Semantic Theory
Week 11 – Incremental Meaning Construction

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Distributional Formal Semantics

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FROM MODELS TO MEANING SPACE

$M_1 = \langle U_1, V_1 \rangle$

$p_1 \wedge \neg p_2 \wedge p_3 \wedge \ldots$

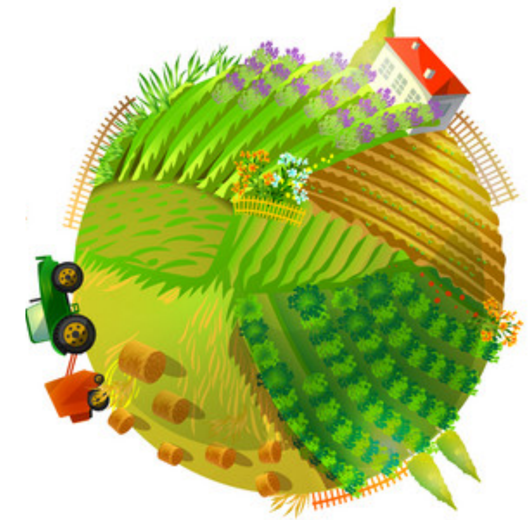
$M_2 = \langle U_2, V_2 \rangle$

$\neg p_1 \wedge p_2 \wedge p_3 \wedge \ldots$

$M_3 = \langle U_3, V_3 \rangle$

$\neg p_1 \wedge p_2 \wedge \neg p_3 \wedge \ldots$

…



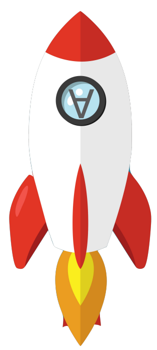
$M_n = \langle U_n, V_n \rangle$

$\neg p_1 \wedge \neg p_2 \wedge \neg p_3 \wedge \ldots$

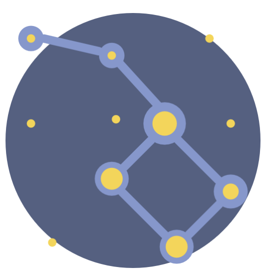
- The set of models $\mathcal{M}_{\mathcal{P}}$ — describing states-of-affairs over propositions in $\mathcal{P}$ — defines a meaning space
- Propositional meaning defined by co-occurrence across models

Venhuizen, Hendriks, Crocker, Brouwer (2019, WoLLIC; 2022, Inf. Comp)

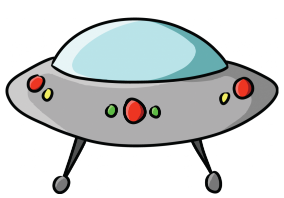
A FRAMEWORK FOR DISTRIBUTIONAL FORMAL SEMANTICS



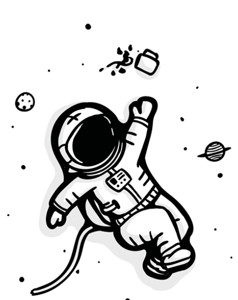
A meaning space for Distributional Formal Semantics



