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**Measuring mutual information in
Neural Networks**

Computer Science Tripos – Part II

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Proforma

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Original Aims of the Project

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Special Difficulties

¹This word count was computed by `detex *.tex | tr -cd '0-9A-Za-z \n' | wc -w`

Declaration

I, Andrius Grabauskas of Robinson College, being a candidate for Part II of the Computer Science Tripos, hereby declare that this dissertation and the work described in it are my own work, unaided except as may be specified below, and that the dissertation does not contain material that has already been used to any substantial extent for a comparable purpose.

Signed

Date

Contents

1	Introduction	9
1.1	The Information plane	10
2	Preparation	13
3	Implementation	15
3.1	Mutual Information Estimation	15
3.1.1	Mutual Information Definition	15
3.1.2	Theoretically undefined	15
3.2	Calculating Mutual Information	16
3.2.1	Experimental setup	16
3.2.2	Discrete method	17
3.2.3	Kernel Density Estimation	18
3.2.4	Advanced methods	19
3.3	Implementation Optimizations	20
3.3.1	Maximising Resource Utilization	20
3.3.2	Minimising the Workload	20
3.4	As If Random Experiment	22
4	Evaluation	23
4.0.1	Deterministic networks	23
5	Conclusion	25
	Bibliography	25
A	Project Proposal	27

List of Figures

1.1	information plane for a neural network with 5 layers, which was only trained for one epoch.	10
1.2	Information plane for a neural network with 4 layers, which was trained for approximately 10 000 epochs	11
3.1	The general algorithm for calculating mutual information inside a neural network.	16
3.2	Pseudo code for computing mutual information refer to Figure 3.3 and Figure 3.4 for entropy computation.	17
3.3	Algorithm for computing entropy – Discrete method	17
3.4	Algorithm for computing conditional entropy	18
3.5	Algorithm for computing entropy – Kernel Density Estimation method. The same algorithm as used by Saxe.	19
3.6	Example how distance between two epochs is measured.	21
3.7	Delta Skip Approximate	22

Acknowledgements

Chapter 1

Introduction

Deep Neural Networks (DNNs) are an extremely successful tool, they are widely adopted commercially and closely studied academically, however even given the attention they have gathered there is no comprehensive understanding of how these models generalize data and provide such impressive performance - in fact very little is known about how DNNs learn or about their inner workings. Recently Prof. Tishby produced a paper claiming to understand the basic principle of how DNNs work. He suggested that there are two phases that the network goes through while being trained - the fitting phase and the compression phase. During the fitting phase the network memorizes the training data and makes predictions based on what it has seen before, during the compression phase the network generalizes, it forgets the unnecessary information from the training data. Tishby suggested that the incredible performance that DNNs are able to achieve is due to this compression phase, and that this process of compression is a result of randomness inherent in Stochastic gradient descent. Tishby showed this by looking at DNNs through the information domain, most notably he used what is now called the information plane. The information plane summarizes how the information is flowing through the DNN, for every neuron layer the plane shows mutual information it has with the input data and the label data. In his experiments Tishby has concluded that every layer loses unnecessary information from the input data and tries to keep information of the label. Tishby made some interesting and significant claims about how DNNs work, however he did not provide a formal proof, his conclusions are based only on experimental evidence.

In our work we look at Tishby's claim that DNNs compress data and throw away unnecessary information about the input. We reimplement his experiments as a form of independent verification, showing that the results Tishby got are robust and are stable to parameter changes. We also take a look at a paper produced by Saxe that provides an opposing view to that of Tishby's. Saxe showed that compression that Tishby showed is only a result of Tishby's choice of activation function for the neural network. He showed that compression only happens when Tanh activation function is used and does not happen when ReLU is used.

Lastly, we think that the experiments presented in both papers don't fully align with the ideas that Tishby presented to us, specifically his idea that weights should be treated "as if" they are random variables. Tishby's and Saxe's experiment deal with this "as if" random notion quite crudely or try to sidestep it completely. As a result we devised an

experiment that tries to capture this idea more explicitly, although it is still relatively crude and more work should be put into it in the future.

