Quantum NLP with lambeq

Dimitri Kartsaklis Ian Fan Richie Yeung Thomas Hoffmann Vid Kocijan
Charles London Anna Pearson Robin Lorenz Alexis Toumi
Giovanni de Felice Konstantinos Meichanetzidis Stephen Clark
Bob Coecke

Cambridge Quantum / Quantinuum
17 Beaumont Street, Oxford, OX1 2NA, UK
`{firstname.lastname}@cambridgequantum.com`

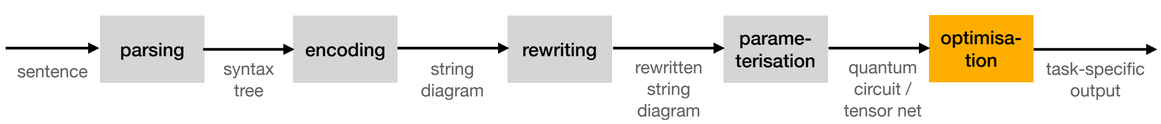
We present `lambeq`, the first high-level Python library for Quantum Natural Language Processing (QNLP). The open-source toolkit offers classes to implement all stages of an experimental QNLP pipeline, from text to string diagrams, tensor networks, and quantum circuits ready to be used on quantum hardware. `lambeq` supports syntactic parsing, rewriting of string diagrams, ansatz manipulation, and compositional models for preparing quantum-friendly representations of sentences. We present the architecture and modules in detail, demonstrating usage with illustrative examples, as well as testing the toolkit in practice with a simple NLP experiment to show that it is ready for use in real-world quantum settings.

1 Introduction

Quantum Natural Language Processing (QNLP) is a rapidly-growing area of research that explores how approaches to natural language tasks can utilise quantum phenomena, such as superposition, entanglement and interference. Current NISQ[1] computers allow researchers to run simple experiments on quantum hardware [15, 12, 14], but it requires a lot of low-level work to prepare even simple QNLP models.

To facilitate easier preparation and execution of QNLP experiments, we have developed `lambeq`[2,3], an open-source, modular, extensible high-level Python library that provides the tools for implementing a pipeline for experimental QNLP. `lambeq` is under active development, informed by real-world usage.

A high-level overview of a standard QNLP pipeline with `lambeq` is shown below:



`lambeq` provides routines for each of the stages shown, allowing researchers to easily set up a QNLP pipeline for any experiment. Modularity allows any of these stages to be replaced with a custom implementation that is more finely tuned to an experiment's needs, whilst keeping the same high-level structure. Finally, `lambeq` provides a training sub-package that encapsulates the entire pipeline.

In addition to being a library, `lambeq` also provides a web demo[4] and a fully-featured command-line interface, allowing `lambeq` to act as a standalone pregroup [11] parser[5], the first of its kind.

[1] Noisy Intermediate-Scale Quantum

[2] The name is a tribute to mathematician Joachim Lambek (1922-2014), whose seminal work lay at the intersection of mathematics, logic, and linguistics [10].

[3] `https://github.com/CQCL/lambeq`

[4] `https://qnlp.cambridgequantum.com/generate.html`

[5] An example of this usage is shown in Appendix B.

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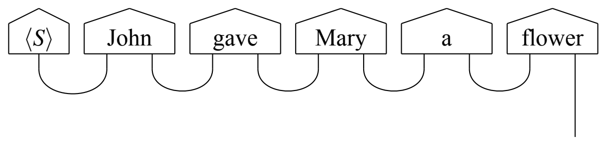
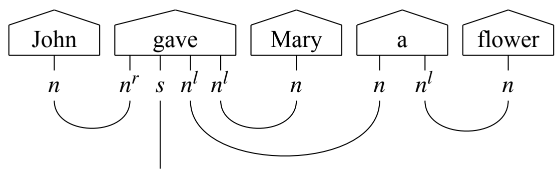
2 Parsing and encoding

This first step converts text into a string diagram, based on the graphical calculus for monoidal categories. The underlying data structures for these diagrams are handled by DisCoPy [4], a specialised Python library for manipulating string diagrams. Though DisCoPy is powerful and intuitive to use, it is cumbersome to define large diagrams and the many levels of abstractions which are commonly encountered in QNLP to represent text. Accordingly, `lambeq` defines several ways of easily transforming text into string diagrams. One way is to combine the words in a simple left-to-right manner:



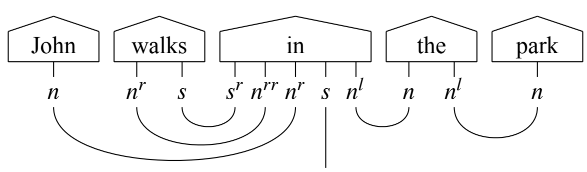
Another way is to follow the syntactic structure of the sentence. A framework for doing this syntax-guided interaction is DisCoCat[6]. The process involves parsing the sentence with a CCG[7] parser, then turning the resulting parse tree into a string diagram [21]:



`lambeq` includes a state-of-the-art CCG parser, named *Bobcat* [1, 2], as well as a simple way to extend the toolkit's functionality to use external CCG parsers, such as *depccg* [22]. Furthermore, `lambeq` also contains a class that provides string diagram conversions for the entire CCGBank corpus [8][8].

