Bob Coecke

Compositional intelligence

Bob Coecke

~~Oxford University~~

UNIVERSITY OF OXFORD

DEPARTMENT OF COMPUTER SCIENCE

Professor Bob Coecke

Professor of Quantum Foundations, Logics and Structures

Fellow, Wolfson College

Leaving date: 31st December 2020

Bob Coecke

Cambridge Quantum

BUSINESSWEEKLY
A WORLDWIDE WINDOW TO CAMBRIDGE BUSINESS, INNOVATION & TECHNOLOGY

6 January, 2021 - 10:54 By Tony Quested

Global guru named chief scientist of Cambridge Quantum Computing

World leading authority and Oxford don Bob Coecke has added yet another dimension to the non-stop progress of Cambridge Quantum Computing (CQC) by becoming chief scientist.

Bob Coecke

Quantinuum

Forbes

Jun 8, 2021, 09:04am EDT | 49,374 views

Honeywell Quantum Solutions And Cambridge Quantum Computing Merge With Go-Public In Mind

Paul Smith-Goodson Contributor
Moor Insights and Strategy Contributor Group
Cloud
Analyst-in-residence, Quantum Computing

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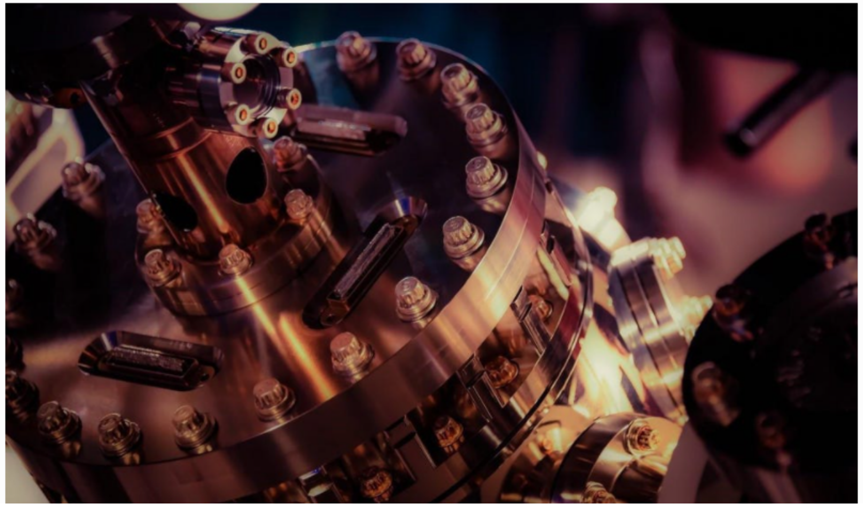
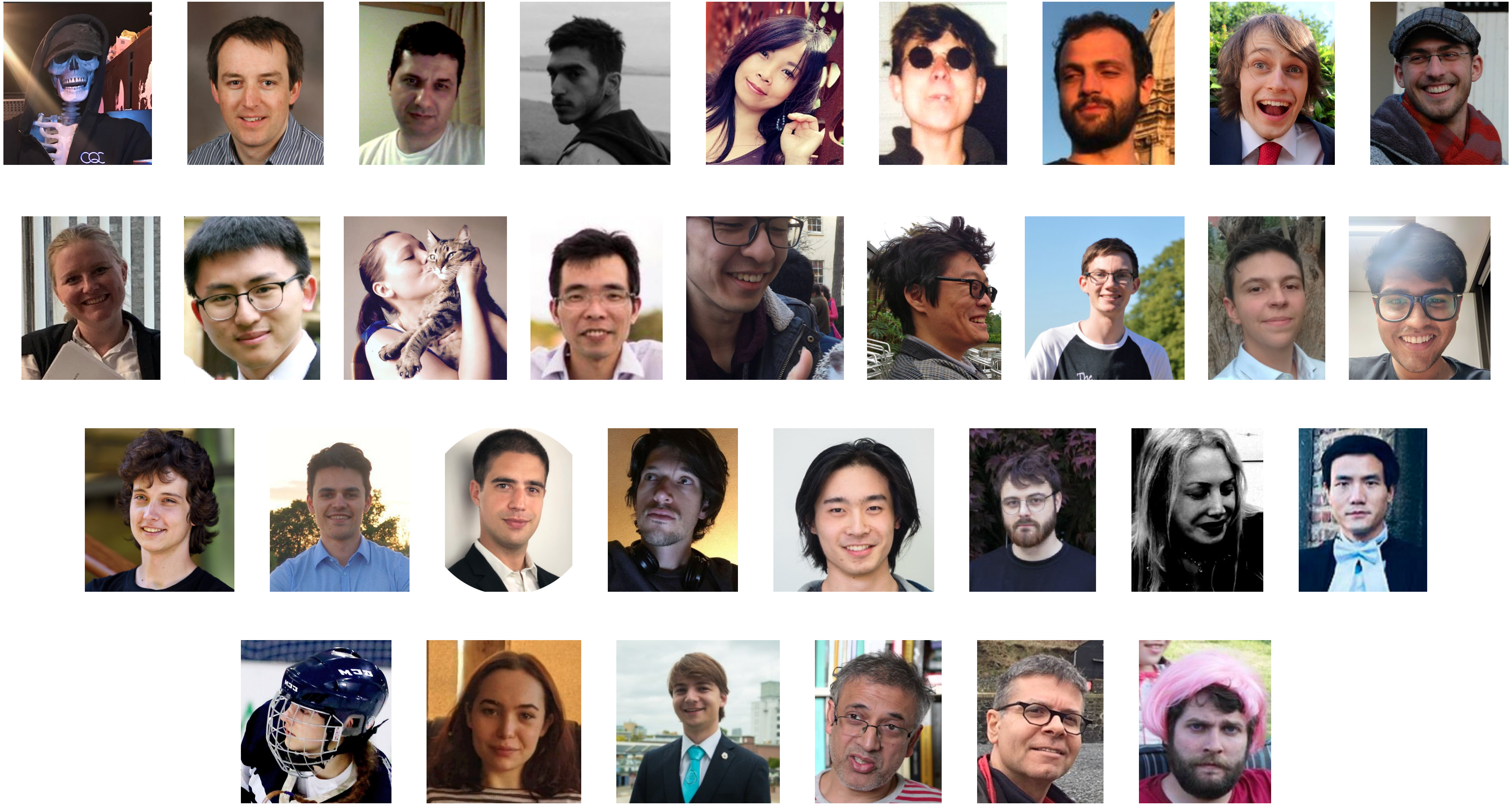
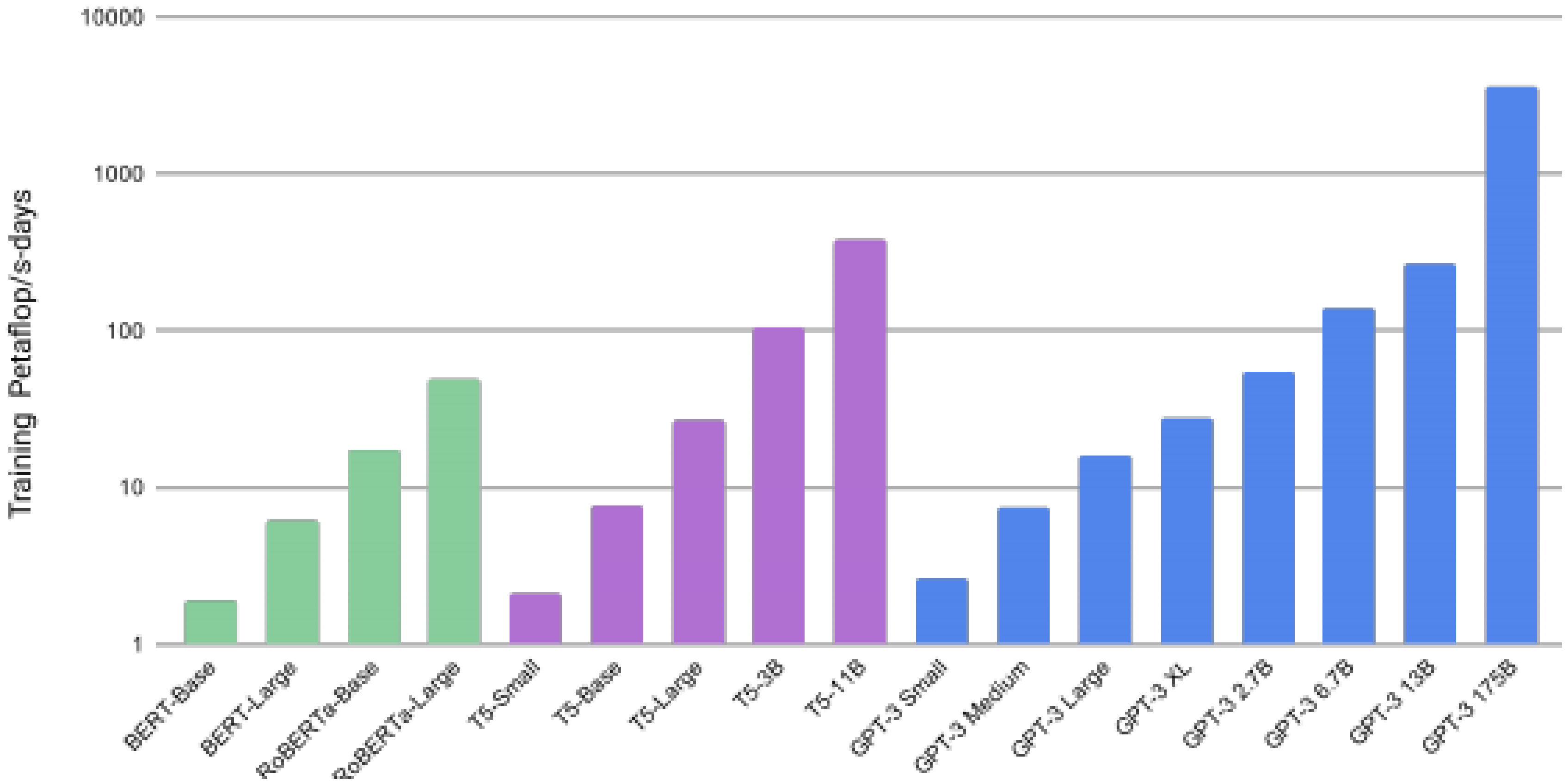


Oxford-based team



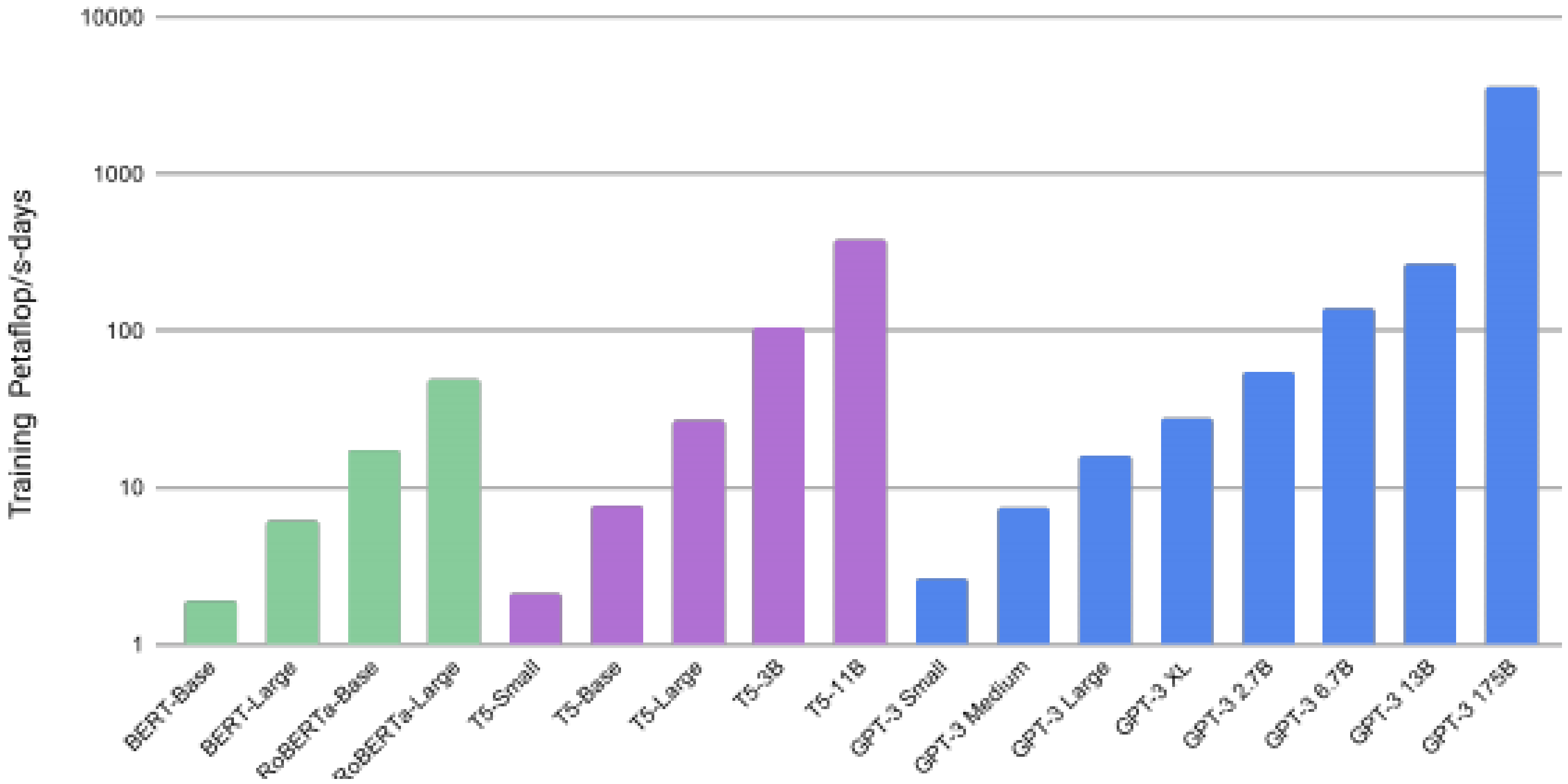
NLP/AI today

The amazing progress in NLP/AI is due to:



The amazing progress in NLP/AI is due to:

- Huge increase in **computational power** (multiple GPUs)
-
-



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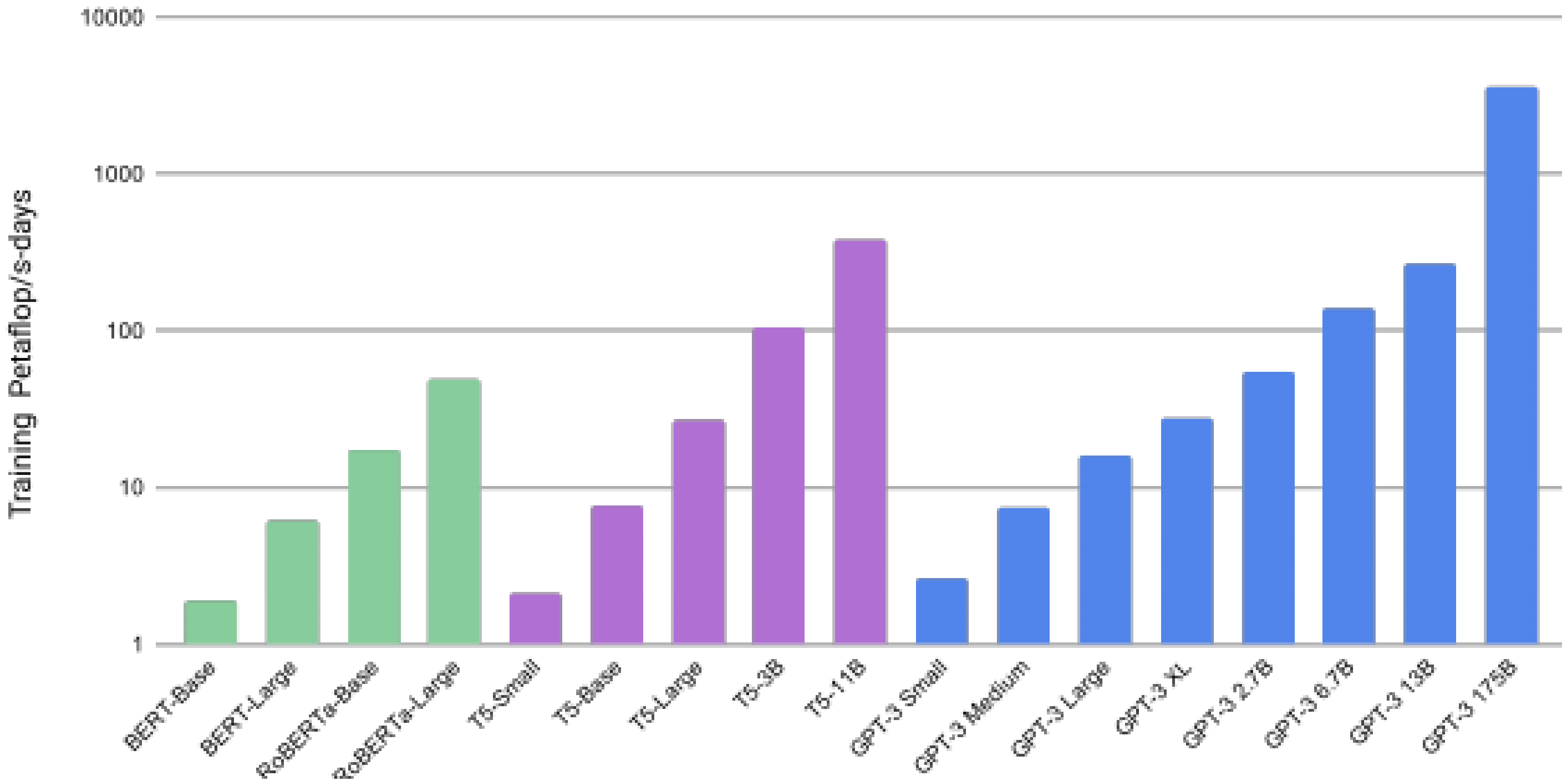
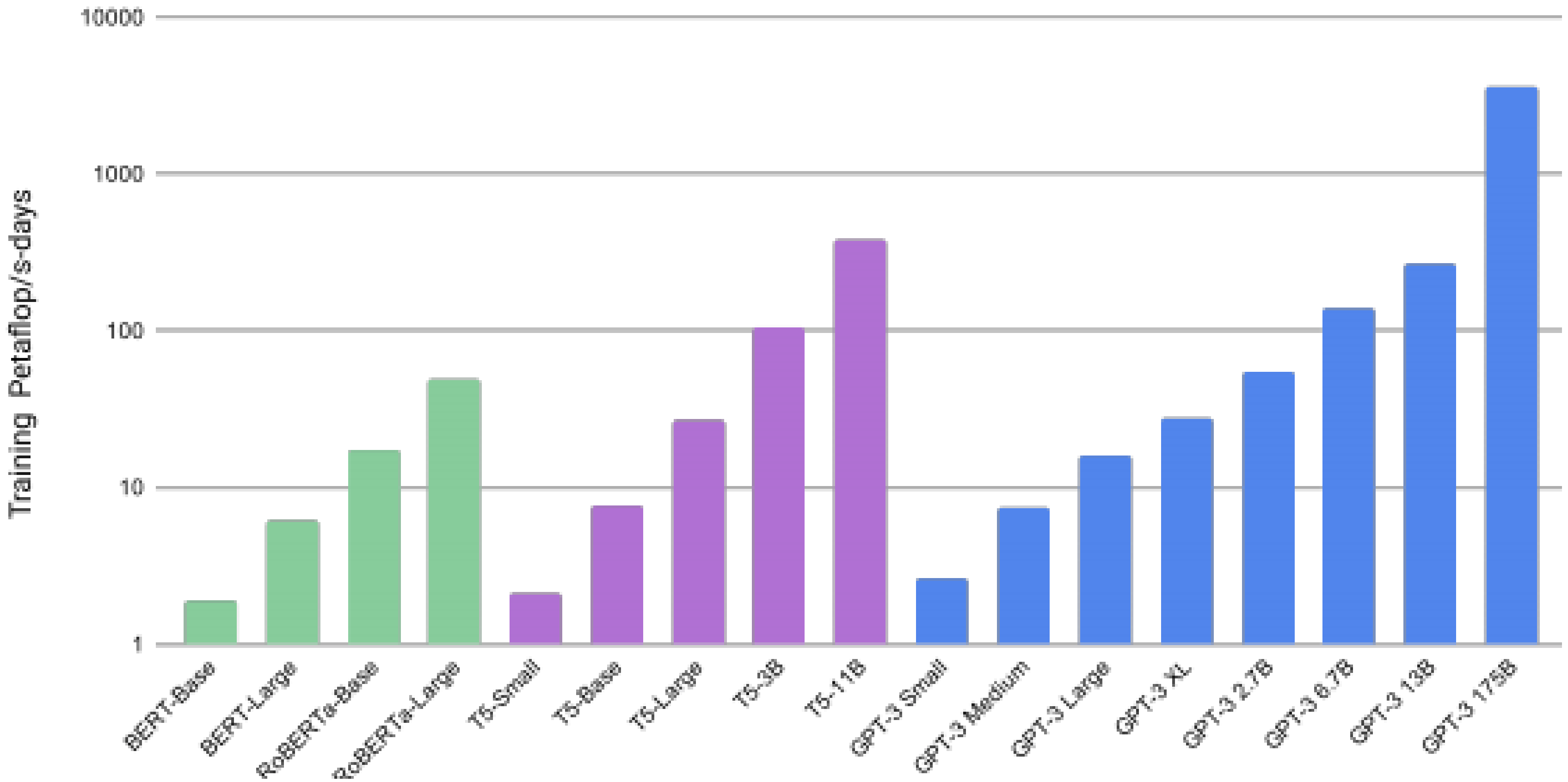
- Huge increase in **available data** (factor 10^6 since 1997)
-



The amazing progress in NLP/AI is due to:

- Huge increase in **computational power** (multiple GPUs)
- Huge increase in **available data** (factor 10^6 since 1997)
- **Not so much** a shift of **conceptual paradigm** (NNs since 1870s/1940s)



Some clear shortcomings of current NLP/AI include:

-
-
-

nature

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NEWS FEATURE | 03 March 2021

Robo-writers: the rise and risks of language-generating AI

A remarkable AI can write like humans — but with no understanding of what it's saying.

Some clear shortcomings of current NLP/AI include:

- **Lack of interpretability**, verifiability, safety, fairness...
-
-

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Modern CS deals with some of these using _____ compositionality:

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-
-

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- Composability of different tools/methods...
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Modern CS deals with some of these using Frege compositionality:

- Increased interpretability, verifiability, safety...
- Composability of different tools/methods...
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$$\boxed{\text{“meaning of whole := meaning of parts + structure”}}$$

Modern CS deals with some of these using Frege compositionality:

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- Composability of different tools/methods...
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“meaning of whole := meaning of parts + structure”

For example:

- word-meanings + grammar; software within phone/laptop; mathematics

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For example:

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However:

- This is not how modern machine learning works...
- ...where the **whole determines a ‘black-box’**.

