CONTEXTUALITY IN ARTIFICIAL INTELLIGENCE AND COGNITIVE SCIENCE

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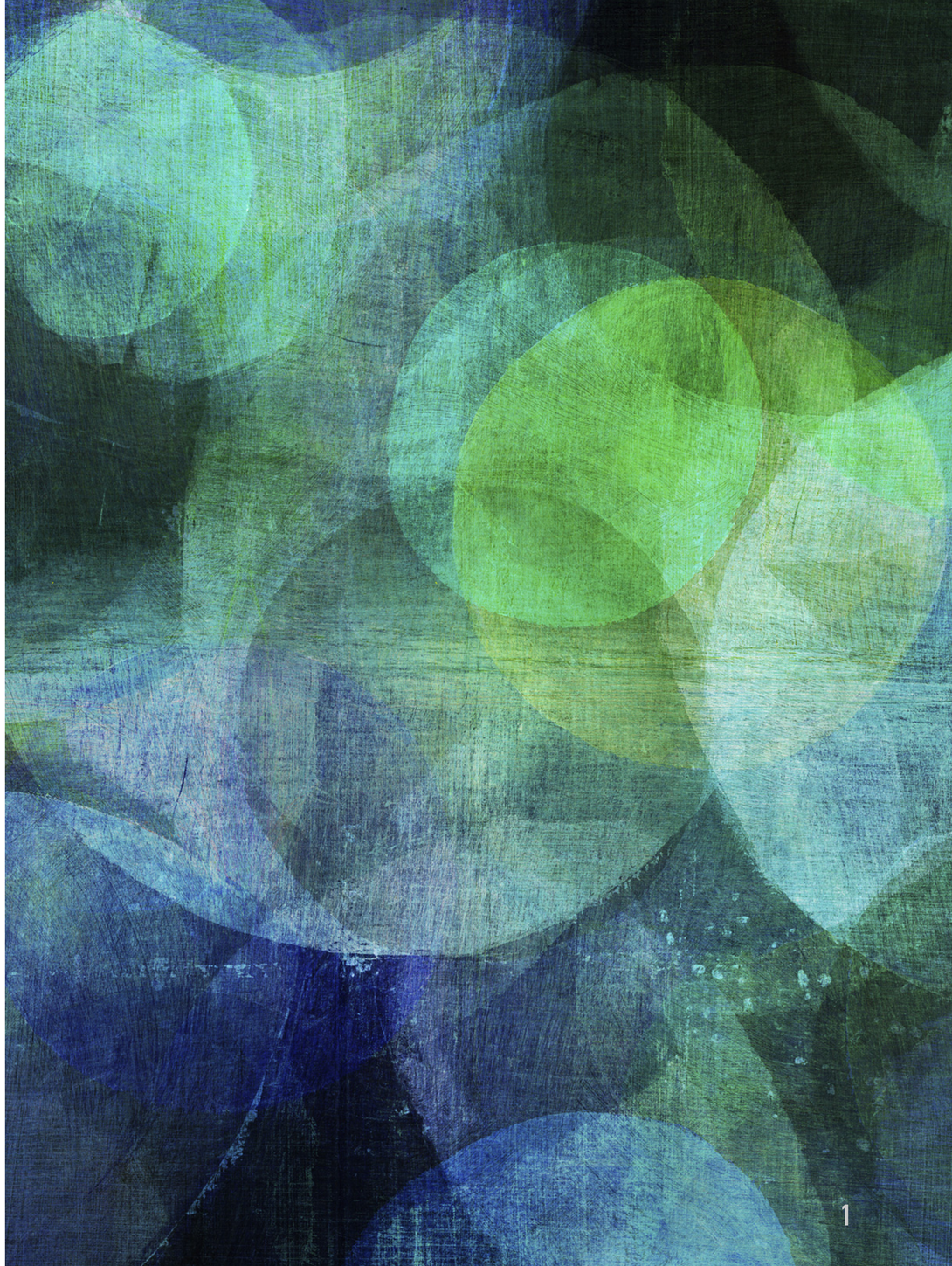

Introduction

Contextuality Studies

CONTEXTUALITY STUDIES

- Contextuality is a family of phenomena observed across the sciences.
  - Some (transdisciplinary) contextuality studies may be possible.
- I will attempt to give a global perspective on different sorts of contextuality first, and then discuss contextuality in local domains.