1.1 The Information plane

If we look at a neural network through the lens of information we can think of it as a form of a Markov chain. Where every node takes in a piece of data processes it and passes to the next node. For every such node $t \in T$ we can measure its mutual information with the input patterns $x \in X$ and labels $y \in Y$.

$$Y - X \rightarrow T_1 \rightarrow \dots \rightarrow T_i \rightarrow \hat{Y}$$

In this analogy a node corresponds to a layer in a non-convolutional neural network. When looking at a neural network in this way we can say that its job is to preserve as much information as possible about the label, or to minimise information loss about the label during the transitions from node to node.

The Information plane summarized this Markov chain view and applies it to the entirety of the training process.

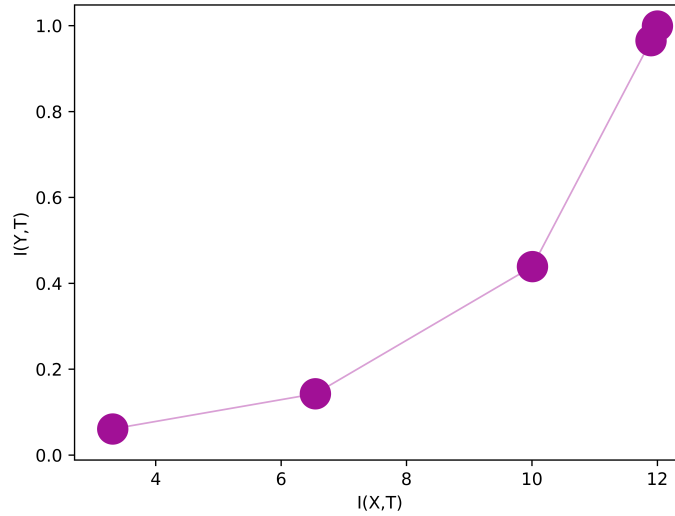


Figure 1.1: information plane for a neural network with 5 layers, which was only trained for one epoch.

Figure 1.1 shows an example of an information plane - in this case the network has 5 layers and has only been trained for one epoch. Every node corresponds to a layer, and the lines between them just help us distinguish the order of the layers. The x -axis shows mutual information between any layer T and the input X , while the y -axis shows mutual information with the label Y .

The figure below corresponds to a network that takes in a 12bit number and maps it to a 1bit number hence the mutual information ranges from 0 to 12 for the x -axis and from 0 to 1 for the y -axis.

The upper right most node corresponds with the very first layer before any data processing occurs, therefore it has maximum mutual information with the input and the label. As the network was only trained for one epoch the weight are essentially random and we see a steep drop in every subsequent layer, with the last layer of the network having close to 0 mutual information with X and Y , which is what we expect if we assume that the network guesses at random before any training is done.

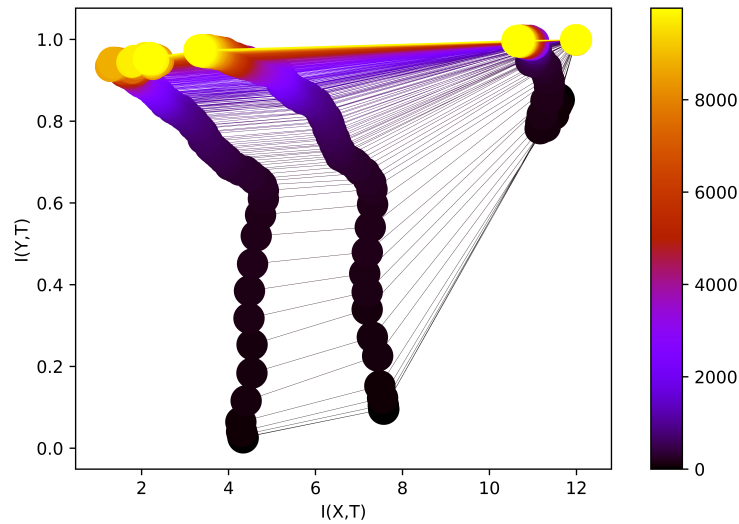


Figure 1.2: Information plane for a neural network with 4 layers, which was trained for approximately 10 000 epochs