Modern CS deals with some of these using Frege compositionality:

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"meaning of whole := meaning of parts + structure"

For example:

- word-meanings + grammar; software within phone/laptop; mathematics

However:

- This is not how modern machine learning works...
- ...where **GOFAI structures have no place**.

our prehistory

Around 2008 @ Oxford Uni. there were 3 people:

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- One knew grammar algebra:

$$n \cdot {}^{-1}n \cdot s \cdot n^{-1} \cdot n \leq 1 \cdot s \cdot 1 \leq s$$

grammar algebra

Lambek's Residuated monoids (1950's):

$$b \leq a \multimap c \Leftrightarrow a \cdot b \leq c \Leftrightarrow a \leq c \multimapinv b$$

Lambek's Pregroups (2000's):

$$a \cdot {}^{-1}a \leq 1 \leq {}^{-1}a \cdot a$$
$$b^{-1} \cdot b \leq 1 \leq b \cdot b^{-1}$$

grammar algebra

For noun type n, sentence type s,

grammar algebra

For noun type n, sentence type s, verb type is ${}^{-1}n \cdot s \cdot n^{-1}$, so:

grammar algebra

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grammar algebra

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grammar algebra

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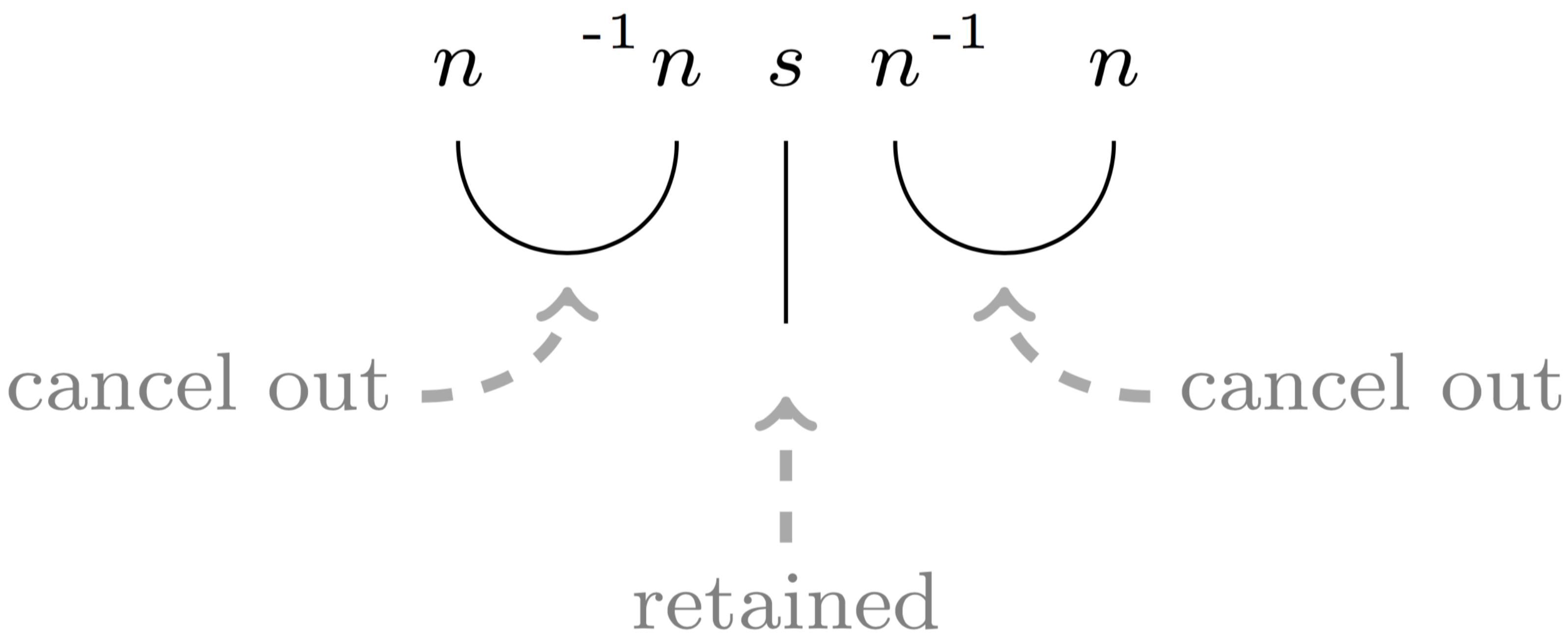
$$n \cdot {}^{-1}n \cdot s \cdot n^{-1} \cdot n \leq s$$

As a diagram:



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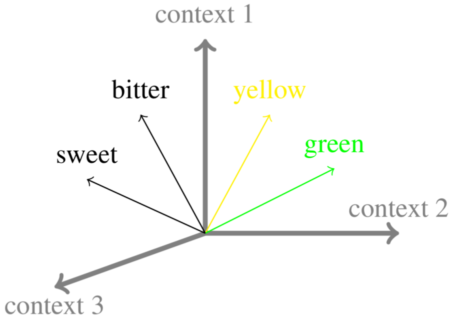

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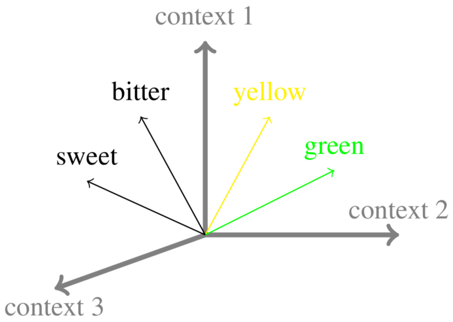
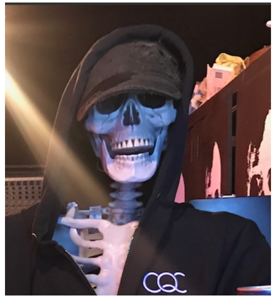
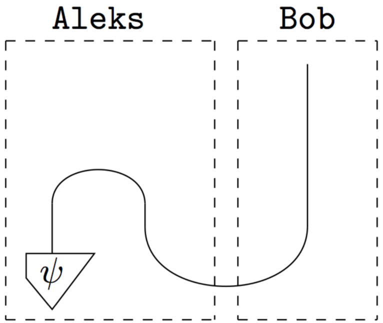
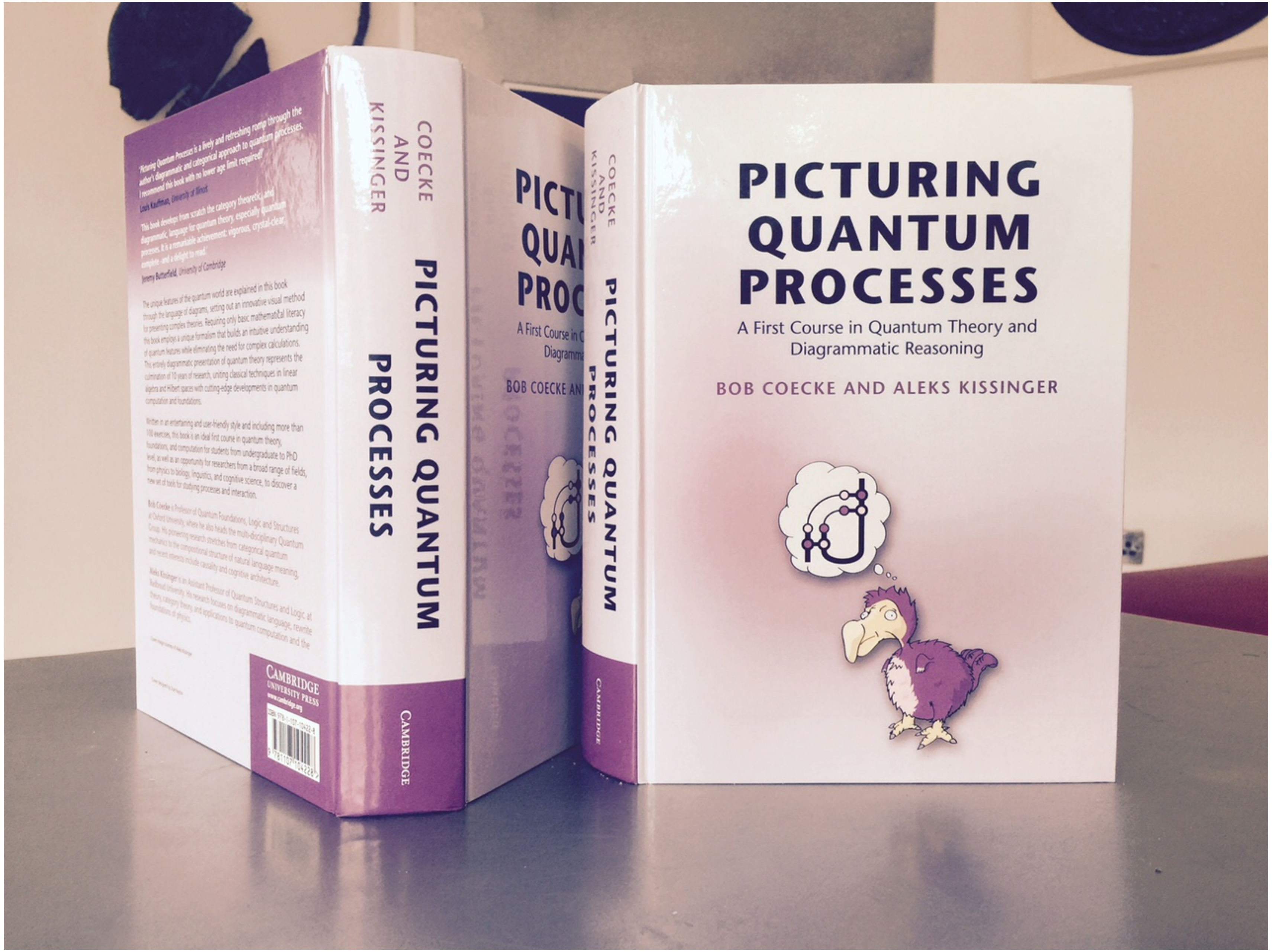


- One knew categorical QM:



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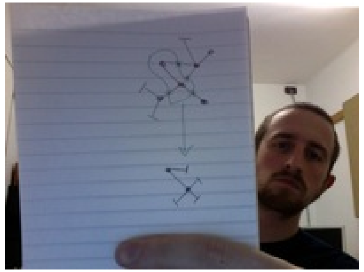
BOB COECKE AND ALEKS KISSINGER

ZX-calculus now used by all major quantum companies



arXiv.org > quant-ph > arXiv:0906.4725

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Quantum Physics

[Submitted on 25 Jun 2009 (v1), last revised 21 Apr 2011 (this version, v3)]

Interacting Quantum Observables: Categorical Algebra and Diagrammatics

Bob Coecke, Ross Duncan

This paper has two tightly intertwined aims: (i) To introduce an intuitive and universal graphical calculus for multi-qubit systems, the ZX-calculus, which greatly simplifies derivations in the area of quantum computation and information. (ii) To axiomatise complementarity of quantum observables within a general framework for physical theories in terms of dagger symmetric monoidal categories. We also axiomatize phase shifts within this framework.

Using the well-studied canonical correspondence between graphical calculi and symmetric monoidal categories, our results provide a purely graphical formalisation of complementarity for quantum observables. Each individual observable, represented by a commutative special dagger Frobenius algebra, gives rise to an abelian group of phase shifts, which we call the phase group. We also identify a strong form of complementarity, satisfied by the Z and X spin observables, which yields a scaled variant of a bialgebra.

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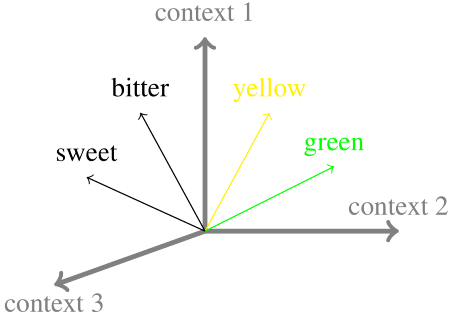
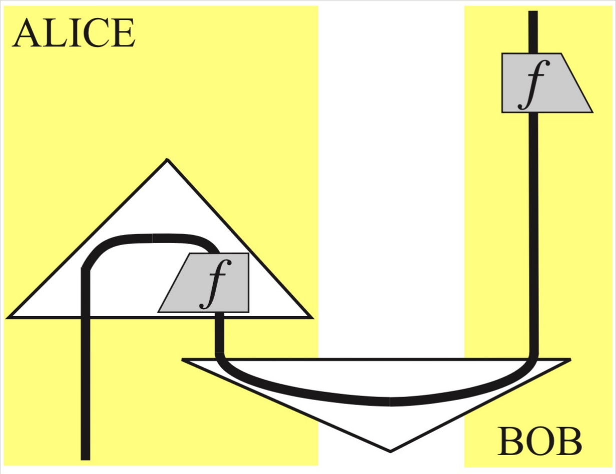


How can we combine grammar and meaning?

McGill, Montreal, 2004

Hello, I present to you quantum teleportation:



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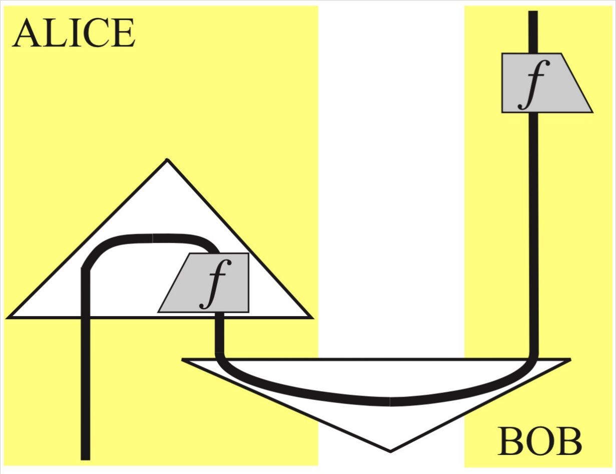

Bob!
This is grammar!

A new model of language



arXiv.org > cs > arXiv:1003.4394

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Computer Science > Computation and Language

[Submitted on 23 Mar 2010]

Mathematical Foundations for a Compositional Distributional Model of Meaning

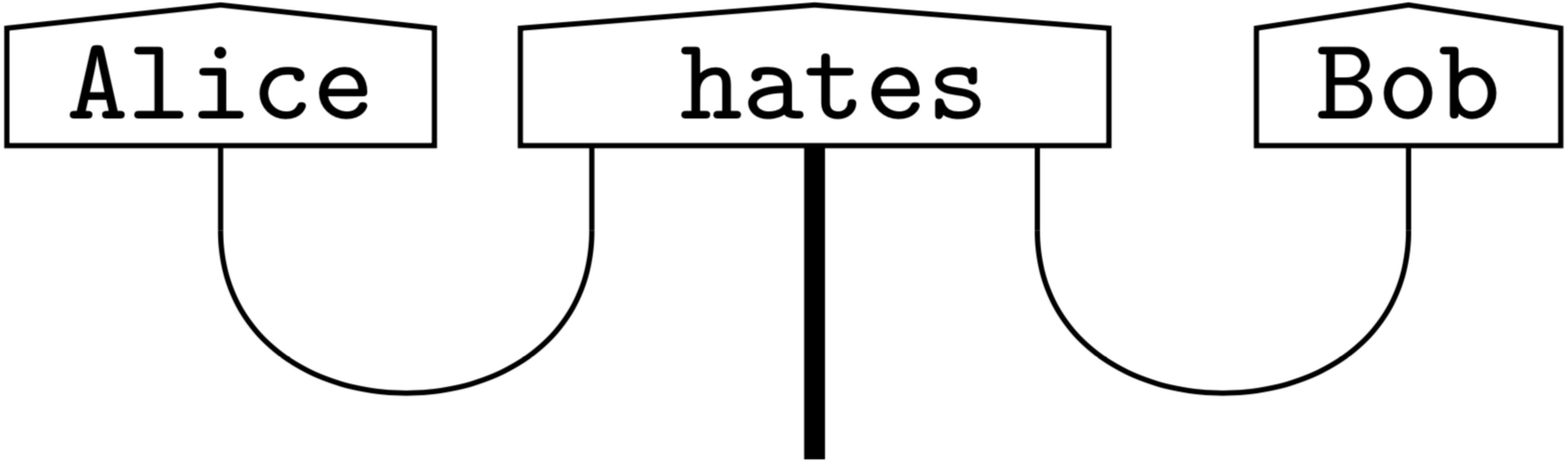
Bob Coecke, Mehrnoosh Sadrzadeh, Stephen Clark

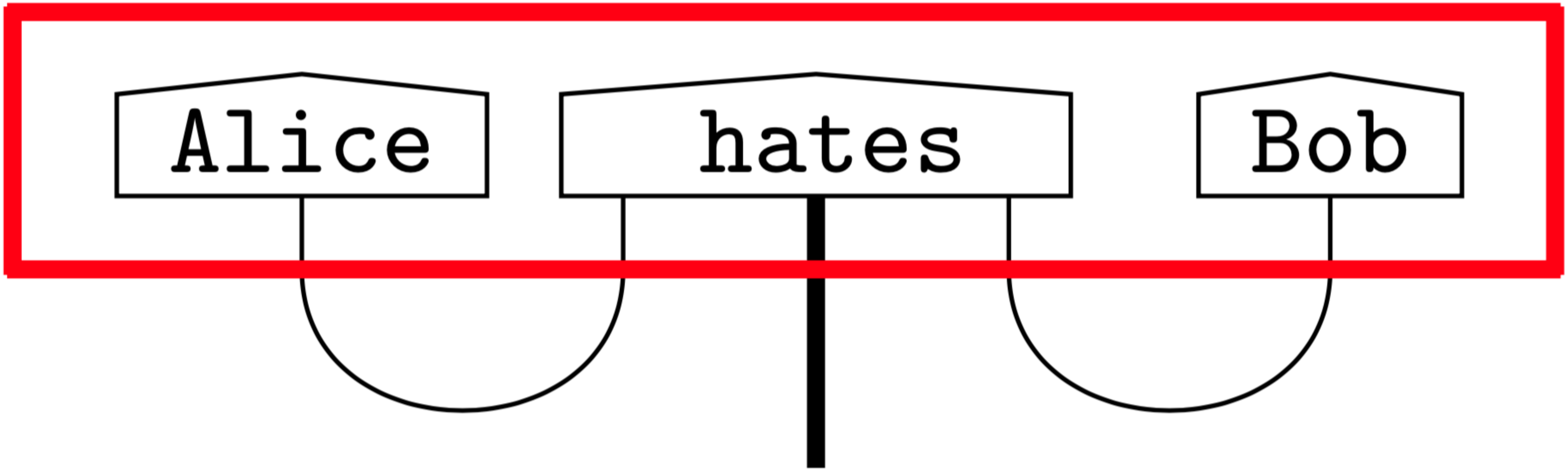
We propose a mathematical framework for a unification of the distributional theory of meaning in terms of vector space models, and a compositional theory for grammatical types, for which we rely on the algebra of Pregroups, introduced by Lambek. This mathematical framework enables us to compute the meaning of a well-typed sentence from the meanings of its constituents. Concretely, the type reductions of Pregroups are `lifted' to morphisms in a category, a procedure that transforms meanings of constituents into a meaning of the (well-typed) whole. Importantly, meanings of whole sentences live in a single space, independent of the grammatical structure of the sentence. Hence the inner-product can be used to compare meanings of arbitrary sentences, as it is for comparing the meanings of words in the distributional model. The mathematical structure we employ admits a purely diagrammatic calculus which exposes how the information flows between the words in a sentence in order to make up the meaning of the whole sentence. A variation of our `categorical model' which involves constraining the scalars of the vector spaces to the semiring of Booleans results in a Montague-style Boolean-valued semantics.

Comments: to appear

Subjects: **Computation and Language (cs.CL)**; Logic in Computer Science (cs.LO); Category Theory (math.CT)

Journal reference: Lambek Festschrift, special issue of Linguistic Analysis, 2010.


Alice
hates
Bob


Alice
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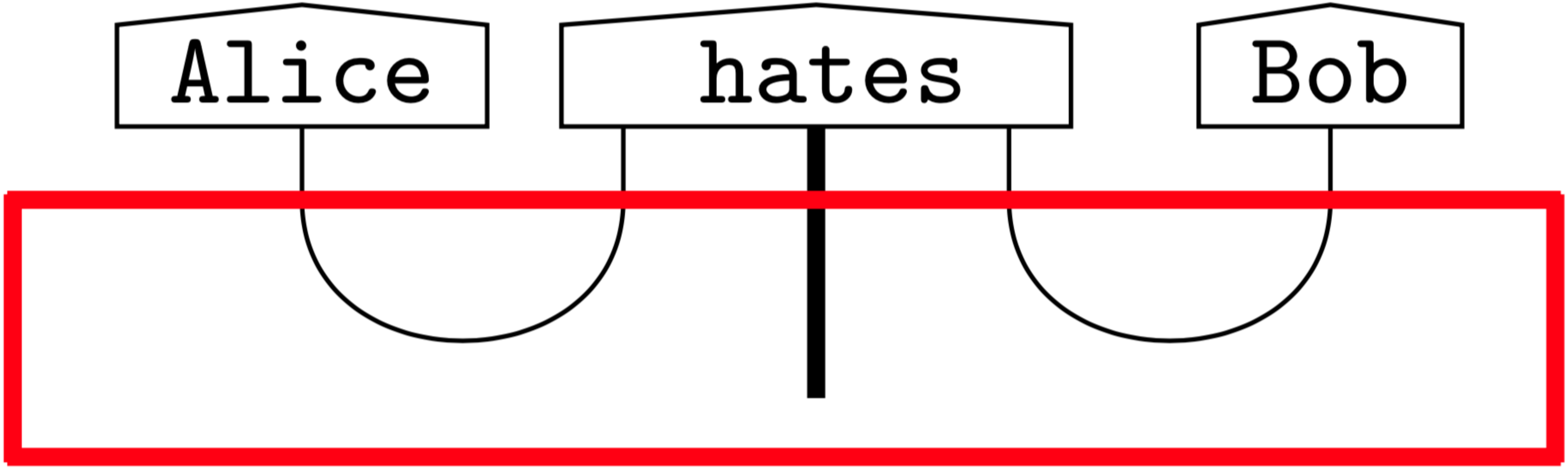
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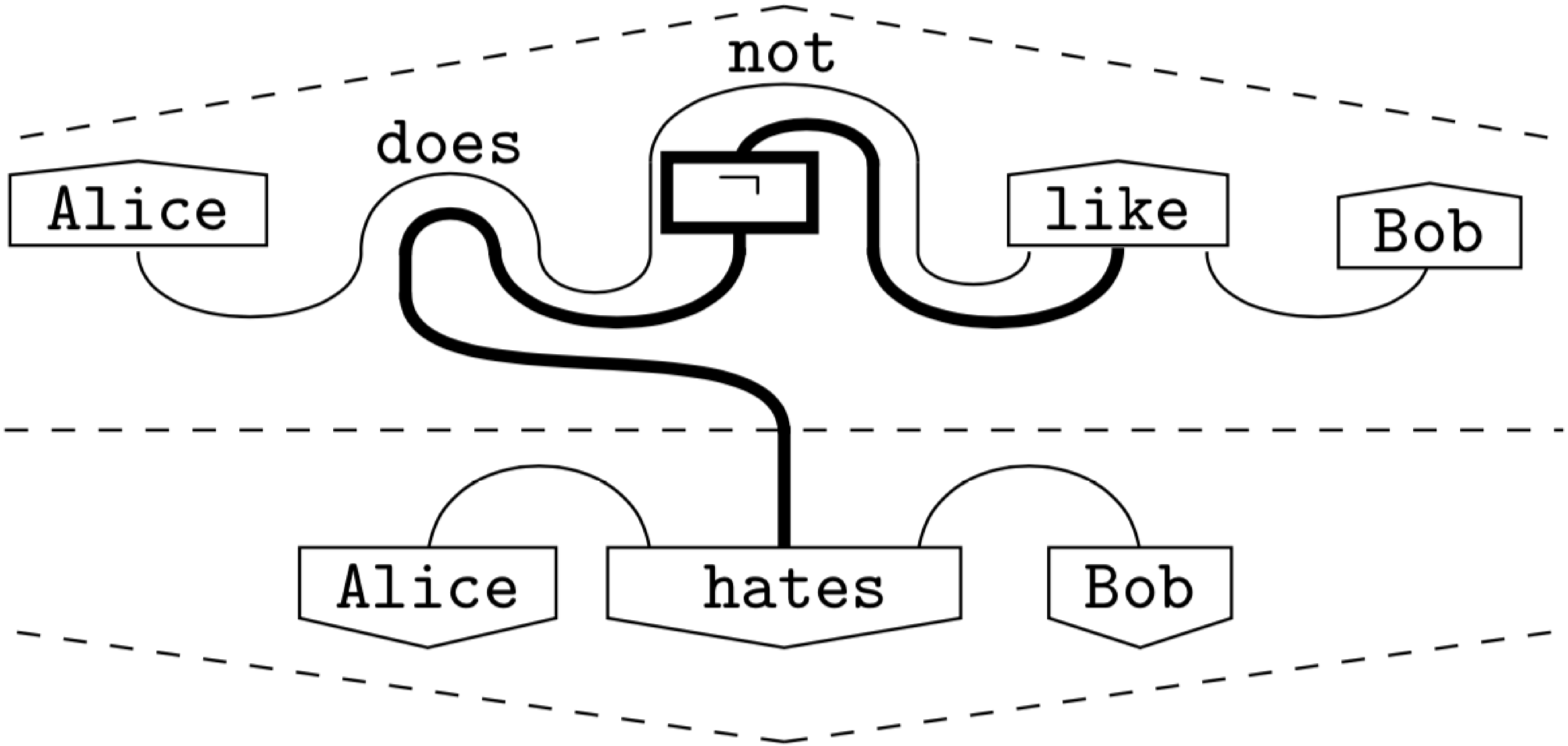

not
does
Alice
¬
like
Bob
Alice
hates
Bob

QUANTUM LINGUISTICS Leap forward for artificial intelligence

NewScientist

WEEKLY 11 December 2010

FQXI ARTICLE September 29, 2013

Video Article: The Quantum Linguist

Bob Coecke has developed a new visual language that could be used to spell out a theory of quantum gravity—and help us understand human speech.

by Sophie Hebden

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Quantum Mechanical Words and Mathematical Organisms

By Joselle Kehoe | May 16, 2013 | 10

	'DisCoCat' then	NLP/AI now
Compositionality I	interpretable	black box
Compositionality II	Frege then	post-Frege
Universality	no	yes
Data need	much less	a lot
Reasoning*	not yet	no
Linguistic structure†	yes	no
Grammatical overhead	yes	no
Evolving meanings*	no	no
Sentence space	non-canonical	no types

*Subject to refining these notions as we did for compositionality in the paper arXiv:2110.05327

†We mean explicit structure here, not implicit like relativity theory within Ptolemy's model.

text circuits

Computer Science > Computation and Language

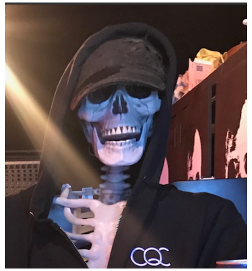
[Submitted on 6 Apr 2019 (v1), last revised 28 Feb 2020 (this version, v2)]

The Mathematics of Text Structure

Bob Coecke

In previous work we gave a mathematical foundation, referred to as DisCoCat, for how words interact in a sentence in order to produce the meaning of that sentence. To do so, we exploited the perfect structural match of grammar and categories of meaning spaces. Here, we give a mathematical foundation, referred to as DisCoCirc, for how sentences interact in texts in order to produce the meaning of that text. First we revisit DisCoCat. While in DisCoCat all meanings are fixed as states (i.e. have no input), in DisCoCirc word meanings correspond to a type, or system, and the states of this system can evolve. Sentences are gates within a circuit which update the variable meanings of those words. Like in DisCoCat, word meanings can live in a variety of spaces e.g. propositional, vectorial, or cognitive. The compositional structure are string diagrams representing information flows, and an entire text yields a single string diagram in which word meanings lift to the meaning of an entire text. While the developments in this paper are independent of a physical embodiment (cf. classical vs. quantum computing), both the compositional formalism and suggested meaning model are highly quantum-inspired, and implementation on a quantum computer would come with a range of benefits. We also praise Jim Lambek for his role in mathematical linguistics in general, and the development of the DisCo program more specifically.



