

Machine Learning methods for Thin Vessel Segmentation

in Fundus Images



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May 2015

I would like to dedicate this thesis to my loving parents ...

Declaration

I hereby declare that except where specific reference is made to the work of others, the contents of this dissertation are original and have not been submitted in whole or in part for consideration for any other degree or qualification in this, or any other university. This dissertation is my own work and contains nothing which is the outcome of work done in collaboration with others, except as specified in the text and Acknowledgements. This dissertation contains fewer than 65,000 words including appendices, bibliography, footnotes, tables and equations and has fewer than 150 figures.

Kushal Khandelwal
May 2015

Acknowledgements

And I would like to acknowledge ...

Abstract

This is where you write your abstract ...

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Chapter 1

Introduction

1.1 What is lorem ipsum? Title with math σ

Lorem Ipsum is simply dummy text of the printing and typesetting industry (see Section 1.3). Lorem Ipsum [3] has been the industry's standard dummy text ever since the 1500s, when an unknown printer took a galley of type and scrambled it to make a type specimen book. It has survived not only five centuries, but also the leap into electronic typesetting, remaining essentially unchanged. It was popularised in the 1960s with the release of Letraset sheets containing Lorem Ipsum passages, and more recently with desktop publishing software like Aldus PageMaker including versions of Lorem Ipsum [1, 4, 5].

The most famous equation in the world: $E^2 = (m_0c^2)^2 + (pc)^2$, which is known as the **energy-mass-momentum** relation as an in-line equation.

A *LaTeX class file* is a file, which holds style information for a particular *LaTeX*.

$$CIF : \quad F_0^j(a) = \frac{1}{2\pi i} \oint_{\gamma} \frac{F_0^j(z)}{z-a} dz \quad (1.1)$$

1.2 Why do we use lorem ipsum?

It is a long established fact that a reader will be distracted by the readable content of a page when looking at its layout. The point of using Lorem Ipsum is that it has a more-or-less normal distribution of letters, as opposed to using 'Content here, content here', making it look like readable English. Many desktop publishing packages and web page editors now use Lorem Ipsum as their default model text, and a search for 'lorem ipsum' will uncover many

web sites still in their infancy. Various versions have evolved over the years, sometimes by accident, sometimes on purpose (injected humour and the like).

1.3 Where does it come from?

Contrary to popular belief, Lorem Ipsum is not simply random text. It has roots in a piece of classical Latin literature from 45 BC, making it over 2000 years old. Richard McClintock, a Latin professor at Hampden-Sydney College in Virginia, looked up one of the more obscure Latin words, *consectetur*, from a Lorem Ipsum passage, and going through the cites of the word in classical literature, discovered the undoubtable source. Lorem Ipsum comes from sections 1.10.32 and 1.10.33 of "de Finibus Bonorum et Malorum" (The Extremes of Good and Evil) by Cicero, written in 45 BC. This book is a treatise on the theory of ethics, very popular during the Renaissance. The first line of Lorem Ipsum, "Lorem ipsum dolor sit amet..", comes from a line in section 1.10.32.

The standard chunk of Lorem Ipsum used since the 1500s is reproduced below for those interested. Sections 1.10.32 and 1.10.33 from "de Finibus Bonorum et Malorum" by Cicero are also reproduced in their exact original form, accompanied by English versions from the 1914 translation by H. Rackham

"Lorem ipsum dolor sit amet, consectetur adipisicing elit, sed do eiusmod tempor incididunt ut labore et dolore magna aliqua. Ut enim ad minim veniam, quis nostrud exercitation ullamco laboris nisi ut aliquip ex ea commodo consequat. Duis aute irure dolor in reprehenderit in voluptate velit esse cillum dolore eu fugiat nulla pariatur. Excepteur sint occaecat cupidatat non proident, sunt in culpa qui officia deserunt mollit anim id est laborum."

Section 1.10.32 of "de Finibus Bonorum et Malorum", written by Cicero in 45 BC: "Sed ut perspiciatis unde omnis iste natus error sit voluptatem accusantium doloremque laudantium, totam rem aperiam, eaque ipsa quae ab illo inventore veritatis et quasi architecto beatae vitae dicta sunt explicabo. Nemo enim ipsam voluptatem quia voluptas sit aspernatur aut odit aut fugit, sed quia consequuntur magni dolores eos qui ratione voluptatem sequi nesciunt. Neque porro quisquam est, qui dolorem ipsum quia dolor sit amet, consectetur, adipisci velit, sed quia non numquam eius modi tempora incidunt ut labore et dolore magnam aliquam quaerat voluptatem. Ut enim ad minima veniam, quis nostrum exercitationem ullam corporis suscipit laboriosam, nisi ut aliquid ex ea commodi consequatur? Quis autem vel eum iure reprehenderit qui in ea voluptate velit esse quam nihil molestiae consequatur, vel illum qui dolorem eum fugiat quo voluptas nulla pariatur?"

