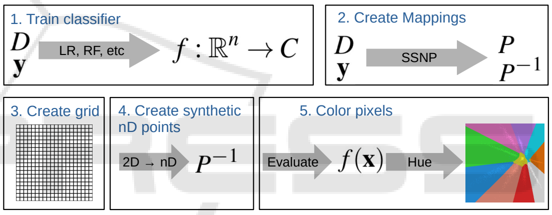

Figure 1: SDBM pipeline.

1. Train Classifier: Train the classifier f to be visualized using the dataset D and its class labels $\mathbf{y}$. This step is identical to DBM. Any single-class-output classifier $f:\mathbb{R}^n \to C$ can be used generically, *e.g.*, Logistic Regression (LR), Random Forests (RF), Support Vector Machines (SVM), or neural networks.

2. Create Mappings: Train SSNP to create the direct and inverse projections P and P^{-1} based on D and $\mathbf{y}$. This step is fundamentally different from DBM which accepts any user-selected projection P and then constructs P^{-1} by deep learning the 2D to nD mapping using deep learning (Espadoto et al., 2019b) (see also Sec. 2). This asymmetric design of DBM makes P^{-1} significantly differ from the mathematical inverse of P for several points $\mathbf{x}$, *i.e.*, $P^{-1}(P(\mathbf{x})) \neq \mathbf{x}$, which is visible as jagged decision boundaries and noise-like small islands scattered all over the dense maps (see Fig. 5 later on). As we shall see in Sec. 4, the *joint* computation of P and P^{-1} used by SDBM significantly reduces such artifacts.

3. Create 2D Grid: Create an image $G \subset \mathbb{R}^2$. This is different from DBM which uses subsampling of the 2D projection space (see Sec. 2). In detail, SDBM

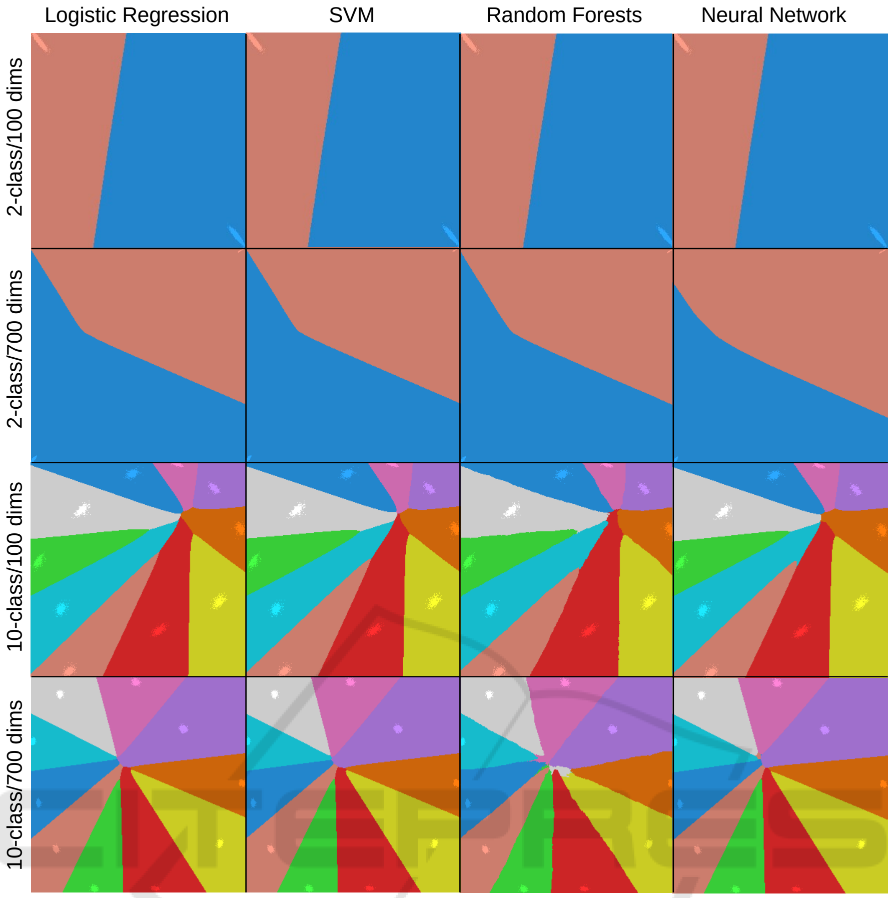

Figure 2: Decision Boundary Maps (DBMs) created with SDBM for several classifiers (columns) and synthetic datasets (rows). Lighter pixels represent training samples from the datasets *D*.

uses the full resolution of G to compute $P(D)$, but then evaluates P^{-1} on a subsampled version thereof. In our case, both P and P^{-1} use the full resolution image G. For the experiments in this paper, we set the resolution of G to 300^2 pixels.

