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**A thesis submitted in partial fulfilment  
of the requirement for the degree of Doctor of Philosophy**

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**Cardiff University  
School of Computer Science & Informatics**

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**To People you care  
for their patience and support.**

# Abstract

We produce interpretable representations, and demonstrate their applicability in interpretable classifiers. Our approach is model-agnostic, given a similarity-based representation, we are able to produce a representation in terms of domain knowledge. We evaluate the interpretability of our representation and provide examples of interpretable classifiers with our representation.

## **Acknowledgements**

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# List of Algorithms

# List of Acronyms

**ML** Machine Learning

**NLP** Natural Language Processing

**NDCG** Normalized Discounted Cumulative Gain

## 0.0.1 Definitions

**Domain** Where the data was originally sourced from  $DOM^I MDB$ , e.g. IMDB movie reviews.

**Word** A string of alphanumeric characters that originated from text in the domain  $DOM_w$ , e.g. the  $w = "Horror"$  from a domain of IMDB movie reviews  $DOM^I MDB$ .

$w$

**Corpus of Documents** A unique group of words, e.g. a review from a domain of IMDB movie reviews  $DOM_I MDB$ .

$C_d w$

**Document** A document of words

$d_w$

**Vector Space** A representation composed of vectors.

$S_v$

**Semantic Space** A representation where spatial relationships between vectors correspond to semantic relationships.

$S_v$

**Word frequency** The frequency of a word  $w$  for its document  $D_w f$ .

$wf$

**Bag-Of-Words** a matrix BOW of documents  $BOW_D$  where each document is composed of unordered frequencies of words  $D = [wf_1, \dots, wf_n]$ . and Conceptual Space we obtain a representation of entities composed of properties. Then, we cover the additional methods we propose to improve this process.

$BOW_d$

**Bag-Of-Words PPMI**

**Feature** A feature is a distinct useful aspect of the domain, corresponding to a numerical value.

$R_f$

**Hyper-plane** The hyper-plane for a word

$H_w$

**Direction vector** The orthogonal direction to a hyper plane that separates a word in a vector space.

$D_w$

**Cluster label** A cluster of words that describe a property.

$C_w$

**Cluster direction** The averaged directions of all words in the label.

$D_C$

**Feature rankings** The rankings induced from a feature direction.

$R_D C$





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# Chapter 1

## Introduction

### 1.1 Motivation

With the rise of services on the web that enable large-scale user-generation of text data, e.g. Social Media sites (Facebook, Twitter), Review sites (IMDB, Rotten Tomatoes, Amazon) and content-aggregation sites (Reddit, Tumblr), the internet has become largely populated by text posts that are related to some specific, niche topic within a domain. For example, a review on Amazon for a product is specially tailored text for that product within the domain of Amazon reviews. Taken from a closer lens, we could even argue that each review-type has its own domain, e.g. Product reviews, Food reviews, Movie reviews. However, the text posts themselves are largely unstructured semantically. Humans can have an intuitive understanding of the semantics that are present in unstructured text, but machines do not.

One task of Natural Language Processing is to obtain this semantic understanding from text by obtaining a machine-readable representation that contains domain knowledge. A basic approach to obtain a representation of this text is to represent entities (e.g. reviews, text-posts) by the frequency of their words, see 1.1.

Below, we show a review with its associated properties labelled.

We can understand these properties to have a degree to which they apply, for example the size of the clothing might be "XXL", "XL", "L", "M" or "S", or the quality may be "Very good", "Good", "Ok", "Bad" or "Very bad". For the former, we may rely

<u>Entity: X</u>		<u>Entity: Y</u>		<u>Entity: Z</u>	
<u>Word</u>	<u>Frequency</u>	<u>Word</u>	<u>Frequency</u>	<u>Word</u>	<u>Frequency</u>
Dog	51	Dog	51	Dog	51
Cat	40	Cat	40	Cat	40
Man	11	Man	11	Man	11
Cheese	0	Cheese	0	Cheese	0
Dog	51	Dog	51	Dog	51
Cat	40	Cat	40	Cat	40
Man	11	Man	11	Man	11
Cheese	0	Cheese	0	Cheese	0

Figure 1.1: Bag-of-words

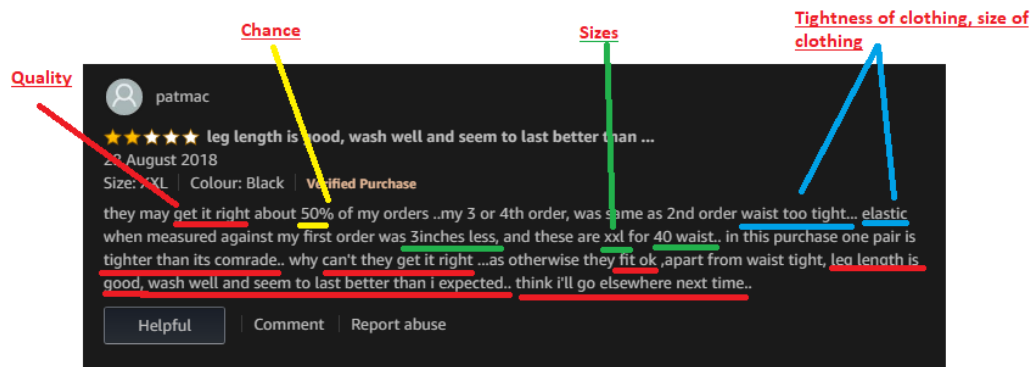


Figure 1.2: Example properties

on the metadata available from the site itself, but for the latter the way to obtain this information is less clear. Although we may infer that the rating has some indication of these properties, it does not describe the properties or the degree to which the review refers to them. This kind of information is valuable for making sense of the world