1914 translation by H. Rackham: "But I must explain to you how all this mistaken idea of denouncing pleasure and praising pain was born and I will give you a complete

account of the system, and expound the actual teachings of the great explorer of the truth, the master-builder of human happiness. No one rejects, dislikes, or avoids pleasure itself, because it is pleasure, but because those who do not know how to pursue pleasure rationally encounter consequences that are extremely painful. Nor again is there anyone who loves or pursues or desires to obtain pain of itself, because it is pain, but because occasionally circumstances occur in which toil and pain can procure him some great pleasure. To take a trivial example, which of us ever undertakes laborious physical exercise, except to obtain some advantage from it? But who has any right to find fault with a man who chooses to enjoy a pleasure that has no annoying consequences, or one who avoids a pain that produces no resultant pleasure?"

Section 1.10.33 of "de Finibus Bonorum et Malorum", written by Cicero in 45 BC: "At vero eos et accusamus et iusto odio dignissimos ducimus qui blanditiis praesentium voluptatum deleniti atque corrupti quos dolores et quas molestias excepturi sint occaecati cupiditate non provident, similique sunt in culpa qui officia deserunt mollitia animi, id est laborum et dolorum fuga. Et harum quidem rerum facilis est et expedita distinctio. Nam libero tempore, cum soluta nobis est eligendi optio cumque nihil impedit quo minus id quod maxime placeat facere possimus, omnis voluptas assumenda est, omnis dolor repellendus. Temporibus autem quibusdam et aut officiis debitis aut rerum necessitatibus saepe eveniet ut et voluptates repudiandae sint et molestiae non recusandae. Itaque earum rerum hic tenetur a sapiente delectus, ut aut reiciendis voluptatibus maiores alias consequatur aut perferendis doloribus asperiores repellat."

1914 translation by H. Rackham: "On the other hand, we denounce with righteous indignation and dislike men who are so beguiled and demoralized by the charms of pleasure of the moment, so blinded by desire, that they cannot foresee the pain and trouble that are bound to ensue; and equal blame belongs to those who fail in their duty through weakness of will, which is the same as saying through shrinking from toil and pain. These cases are perfectly simple and easy to distinguish. In a free hour, when our power of choice is untrammelled and when nothing prevents our being able to do what we like best, every pleasure is to be welcomed and every pain avoided. But in certain circumstances and owing to the claims of duty or the obligations of business it will frequently occur that pleasures have to be repudiated and annoyances accepted. The wise man therefore always holds in these matters to this principle of selection: he rejects pleasures to secure other greater pleasures, or else he endures pains to avoid worse pains."

Chapter 2

Background and Literature Review

This chapter aims to provide the basic background knowledge to understand the work of thesis. Clustering algorithm and Dictionary Learning algorithms are discussed. We further discuss the various evaluation measures.

2.1 Machine Learning

Machine learning is the study dealing with the process to learn characteristic information from data. Given some data, X , a machine learning algorithm learns a function $f(x)$ which maps the input to an output variable y . The learnt model then can be used to make predictions on previously unseen data X' . The aim of a machine learning algorithm is to learn a generalized model which can make the best possible prediction on the new previously unseen data.

To train the algorithm, it is fed with data points (known as training observations/instances). The data points in the set are each described by a set of features, known as feature vectors. These descriptors can be learned from the data or can be computed for each instance. As an example, suppose we have a set of patches from an image as our data points. Descriptors denote the key properties of data points.

Let $X = \{x_1, x_2, \dots, x_n\} \in R^{m \times n}$ be a set of images patches with dimensions $m \times n$. The feature vector describing these data points can then be denoted as

$$X = \begin{pmatrix} x_{1,1} & x_{1,2} & \cdots & x_{1,n} \\ x_{2,1} & x_{2,2} & \cdots & x_{2,n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{m,1} & x_{m,2} & \cdots & x_{m,n} \end{pmatrix}$$

Here each row of the matrix denotes individual data points and $x_{i,j}$ are the gray scale intensities of each pixel of the given patch x_i .

Depending on whether the data is labelled or unlabelled, the machine learning algorithms can be divided into two types namely :

1. Supervised Learning Algorithms
2. Unsupervised Learning Algorithms

2.1.1 Supervised Learning

Given a training set of labelled data, supervised learning algorithms fit a model to the training set with the aim of predicting the unknown labels for the test instances (observations). During the training phase, the algorithms learn the unknown parameters for the model.