Figure 1.2 shows an example of a full information plane. The gradient maps the colour to the epoch. From this figure we can clearly see the fitting and the compression phases Tishby was describing.

- The Fitting phase is the rapid improvement phase at the start of the training period, where information about the label is rapidly increasing while information about the input remains approximately the same. In this case the training is in the fitting phase for less than 1000 epochs.
- The Compression phase begins when the after the fitting phase ends and the rapid improvement stops. We can see during this phase we start losing information about the input while still gaining information about the label. This phase the was majority of the training time.

Chapter 2

Preparation

Before developing a plan for how we are going to realize the project in code we needed to fully understand the ideas presented in the paper:

- We needed to identify the main ideas of the paper and understand why some parts of the paper are not agreed upon in the scientific community. Understand why his ideas are contentious and whether reproducing his experiments could bring more validity to his claims. This involved reading papers published by Tishby and academics who shown an opposing view to him.
- A main tool that the paper relies on is MIE (Mutual Information Estimation). Reading about MIE we quickly understood that MIE is a contentious part of the project as a result we had to do a decent amount of research regarding the subject. MIE is difficult because we are trying to estimate information between two continuous distributions using only a discrete sample set. This area has not seen much academic attention so the tools we ended up using could be greatly improved in the future.

Once we had a reasonable understanding of the ideas in the paper and which areas needed more attention we diverted our attention to figuring out the details of how the experiments were conducted figure out what hyper parameters Tishby decided are important and what assumptions he made whilst devising the experiments.

In addition we needed to find out what resources are available to us online, what programming frameworks we are going to use for the projects implementation, and to think about possible extensions to the project once the success criteria has been achieved.

- Online Resources: The two main papers by Tishby and by Saxe have made their code public online via Github, we made
Online Resources: The two main papers we were looking at has made their code available to the public via Github, the papers are Tishby's paper and the main opposing paper by Saxe.
- Programming frameworks: The original experiment implementation by Tishby has used the Tensorflow framework. We have decided to use the Keras framework as it produces code that is more concise and is easier to read/maintain. Furthermore

rewriting the experiments in a different framework means that we cannot rely on the details of Tishby's and potentially avoid any mistakes that may exist in the original implementation.

- Thinking about how we could extend the project helped us understand the scope of the project and what areas were most important and/or interesting to us.

We came up with a couple of extensions before having written any code but the most interesting one only materialized after a good deal amount of work into the project (that is the AS IF Random experiment described below)

- Different Datasets : the most straight forward extension to the project just using different dataset to the one Tishby used. This is essentially just varying one of the parameters in the Neural Network. (Implemented)
- Quantized Neural Network : the idea behind this was to only allow single neurons to acquire values in a given range say 1...256. This would make the distribution within a DNN later discrete and hence it would make calculating mutual information straightforward. (Not Implemented)
- As If Random : one problem with Tishby's work is that he calculates mutual information for a single epoch at a time which by definition is zero (in his paper he tries to justify the result will explore this later) this extension tries to explore the weights of a neural network as random variables by calculating mutual information for multiple epochs at a time.

Chapter 3

Implementation

3.1 Mutual Information Estimation

As stated before we are trying to validate the fact that compression is happening within the hidden layers in a neural network as such having robust tools to measure mutual information is of utmost importance.

3.1.1 Mutual Information Definition

Mutual information is a measure of dependence between two variables X and Y , it quantifies the number of bits obtained about one when observing the other.