4. Create Synthetic Data Points: Use the trained P^{-1} to map each pixel $\mathbf{p} \in G^2$ to a high-dimensional data point $\mathbf{x} \in \mathbb{R}^n$. This is similar to DBM, except the use of a dense pixel grid and jointly-trained P and P^{-1} (see above).

5. Color Pixels: Color all pixels $\mathbf{p} \in G$ by the values of $f(P^{-1}(\mathbf{p}))$, *i.e.*, the inferred classes of their corresponding (synthetic) data points, using a categorical color map. In this paper we use the 'tab20' color map (Hunter, 2007). This is the same as DBM.

6. Encode Classifier Confidence (Optional): For classifiers f that provide the probability of a sample $\mathbf{x}$ belonging to a class c_k, we encode that probability in the brightness of the pixel $\mathbf{p}$ that back-projects to $\mathbf{x}$. The lower the confidence of the classifier is, the darker the pixel appears in the map, thereby informing the user of the confidence of the decision zone in that area. This is the same as DBM.

4 RESULTS

We next present the results that support our claims regarding SDBM. First, we show how our method performs with synthetic data, where a perfect class separation is possible by most classifiers (Sec. 4.1). This allows us to verify how the technique performs under a controlled setting where we know the 'ground truth' shapes of the decision zones. Next, we show how SDBM performs on more complex real-world datasets and additional classifiers (Sec. 4.2) and also how it compares with DBM. This supports our claim that our technique can be generically used and that it improves quality *vs* DBM. We next show how SDBM compares to the original DBM speed-wise, thereby supporting our claims of improved scalability (Sec. 4.3). Finally, we provide full implementation details for SDBM (Sec. 4.4).