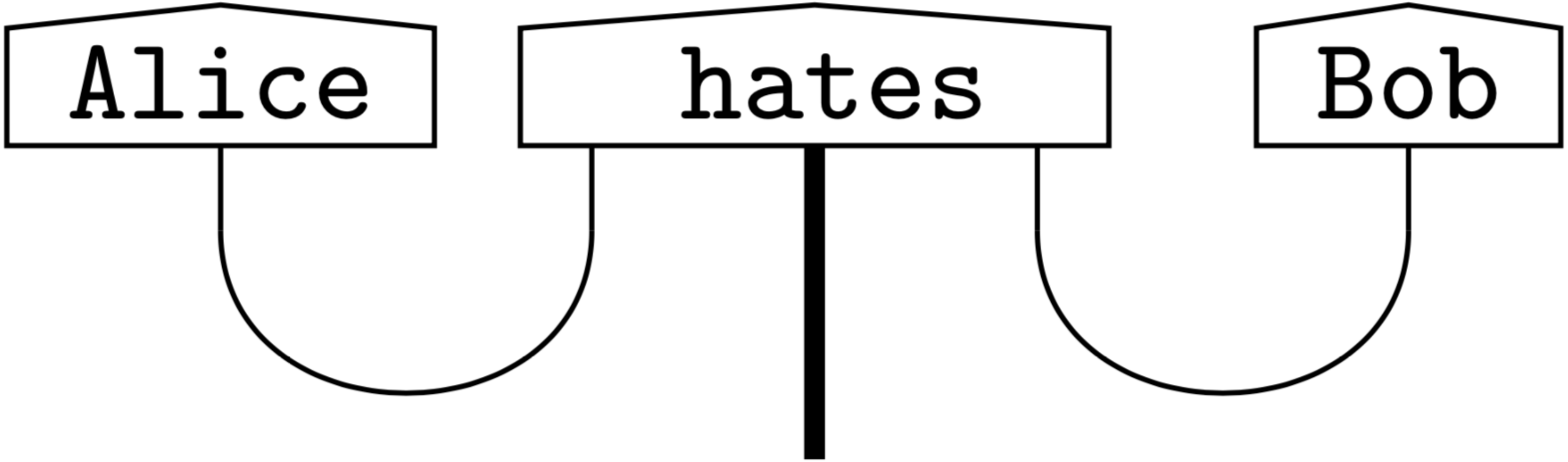


Distilling Text into Circuits

Vincent Wang-Maścianica[†‡], Jonathon Liu[†] and Bob Coecke[†]

[†]Cambridge Quantum, Compositional Intelligence Team, Oxford
[‡]Oxford University, Department of Computer Science

February 23, 2022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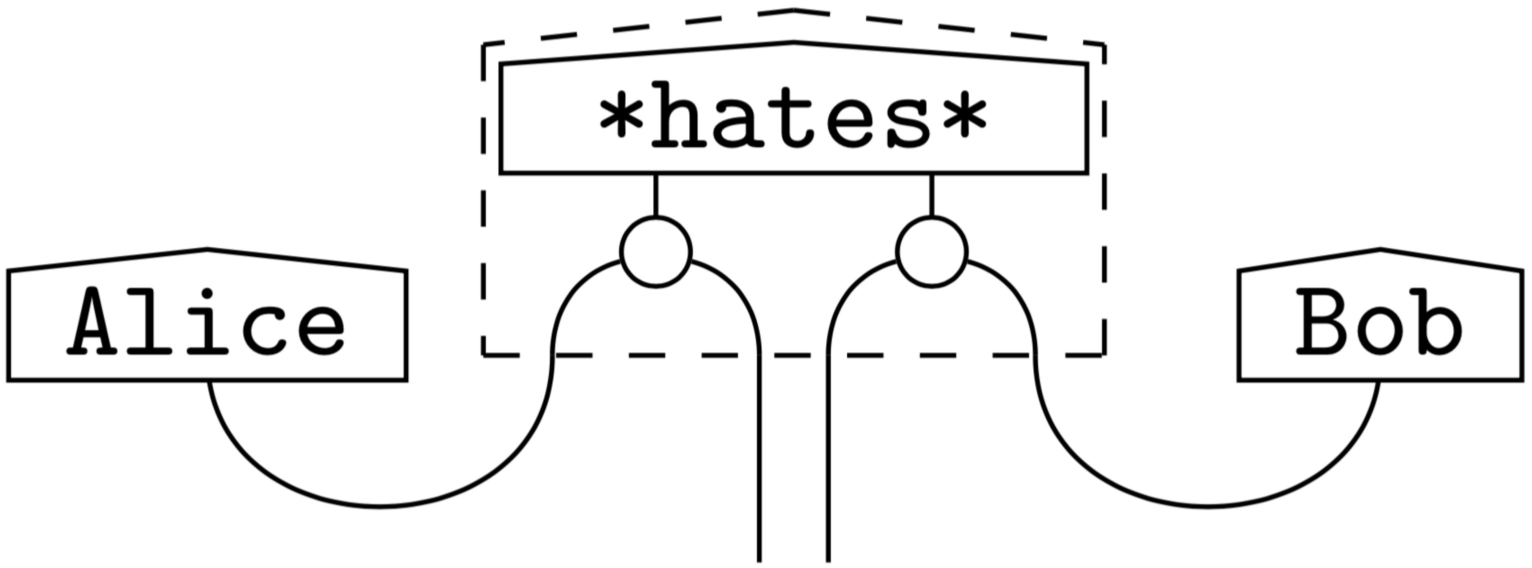
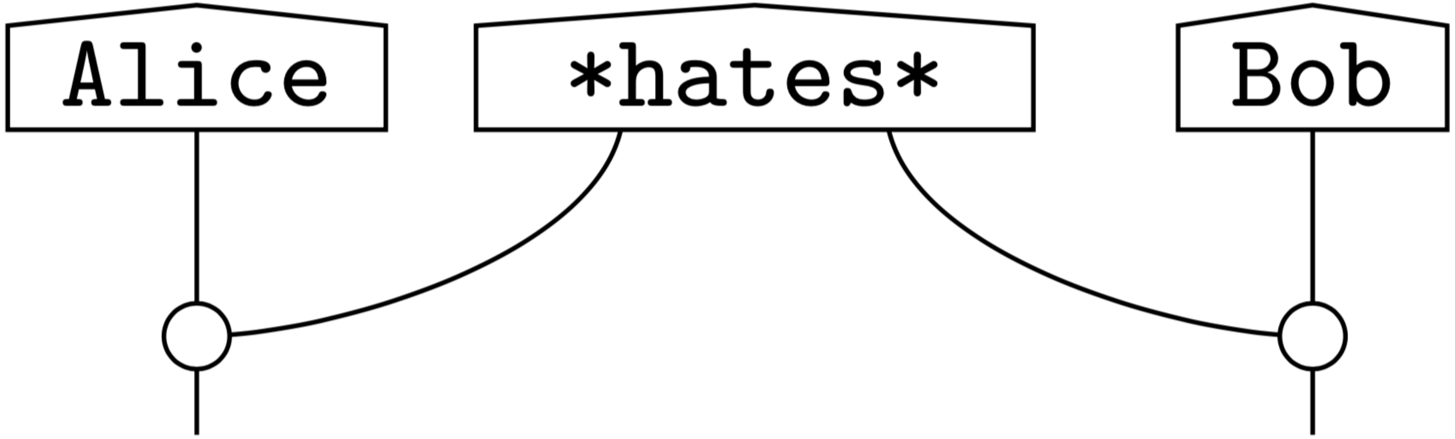
hates
Bob


hates
Alice
Bob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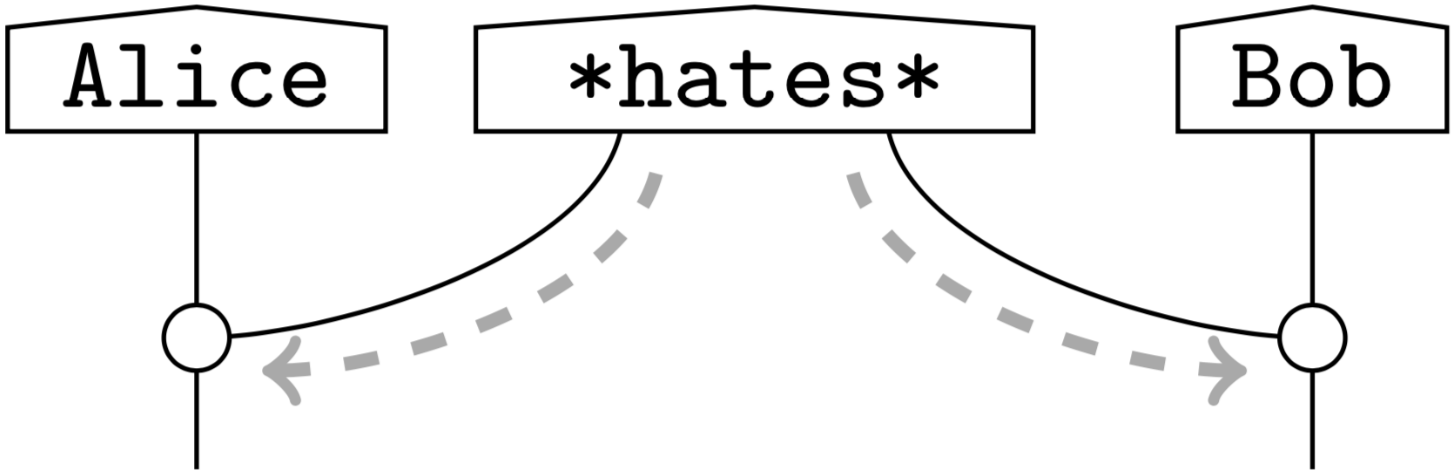
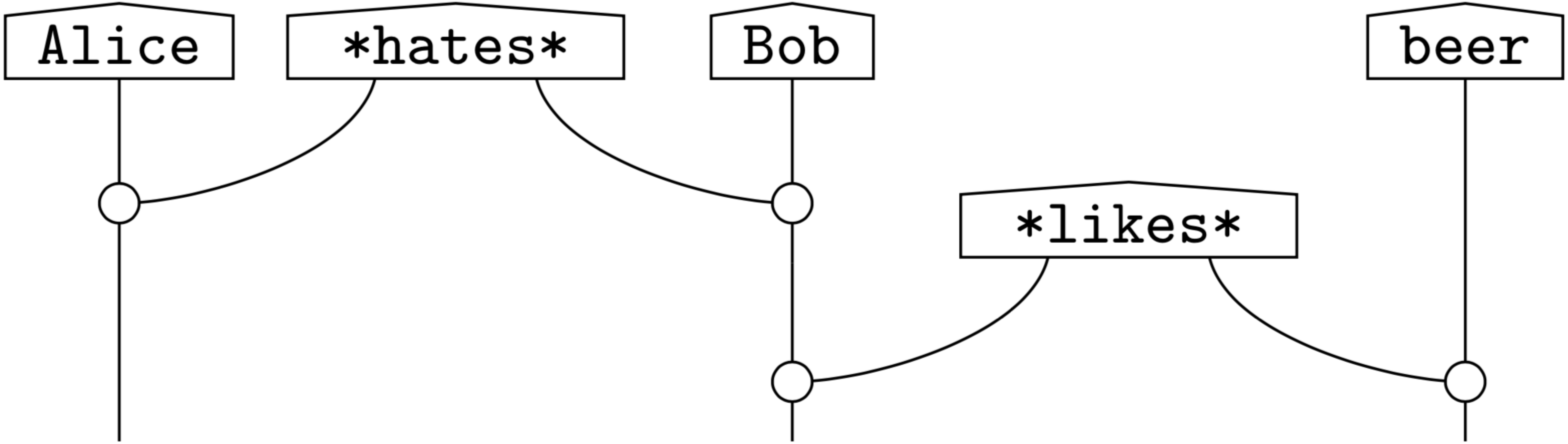

Alice
hates
Bob

COMPOSE!



Advantages of language circuits:

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- evolving meanings

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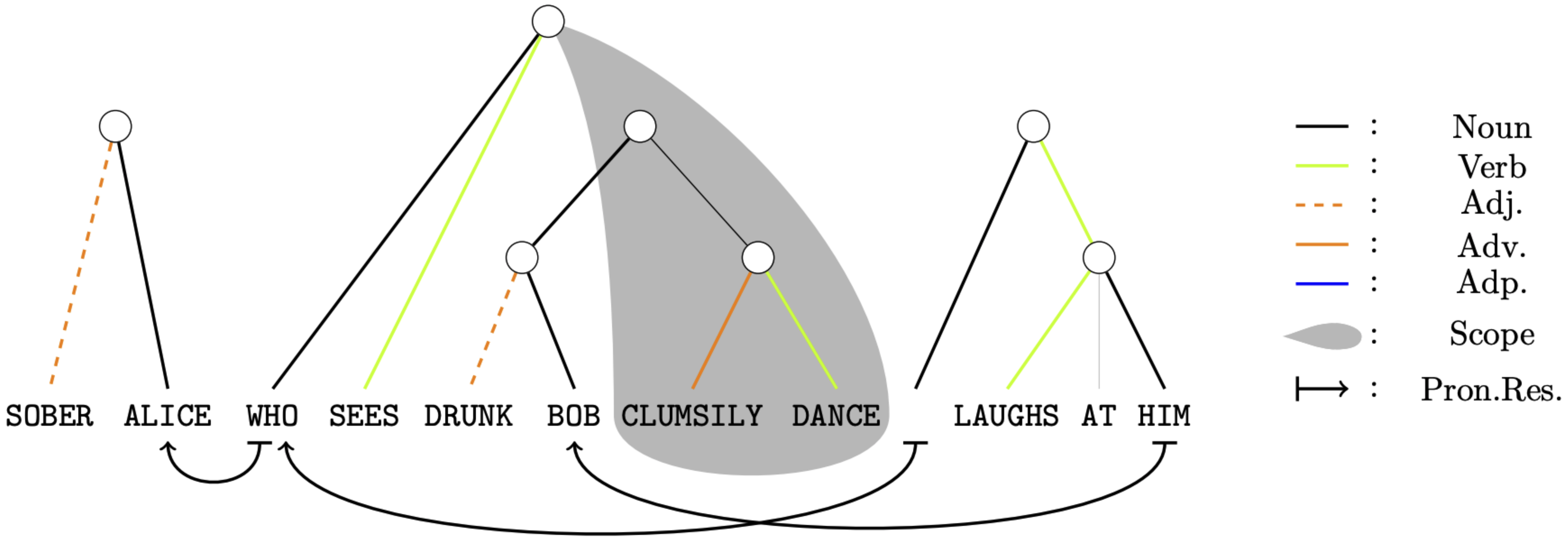
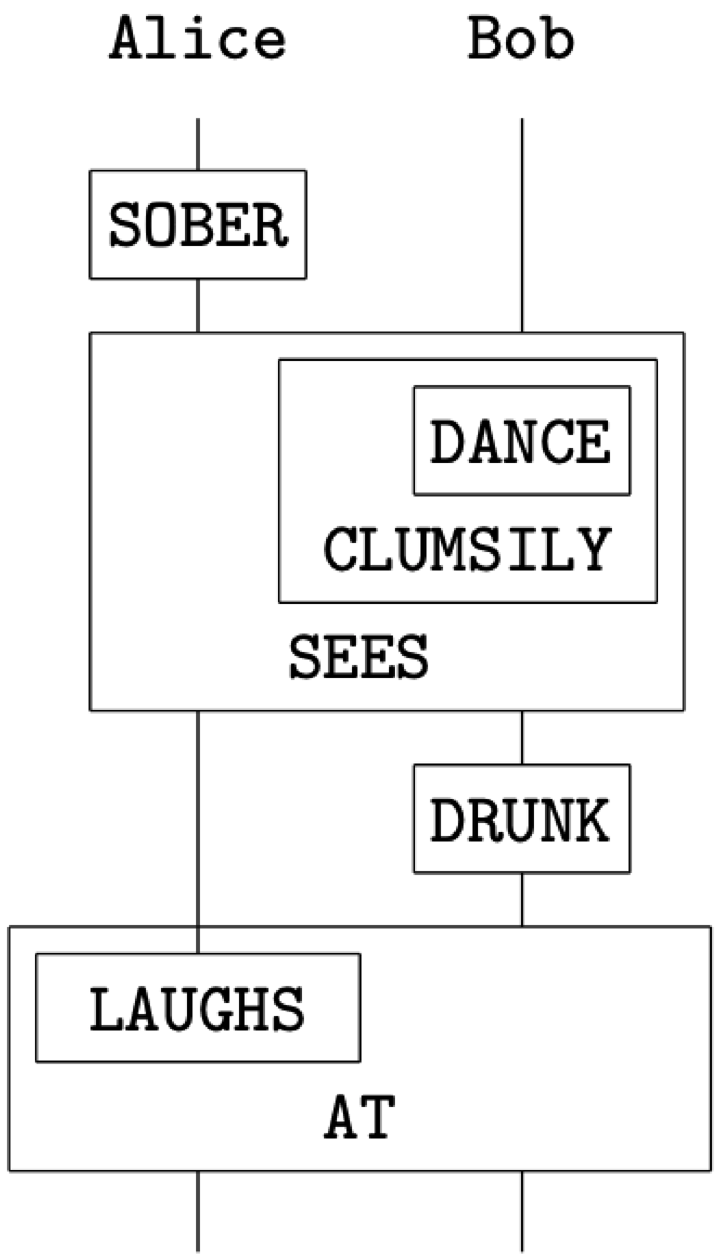
- evolving meanings
- strips off language-dependent overheads


SOBER ALICE WHO SEES DRUNK BOB CLUMSILY DANCE LAUGHS AT HIM
Noun
Verb
Adj.
Adv.
Adp.
Scope
Pron.Res.


Alice
Bob
SOBER
DANCE
CLUMSILY
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DRUNK
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AT

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Advantages of language circuits:

- evolving meanings
- strips off language-dependent overheads
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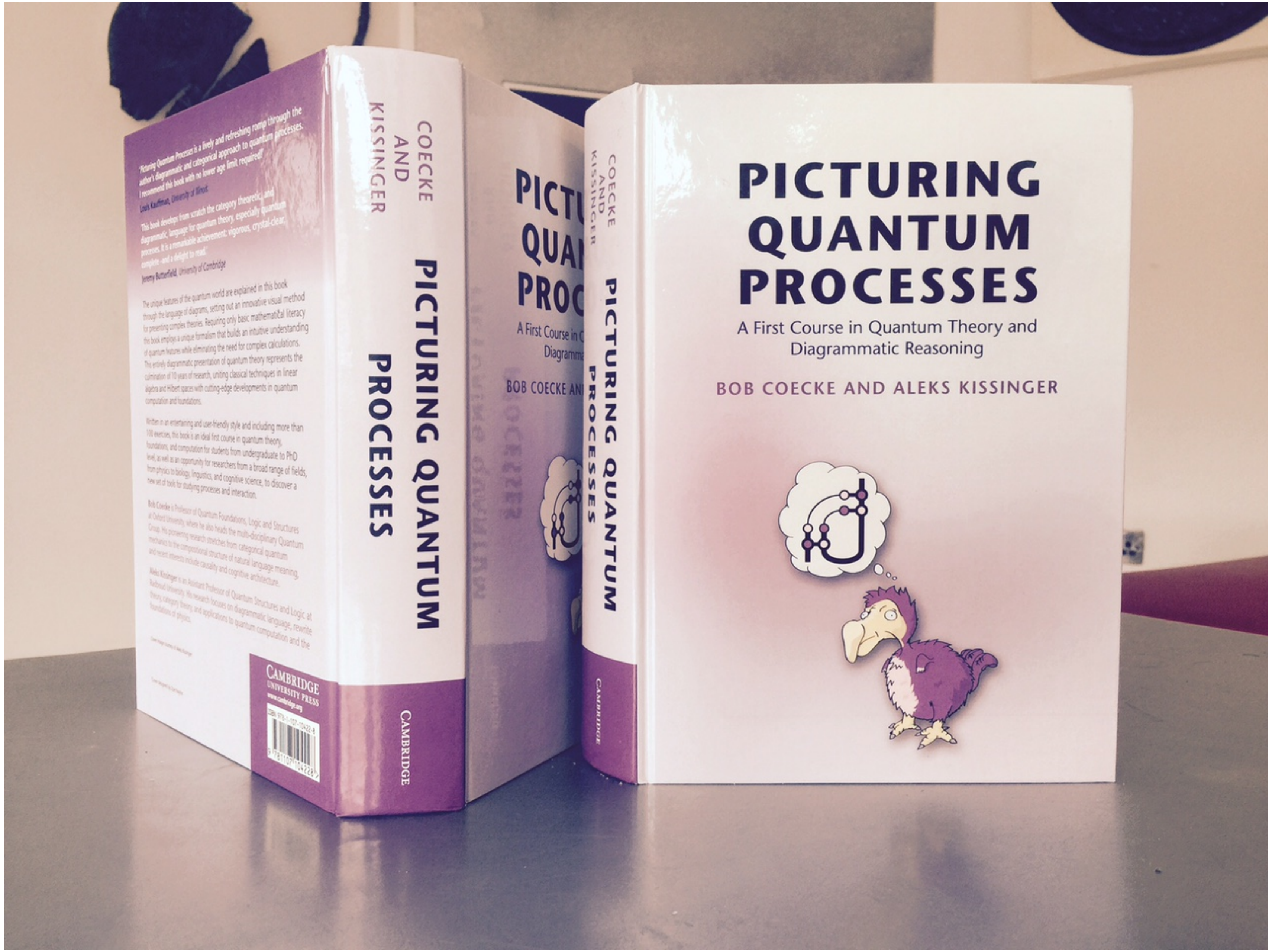
- cheaper (GPT-3 needs 12m in electricity to train)
- the best of both worlds: combinable with reasoning



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CAMBRIDGE

– completeness –

Peter Selinger (2008) ... string diagrams...

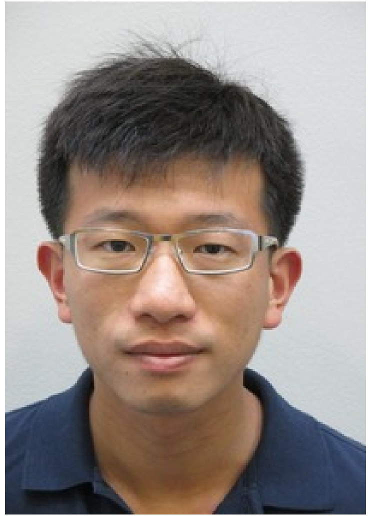
Miriam Backens (2012) ... stabiliser restriction...

Amar Hadzihasanovic (2015) ... Z/W (with some restriction)...

Emmanuel Jeandel, Simon Perdrix & Renaud Vilmart (2017) ... Clifford +T...

Amar Hadzihasanovic (2017) ... Z/W (no restriction)...

Kang Feng Ng and Quanlong Wang (2017) ... everything...



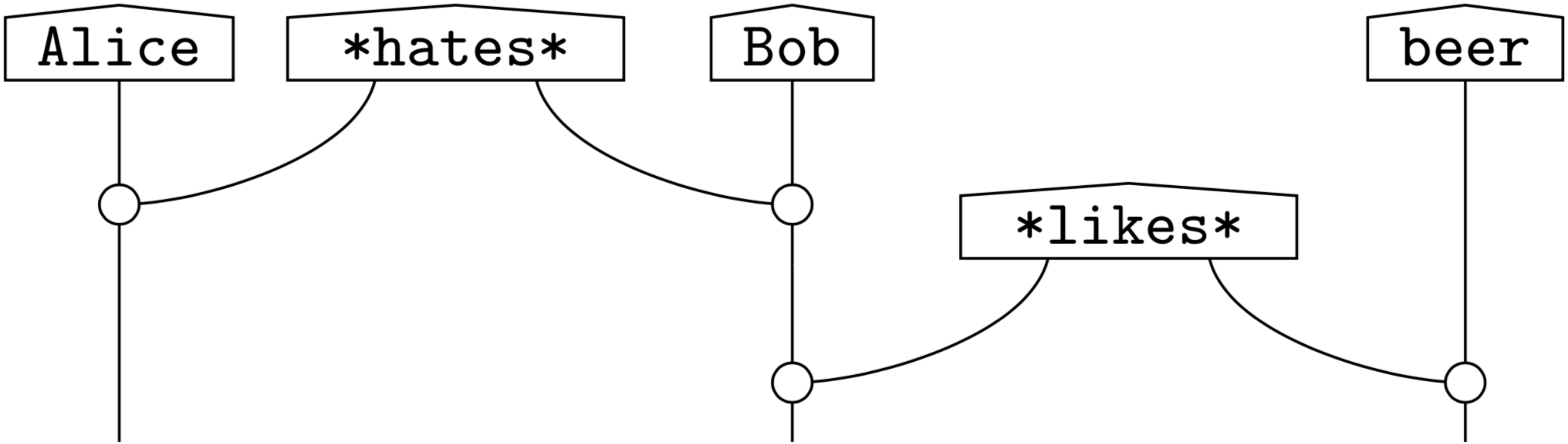
	‘DisCoCat’ then	‘DisCoCirc’ now	NLP/AI now
Compositionality I	interpretable	interpretable	black box
Compositionality II	Frege then	post-Frege	post-Frege
Universality	no	yes	yes
Data need	much less	much less	a lot
Reasoning*	not yet	complete	no
Linguistic structure†	yes	yes	no
Grammatical overhead	yes	no	no
Evolving meanings*	no	yes	no
Sentence space	non-canonical	canonical	no types
General text	no	yes	not well

*Subject to refining these notions as we did for compositionality in the paper arXiv:2110.05327

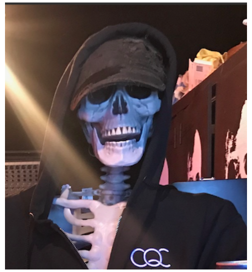
†We mean explicit structure here, not implicit like relativity theory within Ptolemy’s model.

quantum implementations

The grammar/meaning-blend is exponentially expensive!



