

Statistical Relational Learning

Link Prediction with Latent Feature Models



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This dissertation is submitted for the degree of
Master of Sciences

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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.

Luyolo Magangane

June 2019

Abstract

This is where you write your abstract ...

Table of contents

List of figures	xi
List of tables	xiii
1 Introduction	1
1.1 Statistical Relational Learning	1
1.1.1 Artificial General Intelligence	1
1.1.2 General Question Answering	1
1.1.3 Applications of General Question Answering	1
1.1.4 General Question Answering Approaches	2
1.1.5 Uncertainty in Knowledge Representations	2
1.2 Modelling Techniques	3
1.2.1 Latent Feature Modelling	3
1.2.2 Graph Feature Modelling	3
1.2.3 Inductive Probabilistic Logic Programming	4
1.3 Link Prediction with Latent Feature Models	4
1.3.1 Knowledge Graph Latent Feature Models	4
1.3.2 Factorisation of Latent Feature Models	5
1.3.3 Other of Latent Feature Modelling Approaches	5
2 My second chapter	7
2.1 Short title	7
3 My third chapter	13
3.1 First section of the third chapter	13
3.1.1 First subsection in the first section	13
3.1.2 Second subsection in the first section	13
3.1.3 Third subsection in the first section	13
3.2 Second section of the third chapter	14

3.3 The layout of formal tables	14
Appendix A How to install L^AT_EX	17
Appendix B Installing the CUED class file	21

List of figures

2.1	Minion	7
2.2	Best Animations	11

List of tables

3.1	A badly formatted table	15
3.2	A nice looking table	15
3.3	Even better looking table using booktabs	15

Chapter 1

Introduction

1.1 Statistical Relational Learning

1.1.1 Artificial General Intelligence

The ultimate ambition of artificial intelligence (A.I.) research is to produce human-level intelligence. Such intelligence can take form the form of conversational artificial general intelligence (AGI). The problem can be posed as a question and answer game [Alan Turing]. The premise - a human asks a series of questions to an unobservable agent, where the task is for the agent to provide answers indistinguishable from human responses. The challenge of course is the breadth of topics that can be queried, as well as the permutations of possible coherent responses.

1.1.2 General Question Answering

This task is also known as general question answering (GQA) [references]. Typical A.I. implementations operate within well bounded, narrow domains. For example audio to text synthesisers [references]; object detection within images and videos [references]; financial, meteorological and operational forecasting [references]. All of these modelling applications focus more generally on finite perceptive domains [references]. In order to achieve AGI, reasoning capability is also required [requirements for AGI reference].

1.1.3 Applications of General Question Answering

Intelligent virtual assistants (IVA) such as Alexa, Cortana, Google Assistant and Siri are mobile application attempts at AGI; Watson, Wolfram Alpha and Knowledge Engine are

other GQA computer systems. So often a user will ask one of these systems a question which results in a search engine lookup, due to failure in comprehending the question and the capability of providing a coherent response.

1.1.4 General Question Answering Approaches

Reinforcement learning. Will not be covered in this dissertation.... Knowledge representation and reasoning (KRR) is an active area of research being used as an approach to solve this problem [references]. The field aims to use mathematical logic to construct knowledge representations about a domain using knowledge graphs. Knowledge graphs (KG) model information in the form of facts presented as subject-predicate-object triples. These triples are expressed as entity-relational sets (e_1, r, e_2) where e_1 is the subject entity and e_2 is the object entity, and the relationships, r , between them. KGs have been used for information extraction, search query augmentation and general question answering. Google Knowledge Graph, DBPedia and Yago are some of the largest graph-structured database knowledge graphs implemented as knowledge bases.

KGs can be used to generate new knowledge from existing facts. These KGs can then be queried to provide logically consistent answers, more formally ontological reasoning is used to query ontological domains.

1.1.5 Uncertainty in Knowledge Representations

The problem with KRR is it contains no mechanism of capturing the uncertainty in known facts, as well as the uncertainty when new facts are generated, statistical relation learning (SRL) is an approach to solve this problem and active research area. SRL comprises three primary techniques: Latent Feature Modelling - this comprises building entity-rational representations for relationship classification, Graph Feature modelling - Using graphical structures to model entity-relational properties within a domain, and Inductive Probabilistic Logic programing - Building probabilistic models of facts to directly model uncertainty in knowledge bases. Tasks in SRL include link prediction, entity-resolution and link-based clustering. Link prediction Entity-resolution ..., Link-based clustering ... Link prediction with Latent Feature Models is the focus of this dissertation.