of unstructured text, and has broad applications, e.g. The most immediate example is perhaps that they allow for a natural way to implement critique-based recommendation systems, where users can specify how their desired result should relate to a given set of suggestions [?]. For instance, [?] propose a movie recommendation system in which the user can specify that they want to see suggestions for movies that are “similar to this one, but scarier”. If the property of being scary is adequately modelled as a direction in a semantic space of movies, such critiques can be addressed in a straightforward way. Similarly, in [?] a system was developed that can find “shoes like these but shiner”, based on a semantic space representation that was derived from visual features. Semantic search systems can use such directions to interpret queries involving gradual and possibly ill-defined features, such as “*popular* holiday destinations in Europe” [?]. While features such as popularity are typically not encoded in traditional knowledge bases, they can often be represented as semantic space directions.

### 1.1.1 Directions

However, manually labelling these properties and the degrees to which entities (e.g. reviews, text-posts) have them is extremely time-consuming.

A potentially ideal system would be as follows: We collect large amounts of unstructured text data, separated into domains, and obtain the properties of each domain from this data, and rank entities on the degree to which they have these properties. In this way, properties would be understood on a scale built from the domain directly, so that each domain has its own meanings for words according to their own idiosyncrasies. As the process does not require any manual labelling the quality of these properties could be improved simply by obtaining more data. Further, as we are learning from unstructured data, not only would this allow us to understand the data in terms of what we know, but it would also introduce us to new ideas that we may not have previously understood. This kind of representation also has value in application to Machine Learning tasks. If we can separate the semantics of the space linearly into properties,

we are able to learn simple linear classifiers that perform well.

Simple linear classifiers built from a representation composed of rankings on properties have an additional benefit of being more understandable.

## 1.2 Interpretability

Most successful approaches in recent times, like vector-spaces, word-vectors, and others, rely on the distributional model of semantics. This model relies on encoding unstructured text e.g. of a movie review, as a vector, where each dimension corresponds to how frequent each word is, we are able to calculate how similar the entities are, e.g. we know that if two movies have a similar distribution of words in their reviews, like frequent use of the word 'scary', or 'horror', then they would have a higher similarity value. These models, also known as 'semantic spaces' encode this similarity information spatially.

Semantic relationships can be obtained from semantic spaces.

applications/need for good interpretability:

- Safety
- Troubleshooting, bug fixing, model improvement
- Knowledge learning
- EU's "Right to explanation"
- Discrimination

properties of an interpretable classifier:

- Complexity: 'the magic number is seven plus or minus two' [10] also has many positive effects for its users, like lower response times [9, 7], better question answering and confidence for logical problem questions [7] and higher satisfaction [9].
- Transparency:
- Explainability:
- Generalizability:

Properties, entities, the benefits and application of a representation formed of these

Basic introduction to directions, explanation of the utility and application of our approach

## 1.3 Thesis Overview / Contributions

In 3, we focus on further experimenting with one relationship that was formalized in [6]: a ranking of entities on properties. In particular, we use this method of building a representation of entities as a way to convert a vector space into an interpretable representation, for use in an interpretable classifier. The reason that we chose this representation to expand on is because by representing each entity  $e$  with a vector  $v$  that corresponds to a ranking  $r$ , the meaning of each dimension is distinct, and we are able to find labels composed of clusters of words for these dimensions. Here, we make the distinction between a property and a word, a property is a natural property of the space that exists in terms of a ranking of entities, and words are the labels we use to describe this property.

# Background

## 2.1 Text Representations

Need to write about the concept of salient features of a domain here.

### 2.1.1 Bag-of-words

We begin by processing an unstructured text corpus, composed of documents  $C_D$ . We then remove all punctuation, convert any accented characters to non-accented characters, and lowercase the documents to obtain word tokens for each document  $D_W$ . From here, we can assume that any  $W \approx W$  will now  $W = W$ , if a word varied in format but not alphanumeric characters.

Then, we count the occurrences of each word

- Frequency
- Tf-idf
- PPMI

## 2.2 Text classification

### 2.2.1 Decision Trees

- Explanation of what decision trees are
- Explanation that they may not perform well on sparse information

### 2.2.2 Support Vector Machines

- Performance increase for support vector machines on sparse data, balancing, etc

### 2.2.3 Neural Networks

- Difference between SVM and Nnet

### 2.2.4 Semantic Spaces

Bag-Of-Words representations of text result in large sparse vectors for each document,

**How do vector spaces represent semantics? Why do we use them to represent semantics?**

Distributional representations of semantics, known as 'semantic spaces' are well-recognized for their ability to represent semantic information spatially. These representations have been widely adopted for Natural Language Processing (NLP) tasks thanks to their ability to represent complex information in a dense representation. In particular, entity-embeddings have been applied to represent items in recommender systems [?, ?, ?], to represent entities in semantic search engines [?, ?], or to represent examples in classification tasks [?].