Suppose we have two random variables X and Y if we want to measure mutual information between the two of them we usually refer to one of the following equations:

Using the entropy of the distributions to infer the value

$$I(X, Y) = H(X) - H(X|Y) \quad (3.1)$$

$$I(X, Y) = H(X) + H(Y) - H(X, Y) \quad (3.2)$$

Or calculating the mutual information explicitly from probabilities, for discrete and continuous distributions respectively

$$I(X; Y) = \sum_{y \in \mathcal{Y}} \sum_{x \in \mathcal{X}} p(x, y) \log \left(\frac{p(x, y)}{p(x)p(y)} \right) \quad (3.3)$$

$$I(X; Y) = \int_{\mathcal{Y}} \int_{\mathcal{X}} p(x, y) \log \left(\frac{p(x, y)}{p(x)p(y)} \right) dx dy \quad (3.4)$$

3.1.2 Theoretically undefined

Calculating mutual information is mathematically defined for both continuous and discrete distributions by using one of the functions above. However since we are looking at neural networks we do not have the full distribution – only an empirical sample of the unknown joint distribution $P(X, Y)$. As such we cannot use conventional methods to calculate the mutual information and instead have to use tools to estimate it.

The field of estimating mutual information is relatively new as a result the tools that are available are quite primitive. There has been some papers published that use more advanced techniques to tackle the problem, we will talk about in subsection 3.2.4

3.2 Calculating Mutual Information

3.2.1 Experimental setup

```

1  Input:
2   $T$  = number of layers
3   $X$  = training data
4   $Y$  = label data
5   $N$  = number of epochs
6  Output:
7   $I_x(\text{epoch}, \text{layer})$ , # mutual information with  $X$ 
8   $I_y(\text{epoch}, \text{layer})$  # mutual information with  $Y$ 
9  Algorithm:
10 NN = setup_neural_network( $T$ ,  $X$ ,  $Y$ )
11 for e in 0.. $N$ :
12     NN.run_SGD_once()
13     for t in 0.. $T$ :
14         data = []
15         for  $x \in X$ :
16              $\hat{t} = \text{NN.predict}(x).layer\_activation(t)$ 
17             data.append( $\hat{t}$ )
18          $I_x(e, t) = \text{calculate\_mutual\_information}(\text{data}, X)$ 
19          $I_y(e, t) = \text{calculate\_mutual\_information}(\text{data}, Y)$ 

```

Figure 3.1: The general algorithm for calculating mutual information inside a neural network.

- X input is an empirical sample of all possible inputs.
- Y label data. Every $x \in X$ has a corresponding label $y \in Y$.
- $T_{e,i}$ data for a specific epoch e and specific layer i in the neural network. The dataset is generated by feeding every $x \in X$ through the neural network and recording the activations.

3.2.2 Discrete method

The method used by Tishby in his paper. The method estimates mutual information between the X or Y and the hidden layer T by assuming the observed empirical distribution of input samples is the true distribution. We use this assumption to compute entropies of T and varying subsets as outlined in Equation 3.2.2

$$I(X, Y) = H(X) - H(X|Y) = H(X) - \sum_{y \in Y} H(X|Y = y)p(Y = y) \quad (3.5)$$

However just calculating mutual information for a discrete distribution is not enough as this yields mutual information equal to 0, in order to sidestep this issue we need to simulate randomness Tishby achieves this by grouping multiple values together, which he calls binning. A more detailed explanation why this is done is given in subsection 4.0.1

Figure 3.2 through to Figure 3.4 outline the full algorithm.

```

1  Input:
2   $X = x_1, x_2, \dots, x_n$ 
3   $Y = y_1, y_2, \dots, y_n$ 
4  Output:  $I(X : Y)$ 
5   $X$  = Bin close values of  $X$  together
6   $Y$  = Bin close values of  $Y$  together
7   $H(X)$  = Calculate entropy of  $X$ 
8   $H(X|Y)$  = Calculate conditional entropy of  $X$  given  $Y$ 
9   $I = H(X) - H(X|Y)$ 