A *L^AT_EX* class file is a file, which holds style information for a particular L^AT_EX.

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

1.2 Modelling Techniques

1.2.1 Latent Feature Modelling

Entities and relations are words that can be represented as real-valued vectors [references]. These real-valued vectors form part of a euclidean embedding space that represents a knowledge domain [references]. The entity and relational vectors can be randomly generated, or be pre-computed to capture semantic meaning [references]. A classification model can then be constructed that generates a probability distribution over probable facts within the knowledge domain. In order to compute the probability distribution, a number of latent feature modelling techniques are used, including tensor factorisation [references], circular correlations [reference] and convolutional feature maps [reference]. These methods can broadly be defined as linear and nonlinear. Attractive attributes of linear latent models are their simplicity, ease of implementation and computational efficiency. Linear latent models however suffer from a lack of expressiveness and struggle to model complex, contradictory or incoherent relationships between entities. Nonlinear latent feature models are able to produce more expressive latent feature sets, and so more adept at capturing complex relationships. Non-linear models however suffer from computational inefficiency and poorly generalise concepts.

1.2.2 Graph Feature Modelling

In Graph Feature Modelling, Knowledge Graphs (KG) are used to model domains. KGs are composed of nodes and edges, where nodes represent entities and edges represent relations. The graphical structure then captures local, quasi-local and global domain properties. This global structure exhibits particular properties about relations within the domain, characteristics of the entities of the domain, and local entity-relational sub-structures. These graph structure properties are used in supervised [reference] and unsupervised [Graph Infomax] settings for SRL tasks such as link prediction and entity-resolution. The directional nature of edges in graph structures (uni-relational and bi-relational) is also exploited to further enhance the fulfillment of SRL tasks [reference]. The assumption in general in KGs is that similar entities will be collocated within a local and quasi-local regions, and that global similarity patterns between entities will be captured by the ensemble of all paths between entities. Link-based clustering [reference] is thus used at all these structural scopes, and supports link prediction and entity-resolution tasks.

1.2.3 Inductive Probabilistic Logic Programming

Inductive logic programming uses ontological facts to discover new facts within a knowledge domain [reference]. Logical rules check for things such as consistency, coherence and contradiction. Knowledge domains are implemented as knowledge bases (KB) that follow the resource description framework [reference]. KBs initialised in two steps: fact recording and materialisation - the discovery of new facts by running logical queries over the entire KB. KBs are extremely computationally demanding [reference], they also suffer from an inflexibility in modelling complex relationships due to their exactness, a fact is either true or false with no measure of ambiguity. Probabilistic logic programming languages have recently gained a lot of attention as flexible alternatives to logic programming languages as they are able to capture uncertainty in logical assertions through by modelling probability distributions over KB facts using stochastic variational inference. These models are thus more flexible in modelling complex relationships, and are also more computationally efficient [reference]. Inductive probabilistic logic programming has recently gained a lot of research attention due to its capability of extending probabilistic logic programming languages with the capability of knowledge discovery.

1.3 Link Prediction with Latent Feature Models

1.3.1 Knowledge Graph Latent Feature Models

Link prediction with latent feature models involves building entity-relational representations from the nodes and edges of knowledge graphs expressed as subject-predicate object triples. These triples explicitly model facts within a knowledge domain. Entity and relational representations are commonly implemented as real-valued vectors. The vectors are then combined using compositional models, such as neural networks, to produce latent relational representations that can be used to compute the likelihood of plausible relationships between entities. The domain can be said to represent a multidimensional embedding space into which the entities and relations are projected. Knowledge graph based latent feature modelling approaches are similar to semantic embedding representations [reference]. They differ in that knowledge graph approaches explicitly model entity-relational interactions, and semantic embedding approaches rely on the distributional word representation techniques [reference], relying on Skip-Gram [reference] and Continuous Bag of Words [reference] to generate word representations. This is an implicit modelling of relationships between word vectors.