Do it on a ‘hypothetical’ quantum computer!



arXiv.org > cs > arXiv:1608.01406

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Computer Science > Computation and Language

[Submitted on 4 Aug 2016]

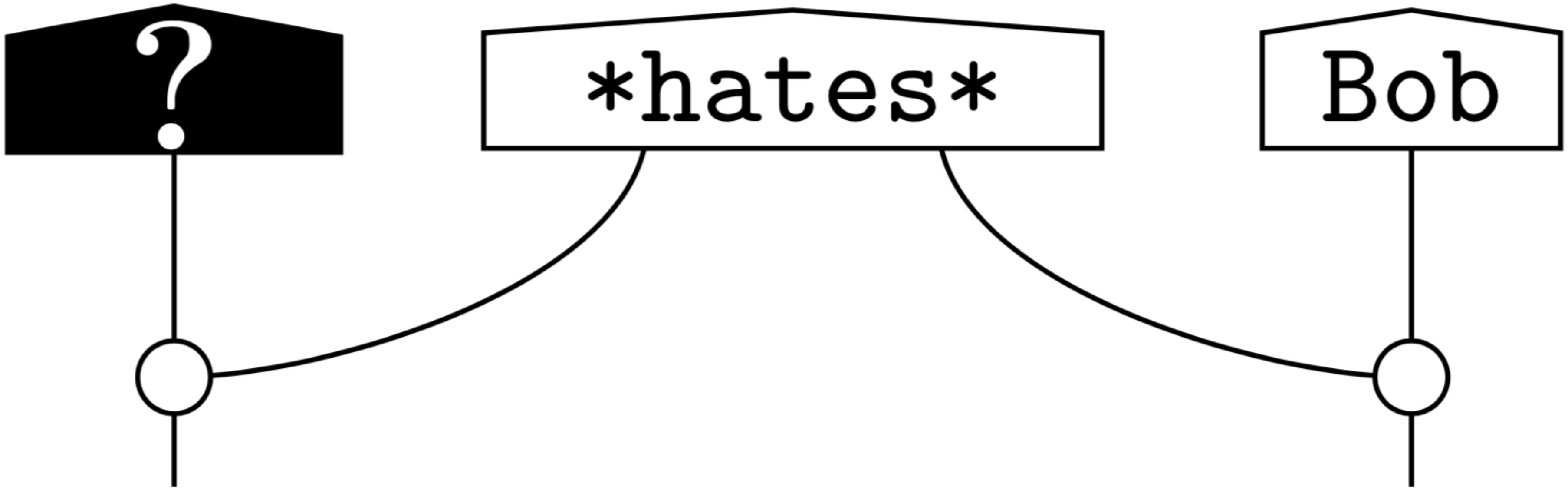
Quantum Algorithms for Compositional Natural Language Processing

William Zeng (Rigetti Computing), Bob Coecke (Univesity of Oxford)

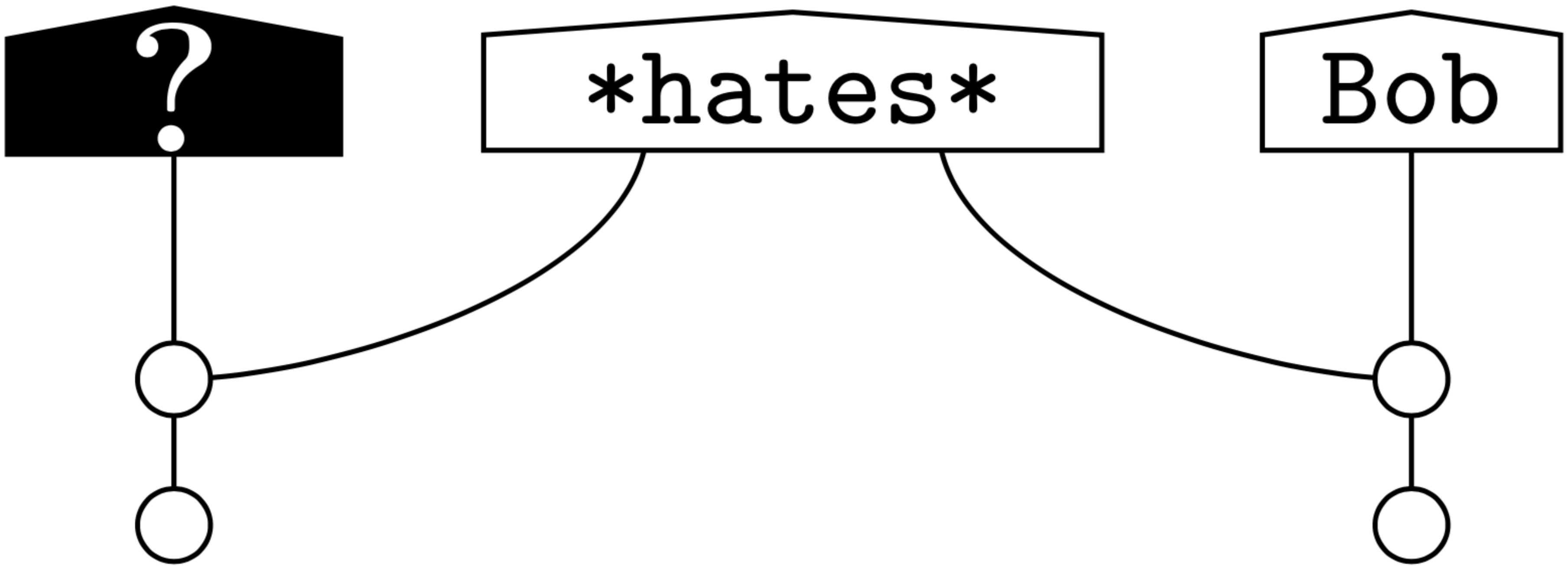
We propose a new application of quantum computing to the field of natural language processing. Ongoing work in this field attempts to incorporate grammatical structure into algorithms that compute meaning. In (Coecke, Sadrzadeh and Clark, 2010), the authors introduce such a model (the CSC model) based on tensor product composition. While this algorithm has many advantages, its implementation is hampered by the large classical computational resources that it requires. In this work we show how computational shortcomings of the CSC approach could be resolved using quantum computation (possibly in addition to existing techniques for dimension reduction). We address the value of quantum RAM (Giovannetti,2008) for this model and extend an algorithm from Wiebe, Braun and Lloyd (2012) into a quantum algorithm to categorize sentences in CSC. Our new algorithm demonstrates a quadratic speedup over classical methods under certain conditions.

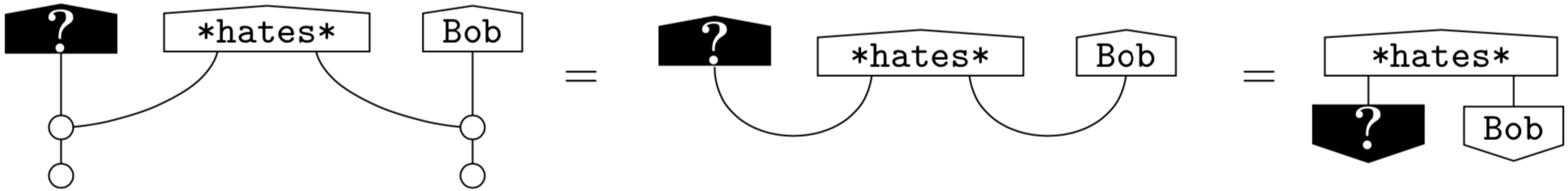
Comments: In Proceedings SLPCS 2016, arXiv:1608.01018

— questions —



— answers —

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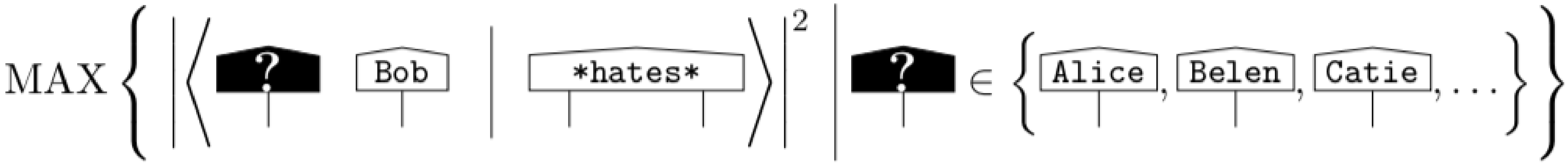
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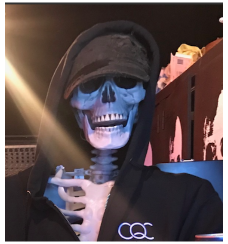
Alice, Belen, Catie, ...

	'DisCoCat' then	'DisCoCirc' now	NLP/AI now
Compositionality I	interpretable	interpretable	black box
Compositionality II	Frege then	post-Frege	post-Frege
Universality	no	yes	yes
Data need	much less	much less	a lot
Reasoning*	not yet	complete	no
Linguistic structure†	yes	yes	no
Grammatical overhead	yes	no	no
Evolving meanings*	no	yes	no
Sentence space	non-canonical	canonical	no types
General text	no	yes	not well
Quantum speed-up	**Grover**		**not (yet?)**

*Subject to refining these notions as we did for compositionality in the paper arXiv:2110.05327

†We mean explicit structure here, not implicit like relativity theory within Ptolemy's model.

Do it on existing quantum computers!

arXiv.org > quant-ph > arXiv:2012.03755

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Quantum Physics

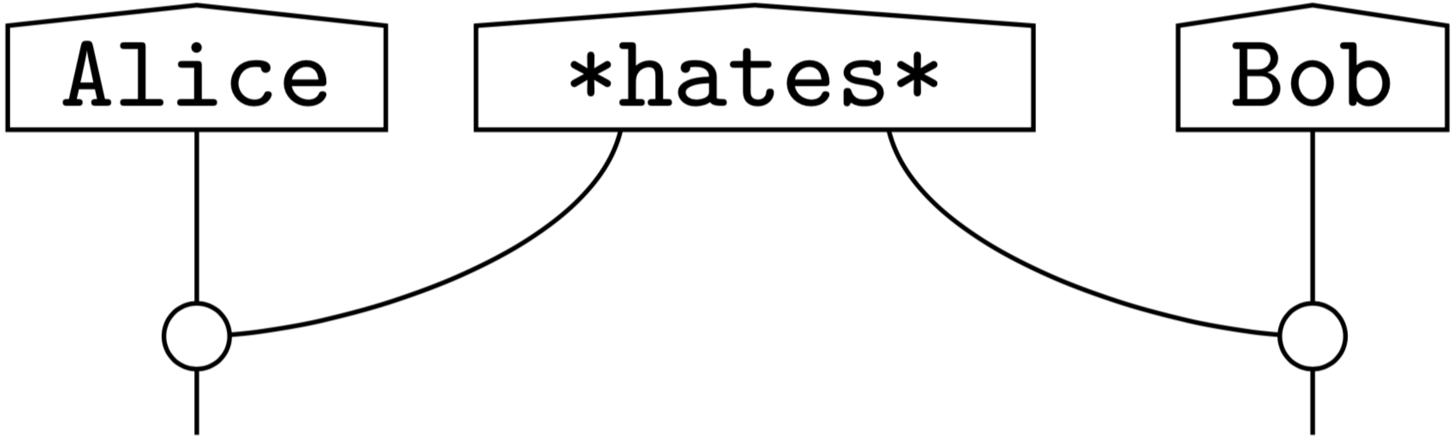
[Submitted on 7 Dec 2020]

Foundations for Near-Term Quantum Natural Language Processing

Bob Coecke, Giovanni de Felice, Konstantinos Meichanetzidis, Alexis Toumi

We provide conceptual and mathematical foundations for near-term quantum natural language processing (QNLP), and do so in quantum computer scientist friendly terms. We opted for an expository presentation style, and provide references for supporting empirical evidence and formal statements concerning mathematical generality.
We recall how the quantum model for natural language that we employ canonically combines linguistic meanings with rich linguistic structure, most notably grammar. In particular, the fact that it takes a quantum-like model to combine meaning and structure, establishes QNLP as quantum-native, on par with simulation of quantum systems. Moreover, the now leading Noisy Intermediate-Scale Quantum (NISQ) paradigm for encoding classical data on quantum hardware, variational quantum circuits, makes NISQ exceptionally QNLP-friendly: linguistic structure can be encoded as a free lunch, in contrast to the apparently exponentially expensive classical encoding of grammar.
Quantum speed-up for QNLP tasks has already been established in previous work with Will Zeng. Here we provide a broader range of tasks which all enjoy the same advantage.
Diagrammatic reasoning is at the heart of QNLP. Firstly, the quantum model interprets language as quantum processes via the diagrammatic formalism of categorical quantum mechanics. Secondly, these diagrams are via ZX-calculus translated into quantum circuits. Parameterisations of meanings then become the circuit variables to be learned.
Our encoding of linguistic structure within quantum circuits also embodies a novel approach for establishing word-meanings that goes beyond the current standards in mainstream AI, by placing linguistic structure at the heart of Wittgenstein's meaning-is-context.

Comments: 43 pages, lots of pictures


Alice
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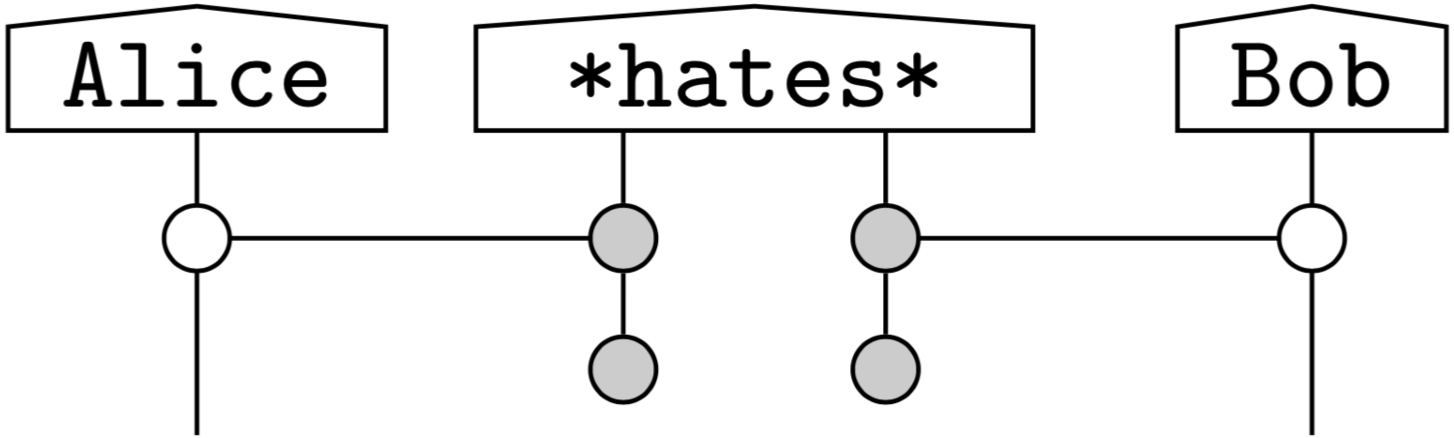
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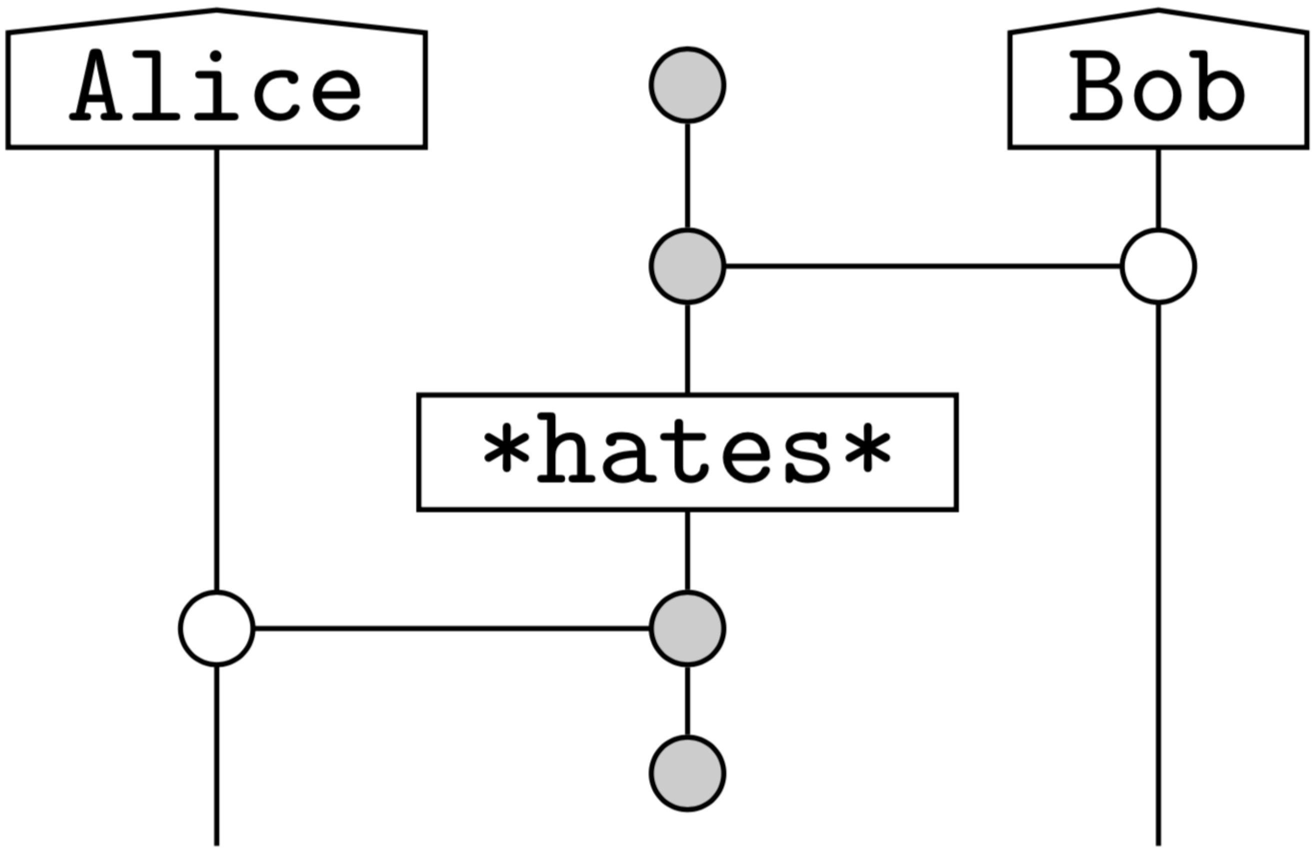
Alice
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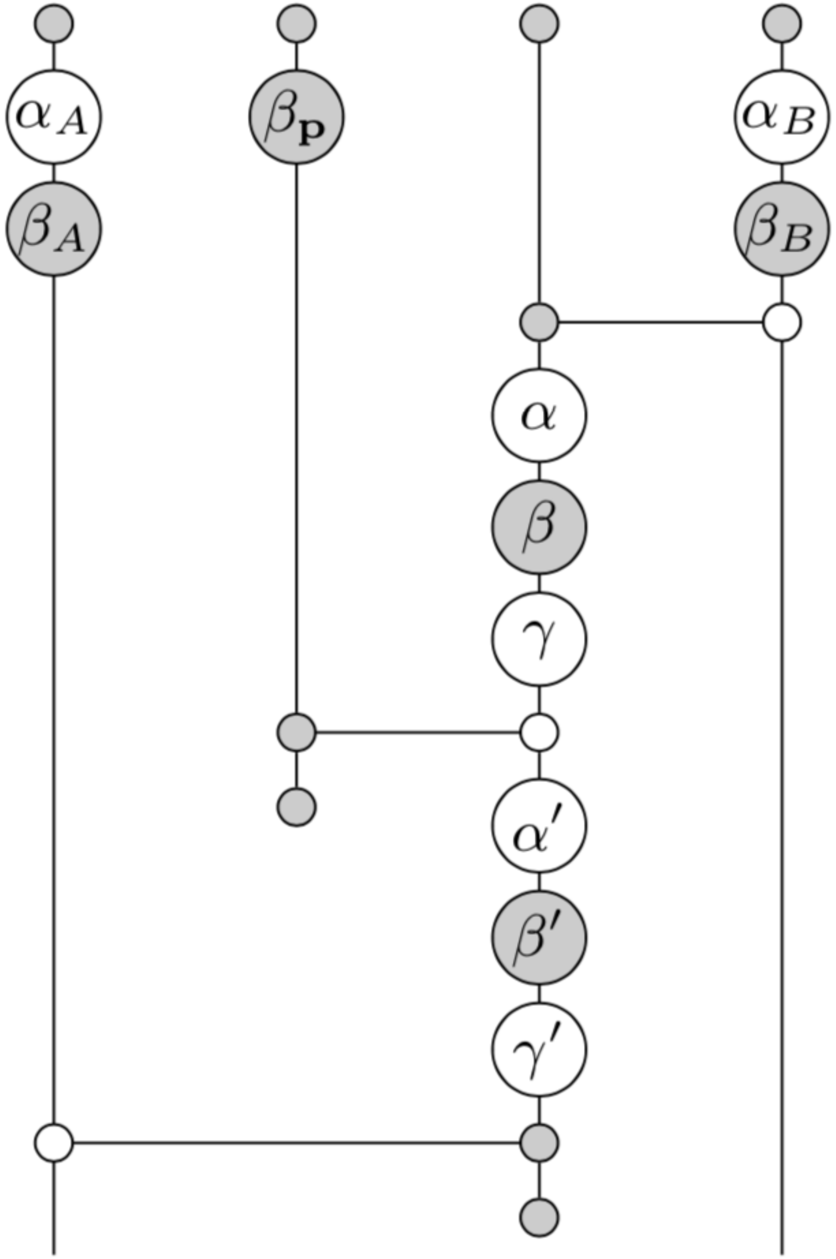
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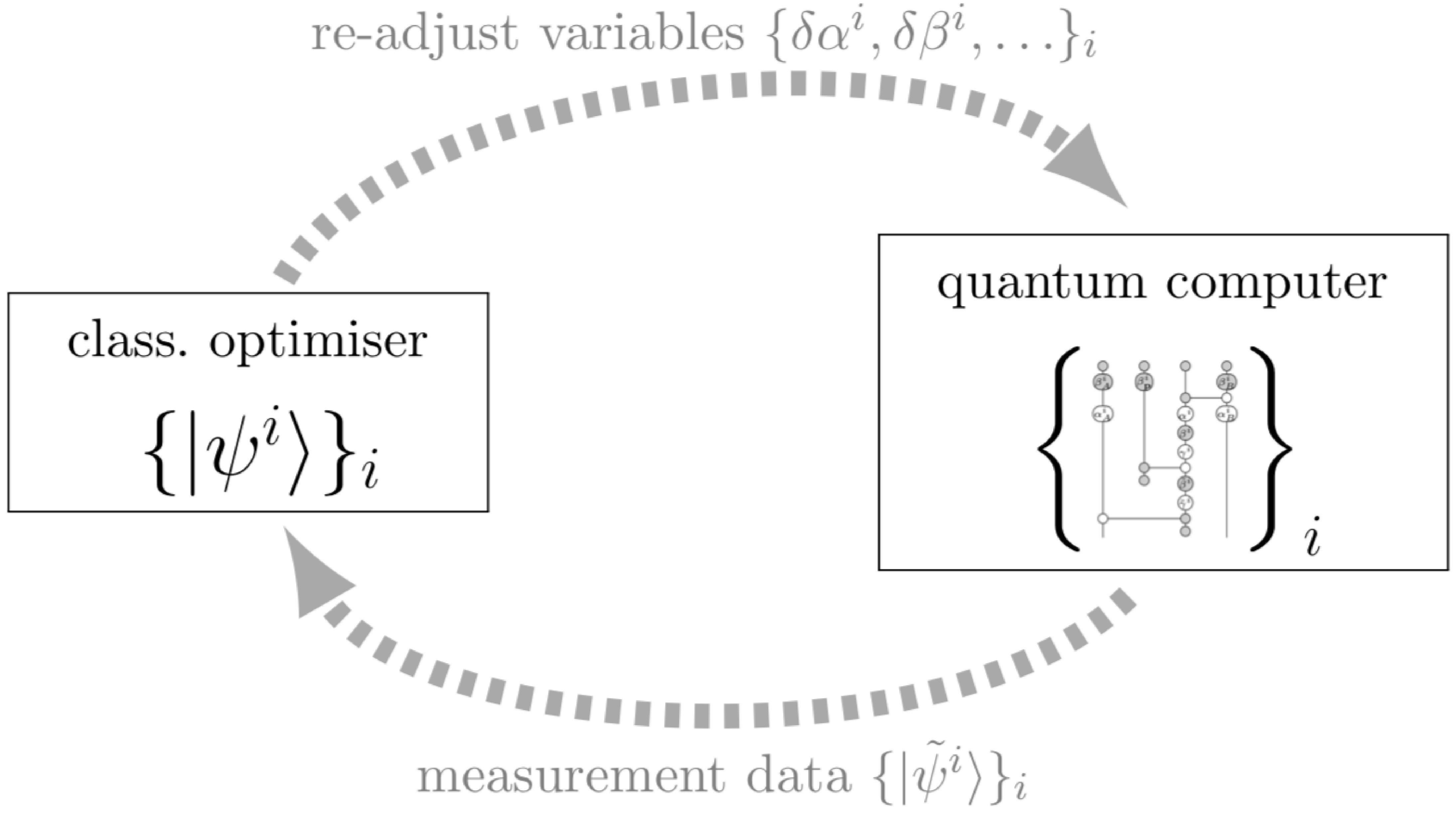
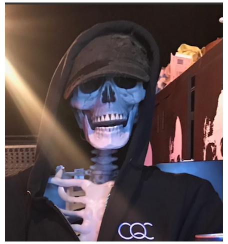
γ'


re-adjust variables $\{\delta\alpha^i, \delta\beta^i, \ldots\}_i$
quantum computer
class. optimiser
$\{|\psi^i\rangle\}_i$
measurement data $\{|\tilde{\psi}^i\rangle\}_i$

Just do it!

arXiv.org > quant-ph > arXiv:2012.03756

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Quantum Physics

[Submitted on 7 Dec 2020]

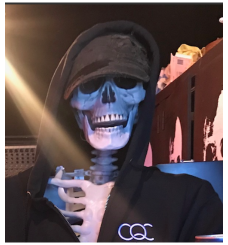
Grammar-Aware Question-Answering on Quantum Computers

Konstantinos Meichanetzidis, Alexis Toumi, Giovanni de Felice, Bob Coecke

Natural language processing (NLP) is at the forefront of great advances in contemporary AI, and it is arguably one of the most challenging areas of the field. At the same time, with the steady growth of quantum hardware and notable improvements towards implementations of quantum algorithms, we are approaching an era when quantum computers perform tasks that cannot be done on classical computers with a reasonable amount of resources. This provides a new range of opportunities for AI, and for NLP specifically. Earlier work has already demonstrated a potential quantum advantage for NLP in a number of manners: (i) algorithmic speedups for search-related or classification tasks, which are the most dominant tasks within NLP, (ii) exponentially large quantum state spaces allow for accommodating complex linguistic structures, (iii) novel models of meaning employing density matrices naturally model linguistic phenomena such as hyponymy and linguistic ambiguity, among others. In this work, we perform the first implementation of an NLP task on noisy intermediate-scale quantum (NISQ) hardware. Sentences are instantiated as parameterised quantum circuits. We encode word-meanings in quantum states and we explicitly account for grammatical structure, which even in mainstream NLP is not commonplace, by faithfully hard-wiring it as entangling operations. This makes our approach to quantum natural language processing (QNLP) particularly NISQ-friendly. Our novel QNLP model shows concrete promise for scalability as the quality of the quantum hardware improves in the near future.