```

Figure 3.2: Pseudo code for computing mutual information refer to Figure 3.3 and Figure 3.4 for entropy computation.

```

1  Input:  $X = x_1, x_2, \dots, x_n$ 
2  Output:  $H(X)$ 
3  for  $\hat{x} \in \text{Unique}(X)$ :
4      count = 0
5      for  $x \in X$ :
6          if  $\hat{x} = x$ :
7              count = count + 1
8       $P_x = \text{count} / \text{len}(X)$ 
9   $H(X) = - \sum_{x \in \text{Unique}(X)} P_x \log(P_x)$ 

```

Figure 3.3: Algorithm for computing entropy – Discrete method

```

1  Input:
2   $X = x_1, x_2, \dots, x_n$ 
3   $Y = y_1, y_2, \dots, y_n$ 
4  Output:  $H(X|Y)$ 
5   $H(X|Y) = H(X)$ 
6  for  $\hat{y} \in \text{Unique}(Y)$ :
7       $\hat{X} = []$ 
8      for  $x, y \in \text{zip}(X, Y)$ :
9          if  $\hat{y} = y$ :
10              $\hat{X}.\text{append}(x)$ 
11              $H(X|Y) = H(X|Y) - H(\hat{X})$ 

```

Figure 3.4: Algorithm for computing conditional entropy

When computing mutual information between a hidden layer T and the input set X we can abuse the fact that every element $x \in X$ is unique and uniquely identifies an element $t \in T$ hence

$$H(T|X) = 0 \quad (3.6)$$

$$I(T, X) = H(T) - H(T|X) = H(T) \quad (3.7)$$

This does not affect the result but increases performance of our algorithm.

3.2.3 Kernel Density Estimation

The KDE method used in Saxe’s paper but originally devised by Kolchinsky & Tracey (2017); Kolchinsky et al. (2017). As well as the Discrete method KDE assumes that the observed empirical distribution in the hidden layer T is the true distribution.

However, instead of binning values together KDE assumes the distribution is a mixture of Gaussians. Using this fact we can get an upper bound when calculating entropy for a collection of data points.

The algorithm closely follows figures :Figure 3.2, Figure 3.3, and Figure 3.4, however there is a change the way entropy is calculated so instead of Figure 3.3 we have Figure 3.5 below.

```

1  Input:
2   $X = x_1, x_2, \dots, x_n$ 
3  var = noise variance 0.05 by default
4  Output:  $H(X)$ 
5  dists = compute distance matrix of  $X$ 
6  dists = dists / 2*var # divide every distance by a value
7  # an  $x$  is an observation of a hidden layer so, hence it's a vector
8  # which has an associated dimension
9  dim =  $x_1$ .dimension
10 normconst = (dim / 2)*log(2* $\pi$ *var)
11 lprobs = []
12 for row in dists:
13     lprobs.append(log(sum(exp(-row))) - log(n) - normconst)
14 H(X) = mean(lprobs) + (dim / 2)

```

Figure 3.5: Algorithm for computing entropy – Kernel Density Estimation method. The same algorithm as used by Saxe.

As before when computing mutual information between a hidden layer T and the input set X we can use the fact that every element $x \in X$ is unique and hence uniquely identifies an element in $t \in T$.

3.2.4 Advanced methods

Since mutual information estimation is a contentious part of the project we wanted to experiment with more advanced techniques however we were not able to adopt the methods for this project, the methods that we have tried are outlined below.