1.3.2 Factorisation of Latent Feature Models

Factorisation attempts to model concepts between words, these facts are discovered using unsupervised techniques such as singular value decomposition. In the case of knowledge graphs, we obtain explicit representations of these concepts and can use them for entity-relational transformations that represent intermediate relational concepts that can then be used to determine plausible relationships when tested against subject entities. Tensor factorisation is an approach used for link prediction with latent feature models. It involves modelling entity relationships as matrix slices that comprise a relational tensor. The entity between entities is then computed using a bilinear tensor product [reference], where the inner product of the object entity is taken with the matrix relational representation before an inner product of the resultant representation is taken with the subject entity. Bilinear tensor factorisation models are efficient in their number of parameters but lack expressiveness. Multilayer perceptrons have been used to overcome the lack of expressiveness however often suffer from overfitting. Recently convolutional neural networks have been proposed to allow expressive factorisation [references], do not suffer from overfitting and remain computationally efficient.

1.3.3 Other of Latent Feature Modelling Approaches

A number of alternative approaches to latent feature model factorisation have been proposed for link prediction, including circular correlation [reference], holographic entity-relational transformations [reference], toroidal representations [reference]. The rest of this dissertation focuses on factorisation of latent feature models, with the explicit representation of relational concepts.

Chapter 2

My second chapter

2.1 Reasonably long section title

I'm going to randomly include a picture Figure 2.1.

If you have trouble viewing this document contact Krishna at: kks32@cam.ac.uk or raise an issue at <https://github.com/kks32/phd-thesis-template/>

Fig. 2.1 This is just a long figure caption for the minion in Despicable Me from Pixar

Enumeration

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1. The first topic is dull
2. The second topic is duller
 - (a) The first subtopic is silly
 - (b) The second subtopic is stupid
3. The third topic is the dullest

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Itemize

- The first topic is dull
- The second topic is duller
 - The first subtopic is silly
 - The second subtopic is stupid
- The third topic is the dullest

Description

The first topic is dull

The second topic is duller

The first subtopic is silly

The second subtopic is stupid

The third topic is the dullest

2.2 Hidden section

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¹My footnote goes blah blah blah! ...

(a) Tom and Jerry (b) Wall-E (c) Minions

Fig. 2.2 Best Animations

Subplots

I can cite Wall-E (see Fig. 2.2b) and Minions in despicable me (Fig. 2.2c) or I can cite the whole figure as Fig. 2.2

Chapter 3

My third chapter

3.1 First section of the third chapter

And now I begin my third chapter here ...

And now to cite some more people ? ?]

3.1.1 First subsection in the first section

...and some more

3.1.2 Second subsection in the first section

...and some more ...

First subsub section in the second subsection

...and some more in the first subsub section otherwise it all looks the same doesn't it? well we can add some text to it ...

3.1.3 Third subsection in the first section

...and some more ...

First subsub section in the third subsection

...and some more in the first subsub section otherwise it all looks the same doesn't it? well we can add some text to it and some more and some more and some more and some more and some more and some more and some more ...

Second subsub section in the third subsection

... and some more in the first subsub section otherwise it all looks the same doesn't it? well we can add some text to it ...

3.2 Second section of the third chapter

and here I write more ...

3.3 The layout of formal tables

This section has been modified from “Publication quality tables in L^AT_EX^{*}” by Simon Fear.

The layout of a table has been established over centuries of experience and should only be altered in extraordinary circumstances.

When formatting a table, remember two simple guidelines at all times:

1. Never, ever use vertical rules (lines).
2. Never use double rules.

These guidelines may seem extreme but I have never found a good argument in favour of breaking them. For example, if you feel that the information in the left half of a table is so different from that on the right that it needs to be separated by a vertical line, then you should use two tables instead. Not everyone follows the second guideline:

There are three further guidelines worth mentioning here as they are generally not known outside the circle of professional typesetters and subeditors:

3. Put the units in the column heading (not in the body of the table).
4. Always precede a decimal point by a digit; thus 0.1 *not* just .1.
5. Do not use ‘ditto’ signs or any other such convention to repeat a previous value. In many circumstances a blank will serve just as well. If it won't, then repeat the value.

A frequently seen mistake is to use ‘`\begin{center}`’ ... ‘`\end{center}`’ inside a figure or table environment. This center environment can cause additional vertical space. If you want to avoid that just use ‘`\centering`’

Table 3.1 A badly formatted table

	Species I		Species II	
Dental measurement	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

Table 3.2 A nice looking table

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

Table 3.3 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

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. \TeX Live 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 .