Subjects: **Quantum Physics (quant-ph)**; Computation and Language (cs.CL)

Just do it BIGGER!

arXiv.org > cs > arXiv:2102.12846

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Computer Science > Computation and Language

[Submitted on 25 Feb 2021]

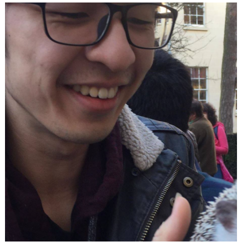
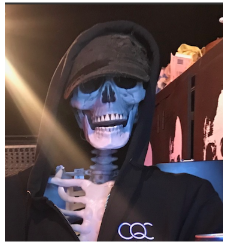
QNLP in Practice: Running Compositional Models of Meaning on a Quantum Computer

Robin Lorenz, Anna Pearson, Konstantinos Meichanetzidis, Dimitri Kartsaklis, Bob Coecke

Quantum Natural Language Processing (QNLP) deals with the design and implementation of NLP models intended to be run on quantum hardware. In this paper, we present results on the first NLP experiments conducted on Noisy Intermediate-Scale Quantum (NISQ) computers for datasets of size >= 100 sentences. Exploiting the formal similarity of the compositional model of meaning by Coecke et al. (2010) with quantum theory, we create representations for sentences that have a natural mapping to quantum circuits. We use these representations to implement and successfully train two NLP models that solve simple sentence classification tasks on quantum hardware. We describe in detail the main principles, the process and challenges of these experiments, in a way accessible to NLP researchers, thus paving the way for practical Quantum Natural Language Processing.

Subjects: **Computation and Language (cs.CL)**; Artificial Intelligence (cs.AI); Machine Learning (cs.LG); Quantum Physics (quant-ph)

YOU just do it!

[Submitted on 8 Oct 2021]

lambeq: An Efficient High-Level Python Library for Quantum NLP

Dimitri Kartsaklis, Ian Fan, Richie Yeung, Anna Pearson, Robin Lorenz, Alexis Toumi, Giovanni de Felice, Konstantinos Meichanetzidis, Stephen Clark, Bob Coecke

We present lambeq, the first high-level Python library for Quantum Natural Language Processing (QNLP). The open-source toolkit offers a detailed hierarchy of modules and classes implementing all stages of a pipeline for converting sentences to string diagrams, tensor networks, and quantum circuits ready to be used on a quantum computer. lambeq supports syntactic parsing, rewriting and simplification of string diagrams, ansatz creation and manipulation, as well as a number of compositional models for preparing quantum-friendly representations of sentences, employing various degrees of syntax sensitivity. We present the generic architecture and describe the most important modules in detail, demonstrating the usage with illustrative examples. Further, we test the toolkit in practice by using it to perform a number of experiments on simple NLP tasks, implementing both classical and quantum pipelines.

Subjects: **Computation and Language (cs.CL)**; Artificial Intelligence (cs.AI); Quantum Physics (quant-ph)

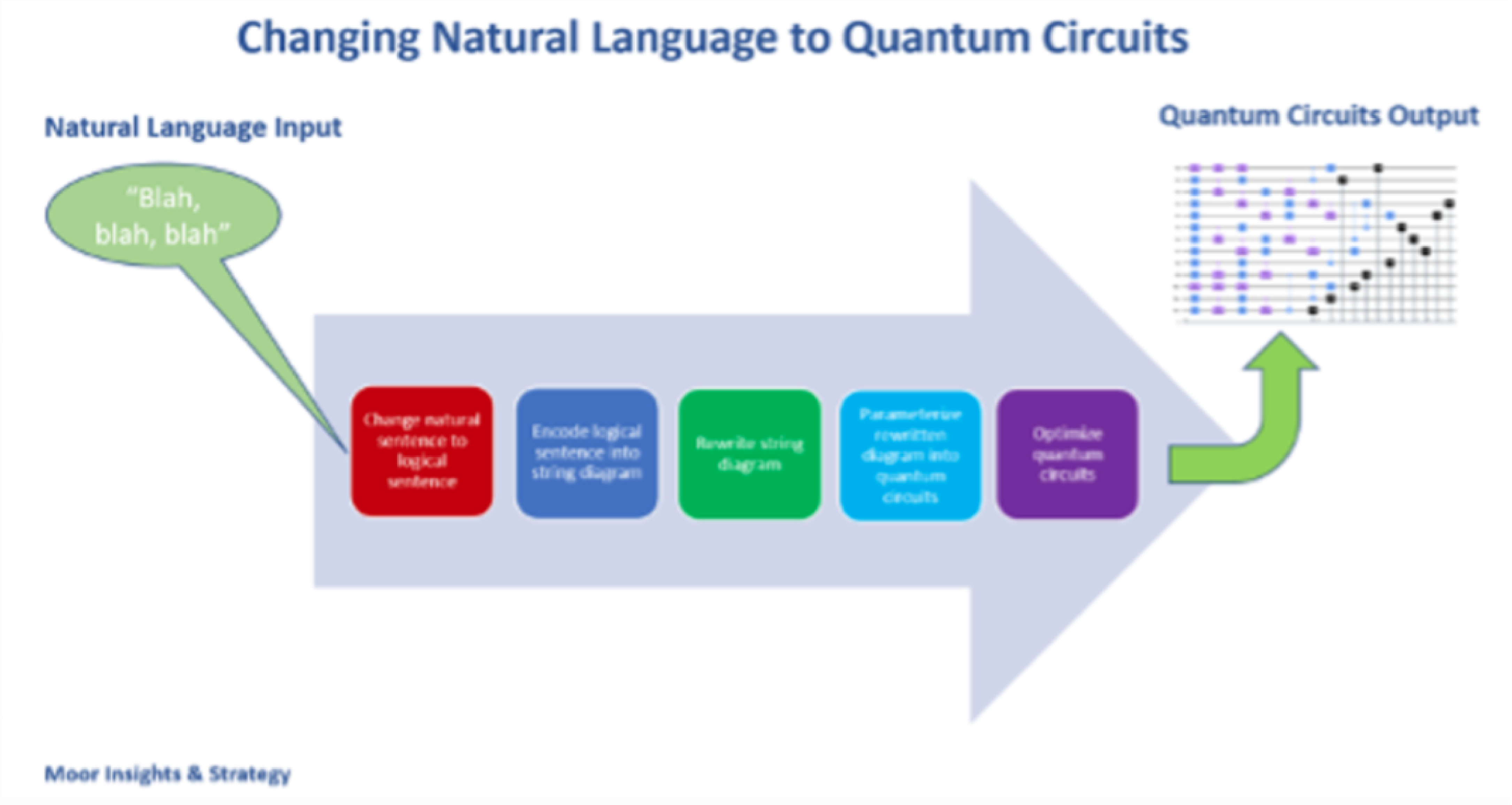
here’s lambe**q**

Cambridge Quantum Makes Quantum Natural Language Processing A Reality

Paul Smith-Goodson Contributor
Moor Insights and Strategy Contributor Group
Cloud
Analyst-in-residence, Quantum Computing

Listen to article 6 minutes

How QNLP works



code and explanation

blog: https://medium.com/cambridge-quantum-computing/quantum-natural-language-processing-ii-6b6a44b319b2

technical: https://arxiv.org/abs/2110.04236

GitHub: https://github.com/CQCL/lambeq

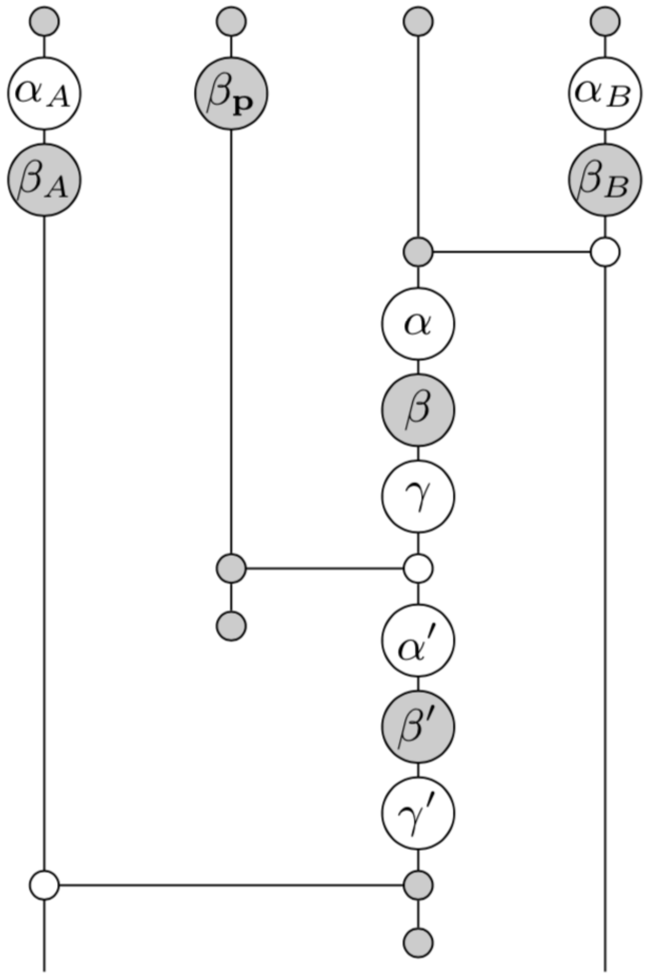
New release on its way!

natural language as quantum simulation

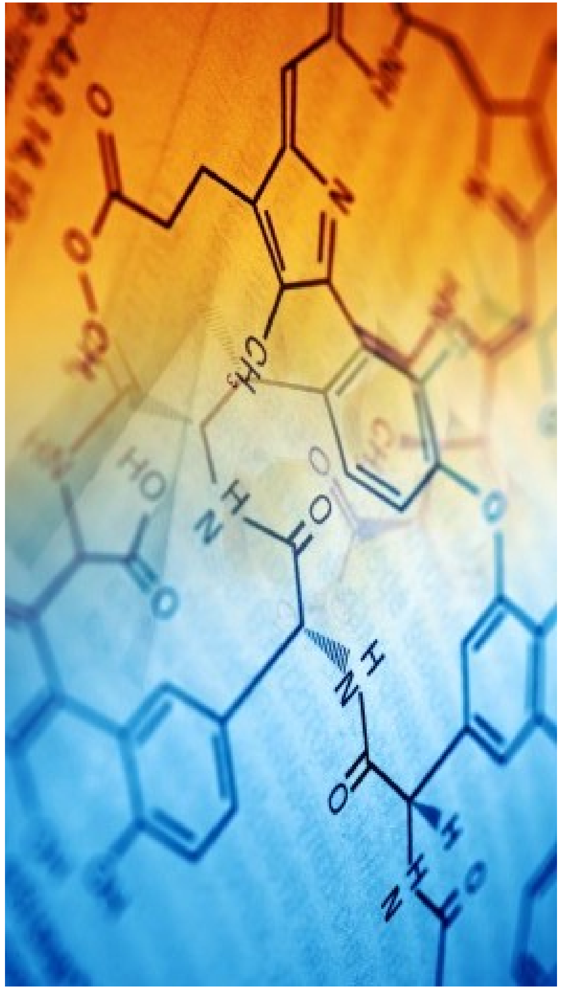
Nature isn't classical, dammit, and if you want to make a simulation of nature, you'd better make it quantum mechanical, and by golly it's a wonderful problem, because it doesn't look so easy.

— Richard P. Feynman —

language circuit (text2qcirc)



chemistry (Hamiltonian)



	‘DisCoCat’ then	‘DisCoCirc’ now	NLP/AI now
Compositionality I	interpretable	interpretable	black box
Compositionality II	Frege then	post-Frege	post-Frege
Universality	no	yes	yes
Data need	much less	much less	a lot
Reasoning*	not yet	complete	no
Linguistic structure†	yes	yes	no
Grammatical overhead	yes	no	no
Evolving meanings*	no	yes	no
Sentence space	non-canonical	canonical	no types
Quantum speed-up	**Grover**	**like simulation**	**not (yet?)**

*Subject to refining these notions as we did for compositionality in the paper arXiv:2110.05327

†We mean explicit structure here, not implicit like relativity theory within Ptolemy’s model.

compositional cognition

arXiv.org > cs > arXiv:1703.08314

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Computer Science > Logic in Computer Science

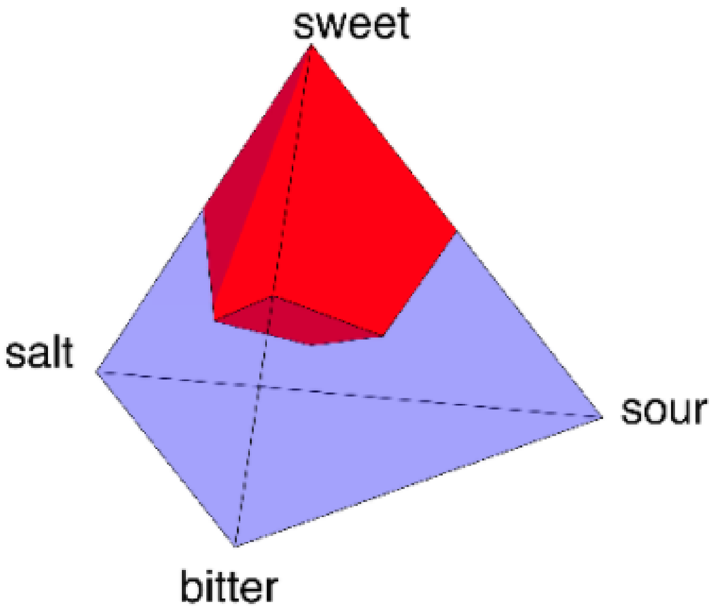
[Submitted on 24 Mar 2017 (v1), last revised 29 Sep 2017 (this version, v2)]

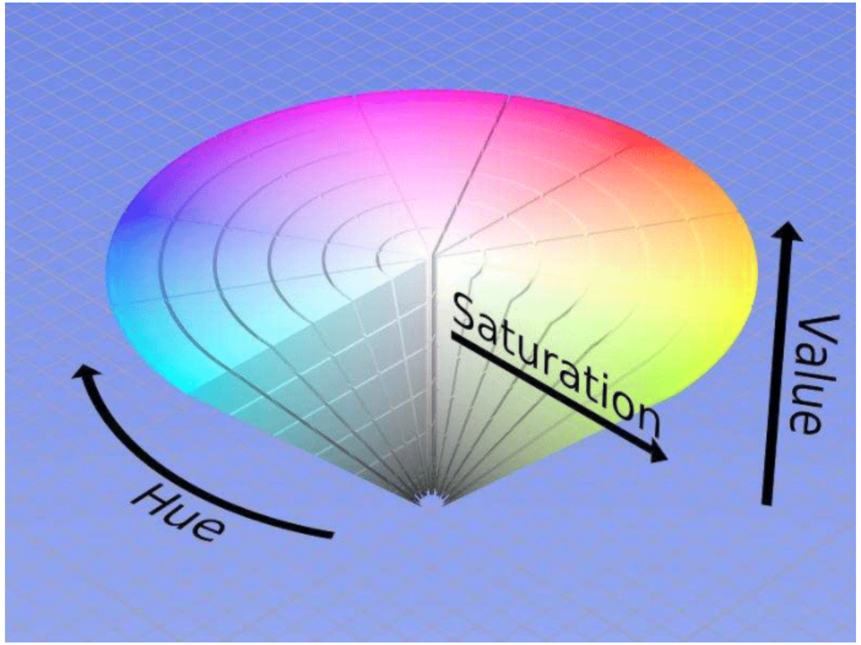
Interacting Conceptual Spaces I : Grammatical Composition of Concepts

Joe Bolt, Bob Coecke, Fabrizio Genovese, Martha Lewis, Dan Marsden, Robin Piedeleu

The categorical compositional approach to meaning has been successfully applied in natural language processing, outperforming other models in mainstream empirical language processing tasks. We show how this approach can be generalized to conceptual space models of cognition. In order to do this, first we introduce the category of convex relations as a new setting for categorical compositional semantics, emphasizing the convex structure important to conceptual space applications. We then show how to construct conceptual spaces for various types such as nouns, adjectives and verbs. Finally we show by means of examples how concepts can be systematically combined to establish the meanings of composite phrases from the meanings of their constituent parts. This provides the mathematical underpinnings of a new compositional approach to cognition.

Subjects: **Logic in Computer Science (cs.LO)**; Computation and Language (cs.CL)





arXiv.org > quant-ph > arXiv:2111.06741

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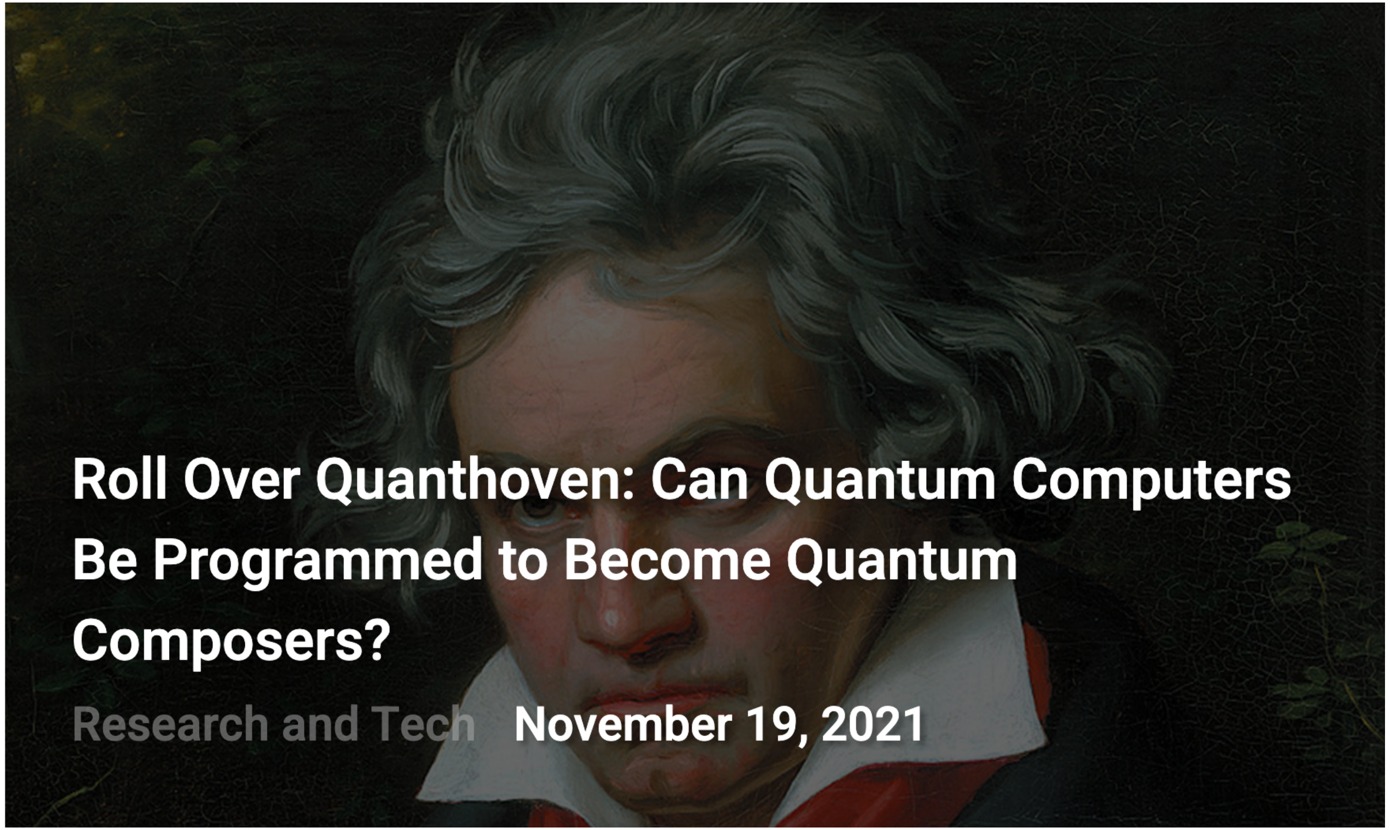
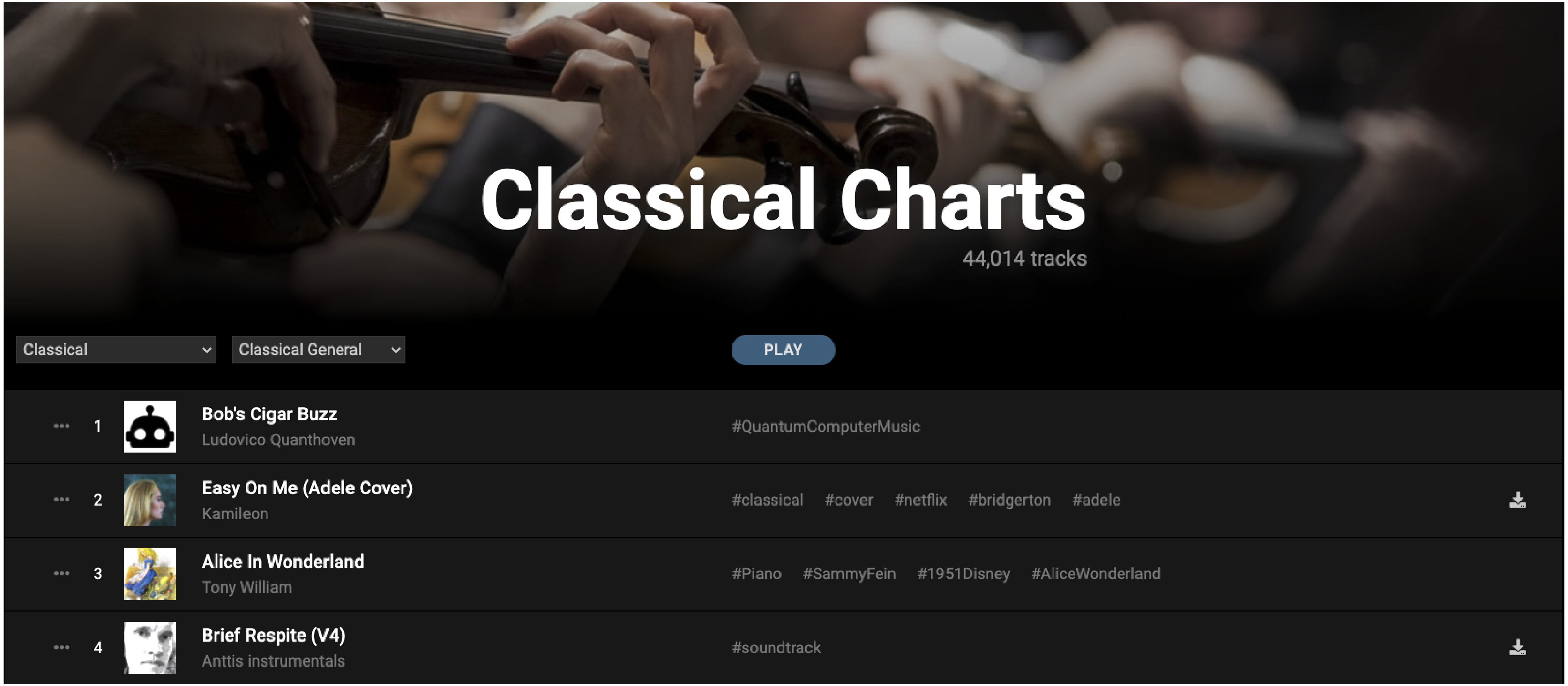
Quantum Physics

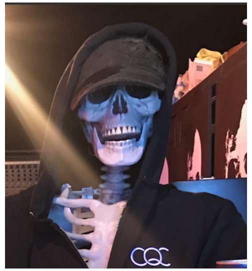
[Submitted on 10 Nov 2021]

A Quantum Natural Language Processing Approach to Musical Intelligence

Eduardo Reck Miranda, Richie Yeung, Anna Pearson, Konstantinos Meichanetzidis, Bob Coecke




Classical Charts
44,014 tracks
Classical
Classical General
PLAY
1
Bob's Cigar Buzz
Ludovico Quanthoven
#QuantumComputerMusic
2
Easy On Me (Adele Cover)
Kamileon
#classical #cover #netflix #bridgerton #adele
3
Alice In Wonderland
Tony William
#Piano #SammyFein #1951Disney #AliceWonderland
4
Brief Respite (V4)
Anttis instrumentals
#soundtrack



Computer Science > Computation and Language

[Submitted on 14 Sep 2021 (v1), last revised 16 Sep 2021 (this version, v2)]

Talking Space: inference from spatial linguistic meanings

Vincent Wang-Mascianica, Bob Coecke

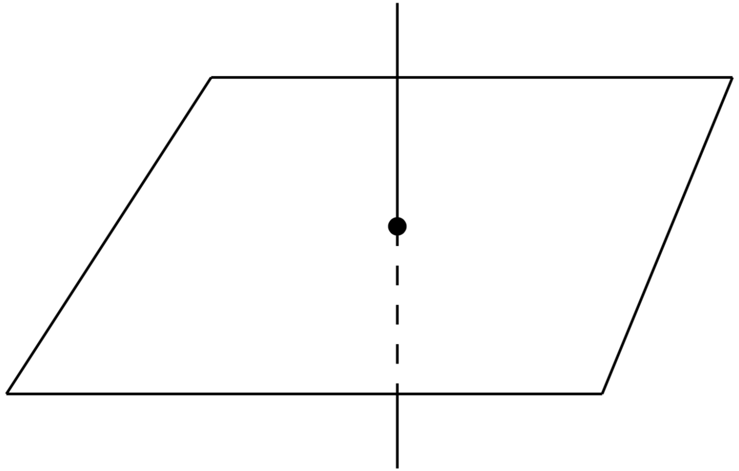
This paper concerns the intersection of natural language and the physical space around us in which we live, that we observe and/or imagine things within. Many important features of language have spatial connotations, for example, many prepositions (like in, next to, after, on, etc.) are fundamentally spatial. Space is also a key factor of the meanings of many words/phrases/sentences/text, and space is a, if not the key, context for referencing (e.g. pointing) and embodiment.