Vector spaces are a popular way to represent unstructured text data, and have been broadly applied to and transformed by supervised approaches. They vary in method, producing structure from Cosine Similarity, Matrix Factorization, Word-Vectors/Doc2Vec, etc. They also vary in how they linearly separate entities. However, their commonality is that they are able to represent semantic relationships spatially. See Section 2.2.4 This brings up an essential point: When using a semantic space, are we taking advantage of relationships that are discriminative or incorrect? The danger of relying on these spaces and the models that use them has greatly affected their adoption in critical application areas like medicine, and has raised legal concerns about their application in e.g. determining if someone is suitable for a loan.

See Section 2.2.4

- Word-vectors

## 2.2.5 Document Representations

### LSA

Principal Component Analysis is a dimensionality reduction method that results in dimensions ordered by importance. Starting with a large data matrix, e.g. our TF-IDF values from before, we first find the covariance matrix for these values. Then, from this covariance matrix we obtain the eigenvalues. We can then linearly transform the old data in-terms of this covariance matrix to obtain a new space of size equal to an arbitrary value smaller than our matrix.

- PCA
- MDS



## 2.3 Interpretable Representations

a. NNSE b. compositional c. 2007 paper as wikipedia similarities d. Topic models e. Infogan, etc

[?] Sparse PCA (Why not compare lol)

Vector space models typically use a form of matrix factorization to obtain low-dimensional document representations. By far the most common approach is to use Singular Value Decomposition [?], although other approaches have been advocated as well. Instead of matrix factorization, another possible strategy is to use a neural network or least squares optimization approach. This is commonly used for generating word embeddings [?, ?], but can similarly be used to learn representations of (entities that are described using) text documents [?, ?, ?]. Compared to topic models, such approaches have the advantage that various forms of domain-specific structured knowledge can easily be taken into account. Some authors have also proposed hybrid models, which combine topic models and vector space models. For example, the Gaussian LDA model represents topics as multivariate Gaussian distributions over a word embedding [?]. Beyond document representation, topic models have also been used to improve word embedding models, by learning a different vector for each topic-word combination [?].

The most commonly used representations for text classification are bag-of-words representations, topic models, and vector space models. Bag-of-words representations are interpretable in principle, but because the considered vocabularies typically contain tens (or hundreds) of thousands of words, the resulting learned models are nonetheless difficult to inspect and understand. Topic models and vector space models are two alternative approaches for generating low-dimensional document representations.

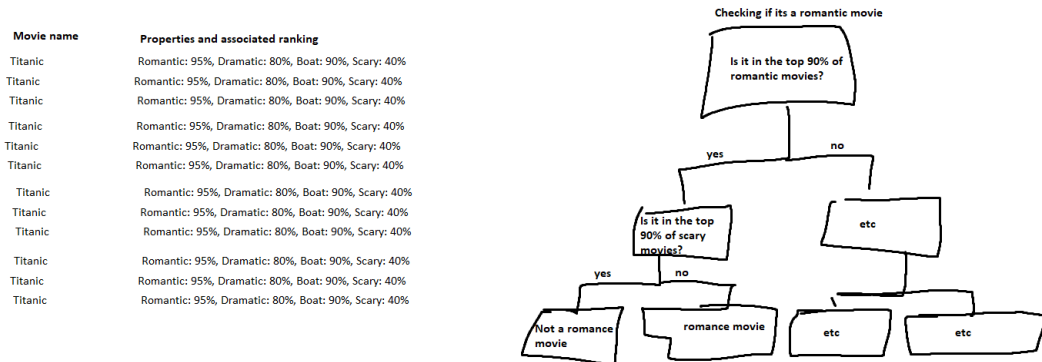
### 2.3.1 Word Vectors

# Converting Vector Spaces into Interpretable Representations

## 3.1 Introduction

The ever more pervasive digital infrastructure that supports our lives has resulted in many opportunities to obtain data and models to make sense of that data. Semantic Spaces that encode semantic relationships between documents spatially have recently achieved strong results on tasks like X, Y, Z. These neural-network learned representations make use of a variety of new information like grammatical structure, word-context and even image data. Further, as domains become more entrenched in the digital world, the need for models in safety critical domains like medicine or legal domains like credit evaluation have increased the need for producing interpretable models, as well as interpretable representations. However, the dimensions of a semantic space do not correspond to human understandable features, and standard approaches to interpretable text representations do not match the performance of these methods. Ideally, we would obtain a representation that makes use of the rich semantic relationships from a high-performing semantic space, but also has dimensions corresponding to interpretable features. To this end, we aim to introduce in this chapter a methodology to linearly transform a semantic space using just its associated bag-of-words as input into an interpretable representation, and demonstrate the applicability of this

and rep.png

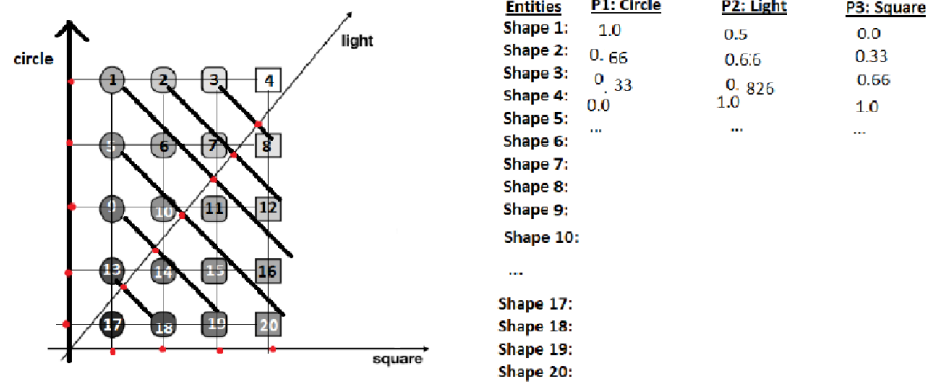


**Figure 3.1: Example movies and selected associated dimensions, chosen according to their relevance to the genre task..**

interpretable representation to simple interpretable classifiers.