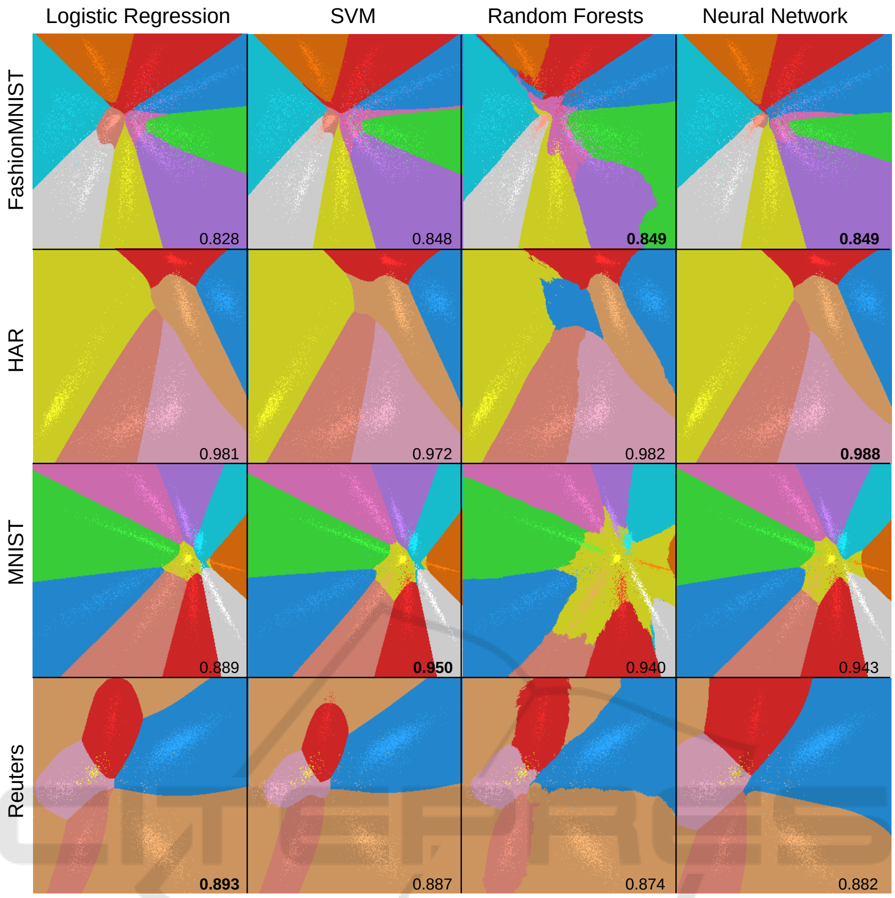

Figure 3: Decision Boundary Maps (DBMs) created with SDBM for several classifiers (columns) and real-world datasets (rows). Numbers inside each map indicate test accuracy obtained by each classifier, bold indicating top performers. Lighter pixels represent training samples from the datasets D.

4.1 Quality on Synthetic Datasets

We assess how SDBM performs in a controlled situation where the ground truth is known, *i.e.*, datasets with clear class separation and known shapes of the expected decision zones. The datasets contain synthetic Gaussian blobs with 5000 samples, with varied dimensionality (100 and 700), and varied number of classes (2 and 10). We used four different classifiers, namely Logistic Regression, SVM (with a RBF kernel), Random Forests (200 estimators), and a Neural Network (multi-layer perceptron having 3 layers of 200 units).

Figure 2 shows the maps created using SDBM for all the different classifier and dataset combinations. Decision zones are categorically colored. Projected samples in $P(D)$ are drawn colored also by their class, but slightly brighter, so as to distinguish them from the maps. We see that the decision zones are compact and with smooth boundaries, as expected for such simple classification problems. They enclose the Gaussian blobs with the same respective labels – *e.g.*, the red and blue zones for the 2-class, 100-dimensional dataset in Fig. 2, top row, contain two clusters of light red, respectively light blue, projected points. We also see that the maps for Logistic Regression show almost perfectly straight boundaries, which is a known fact for this classifier. In contrast, the more sophisticated classifiers, such as Random Forests and Neural Networks, create boundaries that are slightly more complex than the others for the most complex dataset (Fig. 2, bottom row, at the center of the maps for those classifiers).

4.2 Quality on Real-world Datasets

We next show how SDBM performs on real-world datasets. These datasets are selected from publicly available sources, matching the criteria of being high-dimensional, reasonably large (thousands of samples), and having a non-trivial data structure. They are also frequently used in ML classification evaluations and projection evaluations.