[Describe the process]

[Example of a learning algorithm]

2.1.2 Unsupervised Learning

In unsupervised learning settings, the task is to find group relations between instances of the unlabeled training dataset with a subsequent aim of categorizing or clustering the data. The algorithm aims to understand the general properties/structure in the dataset.

[Explain the method]

2.2 Clustering

A cluster is a collection of data points grouped together on the basis of some common properties. The data objects or points within a cluster are similar to each other, whereas the points in different groups are dissimilar.

The process of partitioning of data points into smaller groups (called as clusters) with the aim to minimize the intra cluster variance and maximize the inter cluster variance. The grouping of data points is based on the similarity or dissimilarity of the objects as described by their properties or features. Clustering data objects creates subspaces within the data.

[For example, given a toy dataset with 10 data points]

Similarity or dissimilarity between two objectives can be very subjective and hence various measures are used to describe them quantitatively with distance measure being the most common. The distance measure is used to specify the distance between two objects and can

be used to create a distance matrix called as similarity/disimilarity matrix. The most used distance metric is the Minkowski Distances.

[Minkowski distances]

As the data labels are unknown, cluster analysis is known as an unsupervised method of data partitioning. This is contrast to classification where the data can be partitioned on the basis of their class labels. Thus, clustering segments the data on the basis of the properties of the objects within the dataset and finds previously unknown grouping within the data.

The distance based clustering algorithms can be divided into two types namely Partitioning based and Hierarchical methods.

We look into these different types of Clustering methods.

2.2.1 K-Means Clustering

In this section we look into the K-Means clustering algorithm. We assume that the number of clusters 'K' is given and we use it to initiate our clustering algorithm.

We are given a dataset D with n objects. Each n object in the dataset is described by a feature vector of length m. The feature vector can be anything which can represent the datapoint. For examples, for an image the feature vector can be grayscale values at every pixel. The aim of the clustering algorithm is to partition the dataset D[m x n] into 'K' clusters while optimizing an objective function. The clusters are formed so as to the objects within the same cluster are similar and dissimilar to objects in other clusters.

K-Means is a centroid based partitioning method. I.e the centroid of the cluster is the representative data point for the cluster. The centroid of the cluster is defined by the mean of all the data points within the cluster.

Given a dataset D with n objects in the Euclidean space, the aim is to partition the dataset into k clusters C_1, C_2, \dots, C_k such that C_i subset of D and $C_i \cap C_j$ is nil. That is each point within the dataset is exclusive to one cluster. Each of the clusters C_i is represented by its centroid c_i . Each cluster consists of p points and the distance between the point p and the cluster representative c_i is defined as $\text{dist}(p, c_i)$. If the data points are in m dimensional, then the distance is defined as [euclidean distance]

The clustering algorithm optimizes the inter cluster variation, this is the Sum of Squared Error (SSE) between the data points in the cluster and the centroid. The SSE is defined as

Error =

Algorithm

Algorithm

2.3 Decomposition Methods

2.3.1 PCA

2.3.2 Matrix Factorization

2.4 Dictionary Learning

2.4.1 Sparse Coding

2.5 Preprocessing Methods

2.5.1 Normalization

2.5.2 CLAHE

2.6 Evaluation

Chapter 3

Framework

The chapter aims to present the basic framework for our vessel segmentation algorithm. The chapter is divided into 4 parts. In the first part we discuss the basic framework of our algorithm. Part 2 and Part3 talk about the various preprocessing methods and how the methods was applied to our problem.

3.1 Vessel segmentation Framework

The image segmentation framework takes as its input a list of fundus images

$$I = /I_1, I_2, \dots, I_n/$$

and their correspodng ground truth segmentation maps

$$S = /S_1, S_2, \dots, S_n/$$

. The input fundus images

$$I_j$$

can be grayscale or RGB color images. Each of the given segmentaion maps in S, is the same size as that of correspodng fundus image in I. The ground truth segmentation maps are binary image i.e, each pixel in the segmentation map is either 1 or a 0, deptcting the presenece of vessel or background respectively

Given a training dataset consisting of fundus images I and segmentation maps S , the aim is to define a framework, to predict the segmentation map S' for an unknown new image I' .

The proposed problem is dealt in a patch based framework. Each image pixel in the image is represented by a patch centered around the pixel. The image is decomposed into such dense patches.

Given an Image pixel $I(x,y)$ we compute a patch of size $k \times k$ around the pixel $I(x,y)$. Each image is then described by such patches.