Derrac [6] introduced an unsupervised method to go from a semantic space and its associated bag-of-words to a representation where each dimension is a ranking of documents on a feature of the domain. For example, in the domain of movie reviews genres would be a feature, and the dimension would have a numeric value for each document corresponding to the degree it is a particular genre. The contribution of this Chapter is an analysis and experimentation on the quality of these features applied to document classification. The main insight from our work is that these interpretable features do not suffer a performance drop in a non-linear classifier compared to the original representation, and can outperform the original representation and a baseline interpretable representation in a linear classifier. In addition, we find that if a dimension ranks documents on a feature relevant to the task, it can be competitive with more complex models using a single decision tree node. We show an example of the representation from a domain of IMDB movie reviews in 3.1.

There are many types of semantic relationships in a semantic space. For our work, the representation is composed of rankings of documents on semantic directions in the space, in particular where those directions correspond to features. We show an example of the kind-of directions we use to obtain our representation in 3.2. Directions



**Figure 3.2: An example in a toy domain of shapes.**

from domain-specific semantic spaces have been used previously in a variety of ways, For instance, [?] found that features of countries, such as their GDP, fertility rate or even level of CO<sub>2</sub> emissions, can be predicted from word embeddings using a linear regression model. Similarly, in [?] directions in word embeddings were found that correspond to adjectival scales (e.g. bad < okay < good < excellent) while [?] found directions indicating lexical features such as the frequency of occurrence and polarity of words.

This chapter continues as follows: We begin by describing related work, then explain the method, making explicit the variations we have introduced for our experimental work. We follow this with the results of our experiments accompanied by qualitative examples and explanations, and finish with a conclusion on the benefits and limitations of this approach.

## 3.2 Related Work

### 3.2.1 Semantic Relations & Their Applications

Our method uses the relationships inherent in a semantic space. Other work has formalized the relationships found in semantic spaces, for example in word-vectors, linear analogies (see Section ??, were found where the vector between king and queen was parallel to the vector between prince and princess. These relationships have been expanded on, for example [11] found that "equivalent relations tended to correspond to parallel vector differences" [8], and [8], found that by decomposing representations into orthogonal semantic and syntactic subspaces they were able to produce substantial improvements on various tasks. Additionally, they have also been found to hold inherent gender bias [?] as word distances between gendered words (e.g. male, female, she, her) and occupational words e.g. (nurse, programmer) were correlated to the percentage of occupation that gender had for that role in different time periods. **Linear Classifiers** Decision trees, linear SVM's, logistic regression, decision tables, IF Then rules.

What are the available options for interpretable linear classification?

How have each of these methods been measured or validated in the literature in regards to interpretability? How about application to real world situations?

**Non linear classifiers** What non linear classifiers networks are interpretable? How have they done it? How have they measured it? How does it compare to a linear method?

*Neural networks* Approximating w/linear model, Interpretable nodes/weights

*Other Stuff*

### 3.2.2 Interpretable Representations

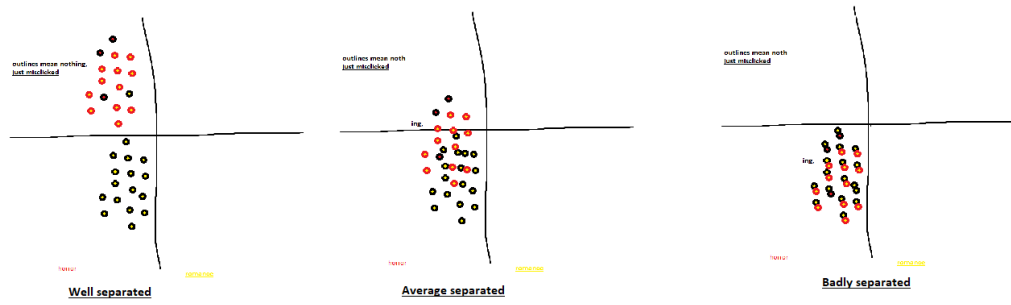
There are two ways in which topic models can be used for document classification. First, a supervised topic model can be used, in which the underlying graphical model is explicitly extended with a variable that represents the class label [4]. Second, the parameters of the multinomial distribution corresponding to a given document can be used as a feature vector for a standard classifier, such as a Support Vector Machine (SVM) or Decision Tree. LDA has been extended by many approaches, e.g. aiming to avoid the need to manually specify the number of topics [?], modelling correlations between topics [3], or by incorporating meta-data such as authors [?] or time stamps [?].

Broadly speaking, in the context of document classification, the main advantage of topic models is that their topics tend to be easily interpretable, while vector space models tend to be more flexible in the kind of meta-data that can be exploited. The approach we propose in this paper aims to combine the best of both worlds, by providing a way to derive interpretable representations from vector space models.

One of the more popular models for text representation that labels features in a similar way to our method are Topic Models.