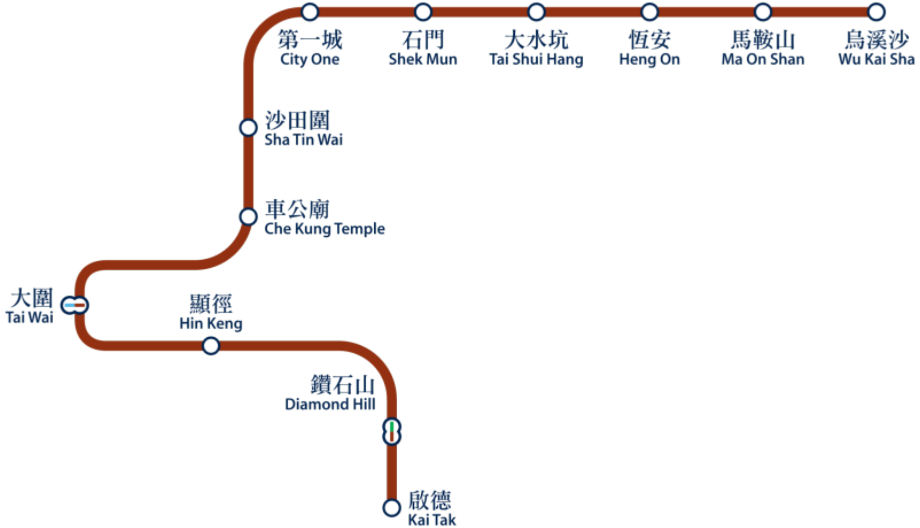
We propose a mechanism for how space and linguistic structure can be made to interact in a matching compositional fashion. Examples include Cartesian space, subway stations, chesspieces on a chess-board, and Penrose's staircase. The starting point for our construction is the DisCoCat model of compositional natural language meaning, which we relax to accommodate physical space. We address the issue of having multiple agents/objects in a space, including the case that each agent has different capabilities with respect to that space, e.g., the specific moves each chesspiece can make, or the different velocities one may be able to reach.

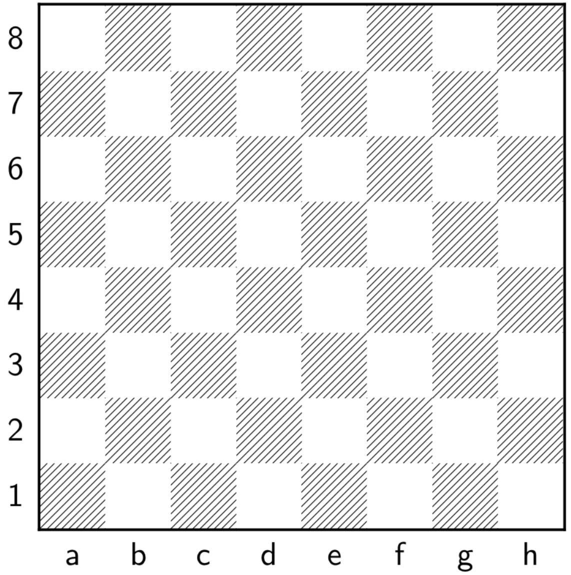
Once our model is in place, we show how inferences drawing from the structure of physical space can be made. We also how how linguistic model of space can interact with other such models related to our senses and/or embodiment, such as the conceptual spaces of colour, taste and smell, resulting in a rich compositional model of meaning that is close to human experience and embodiment in the world.

Spacetime in language:

- Prepositions in, next to, after, on, etc.
- Many words/phrases/sentences/text meanings.
- Key context for referencing (e.g. pointing) and embodiment.
- The “theatre” of language origin?




第一城
City One
石門
Shek Mun
大水坑
Tai Shui Hang
恆安
Heng On
馬鞍山
Ma On Shan
烏溪沙
Wu Kai Sha
沙田圍
Sha Tin Wai
車公廟
Che Kung Temple
大圍
Tai Wai
顯徑
Hin Keng
鑽石山
Diamond Hill
啟德
Kai Tak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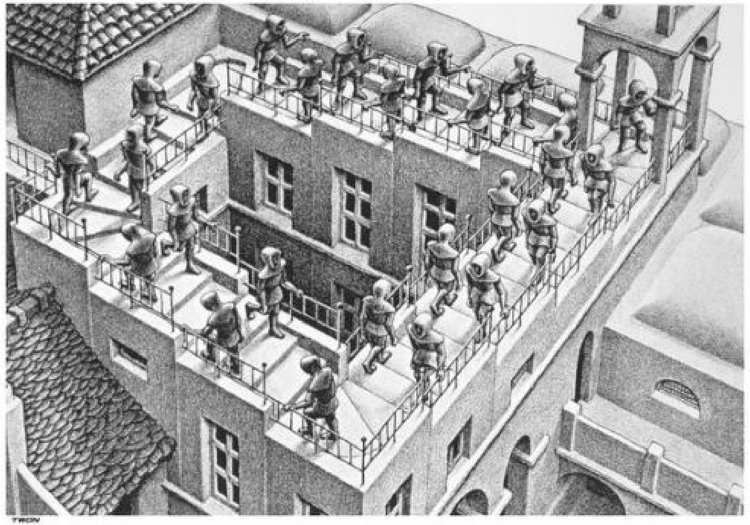

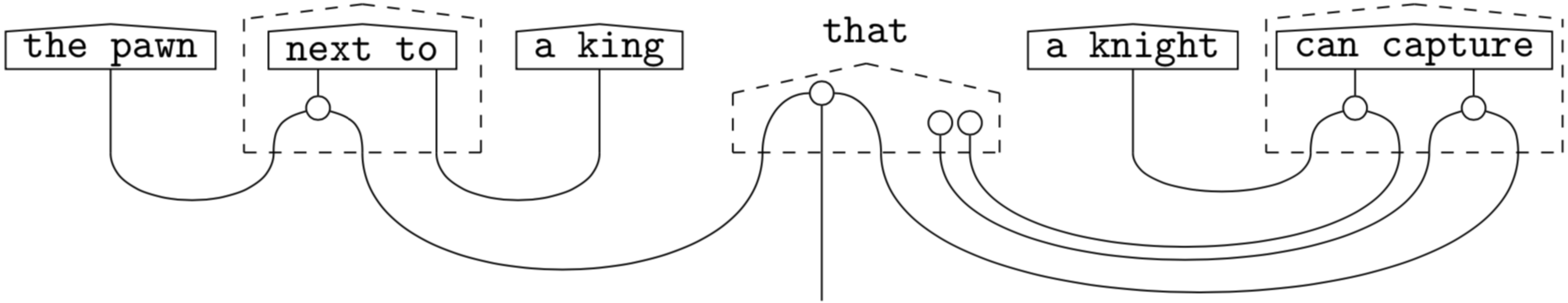
the pawn
next to
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that
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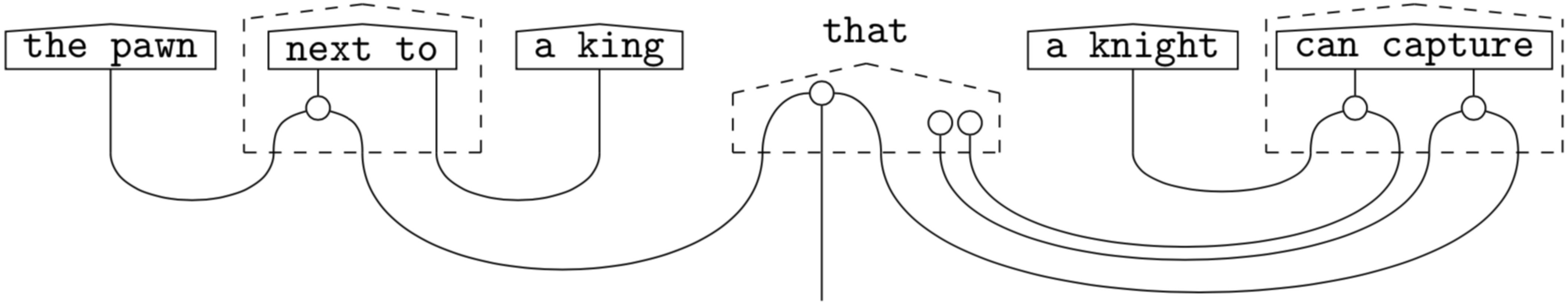
can capture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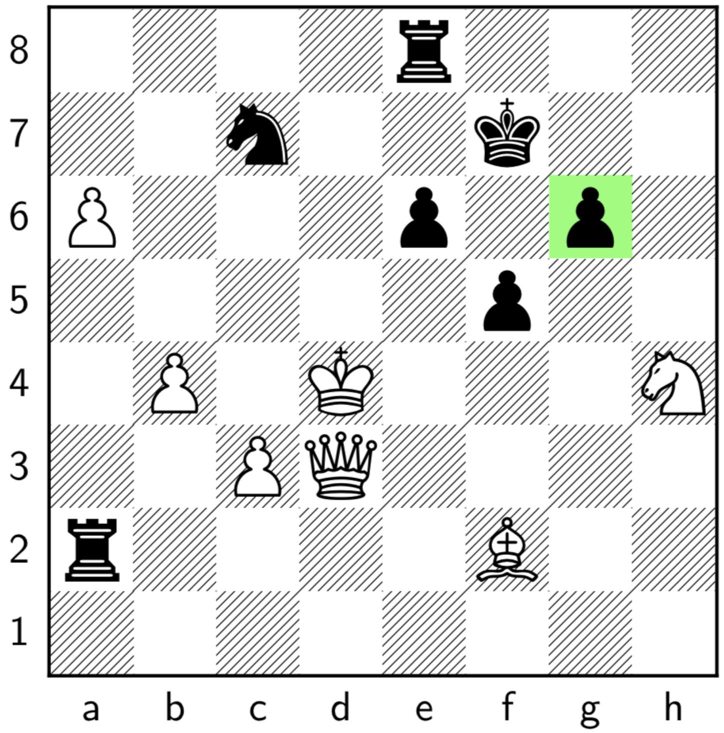
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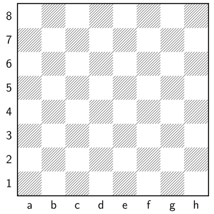
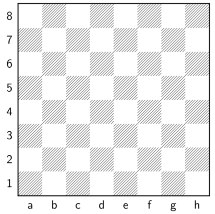
- Orpheus chases Eurydice
- Eurydice is Hades

- Orpheus chases Eurydice
- Eurydice is in Hades

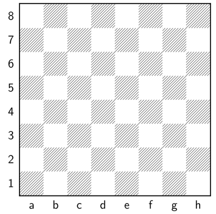
$\Longrightarrow$

- Orpheus is in Hades

Monoidal subcategory of **Rel**:

-  $\times \ldots \times$ 

Monoidal subcategory of **Rel**:

- 

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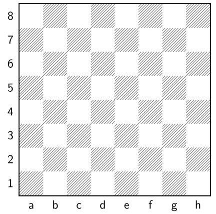
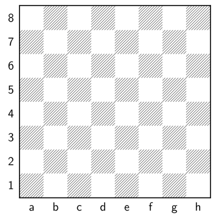


- “spatial relations” $R \subseteq X \times \ldots \times X$

Monoidal subcategory of **Rel**:

- 

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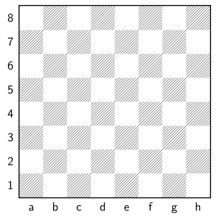
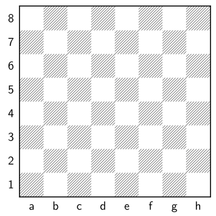


- “spatial relations” $R \subseteq X \times \ldots \times X$

- $S \circ R := \left\{(x, z) \,\middle|\, \exists x' : R(x, y), S(y, z)\right\}$ & $S \times R := \left\{((x, y), (z, u)) \,\middle|\, R(x, y), S(z, u)\right\}$

Monoidal subcategory of **Rel**:

- 

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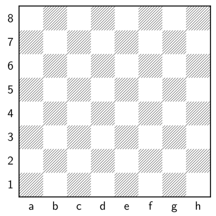

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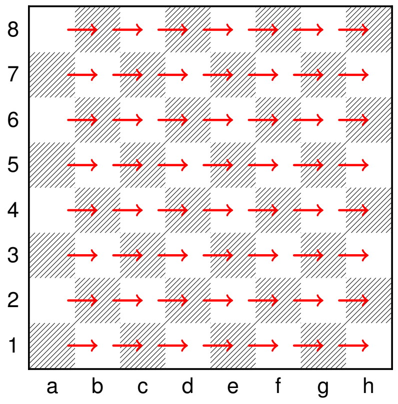
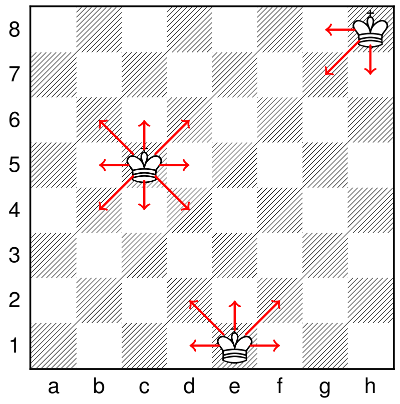
`move right` :=

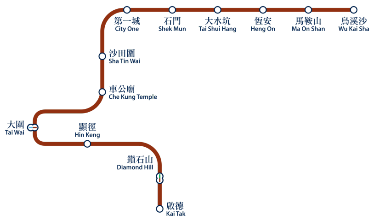


`king's moves` :=



Monoidal subcategory of **Rel**:

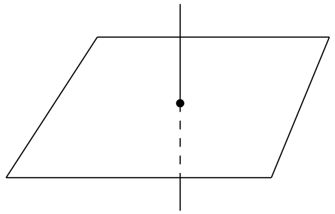
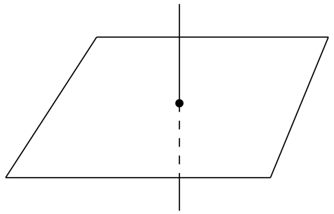
- 

$\times \ldots \times$


- "spatial relations" $R \subseteq X \times \ldots \times X$
- $S \circ R := \left\{(x, z) \;\middle|\; \exists x' : R(x, y), S(y, z)\right\}$ & $S \times R := \left\{((x, y), (z, u)) \;\middle|\; R(x, y), S(z, u)\right\}$

- $\texttt{next stop} := \{(\texttt{Kai Tak}, \texttt{D. H.}), (\texttt{D. H.}, \texttt{Hin Keng}), \ldots\}$
- $\texttt{in-between} := \{(\texttt{Kai Tak}, \texttt{D. H.}, \texttt{Hin Keng}), \ldots\}$
- $\texttt{my station} := \{\texttt{Wu Kai Sha}\}$

Monoidal subcategory of **Rel**:

-  $\times \ldots \times$ 

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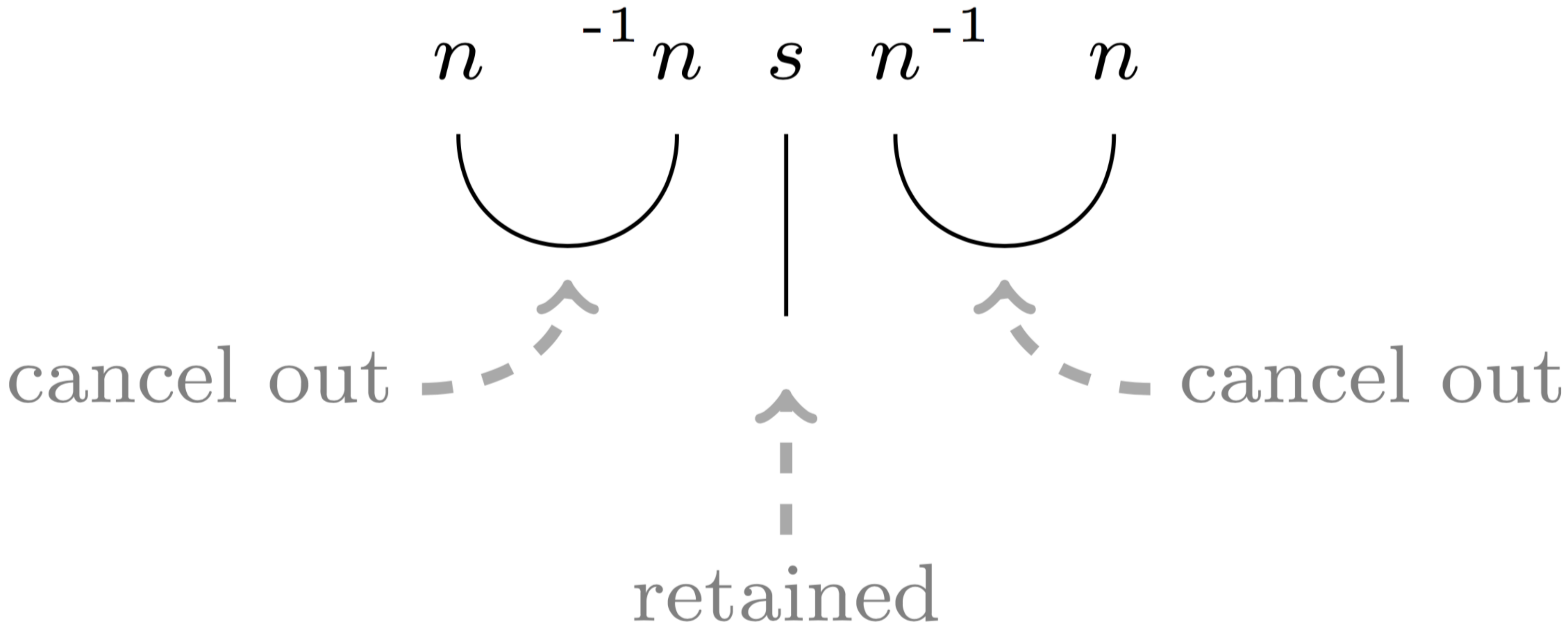
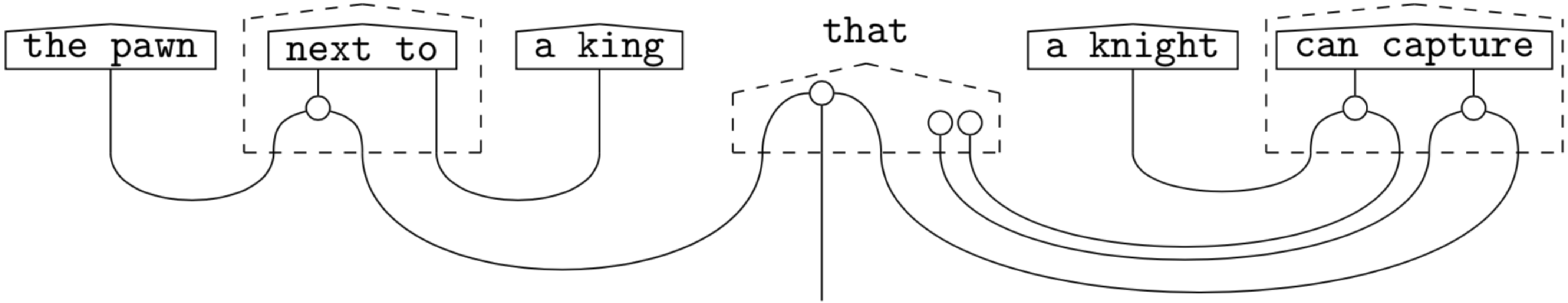
- $\texttt{higher than} := \left\{((x, y, z), (x', y', z')) \,\middle|\, z > z'\right\}$

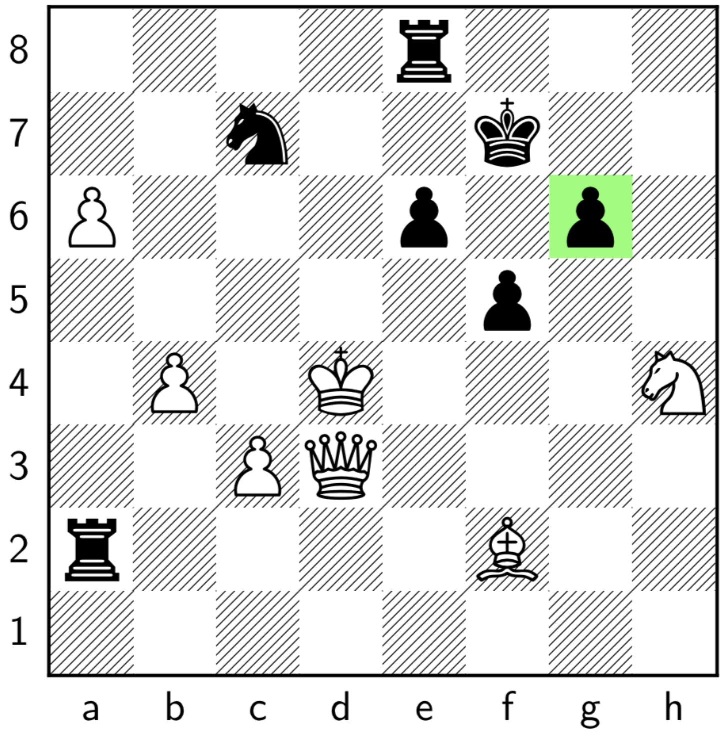
- $\texttt{above} := \left\{((x, y, z), (x', y', z')) \,\middle|\, x = x' \,,\; y = y' \,,\; z > z'\right\}$

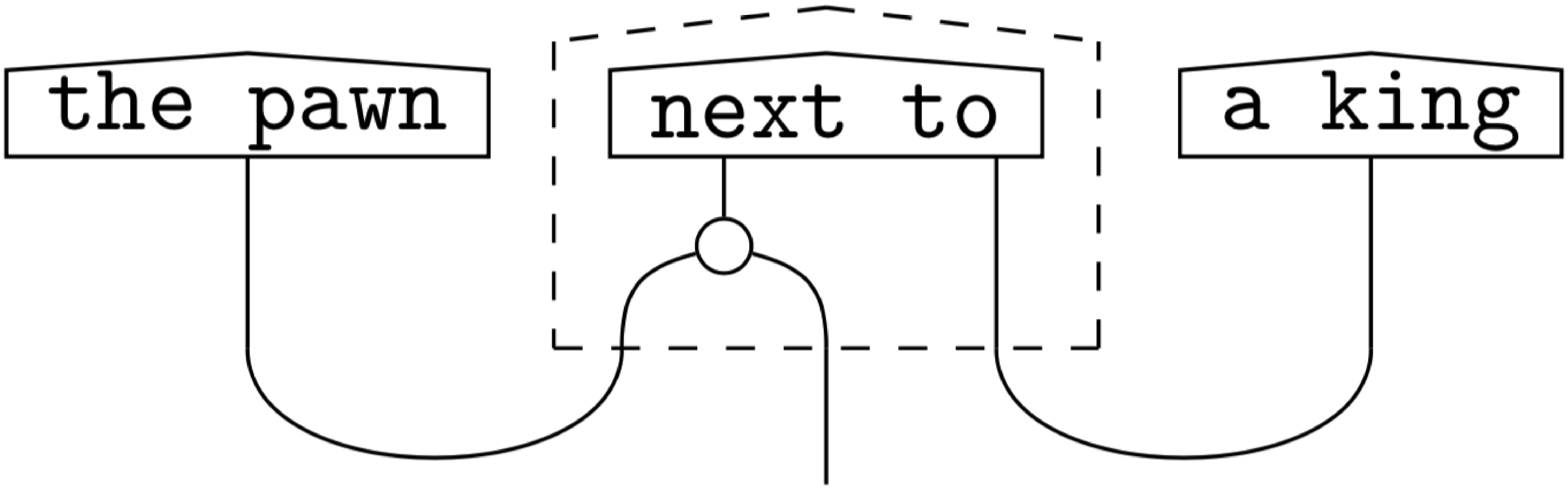
- $\texttt{chases}_{\delta t > 0} := \left\{((x, y, z, t), (x, y, z, t')) \,\middle|\, t = t' + \delta t\right\}$

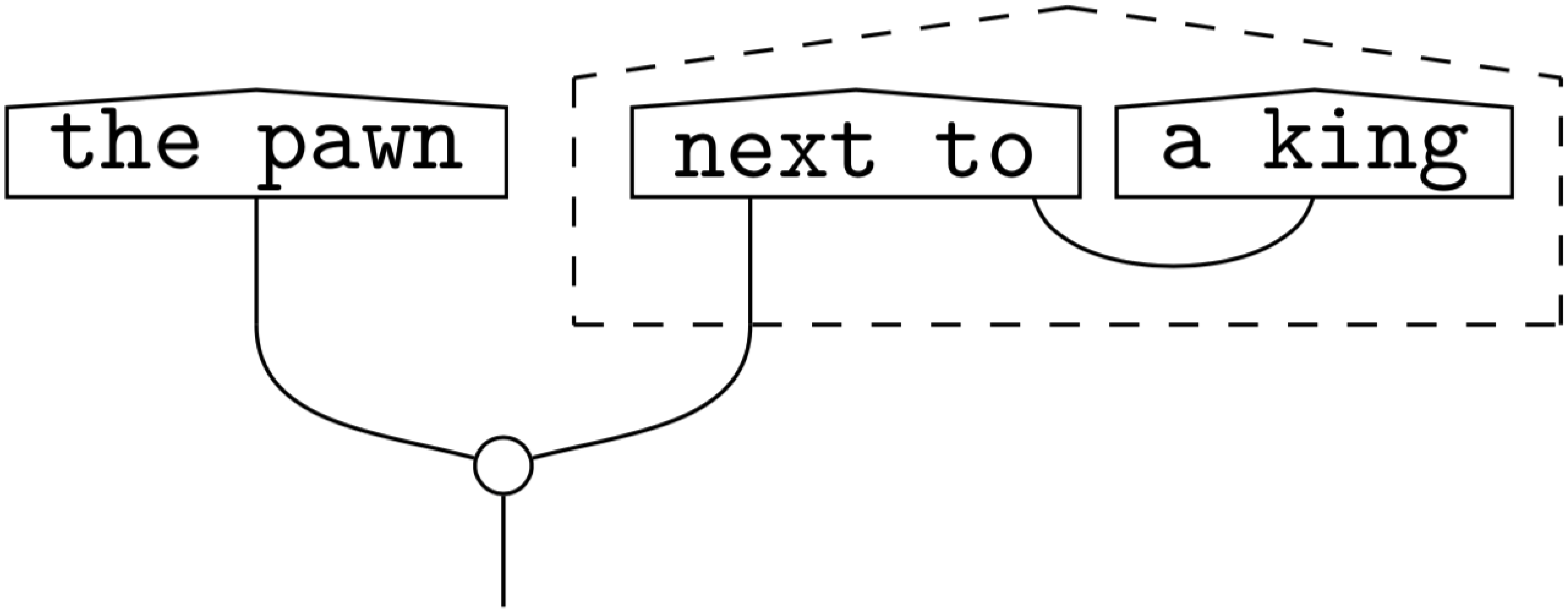


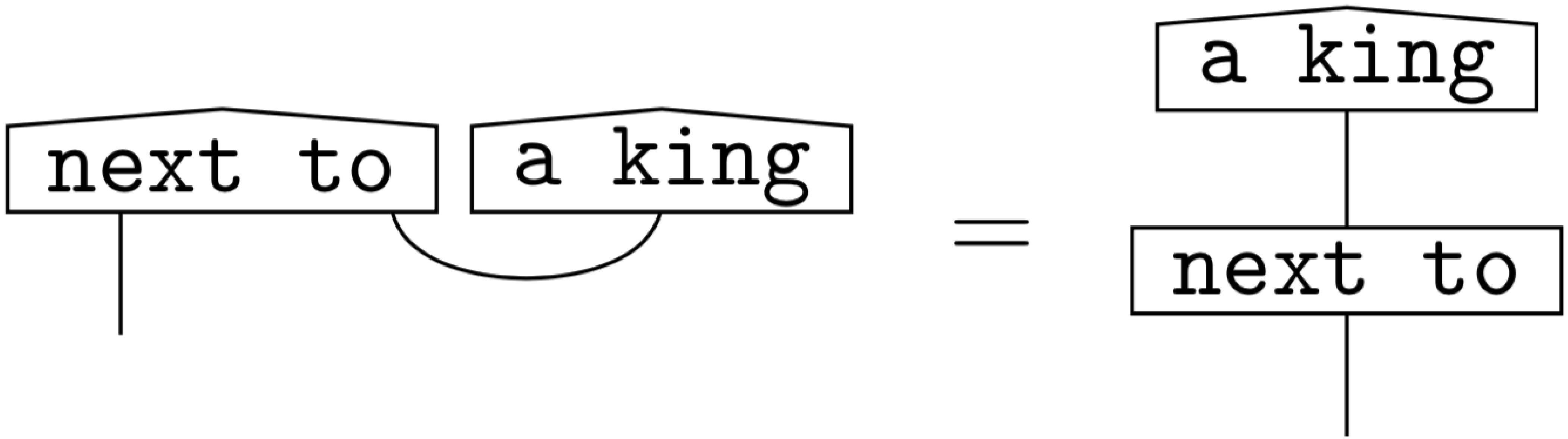
$$\left\{((x,x),*)\;\middle|\;x\in X\right\}\times\left\{(y,y)\;\middle|\;y\in Y\right\}\times\left\{((x,x),*)\;\middle|\;x\in X\right\}$$