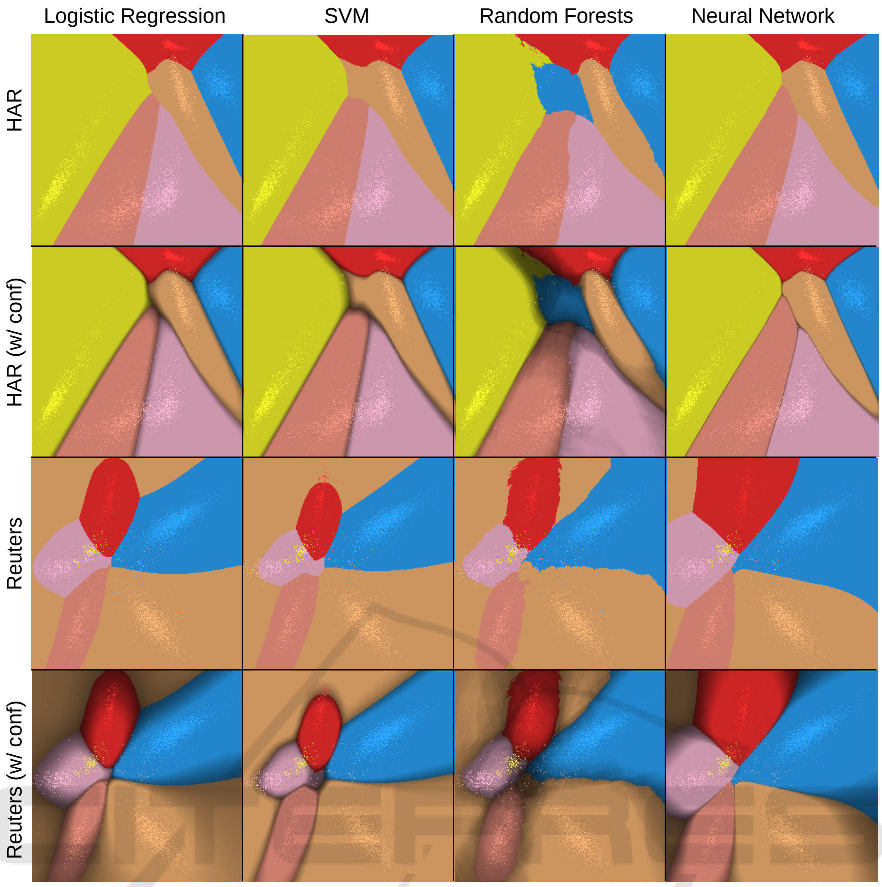

Figure 4: Decision Boundary Maps created with SDBM for several classifiers, HAR and Reuters datasets. Columns show different classifiers. Rows show different datasets, with and without confidence encoded into brightness.

FashionMNIST (Xiao et al., 2017)**:** 70K samples of $K = 10$ types of pieces of clothing, rendered as 28x28-pixel gray scale images, flattened to 784-element vectors. We also use a subset of this dataset containing only two classes, namely *Ankle Boot* and *T-Shirt*, to provide an example of a problem where classes are more easily separable. This dataset was downsampled to 10K observations for all uses in this paper.

Human Activity Recognition (HAR) (Anguita et al., 2012)**:** 10299 samples from 30 subjects performing $K = 6$ activities of daily living used for human activity recognition, described with 561 dimensions that encode 3-axial linear acceleration and 3-axial angular velocity measured on the subjects.

MNIST (LeCun and Cortes, 2010)**:** 70K samples of $K = 10$ handwritten digits from 0 to 9, rendered as 28x28-pixel gray scale images, flattened to 784-element vectors. This dataset was downsampled to 10K observations for all uses in this paper.

Reuters Newswire Dataset (Thoma, 2017)**:** 8432 observations of news report documents, from which 5000 attributes were extracted using TF-IDF (Salton and McGill, 1986), a standard method in text processing. This is a subset of the full dataset which contains data for the $K = 6$ most frequent classes.

Figure 3 shows the maps created by SDBM for these datasets, with the same types of classifiers used in Sec. 4.1. Even though the current real-world datasets are considerably more complex and harder to separate into classes, the classifiers' decision boundaries are clearly visible. Simpler classifiers (Logistic Regression and SVM) show decision zones that are more contiguous and have smoother, simpler, boundaries. More complex classifiers (Random Forests and Neural Networks) show more complex shapes and topologies of the decision zones. In particular, the maps created for the Random Forest classifiers show very jagged boundaries. This can be a result of having an ensemble of classifiers working together.

Encoding Classifier Confidence: Figure 4 shows maps created by SDBM with classifier confidence encoded as brightness, as described in Sec. 3. This allows us to see how different classifiers model probability very differently, and thus produce different results.

The added value of encoding confidence can be seen if we compare the first-*vs*-second, respectively third-*vs*-fourth, rows in Fig. 4. The confidence-encoding maps show a smooth brightness gradient, dark close to the decision boundaries (where colors change in the images) and bright deep in the decision zones. The effect is slightly reminiscent of shaded cushion maps (van Wijk and van de Wetering, 1999), *i.e.*, it enhances the visual separation of the color-coded decision zones. More importantly, the shading gradient effectively shows how confidence increases as we go deeper into the decision zones for different classifiers: For example, for the HAR dataset, these shaded bands are quite thin for Logistic Regression and SVM, thicker and less informative for Random Forests, and extremely and uniformly thin for Neural Networks. This tells us that Neural Networks have an overall very high confidence everywhere (except very close to the decision boundaries); Logistic Regression and SVM are less confident close to the boundaries; and Random Forests have a higher variation of confidence over the data space. For Random Forests, we see that the darkest region falls in the area of the central blue decision zone and the top-right of the left yellow zone. This are precisely the areas where the map of this classifier significantly differs from those of all the other three classifiers. Hence, we can infer that the isolated blue decision zone that Random Forests created is likely wrong, as it is low confidence *and* different from what all the other three classifiers created in that area. For the Reuters dataset (Fig. 4 bottom row), we see that all classifiers produced a beige region at the top left corner. The confidence information (brightness) shows us that all classifiers but one (SVM) treat this region as a low confidence one. This can be explained by the total absence of training samples in that region. More importantly, this tells us that the behavior of SVM in this region is likely wrong.