CONTEXTUALITY STUDIES

- Contextuality across different domains of knowledge:
  - Contextuality of truth: truth is a function of contexts; truth value assignment is contextual.
    - Contextuality of physical truth: truths about (quantum) observables only exist within contexts; no globally coherent assignment of values possible.
      - It may be called truth contextualism. (It's not antirealism about truth.)

CONTEXTUALITY STUDIES

- Contextuality across different domains (cont'd):
  - Contextuality of being: entities only exist within contexts; being is inseparable from contexts such as environments.
    - Contextuality of physical entities: Unruh effect (vacuumness depends on observer contexts; some see particles while others see nothing).
    - Contextuality of agents/agency: Situated AI; 4E (Embedded-Embodied-Extended-Enacted) Cognition; Heideggerian AI.
      - It may be called entity contextualism. (It's not antirealism about entities.)

CONTEXTUALITY STUDIES

- Contextuality across different domains (cont'd):
  - Contextuality of meaning: words get meaning within contexts; indispensability of contexts in the meaning determination process; no meaning without some wider context as a whole.
    - The distributional hypothesis: words that occur in similar contexts have similar meanings.
    - The standard model of natural language processing builds on this, and semantic state vectors are contextually constructed. BERT is even more contextual (but Transformer-based models may become obsolete soon; Lie et al. 2021. SM remains still).
      - It may be called semantic contextualism.

CONTEXTUALITY STUDIES

- Contextuality across different domains (cont'd):
  - Contextuality of cognition/reason: cognitive behaviour is a function of contexts; the same question may have different answers in different contexts; contextual effects such as coexisting information and environmental noise may affect and change results of decision making in human and other cognitive systems.
    - Quantum cognitive science: the order effect, the conjunction effect, the disjunction effect, etc. (It's substructural logic, similar to no-cloning/deleting.)
      - It may be called cognitive contextualism.

Part I

Cognitive Contextualism

BACKGROUND

- I have no psychology background, but come to learn quantum cognitive science through some project.
  - I talked to psychology students, and read some course materials.
  - And I learned some general lessons.
    - Psychology is the data science of cognition.
    - The success of data science does not mean reality is statistical or contextual.
    - Yet it makes sense even when there is no actually probabilistic phenomenon.
      - Because cognitive behaviour is too difficult to predict even if it is classical.

QUANTUM COGNITIVE QUESTIONS

- What exactly quantum cognitive science proves?
  - It does not prove that the material brain is driven by quantum effects.
  - Tegmark (2000): “Based on a calculation of neural decoherence rates [...] the degrees of freedom of the human brain that relate to cognitive processes should be thought of as a classical rather than quantum system [...] This conclusion disagrees with suggestions by Penrose and others that the brain acts as a quantum computer, and that quantum coherence is related to consciousness in a fundamental way.”
    - The human brain is a (physically) classical system.
  - NB: Penrose does not claim the brain acts as a quantum computer, but Hameroff does.

DETOUR

- Penrose has been criticised so much, due to his (and Lucas') Gödelian argument, but Gödel is actually even more controversial than Penrose.
  - The conclusion of the Lucas-Penrose argument comes from Gödel himself.
  - Gödel makes an even more controversial argument:
  - "[T]he development of philosophy since the Renaissance has by and large gone from right to left [...] Particularly in physics, this development has reached a peak in our own time, in that, to a large extent, the possibility of knowledge of the objectivisable states of affairs is denied, and it is asserted that we must be content to predict results of observations. This is really the end of all theoretical science in the usual sense."
- Does contextuality entail the "end of all theoretical science" in the usual sense?

MEANING OF CONTEXTUALITY

- What exactly quantum cognitive science proves? (cont'd)
  - It does not prove that human cognition is probabilistic.
    - Human cognitive systems are (physically) classical and deterministic, according to Tegmark.

MEANING OF CONTEXTUALITY

- Then, why can Bell-type inequalities be violated in certain cognitive experiments?
  - When the (experimental) Laplace demon performs those experiments while fixing all relevant (environmental/contextual) parameters involved, the results of them are fully deterministic and Bell-type inequalities are not violated.
  - Hence no contextuality in that case.

