DFT models of compositionality

Daniel Sabinasz
Gregor Schöner

ini.ruhr-uni-bochum.de

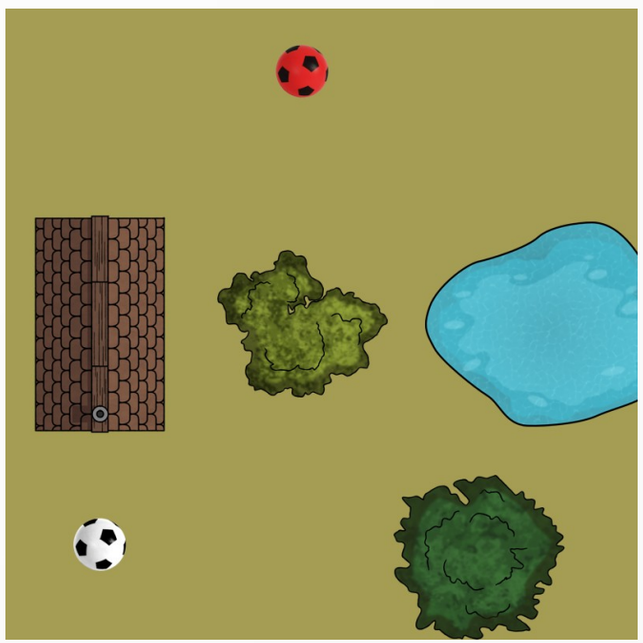
Perceptual grounding

- The process of associating natural language with denoted perceptual representations
- … as a necessary step towards language understanding

the black swan that sits below a tree

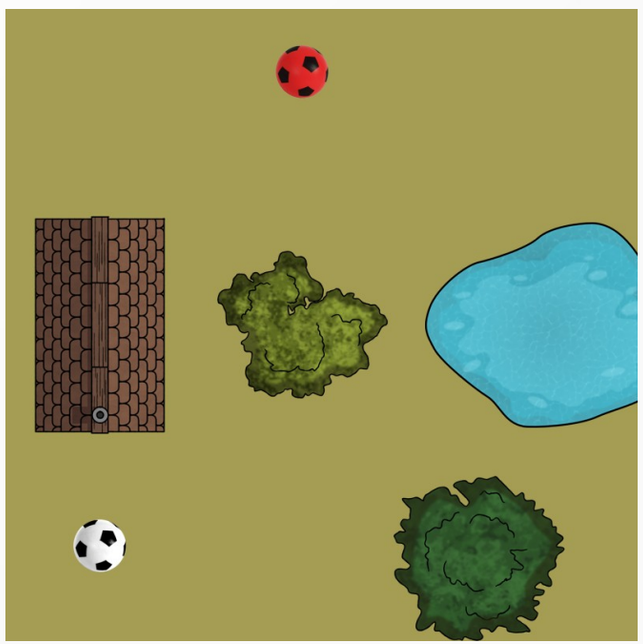
Motivation

- Previous DFT models enable the grounding of
  - Adjectives (“the red”)
  - Nouns (“the tree”)
  - Phrases with a preposition (“the tree to the left of the lake”)
  - Verbs (“the ball that moves towards the tree”)
- But: Natural language is more creative than that!



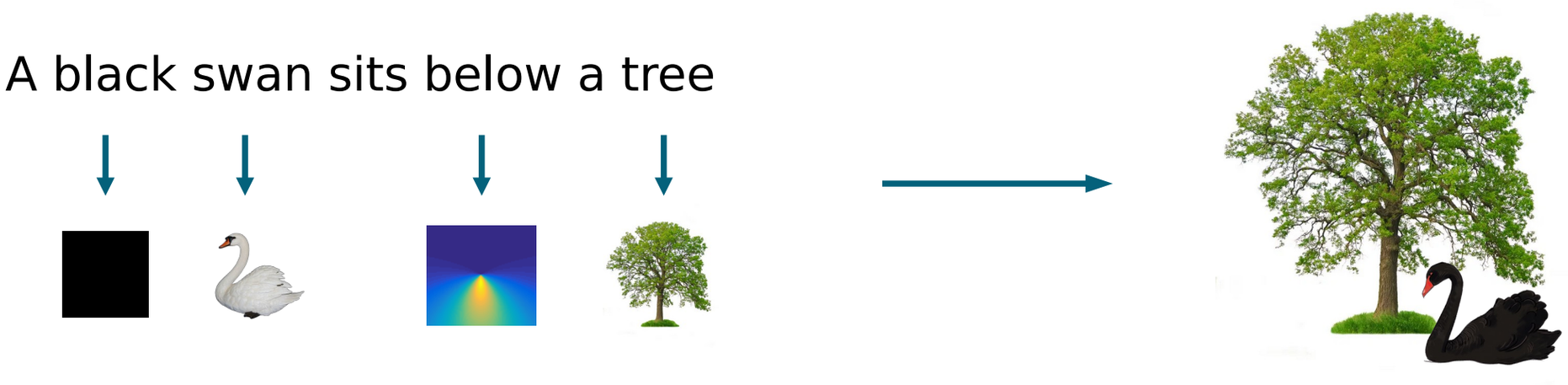
Productivity
(e.g., Chomsky, 1968; Fodor & Pylyshyn, 1988; Jackendoff, 2002)