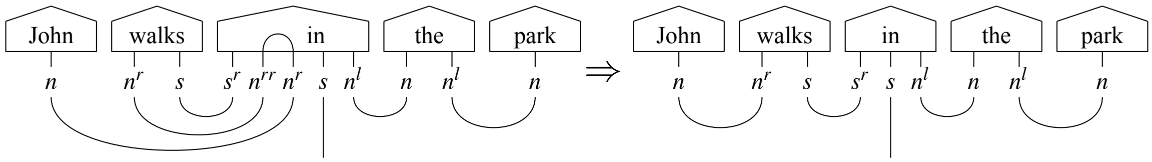
3 Rewriting

Some diagrams can be simplified by incorporating prior assumptions about word interactions. This is helpful for reducing the resource usage of quantum computers when training. `lambeq` includes not only routines for rewriting diagrams, but also a number of standard rewrite rules. For example, the prepositional phrase rewrite rule can be used in the sentence "John walks in the park", the original diagram of which is the following:



This simplification expresses a prior assumption about the preposition "in", namely that the subject noun wires can be bridged by a cap (∩) in the underlying compact-closed monoidal structure, and then "pulled out":

[6] *Dis*tributional *Co*mpositional *Cat*egorical [3].
[7] Combinatory Categorial Grammar [19].
[8] CCGBank consists of 49,000 human-annotated CCG syntax trees, converted from the original Penn Treebank[13]



This reduces the order of the preposition tensor by 2, lowering resource usage in both quantum circuits and classical tensor networks.

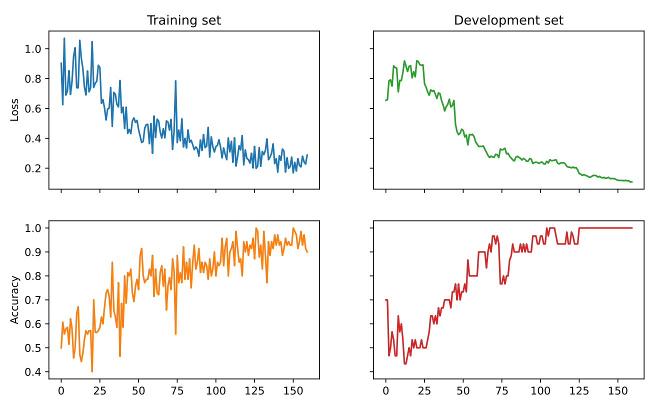
4 Parameterisation

In this module, the symbolic string diagram is turned into a concrete quantum circuit for training, or a tensor network for classical experiments. This is done by applying ansätze, which are maps that determine specific choices in the circuit or network, such as the number of qubits associated with each wire of the string diagram. `lambeq` provides several ways for applying ansätze in quantum and classical cases. For example, `IQPAnsatz` is a class that turns a string diagram into a standard IQP[9] circuit.[10]

5 Optimisation and training

The outputs of the pipeline in `lambeq` can be chosen to work with a number of existing optimisation libraries, including NumPy [6], PyTorch [16], JAX [5] and t|ket⟩ [17], which interfaces with several quantum hardware platforms. Furthermore, `lambeq` provides a training sub-package that can manage the optimisation itself.

To demonstrate its capabilities, we train a model to classify simple sentences from the meaning classification dataset in [12] into two categories: Food or IT. We convert the 130 sentences from the dataset into string diagrams, and then into quantum circuits using `IQPAnsatz`. We optimise using *Simultaneous Perturbation Stochastic Approximation* [18]. We evaluate the model on `qiskit`'s [20] Aer simulator[11], using a noise model to best approximate real quantum hardware. The results show that the model is able to converge to perfect accuracy:



Further details about this experiment, including parameterisation details and other pipelines, are available in [9], as well as further information about the `lambeq` package itself.

[9] Instantaneous Quantum Polynomial: a circuit which interleaves layers of Hadamard gates with diagonal unitaries [7].
[10] An example of a generated IQP circuit is shown in Appendix A.
[11] This is available through t|ket⟩'s Python interface, `pytket`.