MEANING OF CONTEXTUALITY (CONT'D)

- Why is probabilistic contextuality observed in the actual experiments then?
  - Contextual statistics emerge because of the practical impossibility of fixing all those parameters (and because of the specific structure of experiments).
    - Psychology experiments, in general, mix different mental states, since it is practically impossible to fix mental states.
      - It's same with data science. We cannot actually determine all parameters to predict, e.g., the result of an election or soccer game even if it's deterministic.

MEANING OF CONTEXTUALITY (CONT'D)

- How are cognitive and quantum contextualities compared with each other in terms of their content beyond the formal violations of Bell-type inequalities?
  - In physics, in contrast to psychology, states of systems can be fixed or controlled, and even then, quantum contextuality emerges, and cannot be erased.
    - This erasability/non-erasability is a crucial difference between cognitive and quantum contextualities.

MEANING OF CONTEXTUALITY (CONT'D)

- Bell's theorem refuted classical (local) realism about the world.
- Bell-type results in cognitive science (violations of Bell-type inequalities) may refute classical models of cognition, but they do not refute classical realism about cognition.
  - Because non-classicality of cognition is erasable in the above sense.

Part II

Meaning Contextualism

HISTORIOGRAPHY OF CONTEXTUALITY

- Contextuality in language has been discussed in various forms.
  - Frege is supposed to have proposed both compositionality and contextuality.
    - But they somehow look contradictory with each other.
    - Were Frege's foundations of natural language semantics inconsistent as well as his foundations of mathematics (arithmetic)?

HISTORIOGRAPHY OF CONTEXTUALITY

- Compositionality has been emphasised in logic, formal semantics, theoretical computer science, and category theory.
  - The meaning of wholes is determined by the meaning of parts (and the way they are combined with each other.)
- Contextuality has been emphasised in statistical semantics and natural language processing, and almost replaced compositional semantics in artificial intelligence.
  - The meaning of parts is determined in relation with wholes (and the way they are used within wholes).
- Burge, Dummett, etc. have pointed out that they are contradictory with each other (cf. hermeneutic circularity in continental philosophy).

WHY COMPOSITIONALITY MATTERS

- Compositionality is supposed to be essential for learnability, understandability, productivity, systematicity, and creativity of language.
  - Davidson (1967) argues: without compositionality, “there would be no explaining the fact that we can learn the language: no explaining the fact that, on mastering a finite vocabulary and a finitely stated set of rules, we are prepared to produce and to understand any of a potential infinitude of sentences.”
  - Chomsky (1978) argues: “The most striking aspect of linguistic competence is what may call the ‘creativity of language’, that is, the speaker’s ability to produce new sentences that are immediately understood by other speakers although they bear no physical resemblance to sentences that are ‘familiar’.”

FREGE STUDIES

- Frege (1923): “It is astonishing what language can do. With a few syllables it can express an incalculable number of thoughts, so that even a thought grasped by a terrestrial being for the very first time can be put into a form of words which will be understood by someone to whom the thought is entirely new.”

- But Frege studies based on detailed textual analysis, such as Janssen (2001) and Pelletier (2001), conclude Frege did not really endorse the principle of compositionality.

  - Cf. Feynman’s dictum “Shut up and calculate!” is not really Feynman’s.

- Janssen (2001) argues Frege rather endorsed contextuality; Pelletier (2001) concludes any of compositionality and contextuality should not be called Frege’s principle.

  - Frege was not inconsistent in this linguistic respect anyway.

COMPOSITIONALITY IN ANIMAL COGNITION

- Does (syntactic) compositionality exist in animal cognition?
- Gentner et al. (2006) argue:
  - “Recent hypotheses make the central claim that the capacity for syntactic recursion forms the computational core of a uniquely human language faculty. [...] European starlings [...] accurately recognize acoustic patterns defined by a recursive, self-embedding, context-free grammar. They are also able to classify new patterns defined by the grammar and reliably exclude agrammatical patterns. Thus, the capacity to classify sequences from recursive, centre-embedded grammars is not uniquely human.
- Yet there are some negative arguments as well.

CONTEXTUALITY YIELDS COMPOSITIONALITY

- In recent NLP, contextuality is even allowing for reconstruction of compositionality.
- Manning et al. (2020) indeed argue as follows:
  - "[L]anguage understanding requires constructing rich hierarchical structures that are never observed explicitly. The mechanisms for this have been a prime mystery of human language acquisition [...] [M]odern deep contextual language models learn major aspects of this structure, without any explicit supervision. [...] Indeed, [...] allowing approximate reconstruction of the sentence tree structures normally assumed by linguists."
- Compositionality is a consequence of contextuality in this sense.