Patches are computed both for the Fundus images and their corresponding binary segmentation map images. For an Image I , and its segmentation map S , the patches are denoted by

$$I [Ip_1, Ip_2, \dots]$$

and

$$S [Sp_1, Sp_2, \dots]$$

The aim of our thesis is to develop algorithms which predict the Segmentation patch for a given image patch.

During the training process, the algorithms aim to learn a set of image representation patches describing the patches from the training set.

Given a training set consisting of image patches $X = X_1, X_2, X_3, \dots$ and their corresponding ground truth patches $Y = Y_1, Y_2, Y_3, \dots$, we aim to learn a set $X_r = X_{r1}, X_{r2}, \dots$ which can represent each and every patch of in the training images X .

In the prediction phase, a single channel of the image is taken and dense patches (patches per pixel are calculated) and fed to the classifier. The classifier predicts the GT patches for each image patch. The ground truth patches are then recombined to obtain the segmentation map for the image.

3.1.1 Preprocessing

In our task we have explored some of the preprocessing steps including Patch Normalization, Contrast stretching, Local contrast normalization.

All the input patches are normalized by subtracting the mean and standard deviation per patch. In addition to this we also test with normalizing the entire image before patch generation.

In some of the experiments, we improve the image contrast by utilizing Contrast Limited Adaptive Histogram Equalization (CLAHE) as explained in section.

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Rotations To provide for rotational invariance and learn better representatives, rotated patches are also included in our learning phase. Each of the training images are additionally rotated at angles of 30,60,90 and patches are calculated.

3.2 Datasets

For testing the performance of our algorithm , we train and test our system on the following publically available datasets. In this section we describe the characteristics of these datasets

3.2.1 DRIVE

The Digital Retinal Images for Vessel Extraction (DRIVE) dataset consists of 40 color retinal images randomly selected from diabetic retinopathy screening program for 400 diabetic patients. Each of these images in dataset are JPEG compressed and have a dimensions of 768 x 584 pixels captured at a resolution on bits per pixel. The images are captures with a 45degree field of view (FOV). Of the 40 images in the dataset, 7 show sign of diabetic retinopathy , while the remaining 33 do not consist of any pathology. Each image is provided with a corresponding mask delineating the FOV.

The dataset is divided is provided with divisions in terms of training and testing set, with each set consisting of 20 images. Each of the 40 images have been manually segmented by human observers trained by an experienced optamologist. For the training set, single ground truth segmentation of the vessels is provided. The test set is provided with two ground truth segmentations, of which the first one is used as gold standard and the other is used to compare the performance with an independent human observer.

3.2.2 STARE

The STARE dataset consists of 20 images with blood vessel segmentations, out of which 10 show signs of pathology. The images have been capture with a FOV of 35degrees at 8 bit per pixel resolution, with dimesnsions of each image as 605 x 700 pixels. The dataset consists of segmentation provided by two human observers. In our experiements, we consider the segmentations provided by the first observer as ground truth.

Table 3.1 Even better looking table using booktabs

Dental measurement	Species I		Species II	
	mean	SD	mean	SD
I1MD	6.23	0.91	5.2	0.7
I1LL	7.48	0.56	8.7	0.71
I2MD	3.99	0.63	4.22	0.54
I2LL	6.81	0.02	6.66	0.01
CMD	13.47	0.09	10.55	0.05
CBL	11.88	0.05	13.11	0.04

For the experiements, the dataset is randomly divided into training and test sets each consisting of 10images.

3.2.3 HRF

he High Resolution Fundus (HRF) image databse consists of 45 images of which 15 images come from healthy patients , 15 from patients with diabetic retinopathy and 15 of glaucumatus patients.

The images were captured with a FOV of 60degrees, at a high resolution of 24bits per pixel. The size of each image is 3504 x 2336 pixels and stored with JPEG compression.

Each image is provided a manual segmentation of vessesl as segmented by three independent human observers trained by experienced optahmologists.The dataset also provides a corresponging mask image of each image delineating the FOV.

3.2.4 ARIA

The ARIA dataset consists of three groups of images. One of the group consists of 92 images with age-related macular degeneration, the other with 59 images from diabetic patients and the last group with 61 images from a control group. The images are captures with a 50degree FOV, stored in uncompressed TIFF format, with a resolution of 8bits oer pixel. Each image has dimensions of 768 x 576 pixels.

The dataset provides with blood vessel segmentation images as manually segmented by experts and a corresponding mask delinating the FOV region.