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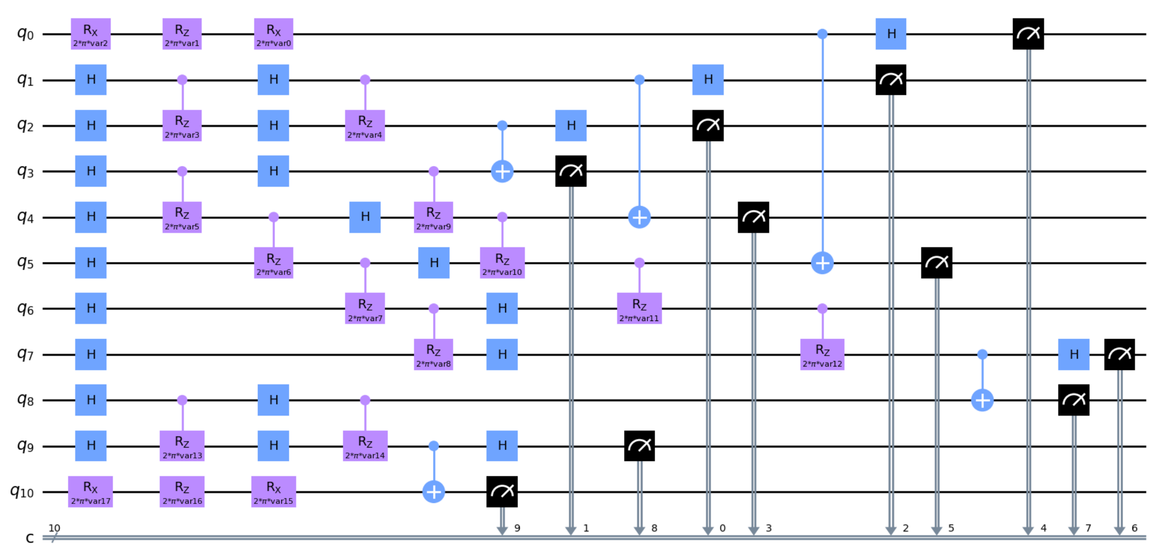
A IQP Ansatz

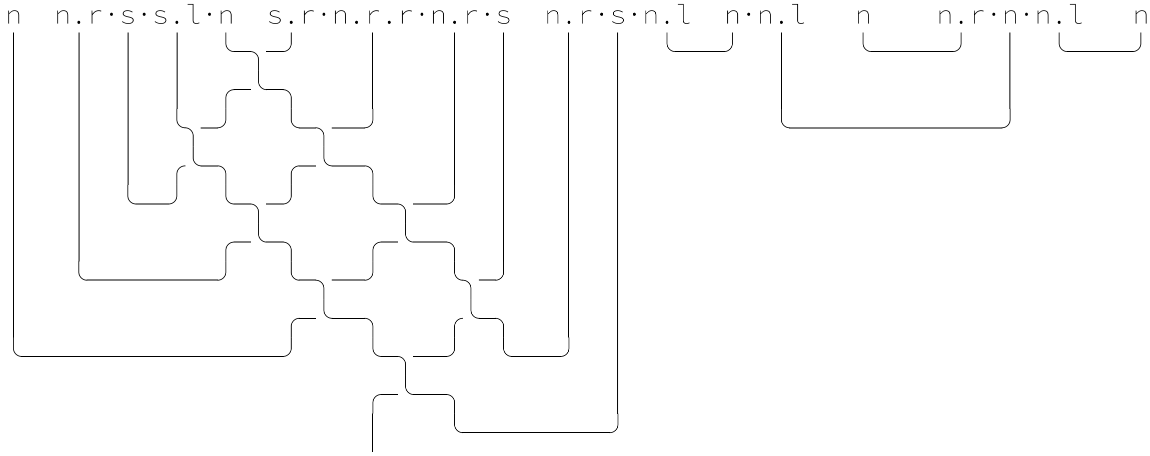
Quantum circuit for the sentence "John walks in the park" in `qiskit` format, where noun and sentence types are assigned 1 qubit each:



B Command-Line Interface

An example of using the `lambeq` command-line interface as a standalone pregroup parser, to parse the sentence "I don't like green eggs and ham":

```
> lambeq --tokenise "I don't like green eggs and ham"
I       do             n't            like    green  eggs     and      ham
─  ─────────────  ───────────────  ─────────  ─────  ────  ─────────  ───
n  n.r·s·s.l·n   s.r·n.r.r·n.r·s  n.r·s·n.l  n·n.l   n    n.r·n·n.l   n
```



The pregroup parser converts the output of a CCG parser into a pregroup derivation [21], which is displayed as a string diagram. The swaps in the diagram correspond to a feature of CCG that is not found in standard pregroup derivations, that of cross-composition.