CONTEXTUALITY YIELDS EVERYTHING?

- Some have argued symbolic tasks are difficult to do with statistical ML/NLP.
- But Lample-Charton (2020) have shown:
  - "[W]e consider mathematics, and particularly symbolic calculations, as a target for NLP models. More precisely, we use sequence-to-sequence models (seq2seq) on two problems of symbolic mathematics: function integration and ordinary differential equations (ODEs). Both are difficult, for trained humans and computer software."
  - "[A] simple transformer model trained on these datasets can perform extremely well both at computing function integrals, and solving differential equations, outperforming state-of-the-art mathematical frameworks like Matlab or Mathematica that rely on a large number of algorithms and heuristics, and a complex implementation."

SYMBOL GROUNDING AND EMERGENCE PROBLEMS

- Is there anything that state-of-the-art contextual AI/ML/NLP cannot do?
  - Purely linguistic contextuality in NLP cannot deal with another kind of contextuality, namely situational contextuality.
  - Our symbol grounding in the process of language learning is made by associating linguistic expressions with real-world situational contexts.

SYMBOL GROUNDING AND EMERGENCE PROBLEMS

- Symbols emerge within environmental contexts, and symbol emergence is enabled via interactions within environments.
  - Purely linguistically contextual NLP does not solve the symbol emergence problem.
- Language is not an abstract, closed system; it does interact with different elements of reality, such as physical objects, (human or artificial) agents, and social constructs in environments.
- Current NLP regards the linguistic world as a closed world, and only analyses certain types of data (however big it is), having no capacity to enable symbol emergence/grounding.
  - The symbol emergence problem is dual to the symbol grounding problem.

SYMBOL GROUNDING AND EMERGENCE PROBLEMS

- In the closed world of (current) NLP, the meaning of words can be given with no outward reference to reality.
- Linguistic contextual relationships between words are supposed to determine the meaning of them.
  - The autonomy of language as being independent of reality has been emphasised in Wittgenstein's later philosophy and Derrida's philosophy.
  - In contemporary philosophy, inferentialism and proof-theoretic semantics, as represented by Brandom and Dummett, share the same spirit.
- Current NLP does not presuppose the existence of reality, supporting the autonomous conception of language, which is however challenged by symbol emergence/grounding.

MATHEMATICAL SYMBOL GROUNDING AND EMERGENCE PROBLEMS

- The same applies to mathematical cognition.
- The mathematical cognition as in Lample-Charton (2020) is not grounded upon real-world phenomena, and thus it cannot account for physical or biological phenomena by means of differential equations, although it can solve them formally.
  - This is the mathematical symbol grounding problem (cf. Kindergarten QM). This is essentially the problem of applicability of mathematics (Newton, Wigner, Tegmark, etc).
- Dually we have the mathematical symbol emergence problem, i.e., how mathematical symbols emerge through interactions with environments; it is about how agents develop mathematical cognition within real-world environments.

MATHEMATICAL SYMBOL GROUNDING AND EMERGENCE PROBLEMS

- These are essential in science robotics which must ground mathematics upon reality / make the right mathematics emerge from interactions with reality.
  - Even recent major advances like AI Feynman, AI Poincare, etc. still do not allow this, and do not solve the mathematical symbol grounding and symbol emergence problems.
  - They are still based on the (cognitively) closed world assumption of AI in the above sense, and thus cannot solve the mathematical symbol grounding/emergence problems.

Conclusions

CONCLUSIONS

- We could develop a broader theory of contextuality, or contextuality studies.
  - But it is only possible at some level of abstraction.
- Quantum and cognitive contextualities are the same type of phenomena at the level of statistical contextuality theory (apart from the issue of marginal selectivity).
  - At the same time, they are essentially different; Bell's theorem refutes classical (local) realism; by contrast, Bell-type results in cognitive science may refute classical models of cognition, but they do not refute classical realism about cognition.
- In AI, contextuality is powerful enough to allow compositionality and mathematical cognition, but it does not solve the symbol emergence problem or allow symbol grounding, which are essential for science AI/robotics and applicability of mathematics.