Confidence visualization also serves in quickly and globally assessing the *overall quality* of a trained classifier. Consider *e.g.* the Reuters dataset (Fig. 4 bottom row). Compared to all other three rows in Fig. 4, the decision maps for this dataset are darker. This shows that this dataset is harder to *extrapolate from* during inference. Note that this is not the same as the usual testing-after-training in ML. Indeed, for testing, one needs to 'reserve' a set of samples unseen during training to evaluate the trained classifier on. In contrast, SDBM's decision maps do not need to do this as they synthesize 'testing' samples on the fly via the inverse projection P^{-1}. Moreover, classical ML testing only gives a global or per-class accuracy. In contrast, SDBM gives a per-region-of-the-data-space confidence, encoded by brightness.

Comparison with the Original DBM: Figure 5 shows maps created by SDBM side-by-side with maps created by the original DBM technique, using Logistic Regression, Random Forest and k-NN classifiers, for three real-world datasets. In this experiment, we used UMAP (McInnes and Healy, 2018) as the direct projection for DBM, and iLAMP (Amorim et al., 2012) for the inverse projection, respectively Several important observations can be made, as follows.

First, we see that the projections $P(D)$ of the same datasets are not the same with DBM and SDBM – compare the bright-colored dots in the corresponding figures. This is expected, since, as explained in Sec. 3, DBM employs a user-chosen projection technique P, whereas SDBM *learns* P from the label-based clustering of the data, following the SSNP method (see Sec. 3). Since the projections $P(D)$ of the same datasets differ for the two methods, it is expected that the overall shapes of the ensuing decision boundaries will also differ – see *e.g.* the difference between the nearly horizontal decision boundary between the blue and red zones for Random Forests with DBM for FashionMNIST (2-class) and the angled boundary between the same zones for the same classifier, same dataset, with SDBM (Fig. 5, middle row, two leftmost images). For the relatively simple classification problem that FashionMNIST (2-class) is, this is not a problem. Both DBM and SDBM produce useful and usable renditions of the two resulting decision zones, showing that this classification problem succeeded with no issues.

When considering more difficult datasets (FashionMNIST 10-class or HAR), the situation is dramatically different: DBM shows *highly* noisy pictures, where it is even hard to say where and which are the actual decision zones. These images suggest that none of the three tested classifiers could correctly handle these datasets, in the sense that they would change decisions extremely rapidly and randomly as points only slightly change over the data space. This is *known* not to be the case for these datasets and classifiers. Logistic Regression has built-in limitations of how quickly its decision boundaries can change (Rodrigues et al., 2019). k-NN is also known to construct essentially a Voronoi diagram around the same-class samples in the *n*D space, partitioning that space into cells whose boundaries are smooth manifolds. DBM does not show any such behavior (Fig. 5, third and fifth columns). In contrast, SDBM shows a far lower noise level and far smoother, contiguous, decision zones and boundaries. Even though we do not have formal ground truth on how the zones and boundaries of these dataset-classifier combinations actually look, SDBM matches better the knowledge we have on these problems than DBM.