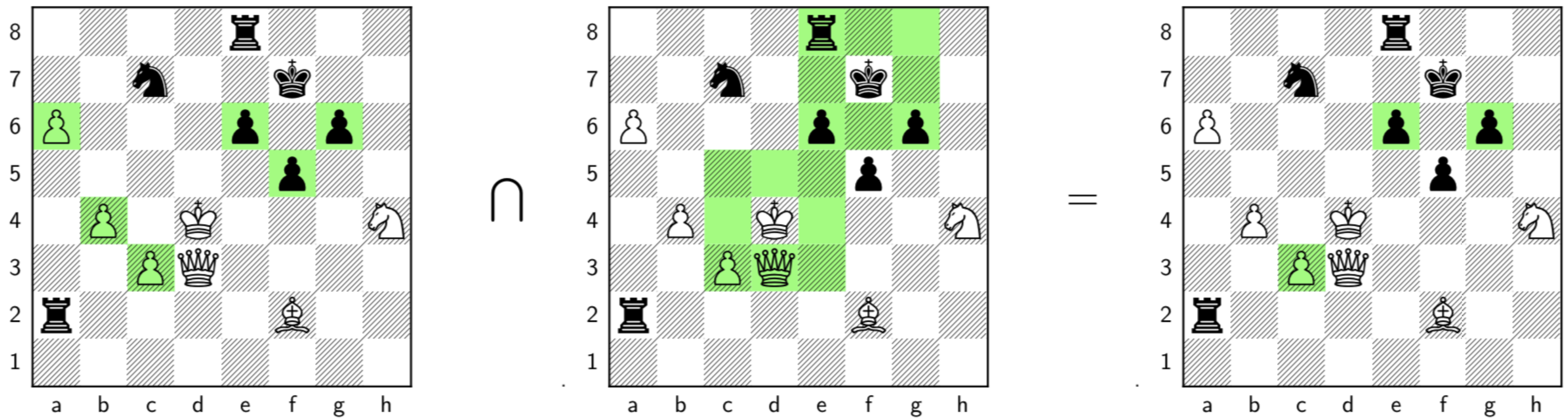

the pawn
next to
a king
that
a knight
can capture


8
7
6
5
4
3
2
1
a
b
c
d
e
f
g
h

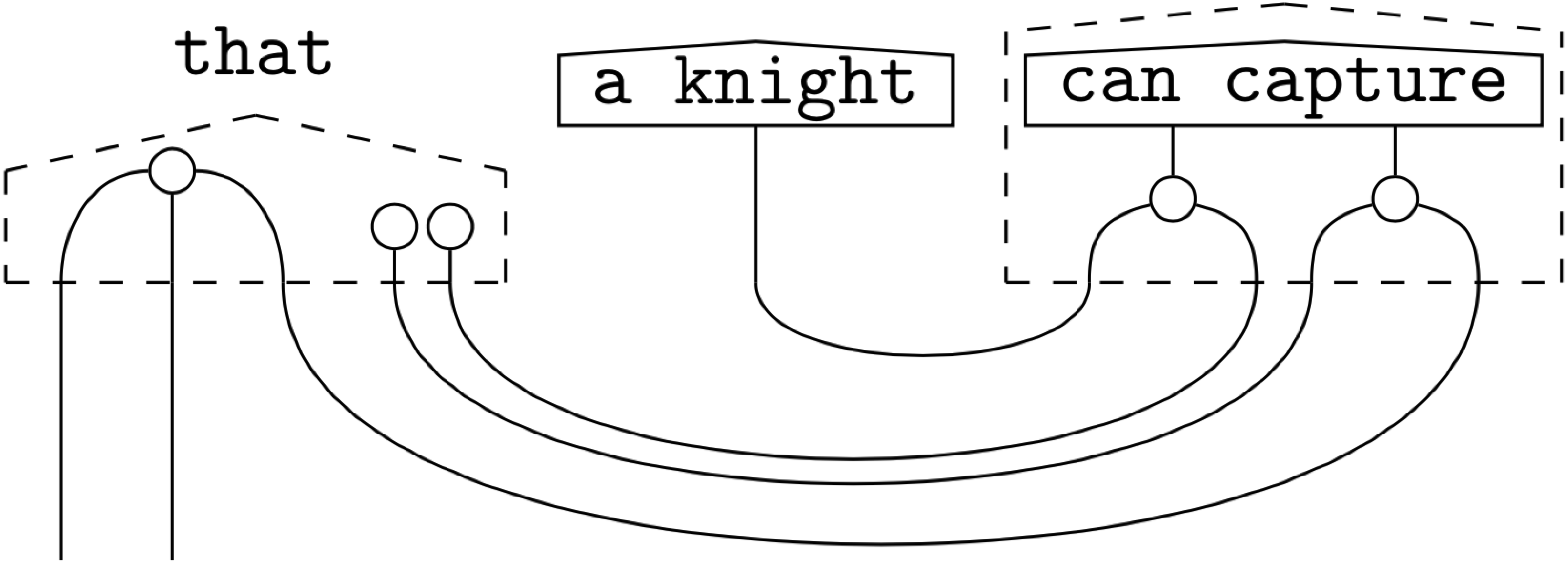

the pawn
next to
a king

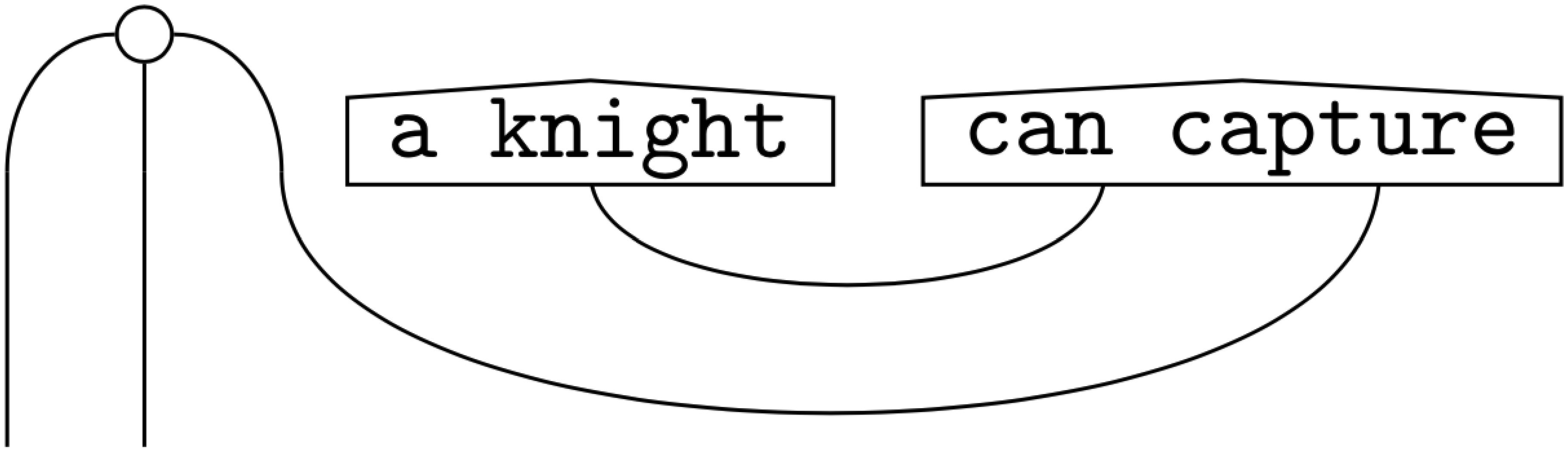

the pawn
next to
a king

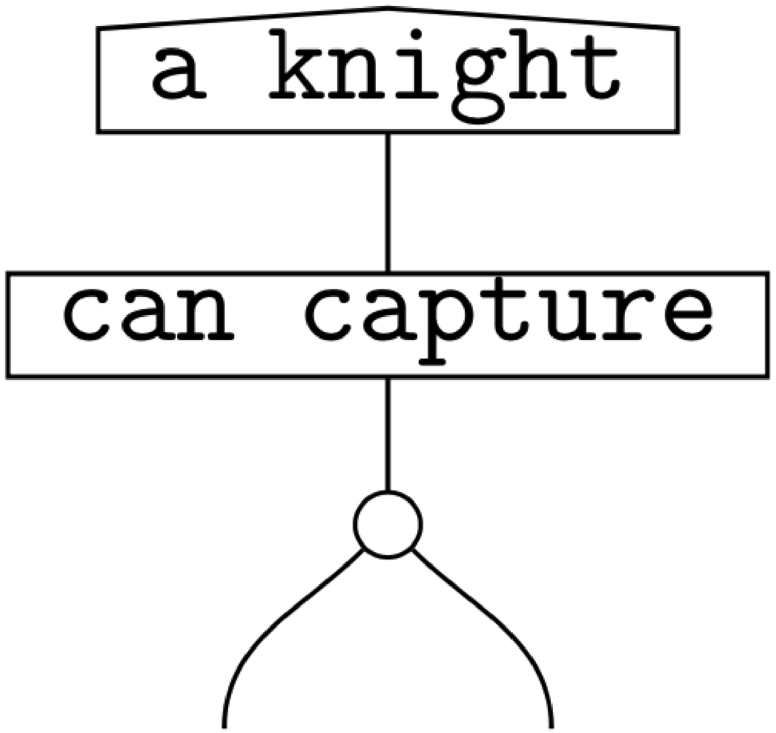

next to
a king
=
a king
next to



8 7 6 5 4 3 2 1
a b c d e f g h
∩
8 7 6 5 4 3 2 1
a b c d e f g h
=
8 7 6 5 4 3 2 1
a b c d e f g h


that
a knight
can capture


a knight
can capture


a knight
can capture

$$\texttt{chessboard} := (\texttt{a-h} \times \texttt{1-8}) \times \{♙'\texttt{s moves}, ♖'\texttt{s moves}, \ldots, ♔'\texttt{s moves}\}$$

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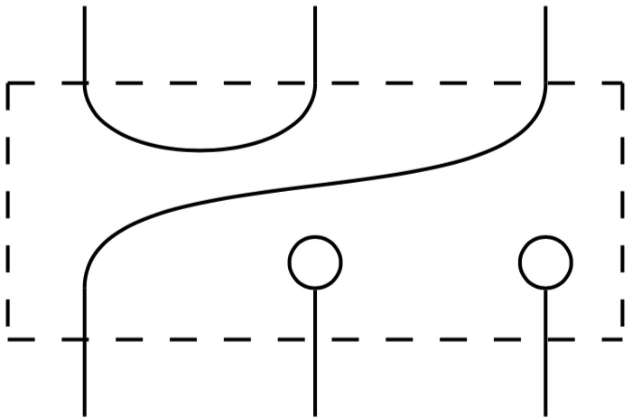
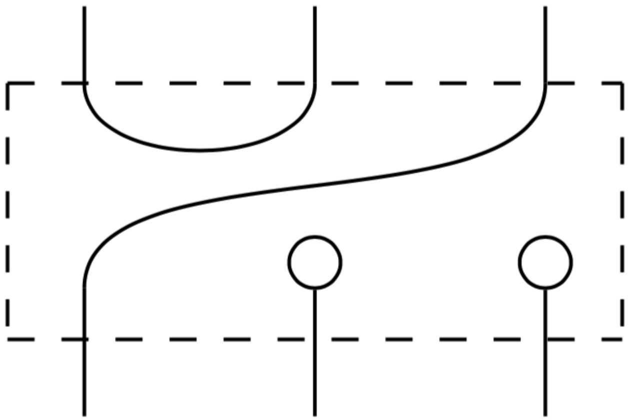
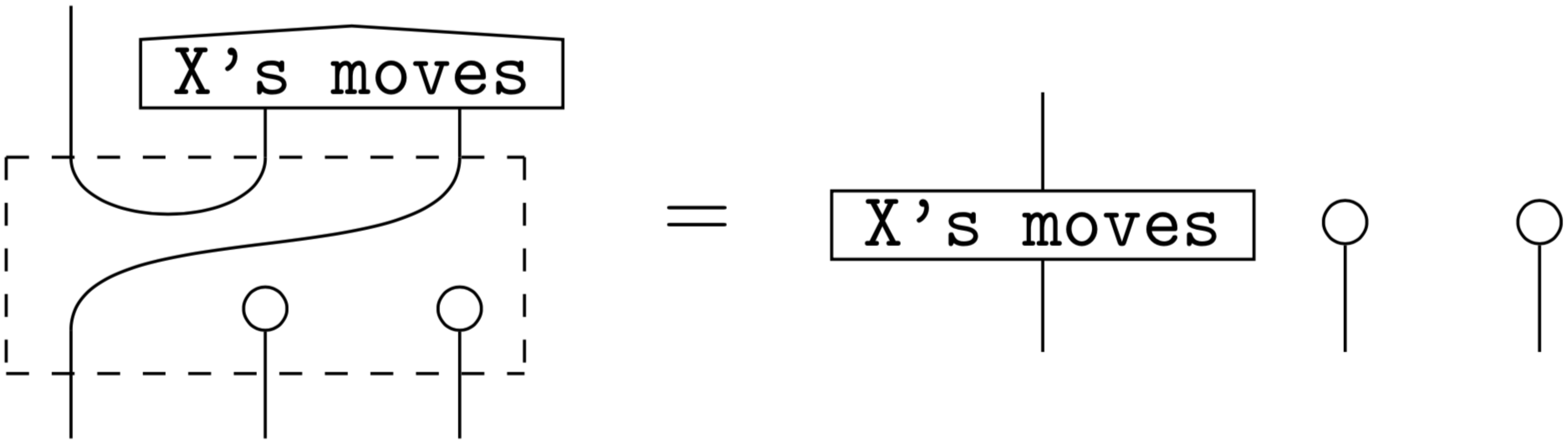
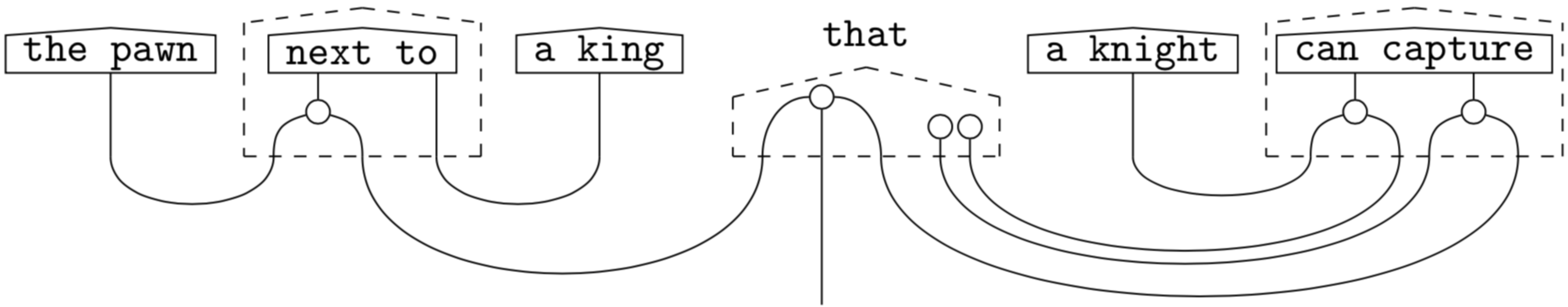
$\texttt{can capture} :=$ 

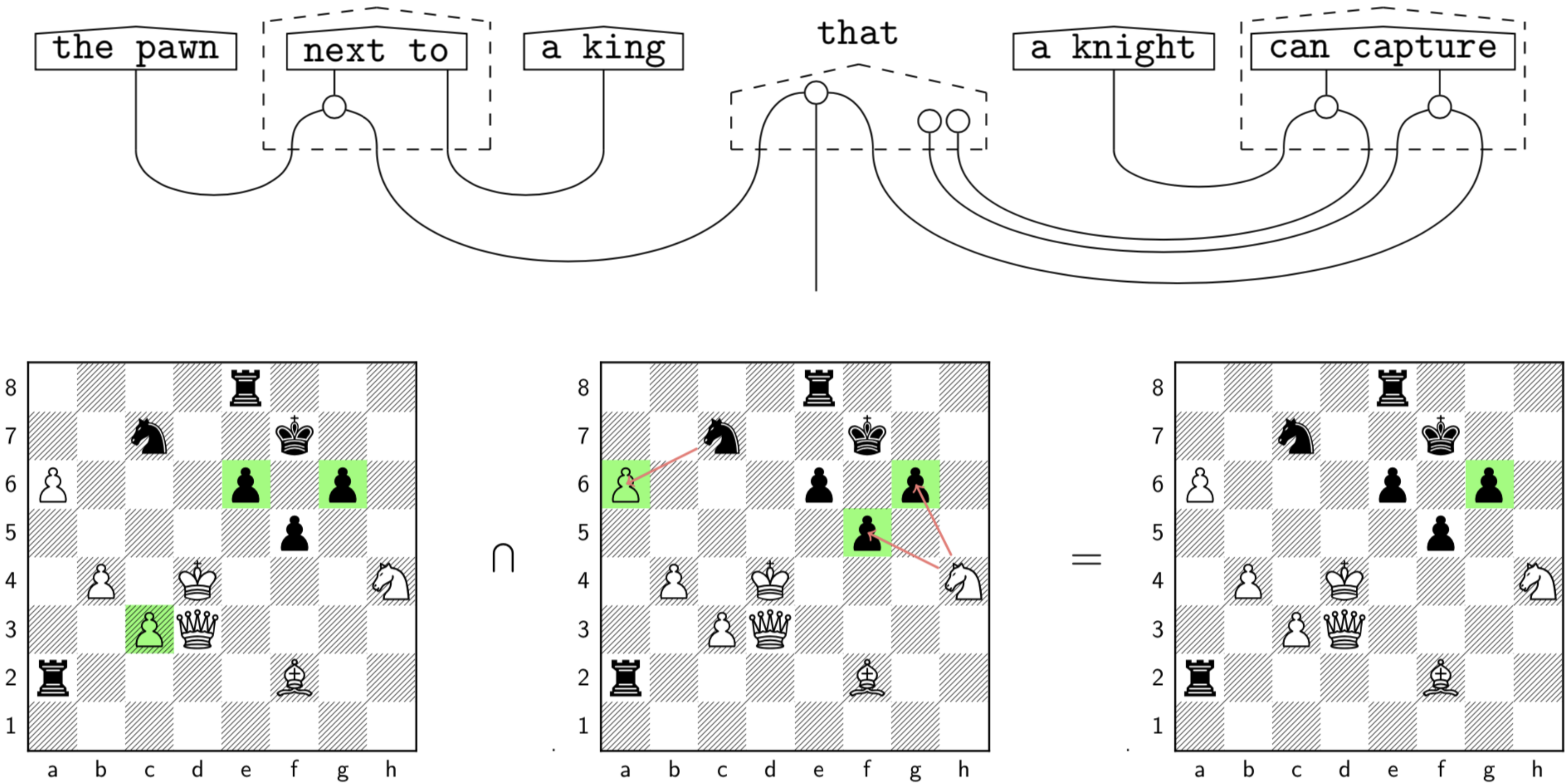
chessboard := (a–h × 1–8) × {♙′s moves, ♖′s moves, …, ♔′s moves}

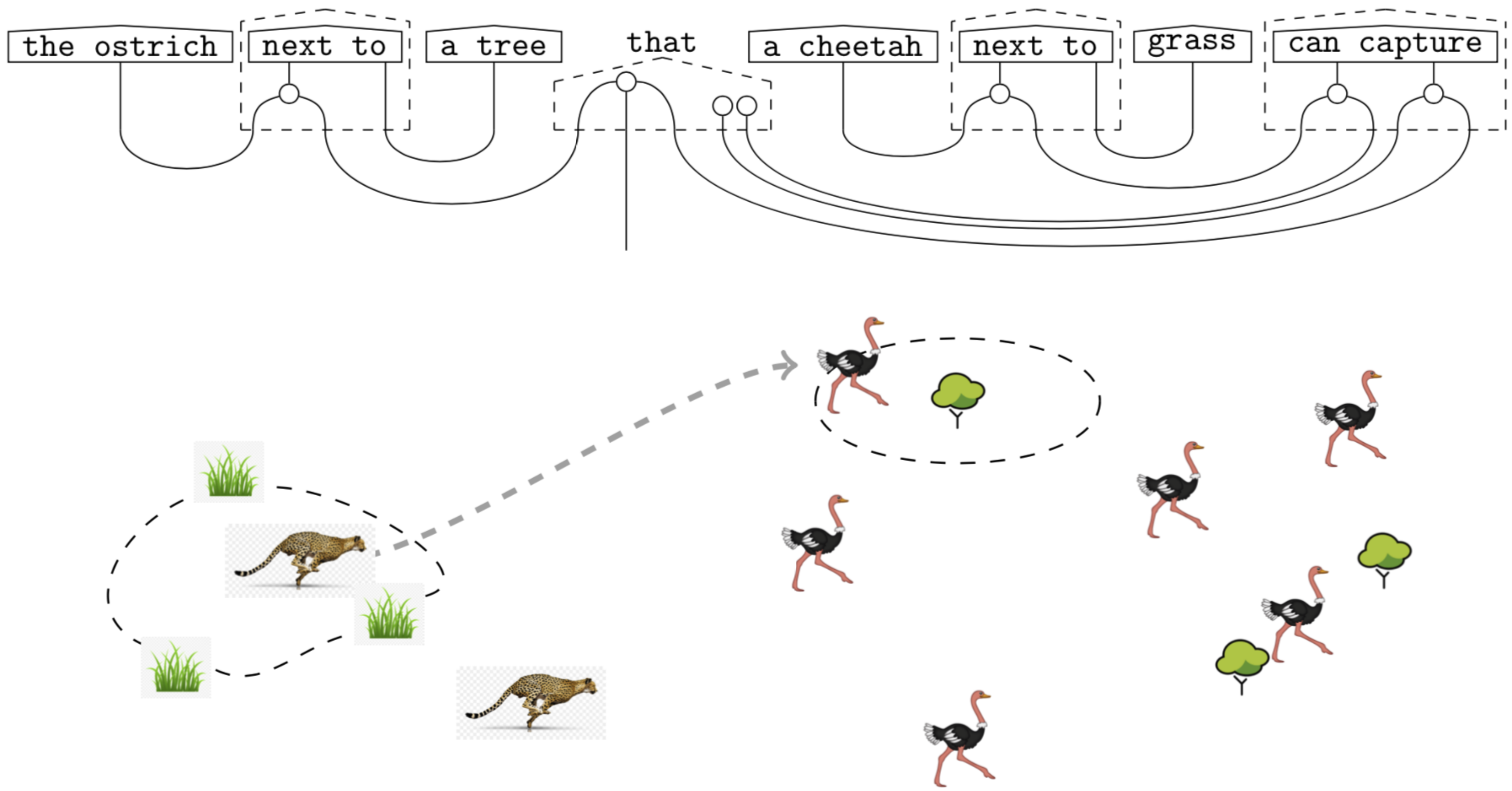
can capture :=



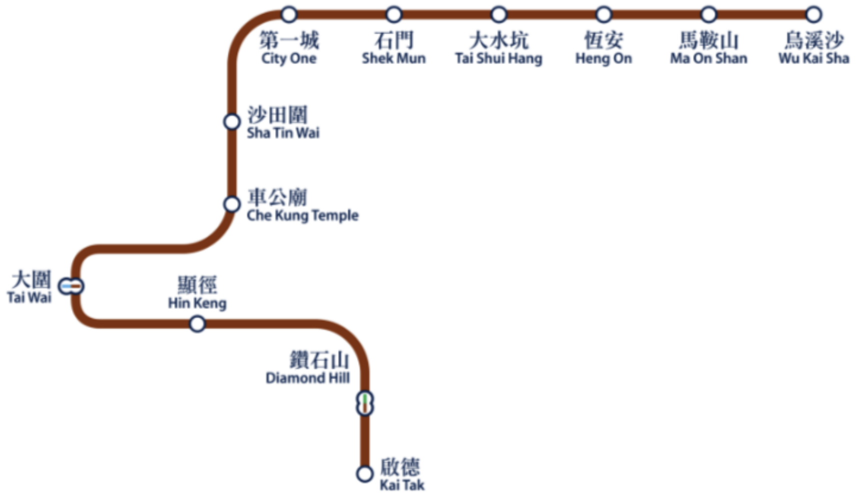



the pawn
next to
a king
that
a knight
can capture

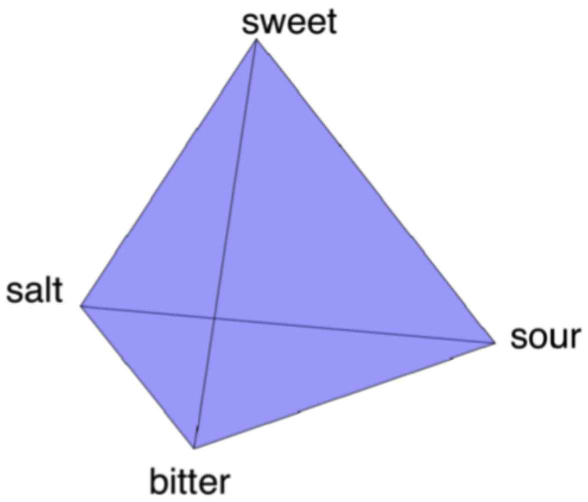

the pawn
next to
a king
that
a knight
can capture
∩
=
a b c d e f g h
1 2 3 4 5 6 7 8