- The ability to flexibly join “atomic“ linguistic units into “molecular“ linguistic units, and to join molecular linguistic units into more complex molecular linguistic units.
- Example:
  - “the house” “the lake”
    → “the house at the lake”,
  - “the big tree next to the house at the lake“
  - “the red ball moves towards the big tree next to the house at the lake”



Compositionality
(e.g., Frege, 1923; Fodor & Pylyshyn, 1988; Jackendoff, 2002)

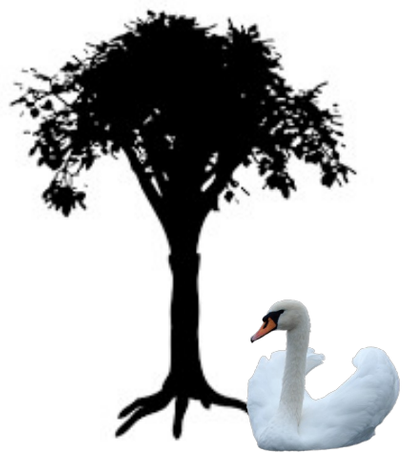
- Humans understand a phrase by
  - Understanding the meanings of the individual words (“concepts”)
  - Combining those concepts in accordance with how the words are arranged syntactically in the phrase



Compositionality

(e.g., Frege, 1923; Fodor & Pylyshyn, 1988; Jackendoff, 2002)

A black swan sits
below a tree

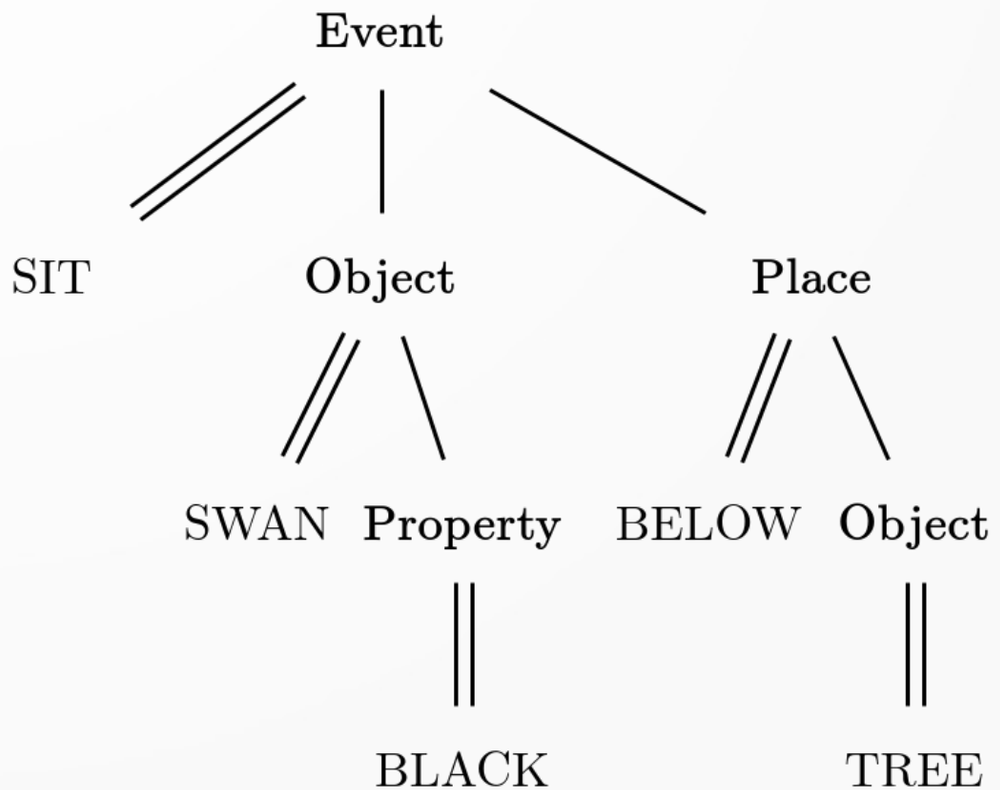


A swan sits
below a black tree

Same words,
different arrangement!