Mutual Information by Gaussian approximation

”Estimating Mutual Information by Local Gaussian Approximation” (Shuyang Gao). A promising way to estimate mutual information. However the implementation proved to be too difficult and time consuming so we abandoned it. We reached out to the author but he was not able to provide any concrete code.

failure

Geometrical Adaptive Entropy Estimation

”Breaking the Bandwidth Barrier: Geometric Adaptive Entropy Estimation” (Weihao Gao). We were pointed to this paper by S. Gao the author of the previous method, as previously this looked like a promising method to measure entropy and mutual information. Furthermore, the code was available online unfortunately we were not able to adapt the code for multidimensional values as a result we were getting wrong and inconsistent

results. We decided making this method work would require too much time and is out of scope of this project.

3.3 Implementation Optimizations

Producing data for the information plane requires a substantial amount of computational power and memory, in order for the computation to complete in a reasonable amount of time we have to utilize all the available resources and minimize the amount of work we are doing.

3.3.1 Maximising Resource Utilization

The obvious way to maximise the resource usage is to parallelize the workload. If we refer to Figure 3.1, we can see two main ways we can do this.

The first way is to parallelize one of the two outer loops and run mutual information calculations in parallel, this is easy to do, however an issue occurs if we need a lot of memory since every instance of mutual information calculation manipulates the datasets creating copies, this is an issue for bigger datasets such as MNIST.

The second way is to parallelize the mutual information calculation itself, this is nice since we use minimal amounts of memory, however might be hard or impossible to implement as it depends on the method.

The second way is to parallelize the mutual information calculation itself, this method has a bonus that uses minimal amounts of memory improving performance for bigger datasets such as MNIST. However implementing this option might be hard as it heavily depends on the maths of the method, or impossible if the method has an inherently linear part to it. In our case KDE parallel performance is very good, however Tishby's Discrete method has some bottlenecks that I wasn't able to remove.

3.3.2 Minimising the Workload

Even when using all the systems resources the calculations take a very long time to complete as such we need to find a way to speed it up. If we consider an information plane graph for ex. Figure 1.1, we see that from epoch to epoch there is very little change that is occurring, skipping some epochs might be a good way to reduce workload while keeping the overall result unchanged. We have implemented a couple of ways to skip the epochs

Simple Skip

A very simple way to skip epochs calculates mutual information for every n^{th} epoch.

It's quite effective and is fast to implement and easy to parallelize, however it yields subpar results. At the beginning of the training period during the fitting phase the step sizes are too big and yields gaps in data as there are big changes between consecutive

epochs. Toward the end of the training period during the compression phase the step size becomes too small and we are wasting computation as the changes between epochs is negligible. The next two methods address this problem, but have their own drawbacks.

Delta Skip – Exact

The Exact Delta Skip method introduces a distance metric which measures mutual information distance between two epochs. Using the distance metric the method tries to skip as many epochs as possible while still guaranteeing that the distance is at most delta δ , and backtracks when necessary.

