# On the surprising capacity
# of linear combinations of embeddings
# for natural language processing

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# Thesis Declaration

I, Lyndon White, certify that:

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Lyndon White
October 2, 2018

In memoriam of
Laurie White
*1927–2018*

# Abstract

As Webster's classic 1900 text *"English: Composition and Literature"* states "A sentence is a group of words expressing a complete thought." People use natural language to represent thoughts. Thus the representation of natural language, in turn, is of fundamental importance in the field of artificial intelligence. Natural language understanding is a research area which revolves around how to represent text in a form that an algorithm can manipulate in such a way as to mimic the ability of a human to truly understand the text's meaning. In this dissertation, we aim to extend the practical reach of this area, by exploring a commonly overlooked method for natural language representation: linear combinations (i.e. weighted sums) of embedded representations. This dissertation is organised as a collection of research publications: with our novel contributions published in conference proceedings or journals; and with a comprehensive literature review published as part of a book.

When considering how to represent English input into a natural language processing system, a common response is to view it as a sequential modelling problem: as a discrete time-series of words. A more complex alternative is to base the input model on the grammatical tree structures used by linguists. But there are also simpler models: systems based on just summing the word embeddings. On a variety of tasks, these work very well – often better than the more complex models. This dissertation examines these linear combinations of embeddings for natural language understanding tasks.

In brief, it is found that a sum of embeddings is a particularly effective dimensionality-reduced representation of a bag of words. The dimensionality reduction is carried out at the word level via the implicit matrix factorization on the collocation probability matrix. It thus captures into the dense word embeddings the key features of lexical semantics: words that occur in similar contexts have similar meanings. We find that summing these representations of words gives us a very useful representation of structures built upon words: such as sentences, phrases, and word senses.

A limitation of the sum of embedding representation is that it is unable to represent word order. This representation does not capture any order related information; unlike for example a recurrent neural network. Recurrent neural networks, and other more complex models, are outperformed by sums of embeddings in tasks where word order is not highly significant. It is found that even in tasks where word order does matter to an extent, the improved training capacity of the simpler model still means that it performs better than more complex models. This limitation thus impacts surprisingly little.

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# Authorship declaration

## Publications

This thesis contains work that has been published and/or prepared for publication.

**Details of the work:**
Lyndon White, Roberto Togneri, Wei Liu, and Mohammed Bennamoun (2018a).
*Neural Representations of Natural Language.* Studies in Computational Intelligence
(Book). Springer Singapore. ISBN: 9789811300615
**Location in thesis: ??**
**Student contribution to work:**
Determined content. Created figures. Wrote book. Supervisors reviewed and
provided useful feedback for improvement.

**Details of the work:**
Lyndon White, Roberto Togneri, Wei Liu, and Mohammed Bennamoun (2015).
"How Well Sentence Embeddings Capture Meaning". In: *Proceedings of the 20th
Australasian Document Computing Symposium.* ADCS '15. Parramatta, NSW,
Australia: ACM, 9:1–9:8. ISBN: 978-1-4503-4040-3. DOI: 10.1145/2838931.2838932
**Location in thesis: ??**
**Student contribution to work:**
Devised problem. Designed and implemented algorithms. Conducted experiments.
Created figures. Wrote publication. Supervisors reviewed and provided useful
feedback for improvement.

**Details of the work:**
Lyndon. White, Roberto. Togneri, Wei. Liu, and Mohammed Bennamoun (2018).
"Learning of Colors from Color Names: Distribution and Point Estimation". In:
*Computational Lingustics (Under Review)*
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**Student contribution to work:**
Devised problem. Designed and implemented algorithms. Conducted experiments.
Created figures. Wrote publication. Supervisors reviewed and provided useful
feedback for improvement.

**Details of the work:**
Lyndon White, Roberto Togneri, Wei Liu, and Mohammed Bennamoun (2018b).
"Finding Word Sense Embeddings Of Known Meaning". In: *19th International
Conference on Intelligent Text Processing and Computational Linguistics (CICLing)*
**Location in thesis: ??**
**Student contribution to work:**
Devised problem. Designed and implemented algorithms. Conducted experiments.
Created figures. Wrote publication. Supervisors reviewed and provided useful
feedback for improvement.

**Details of the work:**

Lyndon White, Roberto Togneri, Wei Liu, and Mohammed Bennamoun (2018b). "NovelPerspective: Identifying Point of View Characters". In: *Proceedings of ACL 2018, System Demonstrations*. Association for Computational Linguistics

**Location in thesis: ??**

**Student contribution to work:**

Devised problem. Designed and implemented algorithms. Conducted experiments. Created figures. Wrote publication. Supervisors reviewed and provided useful feedback for improvement.

**Details of the work:**

Lyndon White, Roberto Togneri, Wei Liu, and Mohammed Bennamoun (2016a). "Generating Bags of Words from the Sums of their Word Embeddings". In: *17th International Conference on Intelligent Text Processing and Computational Linguistics (CICLing)*

**Location in thesis: ??**

**Student contribution to work:**

Devised problem. Designed and implemented algorithms. Conducted experiments. Created figures. Wrote publication. Supervisors reviewed and provided useful feedback for improvement.

**Details of the work:**

Lyndon White, Roberto Togneri, Wei Liu, and Mohammed Bennamoun (2016b). "Modelling Sentence Generation from Sum of Word Embedding Vectors as a Mixed Integer Programming Problem". In: *IEEE International Conference on Data Mining: High Dimensional Data Mining Workshop (ICDM: HDM)*. DOI: `10.1109/ICDMW.2016.0113`

**Location in thesis: ??**

**Student contribution to work:**

Devised problem. Designed and implemented algorithms. Conducted experiments. Created figures. Wrote publication. Supervisors reviewed and provided useful feedback for improvement.

**Details of the work:**

Lyndon White, Roberto Togneri, Wei Liu, and Mohammed Bennamoun (2018a). "DataDeps.jl: Repeatable Data Setup for Reproducible Data Science". In: *Journal of Open Research Software (Under Review)*

**Location in thesis: ??**

**Student contribution to work:**

Primary author of software. Created figures. Wrote publication. Supervisors reviewed and provided useful feedback for improvement.

**Details of the work:**

Lyndon White and Sebastin Santy (2018). "DataDepsGenerators.jl: making reusing data easy by automatically generating DataDeps.jl registration code". In: *Journal of Open Source Software (Under Review)*

**Location in thesis: ??**

**Student contribution to work:**

Original author of software. Provided direction, guidance, and code review for its enhancement. Wrote publication.

**Details of the work:**

Lyndon White and David Ellison (2018). "Embeddings.jl: easy access to pretrained word embeddings from Julia". In: *Journal of Open Source Software (Under Review)*

**Location in thesis: ??**

**Student contribution to work:**

Original and primary author of software. Wrote publication.

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Lyndon White and Jonathan Malmaud (2018). "TensorFlow.jl: An Idiomatic Julia Front End for TensorFlow". In: *Journal of Open Source Software (Under Review)*
**Location in thesis: ??**
**Student contribution to work:**
Co-maintainer and second highest contributor to the software. Co-wrote publication.

# Permission to use work in thesis

The coauthors signing below give permission to use the aforementioned works in this dissertation, and certify that the student's statements regarding their contribution to the respective co-authored works listed above are correct.

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**Sebastin Santy:**                     24/09/18

**David Ellison:**                      02/10/18

**Jonathan Malmaud:**                   24/09/18