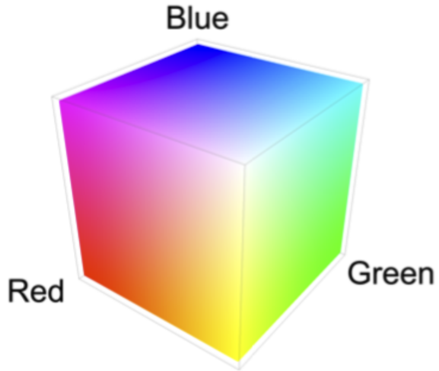
the ostrich
next to
a tree
that
a cheetah
next to
grass
can capture

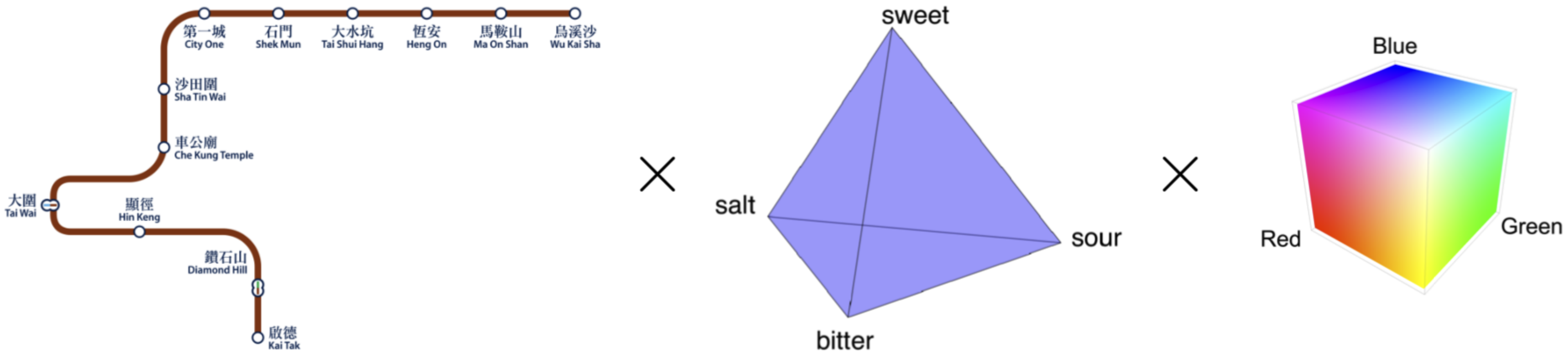

第一城
City One
石門
Shek Mun
大水坑
Tai Shui Hang
恒安
Heng On
馬鞍山
Ma On Shan
烏溪沙
Wu Kai Sha
沙田圍
Sha Tin Wai
車公廟
Che Kung Temple
大圍
Tai Wai
顯徑
Hin Keng
鑽石山
Diamond Hill
啟德
Kai Tak

×


sweet
salt
sour
bitter

×


Blue
Red
Green


第一城
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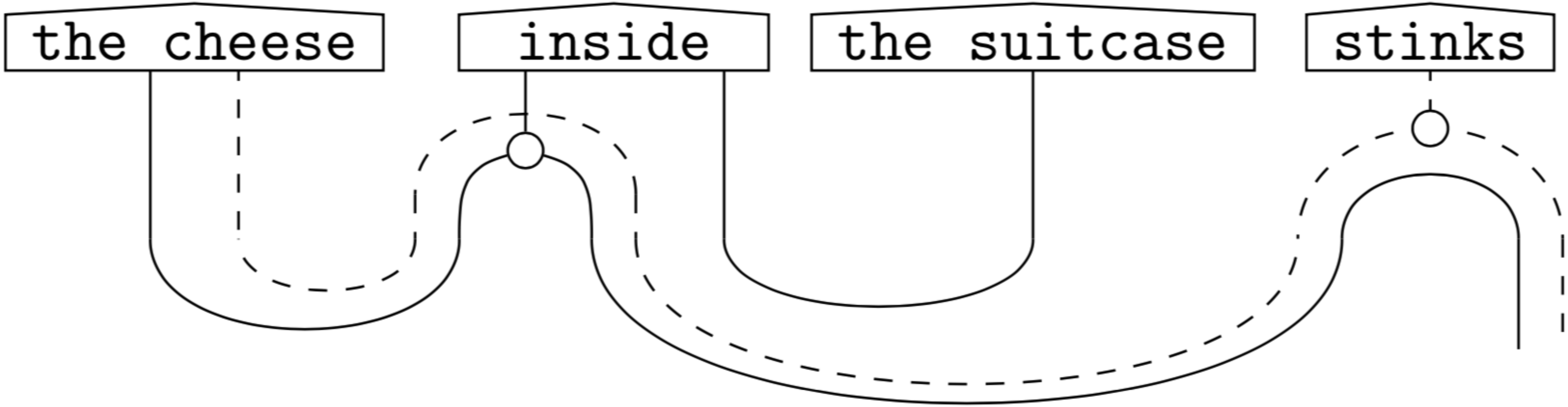
車公廟
Che Kung Temple
大圍
Tai Wai
顯徑
Hin Keng
鑽石山
Diamond Hill
啟德
Kai Tak
×
sweet
salt
sour
bitter
×
Blue
Red
Green


the cheese
inside
the suitcase
stinks

what is compositionality?

arXiv.org > math > arXiv:2110.05327

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Mathematics > Category Theory

[Submitted on 11 Oct 2021]

Compositionality as we see it, everywhere around us

Bob Coecke

There are different meanings of the term "compositionality" within science: what one researcher would call compositional, is not at all compositional for another researcher. The most established conception is usually attributed to Frege, and is characterised by a bottom-up flow of meanings: the meaning of the whole can be derived from the meanings of the parts, and how these parts are structured together.
Inspired by work on compositionality in quantum theory, and categorical quantum mechanics in particular, we propose the notions of Schrodinger, Whitehead, and complete compositionality. Accounting for recent important developments in quantum technology and artificial intelligence, these do not have the bottom-up meaning flow as part of their definitions.
Schrodinger compositionality accommodates quantum theory, and also meaning-as-context. Complete compositionality further strengthens Schrodinger compositionality in order to single out theories like ZX-calculus, that are complete with regard to the intended model. All together, our new notions aim to capture the fact that compositionality is at its best when it is `real', `non-trivial', and even more when it also is `complete'.
At this point we only put forward the intuitive and/or restricted formal definitions, and leave a fully comprehensive definition to future collaborative work.

Frege compositionality in formal linguistics:

Meaning of a whole (cf. sentence) should only depend on meanings of its parts (cf. words) and how they are fitted together (cf. grammar).

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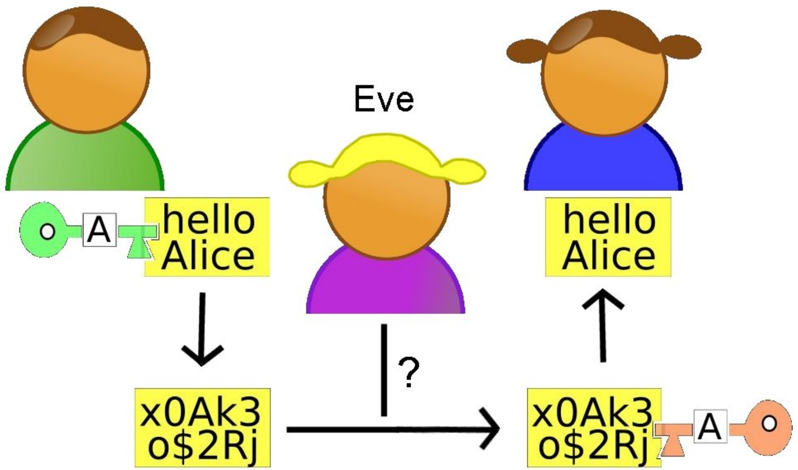
There is also **Frege's context principle**:

Never ask for word meaning in isolation, but only in the context of a sentence.

These Alice's get easily disambiguated by context:



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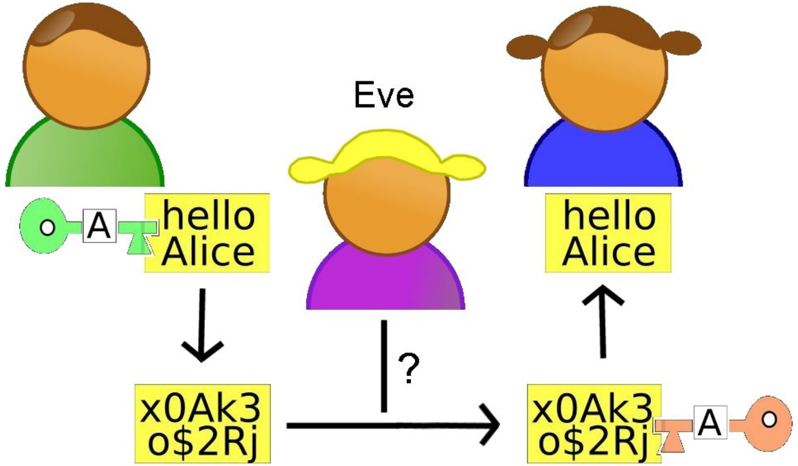

These Alice's get less easy disambiguated by context:

The ambiguity can also intertwine grammar and meaning:

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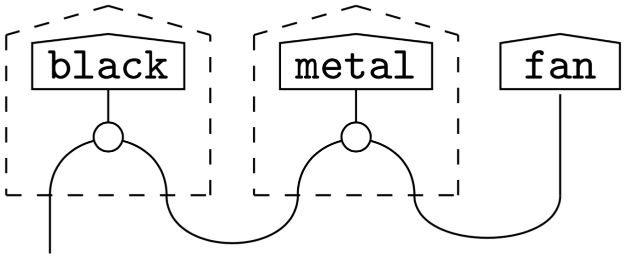
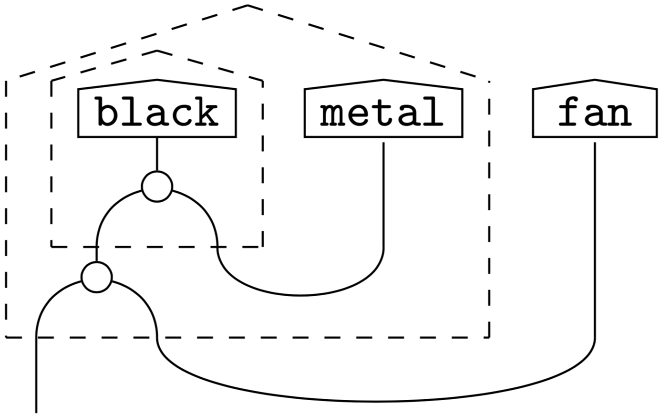
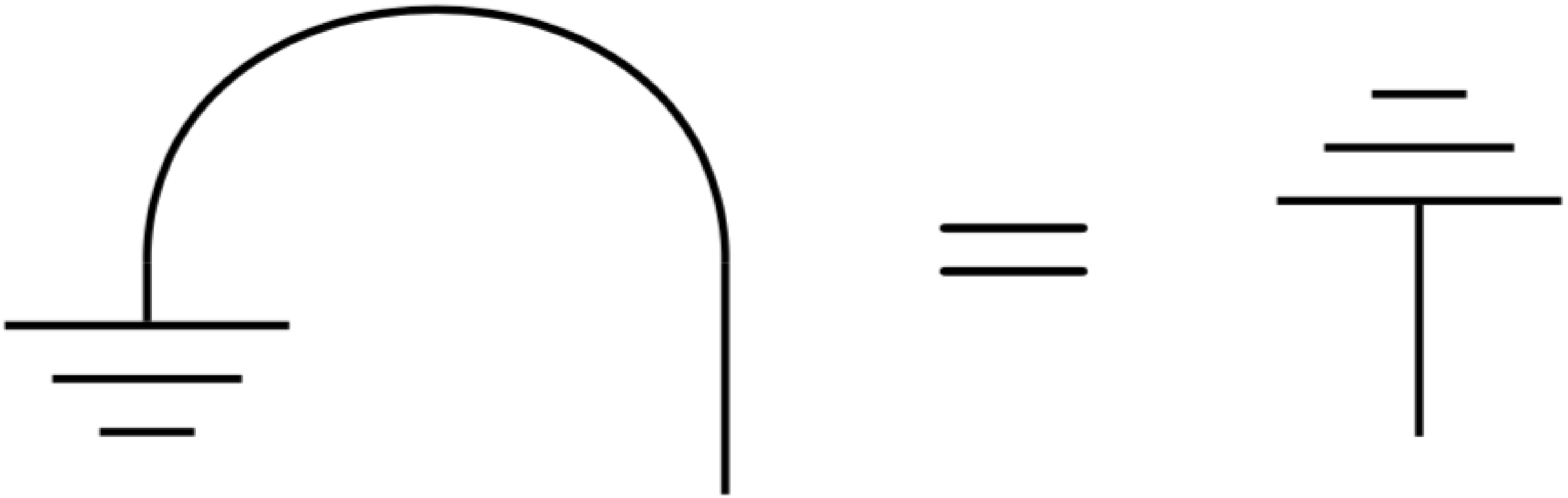
Respectively:

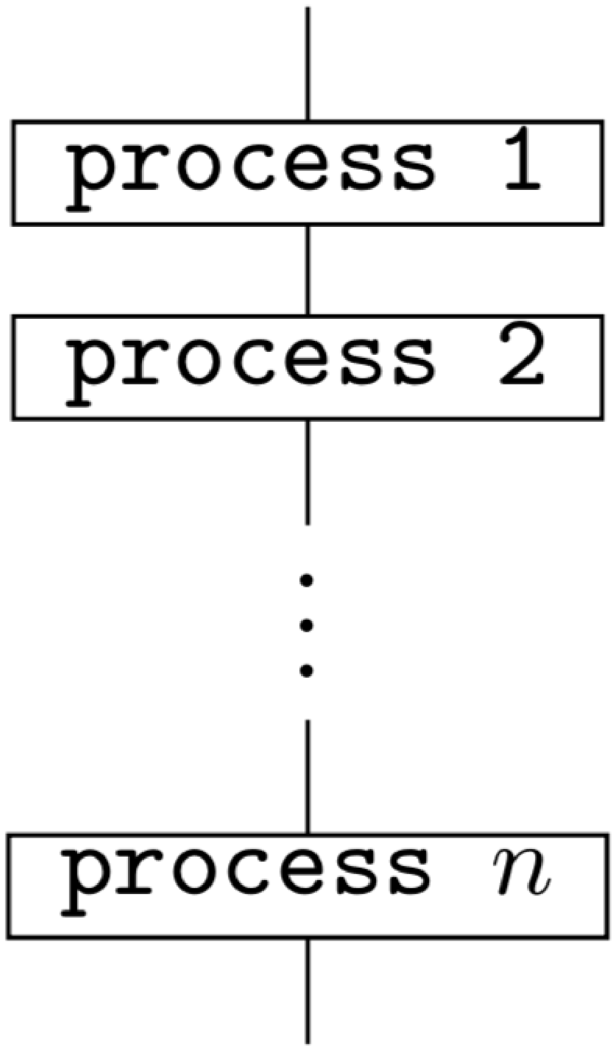




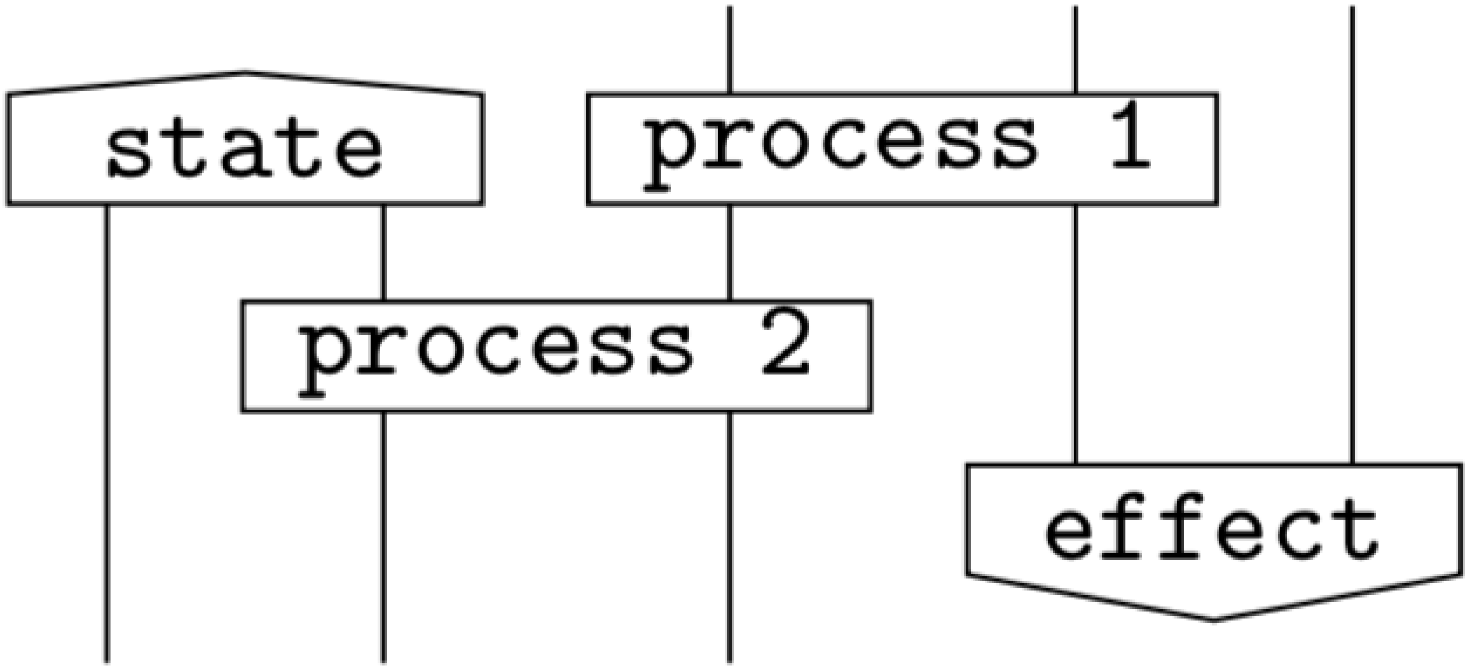
In quantum the situation is even worse e.g. Bell-state:



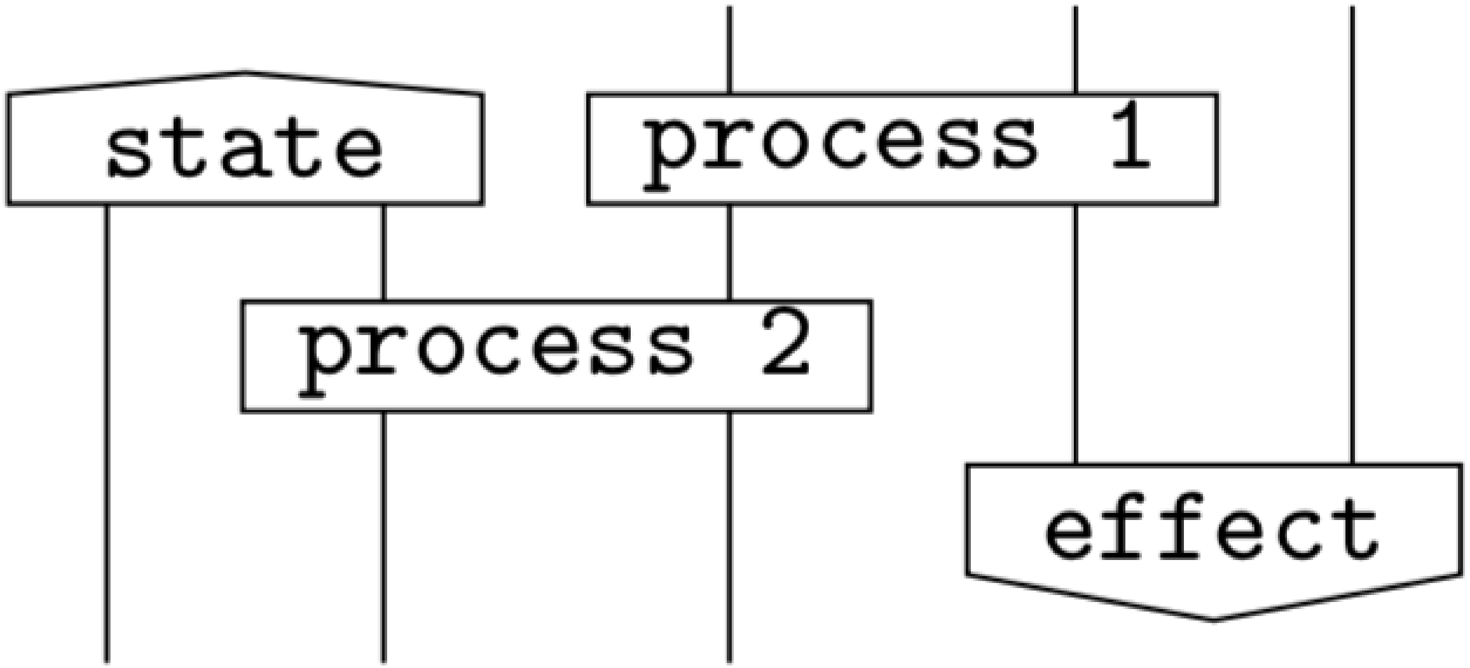
Whitehead-compositional process theory diagrams:



A **Schrödinger-compositional** process diagrams:



A **Schrödinger-compositional** process diagrams:



A **Schrödinger compositional theory** is a (generalised) process theory s.t.:

- Composition is non-trivial, i.e. a whole cannot be decomposed meaningfully.
- All ingredients have clear meaningful ontological counterparts in reality.

[Submitted on 11 Oct 2021]

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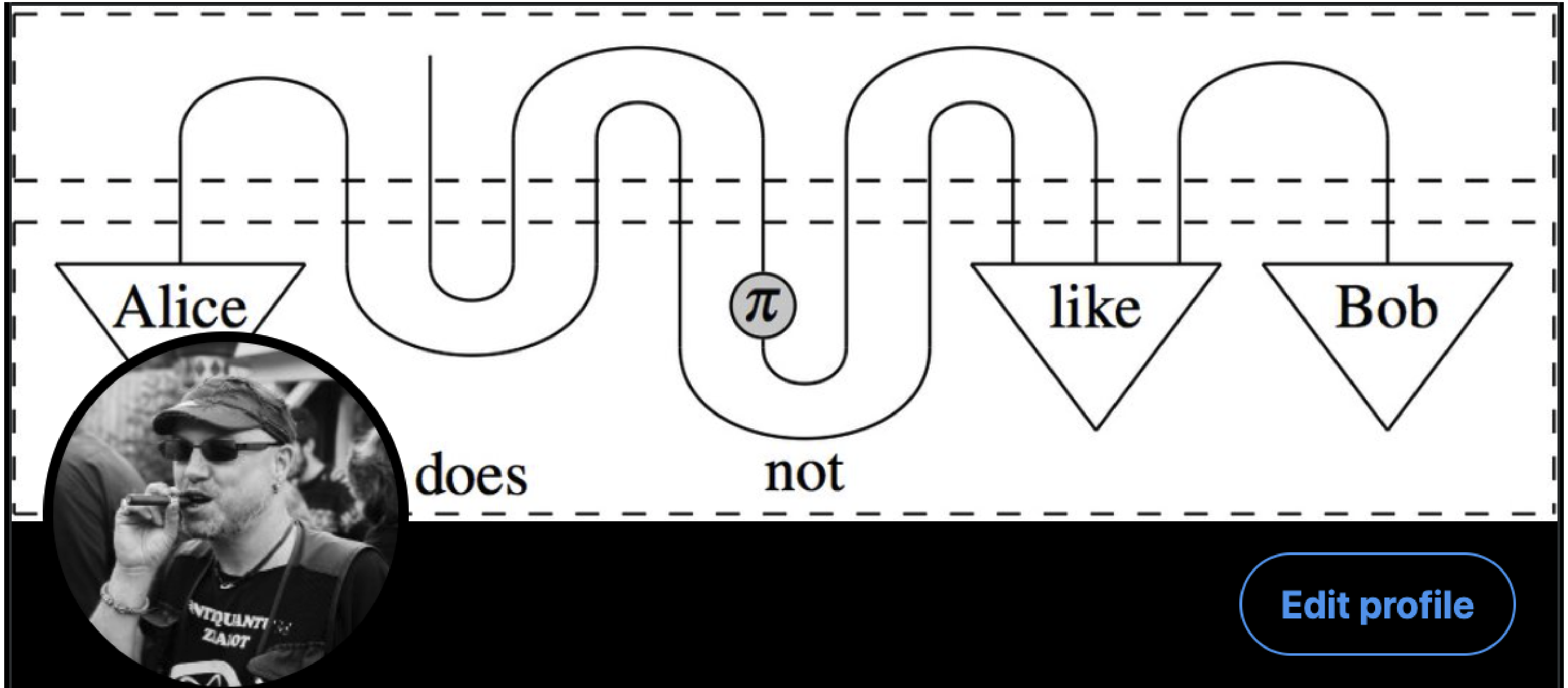

Edit profile

bOb cOeCke

@coecke

Chief Scientist @ CQC
Ex Professor @ Oxford (CS)
Emeritus Professor @ Wolfson College (Ox)
tweeting since 3/2020