## 3.3 Method

This section details the methodology to go from a Bag-Of-Words (BOW) 2.1.1 and Semantic Space 2.2.4, to interpretable vectors that rank documents on features of the domain, e.g. A movie would be ranked on how *Scary*, *Horror*, *Bloody* it is for one dimension of the feature-vector, and how *Romantic*, *Love*, *Cute* it is in another, ideally with as many dimensions as there are distinct salient features of the domain. For the semantic space, we compute the Positive Pointwise Mutual Information (See ??) scores



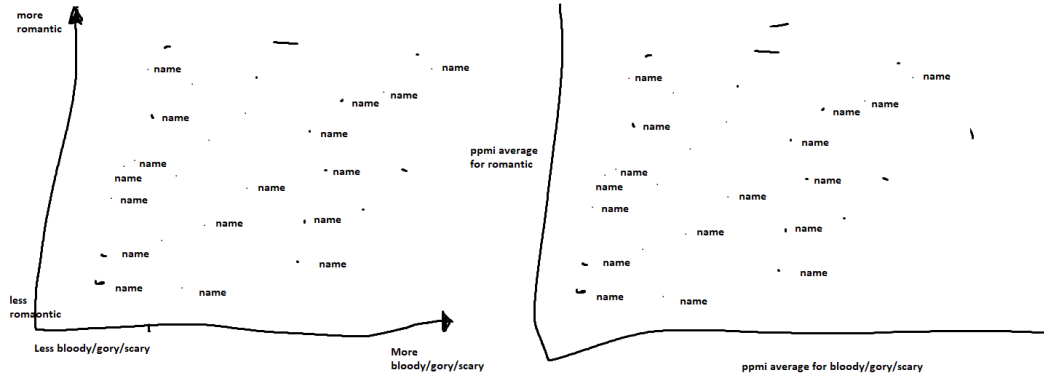
**Figure 3.3: Original And Converted.**

for the Bag-Of-Words, and use that as input to a variety of different off-the-shelf dimensionality reduction algorithms. We explain these in further detail in Section ??.

The method to obtain interpretable feature-vectors is an extension of the work by [?]. This previous work showed how to, filter out words, cluster words to get features, and obtain rankings of documents on those features. In this section, we further analyse and extend this work, in particular by testing a variety of additional filtering methods and clustering methods, and demonstrating how these feature-vectors can produce simple linear interpretable classifiers.

### 3.3.1 Term Rankings

**Structure of a Semantic Space** Salient features of the domain are encoded in the structure of a semantic space, see Section 2.2.4 for more detail. We can expect that for these salient features, they will be more linearly separable than words, and be spatially organized in a way that reflects the similarity between their associated PPMI scores that the space was constructed from. In particular, we expect that documents will be arranged in a direction, where generally the higher the PPMI score for a group of words that correspond to a feature (e.g. *Horror*, *Scary*, *Gore*) the further away they will be from those that have low PPMI scores for those words. We give examples of this in Figure 3.4, by projecting documents into a 2D space of salient features we are able



**Figure 3.4: Original And Converted.**

to show that these documents are structured according to directions for these features. Salient features will typically be a more abstract representation which will be natural in the domain, e.g. in a domain of IMDB movie reviews, genres. However, in this section we show how to extract rankings of documents on words, with the understanding that all words may not be features of the domain. In the next sections, we aim to use these words to extract salient features by filtering and clustering.

**Obtaining directions for each word** For each word  $w$ , a Support Vector Machine (See Section 2.2.2) classifier is trained on the binary Bag-Of-Words representation of that word, where words are labelled as positive if they occurred more than once ( $w_f \geq 1$ ) and negative otherwise. Although the separation of documents is binary, given the structure of the semantic space we can expect for salient features that the documents close to the hyper-plane on the positive side will have lower PPMI scores for the term than those furthest from the hyper-plane on the positive side, as they are closest to the documents that are classified negatively. Following this, we can consider the vector  $v_w$  perpendicular to the hyperplane as the direction that models documents from least relevant at the distance furthest from the hyperplane on the negative side to most relevant for the word  $w$  at the distance furthest from the hyperplane at the positive



side.

**Ranking documents on directions** Once we have obtained a direction vector for each word  $v_w$  the next step is to quantify the degree to which each document has that word, by obtaining a value that corresponds to how far-up it is on the direction vector. These are our rankings of documents on words, if  $p_d$  is the representation of an document in the given vector space as a point then we can think of the dot product between the hyper-plane and the document vector  $H_w \cdot p_d$  as the ranking  $r_{dw}$  of the document  $d$  for the word  $w$ , and in particular, we take  $r_{d1} < r_{d2}$  to mean that  $d_2$  has the property labelled with the word  $w$  to a greater extent than  $e_1$ .

### 3.3.2 Filtering Words

With the rankings  $R_r$ , we could create a representation of each document  $d$ , composed of  $w_n$  dimensions, where each dimension is a ranking of the document  $d$  on that word  $r_{dw}$ . However, many of the words are not spatially important enough in the representation to result in a quality ranking - they are not salient features. In this section, we aim to filter the words that are not separable, we evaluate them using a scoring metric, and remove the words that are not sufficiently well scored. We use three different metrics:

**Classification accuracy.** Evaluating the quality in terms of the accuracy of the SVM classifier: if this classifier is sufficiently accurate, it must mean that whether word  $w$  relates to document  $d$  (i.e. whether it is used in the description of  $d$ ) is important enough to affect the semantic space representation of  $d$ . In such a case, it seems reasonable to assume that  $w$  describes a salient property for the given domain.