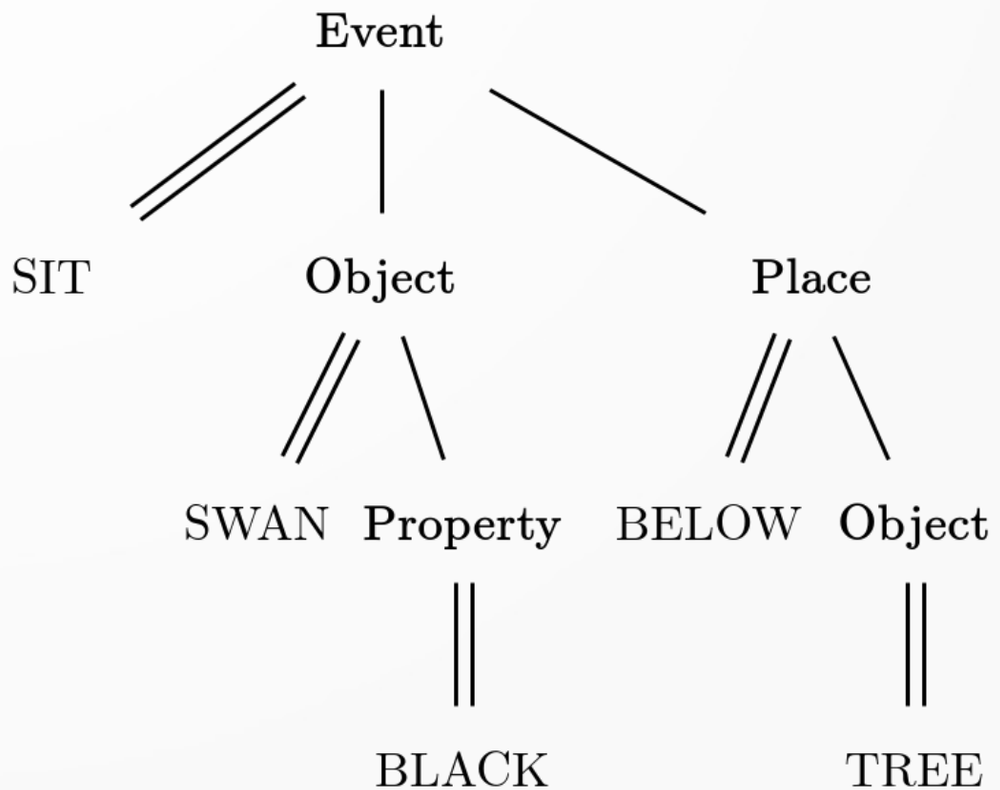
Conceptual structure

- The way that concepts need to be combined can be characterized as a **conceptual structure** (Jackendoff, 2002)
- e.g., “a black swan sits below a tree“



Conceptual structure

- The way that concepts need to be combined can be characterized as a **conceptual structure** (Jackendoff, 2002)
- e.g., “a black swan sits below a tree“
- Entities are **bound** to other entities



Conceptual structure

- As per the principle of compositionality, the processes underlying language grounding must combine concepts in accord with the conceptual structure

Conceptual structure

- Hypothesis (Jackendoff, 2002): Conceptual structure is explicity represented in the brain!