Distance Metric asdlkj lasd laskdj klsad lsa d

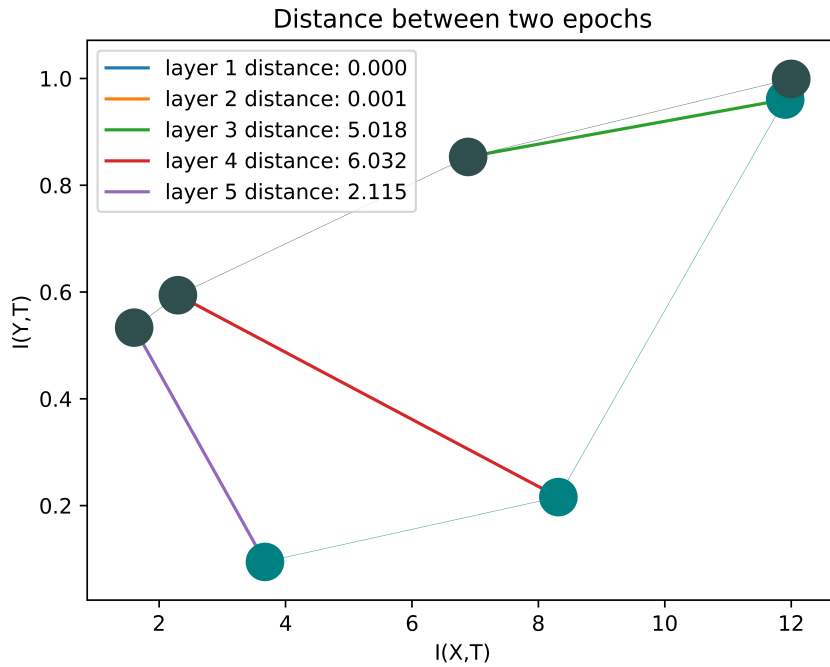


Figure 3.6: Example how distance between two epochs is measured.

Delta Skip – Approximate

The Exact method suffers the same problem as when we try to instantiate too many mutual information calculation instances, namely it runs out of memory if our dataset is too big. In order to solve this we use the approximate method which follows closely the Exact method.

The Algorithm – refer to Figure 3.7, as previously, in the Exact method it uses a distance metric and measures every $n'th$ epoch where n is adaptive and depends on how close the epochs are. The critical difference between Exact and Approximate method happens when the distance between epochs is more than δ , the Exact method attempts to backtrack and fill in the gap whereas the Approximate doesn't backtrack and just

continues to the next epoch, this is justified because the approximate method assumes that distance between epochs only shrinks and never increases.

```
1  Input:
2  prev = mutual information result of the previous epoch
3  curr = mutual information result of the current epoch
4   $\delta$  = user specified maximum "distance" between epochs
5  Output:
6  skip # how many epoch to skip until we measure again. defaults to 1
7  Algorithm:
8  dist = distance(prev, curr)
9  if  $\delta < \text{dist}$ : # the gap is bigger than  $\delta$ 
10     skip = skip
11 else: # the gap is smaller than  $\delta$ 
12     skip = skip*2
```

Figure 3.7: Delta Skip Approximate

3.4 As If Random Experiment

We beleive that Tishby's experiments Saxe's experiments could be improved, with introducing a better notion of randomness. blah blah blah blah not finished.

Chapter 4

Evaluation

4.0.1 Deterministic networks

There's a very real argument to be made against compression in neural networks. Consider a generic neural network we can think of it as a function that is a series of matrix transformation, where a matrix corresponds to weights of a specific layer. However these matrices are all random (at least at the start of training) and hence probability of them being invertible is 100%.

Knowing that every single matrix is invertible allows us to conclude that that neural network as a whole is an invertible function, which means no information is lost and compression is impossible.

Chapter 5

Conclusion

Appendix A

Project Proposal

Measuring mutual information within Neural networks

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Robinson College
Saturday 20th October, 2018

Project Originator: Andrius Grabauskas

Project Supervisor: Dr. Damon Wischik

Director of Studies: Prof. Alan Mycroft

Overseers: Dr. Robert Mullins Prof. Pietro Lio'

Introduction and Description of the Work

The goal of this project is to confirm or deny the results produced by Shwartz-ziv & Tishby in their paper "Opening the black box of Deep Neural Networks via Information"¹

The paper tackles our understating of Deep Neural Networks (DNN's). As of yet there is no comprehensive theoretical understanding of how DNN's learn from data. The authors proposed to measure how information travels within the DNN's layers.

They found that training of neural networks can be split into to two distinct phases: memorization followed by the compression phase.

- memorization - each layer increases information about the input and the label
- compression - this is the generalization stage where each layer tries to forget details about the input while still increasing mutual information with the label thus improving performance of the DNN. This phase takes the wast majority of the training time.

They found that each layer in neural network tries to throw out unnecessary data from the input while preserving information about the output/label. As the network is trained each layer preserves more information about the label

¹<https://arxiv.org/abs/1703.00810>

The results they found were interesting but also contentious as they have not yet provided a formal proof, just experimental data as a result there are many peers that are cautious and sceptical of the theory even a paper² was produced that tries to suggest that the theory is wrong, however this was dismissed by Tishby & Shwartz-Ziv³

Starting Point

I have watched a talk that Prof. Tishby gave on this topic at Yandex, no other preparation was done.