**Cohen's Kappa.** One problem with accuracy as a scoring function is that these classification problems are often very imbalanced. In particular, for very rare words, a high accuracy might not necessarily imply that the corresponding direction is accurate. For this reason, [6] proposed to use Cohen's Kappa score instead. In our experiments,

however, we found that accuracy sometimes yields better results, so we retain Kappa as an alternative metric.

**Normalized Discounted Cumulative Gain** This is a standard metric in information retrieval which evaluates the quality of a ranking w.r.t. some given relevance scores [?]. In our case, the rankings  $r_d$  of the document  $d$  are those induced by the dot products  $v_w \cdot d$  and the relevance scores are determined by the Pointwise Positive Mutual Information (PPMI) score  $ppmi(w, d)$ , of the word  $w$  in the BoW representation of entity  $d$  where  $ppmi(w, d) = \max\left(0, \log\left(\frac{p_{wd}}{p_{w*} \cdot p_{*d}}\right)\right)$ , and

$$p_{wd} = \frac{n(w, d)}{\sum_{w'} \sum_{d'} n(w', d')}$$

where  $n(w, d)$  is the number of occurrences of  $w$  in the BoW representation of object  $d$ ,  $p_{w*} = \sum_{e'} p_{wd'}$  and  $p_{*d} = \sum_{w'} p_{w'd}$ .

By scoring the words on these features, we can apply a simple cut-off (e.g. the top 2000 scored words) to obtain the most salient words. Ideally, this cut-off would be at the point where the words stop corresponding to salient features. However, it is difficult to determine this. In principle, we may expect that accuracy and Kappa are best suited for binary features, as they rely on a hard separation in the space between objects that have the word in their BoW representation and those that do not, while NDCG should be better suited for gradual features. In practice, however, we could not find such a clear pattern in the differences between the words chosen by these metrics despite often finding different words. In Table ??, we show examples of the differences between the largest differences between the scoring methods.

### Clustering Direction Vectors

If we consider two directions, "Blood" and "Gore", we can understand both of these to be approximating a similar feature of movies, as they both relate to how much blood a movie contains. Because of this, we can expect their directions to be very similar to

each other. This is the first idea behind clustering these directions, if we average these directions together we can obtain a direction inbetween them that is a balance between documents that used the word 'Bloody' to describe the blood and the word 'Gore'. To expand on this, some entities would have the property of being bloody films, but did not necessarily use the term gore in their reviews, same as some entities having the property but using the term gore not bloody, we can understand that this new hyper plane and associated direction more accurately represents the property of a bloody film more than either of the terms individually. By extending this to a clustering method, we can find similar abstract features by ensuring that all similar directions are clustered together.

The word direction for "beautiful" can be nebulous to the interpreter, as it is not clear what it means for a movie to be ranked highly on 'beautiful'. Considering this, clustering provides another advantage, once we cluster the terms to find the property ("beautiful", "cinematography" "shots") we are given context for the word and more easily intuit the feature, in this case it is a feature about how well the movie was directed.

We approach clustering the directions with a variety of methods:

**K-Means** K-Means is a clustering algorithm that starts with determining the amount of clusters,  $K$ . To begin,  $K$  centroids  $c$  are randomly placed into the space. Then, the distance between each point  $p$  and centroid  $c$  (in our case, points are determined by rankings) is calculated. Each point  $p$  is then assigned to its closest centroid  $c$ . Then, the centroids are recomputed to be the mean of their assigned points. This process starting with the distance calculation is repeated until the points assigned to the centroids do not change.

**Derrac's K-Means Variation** This is the clustering method used in the previous work [?]. As input to the clustering algorithm, we consider the  $N$  best-scoring candidate feature directions  $v_w$ , where  $N$  is a hyperparameter. The main idea underlying their approach is to select the cluster centers such that (i) they are among the top-scoring candidate feature directions, and (ii) are as close to being orthogonal to each other as

possible.

The output of this step is a set of clusters  $C_1, \dots, C_K$ , where we will identify each cluster  $C_j$  with a set of words. We will furthermore write  $v_{C_j}$  to denote the centroid of the directions corresponding to the words in the cluster  $C_j$ , which can be computed as  $v_{C_j} = \frac{1}{|C_j|} \sum_{w_l \in C_j} v_l$  provided that the vectors  $v_w$  are all normalized. These centroids  $v_{C_1}, \dots, v_{C_k}$  are the feature directions that are identified by our method.

We choose our first cluster centroid by taking the top-scoring direction for its associated metric. Then, we select centroids until we have reached the desired amount by taking the maximum of the summed absolute cosine similarity of all current centroids, in other words taking the most dissimilar direction to all of the current directions. Once we have selected the centroids, for each remaining direction we find the centroid it is most similar to, and the centroid is updated once the direction has been added.

### 3.3.3 Qualitative Results

**Dimension of the Space**

**Space-type**

**Scoring method**

**Clustering method**

**The effect of dimensions**

**The effect of space-type**

**The effect of scoring method**

### 3.3.4 Quantitative Results

From a domain, e.g. movie reviews, where each document is a collection of reviews for a movie, we preprocess the text such that it is converted to lower-case, and non-alphanumeric characters are removed. From here, we remove standard English stop words using the NLTK library [?]. We show an example of a review’s original and converted formats in Figure 3.3. From this preprocessed corpus, we obtain a Bag-Of-Words where we count the frequency of each term  $BOW_w f$ , see 2.1.1.