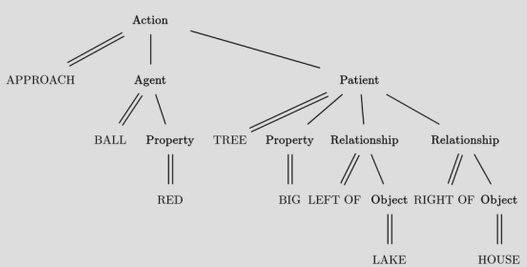
Our hypothesis

Language

“The red ball approaches the big tree, which is to the left of the lake and to the right of the house”

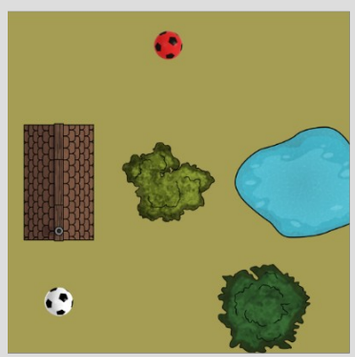
language processing

Neural representation of conceptual structure



Grounding (conceptual combination)

Scene



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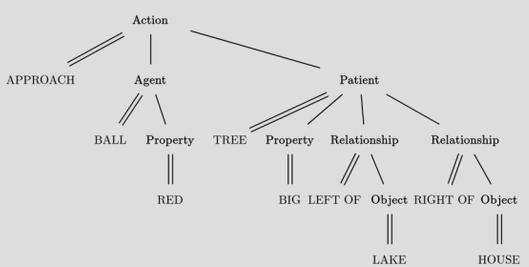
Neural representation of conceptual structure



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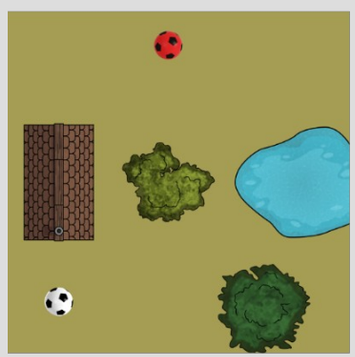


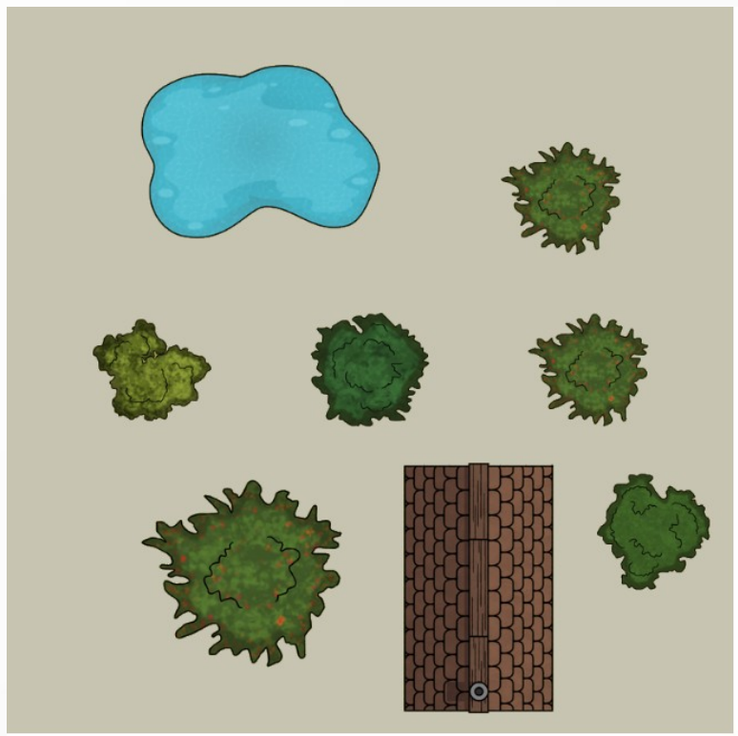
Arguments that this must be a short-term memory (Sabinasz & Schöner, 2022)

STM of conceptual structure

- How can a **structure** be represented in neural short-term memory?

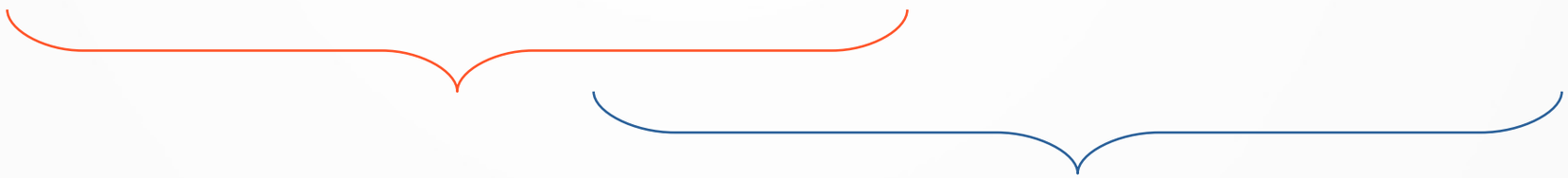
Case study: Nested noun phrases
(Sabinasz & Schöner, 2022)