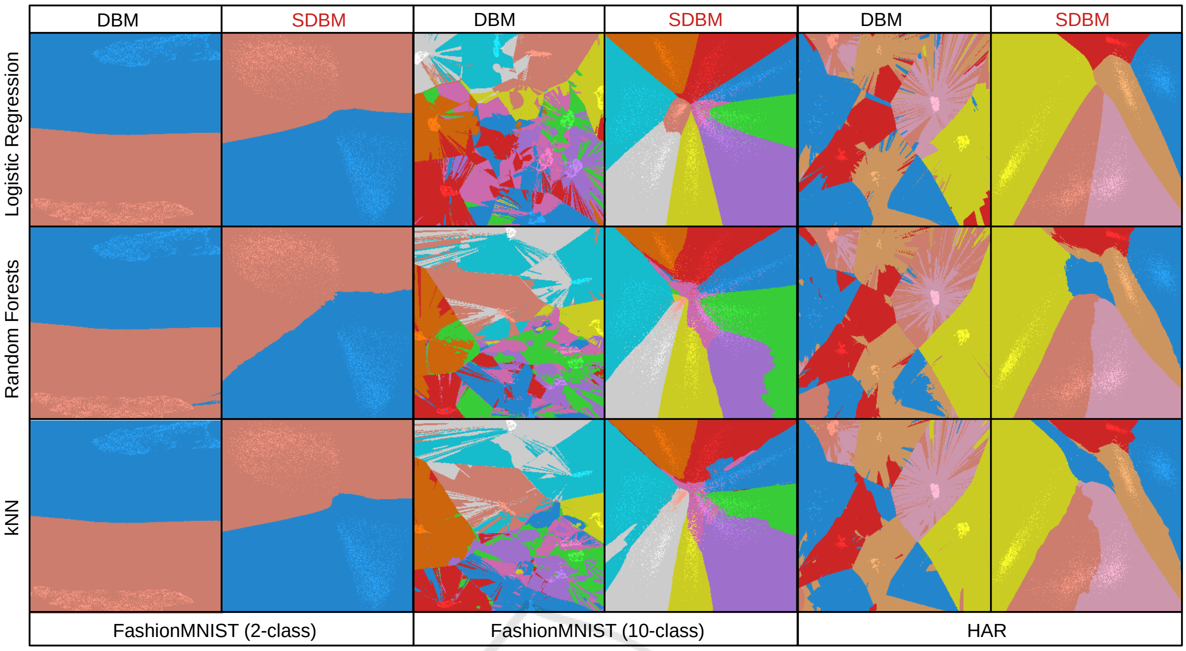

Figure 5: Comparison between SDBM and DBM using three different datasets and three classifiers.

4.3 Computational Scalability

We next study the scalability of SDBM and compare it to the original DBM method. For this, we created maps using synthetic Gaussian blobs datasets with 5 clusters, varying the dimensionality from 10 to 500, and varying the map size from 25^2 to 300^2 pixels. We did not use larger maps since the speed-trends were already clear from these sizes, with DBM getting considerably slower than SDBM. Figure 6 shows the running times of both methods as a function of both the grid size (horizontal axis) and dataset dimensionality (different-color lines). We see that DBM's runtime increases quickly with dimensionality, taking about 5 minutes to create a 300^2 map for the 500-dimensional dataset.

In contrast, SDBM is over an order of magnitude faster, taking roughly 7 seconds to run for the same dataset. Also, we see that SDBM's speed only *marginally* depends on the dimensionality, whereas this is a major slowdown factor for DBM. With respect to the number of samples, we see that both methods exhibit similar trends, with SDBM being closer to a linear trend than DBM. However, the slope of the SDBM graphs is smaller than for DBM for the same dimensionality. All in all, this shows that SDBM is significantly more scalable than DBM. This can be explained by the fact that SSNP, which underlies SDBM, *jointly* trains both the direct and inverse projections by deep learning. As this is GPU-accelerated, linear in the sample and dimension counts both for training and inference, and does not need to use different resolutions and sampling tricks for accelerating the 2D to *n*D mapping (see Sec. 3). In contrast, DBM uses UMAP and iLAMP for the direct, respectively, inverse projections (as mentioned earlier). None of these techniques is GPU-accelerated.

4.4 Implementation Details

All experiments presented above were run on a dual 8-core Intel Xeon Silver 4110 with 256 GB RAM and an NVidia GeForce RTX 2070 GPU with 8 GB VRAM. Table 1 lists all open-source software libraries used to build SDBM and the other tested techniques. Our implementation, plus all code used in this experiment, are publicly available at (The Authors, 2021).

Table 1: Software packages used in the evaluation.

Technique	Software used publicly available at
SSNP	keras.io (TensorFlow backend) (Chollet and others, 2015)
UMAP	github.com/lmcinnes/umap (McInnes and Healy, 2018)

5 DISCUSSION

We discuss how our technique performs with respect to the criteria laid out in Section 1.

Quality (C1): SDBM is able to create maps that show classifier decision boundaries very clearly, and, most importantly, much clearer than the maps created with