#### Datasets

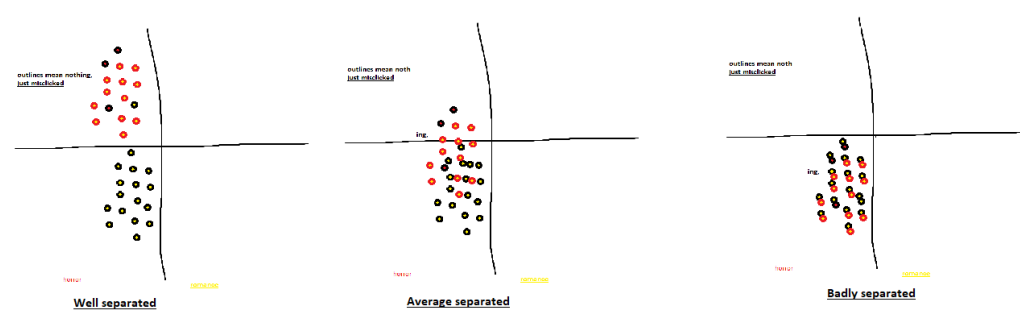
Vocabulary size/entity size/origin of data/classes

#### Semantic Spaces

In this section, we explain how we obtained four different Semantic Spaces.

As the newsgroups contained empty documents after removing all words that do not occur in at least 2 documents, we have removed these empty documents, leaving us with 18302 overall documents. Following this, instead of using the train split as determined by previous literature, we did a simple 2/3 train/test split the same as our IMDB dataset.

This section focuses on using linear classifiers to determine how well our method represents domain knowledge compared to standard baselines. We can understand that an accurate representation of domain knowledge will be one that ensures semantically distinct entities are separated, and semantically similar entities are close together. Put another way, if the space is representing domain knowledge well we can expect that the space should be linearly separable for key semantics of the domain. For example, a good vector space in the domain of movies constructed from IMDB movie reviews should contain a natural separation of entities into genres, where Horror movies are



**Figure 3.5: A conceptual space of movies, where regions correspond to properties and entities are points..**

	Top PPMI scoring terms
Example Horror Entity	Term term term term term term term term term term term term term term
Similar Horror Entity	Term term term term term term term term term term term term term term
Somewhere Inbetween Entity	Term term term term term term term term term term term term term term
Romance Movie	Term term term term term term term term term term term term term term
Similar Romance movie	Term term term term term term term term term term term term term term

**Table 3.1: Two of the following entities: Those classified as horror, those classified as horror and romance, and those classified as romance with their associated highest value PPMI terms. We show the highest positive instances here as the representation is sparse, even though we can also expect the terms that are low scoring to be similar too..**

spatially distant from Romance movies, and movies that are Romantic Horrors would be somewhere inbetween. We can see an example in Figure 3.5. For a Bag-Of-Words, we can expect similar entities to have similarly scoring terms ??.

When selecting the parameters to use for the doc2vec space when obtaining directions, we choose the one that scored the highest for its class on a Linear SVM, rather than tuning the entire process around the doc2vecs vectors. We are not able to obtain an MDS space for sentiment or doc2vec spaces for placetypes/movies.

We obtain results with just these spaces as input, and additionally results for a bag-of-

words PPMI representation. These results act as our baselines for quantitative results, in addition to a Topic Model. We find results using a Linear SVM, and a Decision Tree with an unlimited depth, a depth of 3, a depth of 2, and a depth of 1. Each SVM is tuned using a grid search for the optimal C value, and whether or not to balance the classes. For all trees we attempt to find the best value between [None, 'auto', 'log2'], and additionally try differnet criterion, either the gini score or the information entropy score. In the same way as the SVM's, we include whether or not to balance the classes in the grid search.

### Word Directions

The binary BOW representation for each word that has not been removed by the frequency cut-off is used as a target for a linear SVM, with a Semantic Space as features. We use the scikit-learn libraries LinearSVC implementation with a default C value (1.0). We balance the classes, as many of the binary BOW representations are sparse, and use the primal formulation.

We obtain results for the rankings induced from these word directions on Decision Tree's limited to a depth of 3 in-order to select the best parameters when using directions for each class. The parameters that we want to determine are the type of Semantic Space, the size of the space, the frequency threshold and the score threshold. To do so, for each space-type of each size, we use a grid search to find the best frequency and score cut-offs for that sized space-type. Then, we select from these space-types and sizes the best performing one. We can understand there to be a balance between finding words which are useful for creating salient features in our clustering step without including too many words which do not. As our clustering methods are unsupervised, it is important that we try and limit the amount of junk being entered into them, despite the classifiers that use these directions typically being able to filter out those directions which are not suitable to the class. Additionally, as the vocabulary size varies from dataset to dataset, the threshold will naturally be different for each one.

These results allow us to choose for each class, the best Semantic Space and Scoring-type for that class. For all trees we use grid search to find the best values for the criterion, either the gini score or the information entropy score, the maximum amount of features between [None, 'auto', 'log2'], and additionally, we include whether or not to balance the classes in the grid search.