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Appendix A

How to install L^AT_EX

Windows OS

TeXLive package - full version

1. Download the TeXLive ISO (2.2GB) from
<https://www.tug.org/texlive/>
2. Download WinCDEmu (if you don't have a virtual drive) from
<http://wincdemu.sysprogs.org/download/>
3. To install Windows CD Emulator follow the instructions at
<http://wincdemu.sysprogs.org/tutorials/install/>
4. Right click the iso and mount it using the WinCDEmu as shown in
<http://wincdemu.sysprogs.org/tutorials/mount/>
5. Open your virtual drive and run setup.pl

or

Basic MikTeX - T_EX distribution

1. Download Basic-MiK_TE_X(32bit or 64bit) from
<http://miktex.org/download>
2. Run the installer
3. To add a new package go to Start » All Programs » MikTeX » Maintenance (Admin)
and choose Package Manager

4. Select or search for packages to install

TexStudio - T_EX editor

1. Download TexStudio from
<http://texstudio.sourceforge.net/#downloads>
2. Run the installer

Mac OS X

MacTeX - T_EX distribution

1. Download the file from
<https://www.tug.org/mactex/>
2. Extract and double click to run the installer. It does the entire configuration, sit back and relax.

TexStudio - T_EX editor

1. Download TexStudio from
<http://texstudio.sourceforge.net/#downloads>
2. Extract and Start

Unix/Linux

TeXLive - T_EX distribution

Getting the distribution:

1. TeXLive can be downloaded from
<http://www.tug.org/texlive/acquire-netinstall.html>.
2. TeXLive is provided by most operating system you can use (rpm,apt-get or yum) to get TeXLive distributions

Installation

1. Mount the ISO file in the mnt directory

```
mount -t iso9660 -o ro,loop,noauto /your/texlive####.iso /mnt
```

2. Install wget on your OS (use rpm, apt-get or yum install)
3. Run the installer script install-tl.

```
cd /your/download/directory  
./install-tl
```

4. Enter command 'i' for installation
5. Post-Installation configuration:
<http://www.tug.org/texlive/doc/texlive-en/texlive-en.html#x1-320003.4.1>
6. Set the path for the directory of TexLive binaries in your .bashrc file

For 32bit OS

For Bourne-compatible shells such as bash, and using Intel x86 GNU/Linux and a default directory setup as an example, the file to edit might be

```
edit ~/.bashrc file and add following lines  
PATH=/usr/local/texlive/2011/bin/i386-linux:$PATH;  
export PATH  
MANPATH=/usr/local/texlive/2011/texmf/doc/man:$MANPATH;  
export MANPATH  
INFOPATH=/usr/local/texlive/2011/texmf/doc/info:$INFOPATH;  
export INFOPATH
```

For 64bit OS

```
edit ~/.bashrc file and add following lines  
PATH=/usr/local/texlive/2011/bin/x86_64-linux:$PATH;  
export PATH  
MANPATH=/usr/local/texlive/2011/texmf/doc/man:$MANPATH;  
export MANPATH
```

```
INFOPATH=/usr/local/texlive/2011/texmf/doc/info:$INFOPATH;  
export INFOPATH
```

Fedora/RedHat/CentOS:

```
sudo yum install texlive  
sudo yum install psutils
```

SUSE:

```
sudo zypper install texlive
```

Debian/Ubuntu:

```
sudo apt-get install texlive texlive-latex-extra  
sudo apt-get install psutils
```

Appendix B

Installing the CUED class file

\LaTeX .cls files can be accessed system-wide when they are placed in the $\langle\text{texmf}\rangle/\text{tex}/\text{latex}$ directory, where $\langle\text{texmf}\rangle$ is the root directory of the user's \TeX installation. On systems that have a local texmf tree ($\langle\text{texmflocal}\rangle$), which may be named “ texmf-local ” or “ localtexmf ”, it may be advisable to install packages in $\langle\text{texmflocal}\rangle$, rather than $\langle\text{texmf}\rangle$ as the contents of the former, unlike that of the latter, are preserved after the \LaTeX system is reinstalled and/or upgraded.

It is recommended that the user create a subdirectory $\langle\text{texmf}\rangle/\text{tex}/\text{latex}/\text{CUED}$ for all CUED related \LaTeX class and package files. On some \LaTeX systems, the directory look-up tables will need to be refreshed after making additions or deletions to the system files. For \TeX Live systems this is accomplished via executing “ texhash ” as root. MikTeX users can run “ initexmf -u ” to accomplish the same thing.

Users not willing or able to install the files system-wide can install them in their personal directories, but will then have to provide the path (full or relative) in addition to the filename when referring to them in \LaTeX .