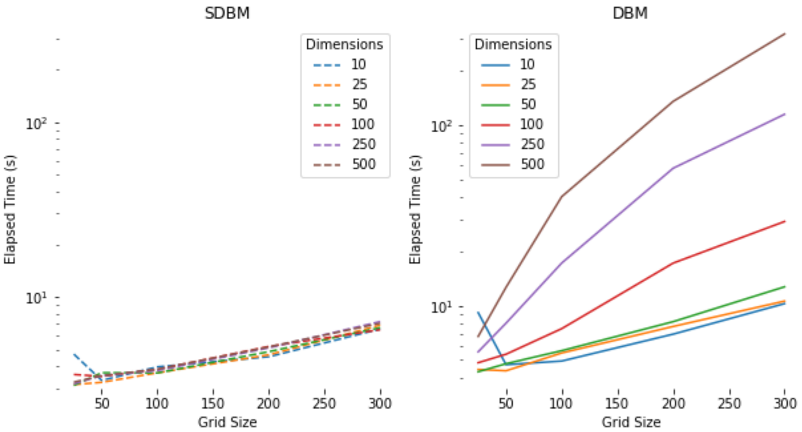

Figure 6: Plot showing the order of growth of time used to create maps of increasing size using DBM and SDBM, using synthetic datasets of varying dimensionality. Vertical axis is in logarithmic scale.

the original DBM. For the same dataset-classifier combinations, SDBM's maps show significantly less noise, more compact decision zones, and smoother decision boundaries, than DBM. These results are in line with what we expect for dataset-classifier combinations for which we have ground-truth knowledge about their decision zones and boundaries (see Fig. 5 and related text). As such, we conclude that SDBM captures the actual decision zones better than DBM can do.

Scalability (C2): SDBM is an order of magnitude faster than DBM. Since SDBM scales linearly in the number of observations during inference/drawing, and it is end-to-end GPU-accelerated, it is able to generate maps having hundreds of thousands of pixels in a few seconds, which makes it practical for handling large datasets and rendering highly detailed decision maps.

Ease of use (C3): SDBM produces good results with minimal tuning. The single performance-sensitive setting is the size of the map image. All maps in this paper have 300^2 pixels. As the figures show, this resolution is already sufficient for rendering detailed decision maps for all the tested dataset-classifier combination. Compared to DBM, SDBM tuning is far simpler, as it does not require tuning of cell and sample sizes required by the former (for details of DBM tuning, we refer to (Rodrigues et al., 2019)).

Genericity (C4): As for the original DBM method, SDBM is agnostic to the nature and dimensionality of the input data, and to the classifier being visualized. We show that SDBM achieves high quality on datasets of different natures and coming from a wide range of application domains, and with classifiers based on quite different algorithms. As such, SDBM does not trade any flexibility that DBM already offered, but increases quality, scalability, and ease of use, as explained above.

Limitations: SDBM shares a few limitations with DBM. First and foremost, it is hard to *formally* assess the quality of the decision maps it produces for dataset-classifier combinations for which we do not have clear ground-truth on the shape and position of their decision zones and boundaries. Current testing shown in this paper has outlined that SDBM produces results fully in line with known ground truth for such simple situations. However, this does not formally guarantee that the same is true for more complex datasets and any classifiers. Finding ways to assess this is an open problem to be studied in future work. Secondly, the interpretation of the SDBM maps can be enhanced. Examples shown in this paper outlined how such maps can help finding out whether a trained classifier can generalize well, and how far, from its training set, and how different classifier-dataset combinations can be compared by such maps. Yet, such evidence is qualitative. A more formal study showing how users actually interpret such maps to extract quantitative information on the visualized classification problems is needed.

6 CONCLUSION

We have presented SDBM, a new method for producing classifier Decision Boundary Maps. Compared to the only similar technique we are aware of – DBM – our method presents several desirable characteristics. First and foremost, it is able to create decision maps which are far smoother and less noisy than those created by DBM and also match the known ground-truth of the visualized classification problems far better than DBM, therefore allowing users to interpret the studied classifiers with less confusion. Secondly, SDBM is about an order of magnitude faster than DBM due to its joint computation of direct and inverse projections on a fixed-resolution image. Finally, SDBM has virtually no parameters to tune (apart from the resolution of the desired final image) which makes it easier to use than DBM.

Future work can target several directions. We believe a very relevant one to be the generation of maps for multi-output classifiers, *i.e.*, classifiers that can output more than a single class for a sample. Secondly, we consider organizing more quantitative studies to actually gauge which are the interpretation errors that SDBM maps generate when users consider them to assess and/or compare the behavior of different classifiers, which is the core use-case that decision maps have been proposed for. Thirdly, we consider adapting SDBM to help the understanding of semantic segmentation models. Last but not least, the packaging of SDBM into a reusable library that can be integrated into typical ML pipelines can help it gain widespread usage.

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