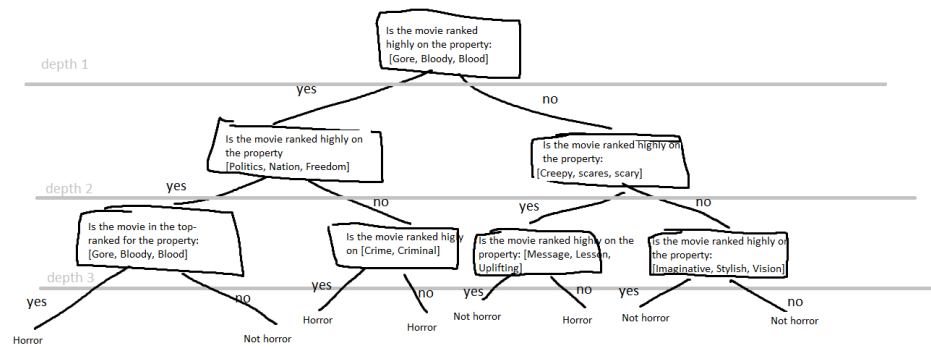
Next, we test single directions, attempting to find a good amount of directions to cluster and not including words which may hamper the unsupervised classification, as well as the best space-type for each domain. We found that generally, X was the best space and as expected classifiers performed better with more data, so we use 20000 as our frequency cutoff and 2000 as our score cutoff. These single directions typically overfit.

### **Clustered Directions**

We continue with the optimal space and score-type chosen by our single direction experiments, and use the same frequency and score thresholds as before. We then experiment with two different clustering algorithms: Derrac and K-Means. As these algorithms select centroids from the top-scoring directions or randomly, we can expect that some clusters may not be salient features of the space. This is because top-scoring directions, e.g. for accuracy could simply infrequent terms that do not have much meaning, and these infrequent terms could also be randomly selected. We could use grid-search on the frequency and score cutoffs when obtaining these results in order to avoid terms that may disrupt existing clusters or form cluster centers that are not salient features of the space, but we chose a more standardized process that would rely on the parameters of the clustering algorithms and the ability of the classifiers to filter out clusters that are not informative, so as to not make a time-costly grid search a necessary part of the process.

With that in mind, we use three clustering algorithms.





**Figure 3.6:** This figure shows an example tree from one of our classifiers. Here, we can see that the model increases in complexity as it increases in depth. In this case, we end-up getting better F-score with just a depth-one tree, as the tree begins to overfit at depth three. .

Mini batch K-means, implemented by scikit-learn <sup>1</sup>, introduced by [?] and kmeans++ to initialize [?]

### Quantitative Results

In Figure 3.6, we demonstrate how depth could affect a Decision Tree that uses salient feature-directions.

<sup>1</sup><https://scikit-learn.org/stable/modules/generated/sklearn.cluster.MiniBatchKMeans.html>

Genres		Keywords			Ratings		
	D1	D2	D3	D1	D2	D3	
Movies	D1						
Space	0.301	0.358	0.354	0.185	0.198	0.201	0.463
Single directions	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Clusters	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Newsgroups		Sentiment			Reuters		
Rep	0.251	0.366	0.356	0.705	0.770	0.773	0.328
Single dir	0.418	0.490	0.537	0.784	0.814	0.821	N/A
Cluster	0.394	0.433	0.513	0.735	0.844	0.813	N/A
Foursquare		OpenCYC			Geonames		
Placetypes	D1	D2	D3	D1	D2	D3	D3
Rep	0.438	0.478	0.454	0.383	0.397	0.396	0.349
Single dir	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Cluster	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Table 3.2: Best-scoring results for each type.

### **3.3.5 Interpretability Results**

## **Fine-tuning Vector Spaces to Improve Their Directions**

"Commonly, these representations are made in a single vector space with similarity being the main structure of interest. However, recent work by Mikolov et al. (2013b) on a word-analogy task suggests that such spaces may have further useful internal regularities. They found that semantic differences, such as between big and small, and also syntactic differences, as between big and bigger, were encoded consistently across their space. In particular, they solved the word-analogy problems by exploiting the fact that equivalent relations tended to correspond to parallel vector differences. [8]

[8] "Explicitly designing such structure into a neural network model results in representations that decompose into orthogonal semantic and syntactic subspaces. We demonstrate that using word-order and morphological structure within English Wikipedia text to enable this decomposition can produce substantial improvements on semantic-similarity, pos-induction and word-analogy tasks."

This means that despite state-of-the-art results in Natural Language Processing tasks like Language Modelling, Machine Translation, Text Classification, Natural Language Inference, Abstractive Summarization, and Dependency Parsing being dominated by neural networks that learn and improve these kind-of representations, it is not clear what information has been represented.

## **4.1 Experiments**

We find that non-linearity is useful.

---

## ***Chapter 5***

# **Investigating Neural Networks In Terms Of Directions**

## **5.1 Appendix**

### **5.1.1 Chapter 3 Space Types**

Genres		Keywords			Ratings		
Movies	D1	D2	D3	D1	D2	D3	D3
Space	50 PCA	50 MDS	100 MDS	200 PCA	200 MDS	200 MDS	50 PCA
Single directions	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Newsgroups		Sentiment			Reuters		
Rep	200 PCA	200 PCA	100 PCA	PCA 100	PCA 50	PCA 50	200 PCA
Single dir	200 MDS	100 D2V	50 D2V	D2V 100	PCA 50	D2V 100	N/A
Foursquare		OpenCYC			Geonames		
Placetypes	D1	D2	D3	D1	D2	D3	D3
Rep	MDS 100	AWV 50	MDS 200	AWV 50	MDS 200	AWV 50	MDS 50
Single dir	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Table 5.1: Space-types, clusters have the same as single directions.

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