- the tree below the lake
- the tree to the right of
  the tree below the lake
- the tree below the lake
  and above the house



Jackendoff's challenges
(Jackendoff, 2002)

- The massiveness of the binding problem:
  e.g., "the lake above the tree above the house"

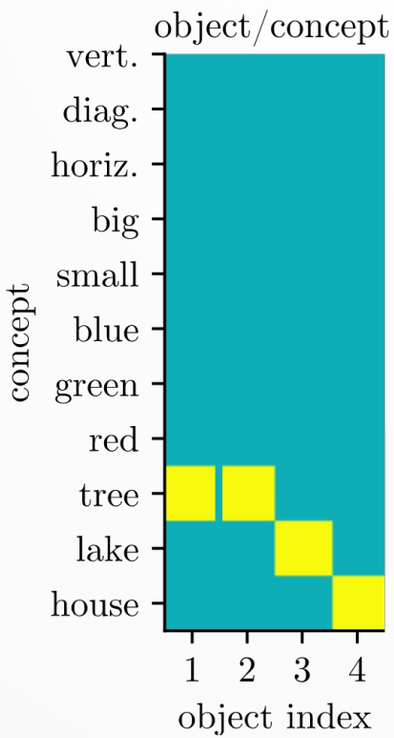


- The problem of 2:
  e.g., "the small tree above the big tree"

Binding through index
(Sabinasz & Schöner, 2022)

- Embed each mentioned object into a discrete index dimension
  - “the tree $_1$ right of the tree $_2$ below the lake $_3$ and above the house $_4$”
- Enable binding objects to concepts

Binding through index
(Sabinasz & Schöner, 2022)



Analogous to binding through space
(Treisman & Gelade, 1980)

Discrete neural field

$$\tau \dot{u}(x,t) = -u(x,t) + h + s(x,t) + c_{\text{exc}} \cdot \sigma(u(x,t)) - \sum_{x' \neq x} c_{\text{inh}} \cdot \sigma(u(x',t))$$

Binding through index
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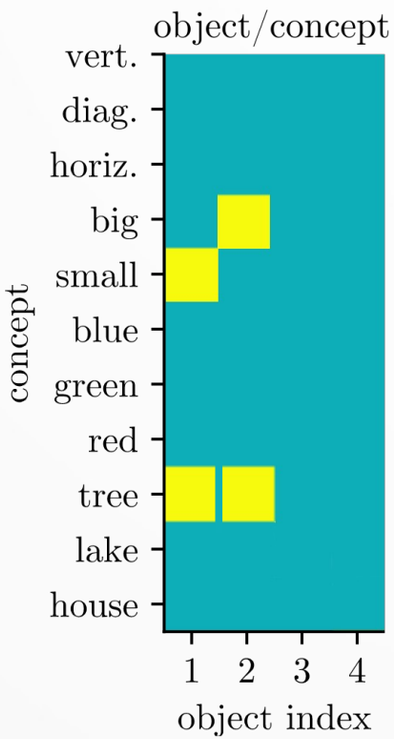