Resources Required

The training DNN's and measuring mutual information will be computationally expensive so I will be using Azure cloud GPU service to acquire the required compute for this project. The GPU credits will be provided by Damon Wischik

For backups I intend to store my work on GitHub and my own personal machine. In case my laptop breaks I will get another one or use the MCS machines.

Substance and Structure of the Project

The aim of this project to reproduce the results provided by Prof. Tishby and his colleagues. The intention of my work is to help settle the debate surrounding the topic either strengthening the arguments in favour of the theory in case my results are inline with the aforementioned results or encourage discussion in case my results contradict the theory.

My work will require me to have a comprehensive understanding of Information theory, Information bottleneck and neural networks.

One of the more contentious parts of my project will be measuring mutual information between the input a layer in the DNN and the label. It will be computationally expensive to measure it in DNN since we will need to retrain the network in order to get a distribution rather than a single value. I will use Gaussian approximation to measure it (relevant paper⁴)

Will need to use Python to train the neural networks and GNUplot or alternative to plot the results.

Success Criteria

Reimplement the code that was used to generate the papers results. Confirm or deny the results produced in "Opening the black box of Deep Neural Networks via Information" paper on the same dataset as the paper. In order to do that I will need to: Train a neural network on the same dataset

²https://openreview.net/pdf?id=ry_WPG-A-

³https://openreview.net/forum?id=ry_WPG-A-¬eId=S1lBxcE1z

⁴<https://arxiv.org/abs/1508.00536>

that was used in the paper and measure mutual information between the layers. Analyse the results produced and address any discrepancies that may have occurred.

Extensions

Provided I achieve the success criteria there are two main ways to extend it.

- Use different datasets to test the theory. Using different datasets would confirm that the results are not data specific. Current datasets we are considering: MNIST⁵ and NOT-MNIST⁶.
- Explore different ways of measuring mutual information. One interesting way would be to explore a discrete neural network where every node would only be able assigned discrete values say 1...256. This would make the distribution within a DNN layer discrete and hence it would make calculating mutual information straightforward. However quantizing the neural network could possibly hurt the performance of the network.

⁵<http://yann.lecun.com/exdb/mnist/>

⁶<https://www.kaggle.com/quanbk/notmnist>

Schedule

- **20th Oct – 2nd Nov**

I expect to spend the first two weeks reading up on Information theory (primarily from Mackay's book⁷) and the information bottleneck method in order to understand the nuances of the paper.

- **3rd Nov – 30th Nov**

The following weeks I intend to spend reading up on DNN's doing some introductory courses, I will train the neural network on the same data as the paper but at this point will not yet try to measure the mutual information between the layers.

At this point I will also start examining the code⁸ provided and start to implement parts of it which don't deal with information measurement.

- **1st Dec – 28th Dec**

Will start reading up on mutual Information measurement with local Gaussian approximation.

Implementing mutual information measurement in code.

At this point I expect the computation to be too demanding for my machine and will need to use provided compute.

- **29th Dec – 1st Feb**

Having a working system to test data sets I will try to reproduce results from the paper on the same dataset. This will achieve my success criteria.

At this point my success criteria should be completed I will spend some time writing the skeleton of the thesis. Look for any discrepancies between my results and the ones provided in the paper.

- **2nd Feb – 2nd Feb**

Assuming everything goes as planned I will start looking into implementing one of the extensions. Which are :

- Testing the theory on different datasets.
- Implementing a quantized neural network implementation.

or both, if time is in my favour.

- **3rd Feb – 2nd Mar**

Will use the remaining time to write up the dissertation.

⁷Information Theory, Inference, and Learning Algorithms by David J. C. MacKay

⁸<https://github.com/ravidziv/IDNNs>