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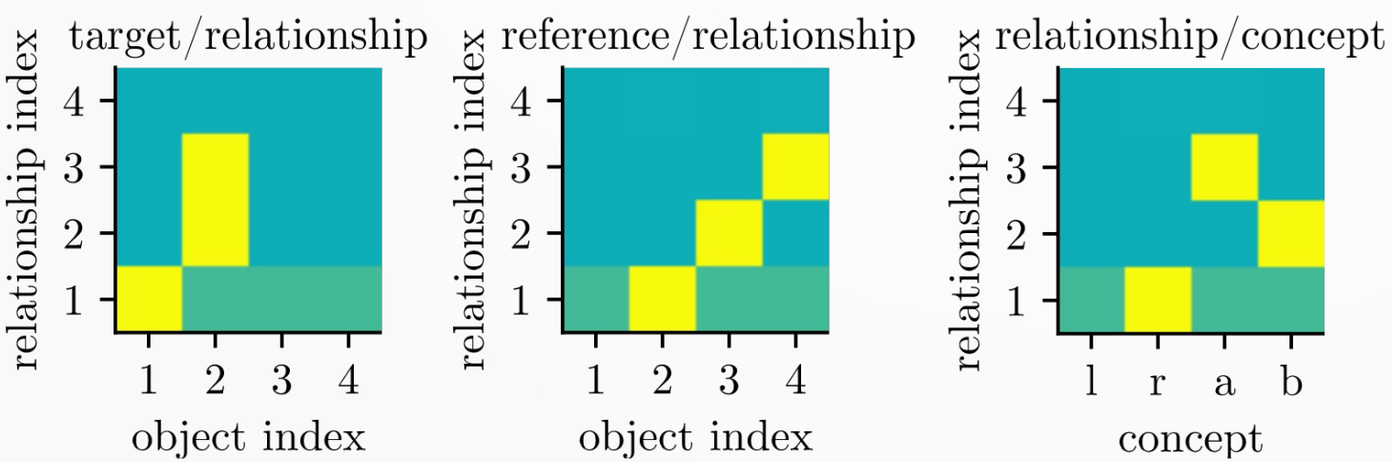
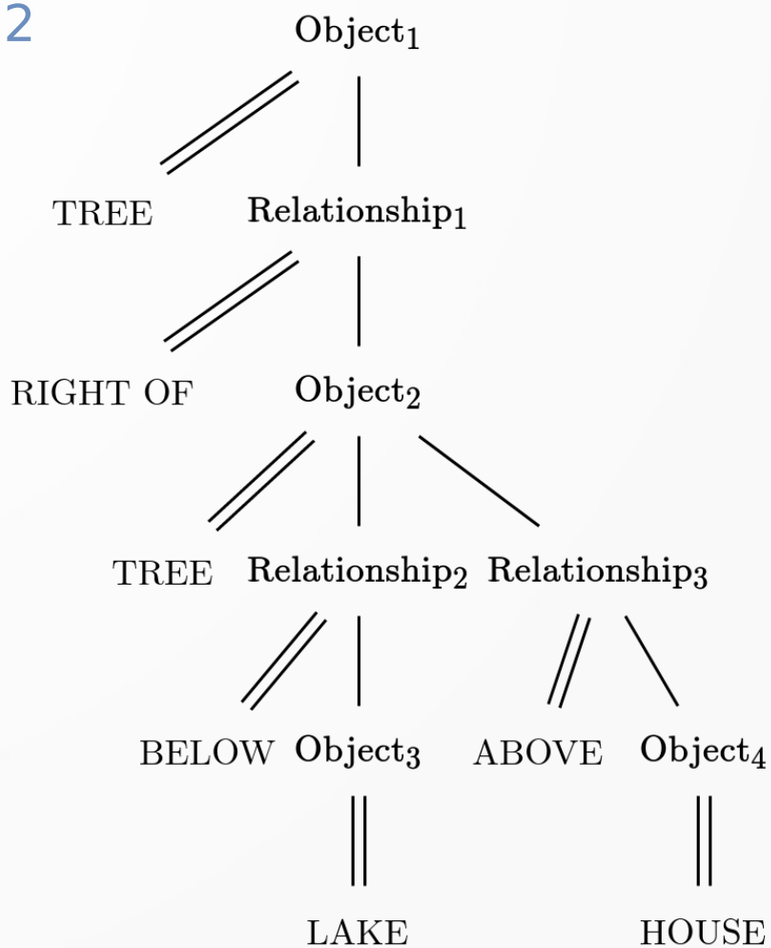
Binding through index
(Sabinasz & Schöner, 2022)

- Embed each mentioned relationship into a discrete index dimension
  - “the tree right of 1 the tree below 2 the lake and above 3 the house”
- Enable binding objects to relationships in particular roles

STM of conceptual structure

"the tree 1 to the right of 1 the tree 2 which is below 2 the lake 3 and above 3 the house 4"





Grounding conceptual structure

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- Not all of the object descriptions can simultaneously have an effect on grounding processes due to limited attentional capacities

Grounding conceptual structure

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- Only one relationship description can be verified at a time (Logan, 1994; Franconeri, 2012)

Conclusion

- Presented neural dynamic process model that can perceptually ground a nested noun phrase
- Consistent with neural principles formalized in DFT
- STM of conceptual structure
  - Filled by language system
  - Provides input to neural process that generates a sequence of searches that together successfully and efficiently find the described object
- The model exhibits productivity and compositionality

Thanks for your attention!

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