Formal properties of the meaning space

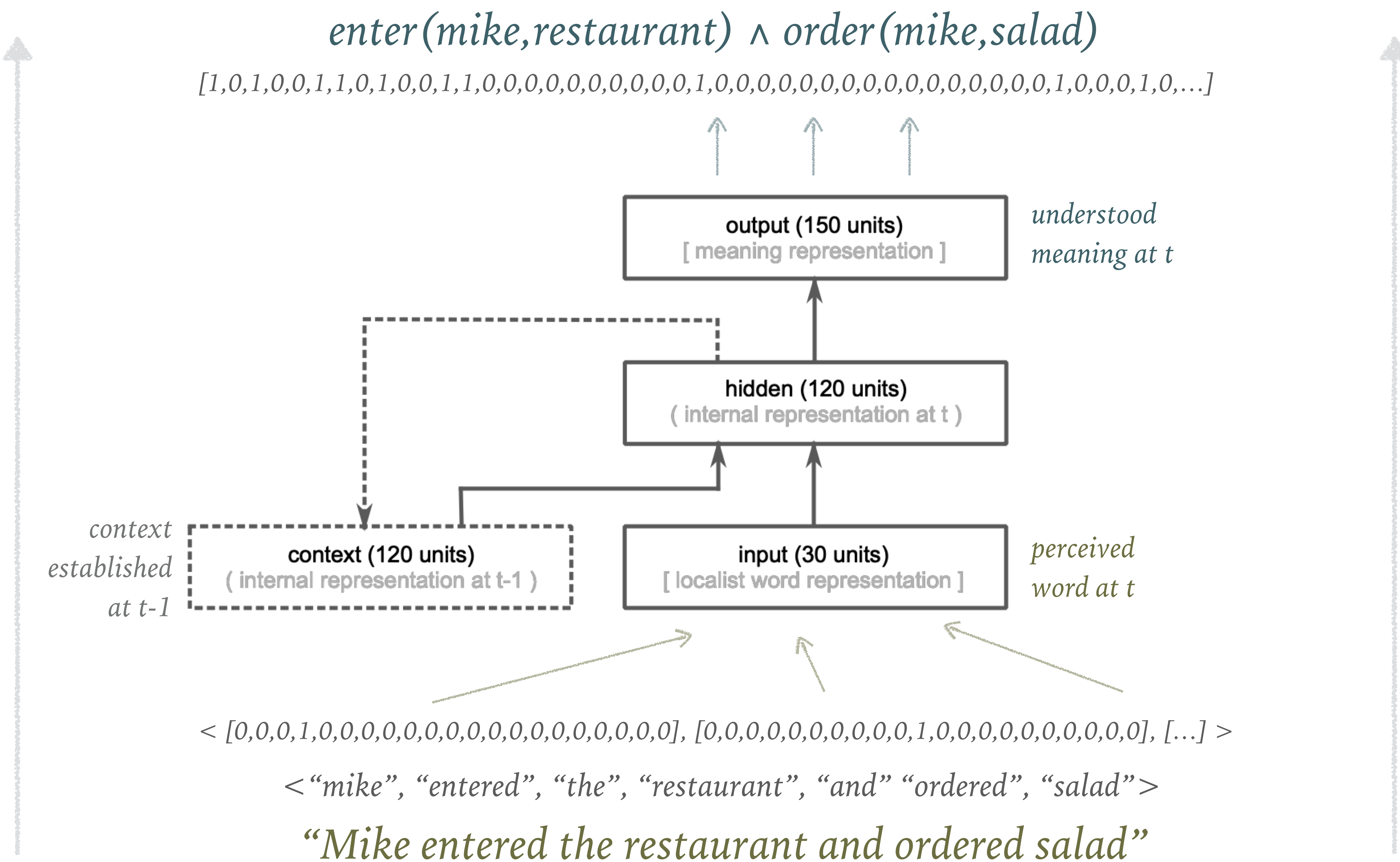


Incremental meaning construction

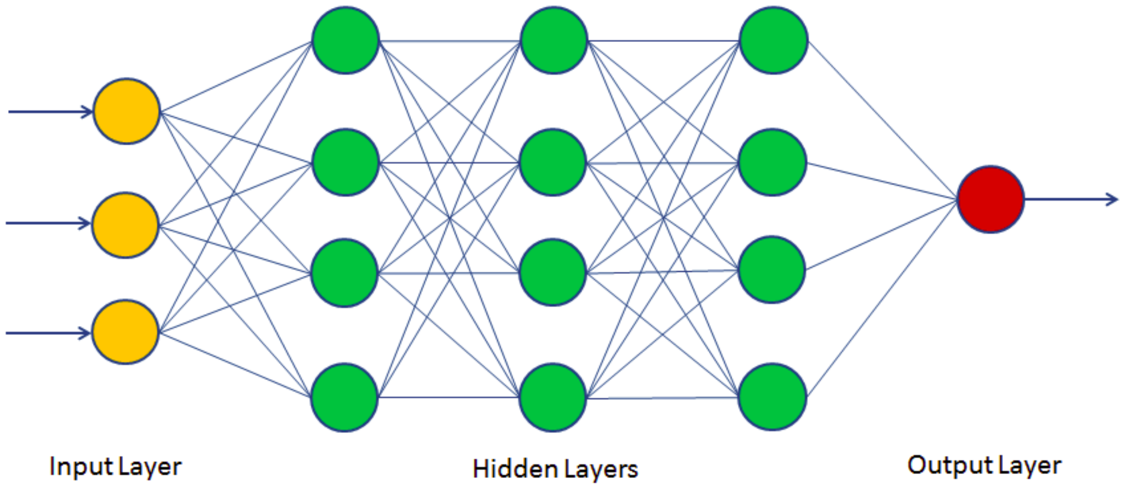


Semantic processing in the meaning space

A MODEL OF INCREMENTAL MEANING CONSTRUCTION



A PRIMER ON NEURAL NETWORKS



Biological Neurons

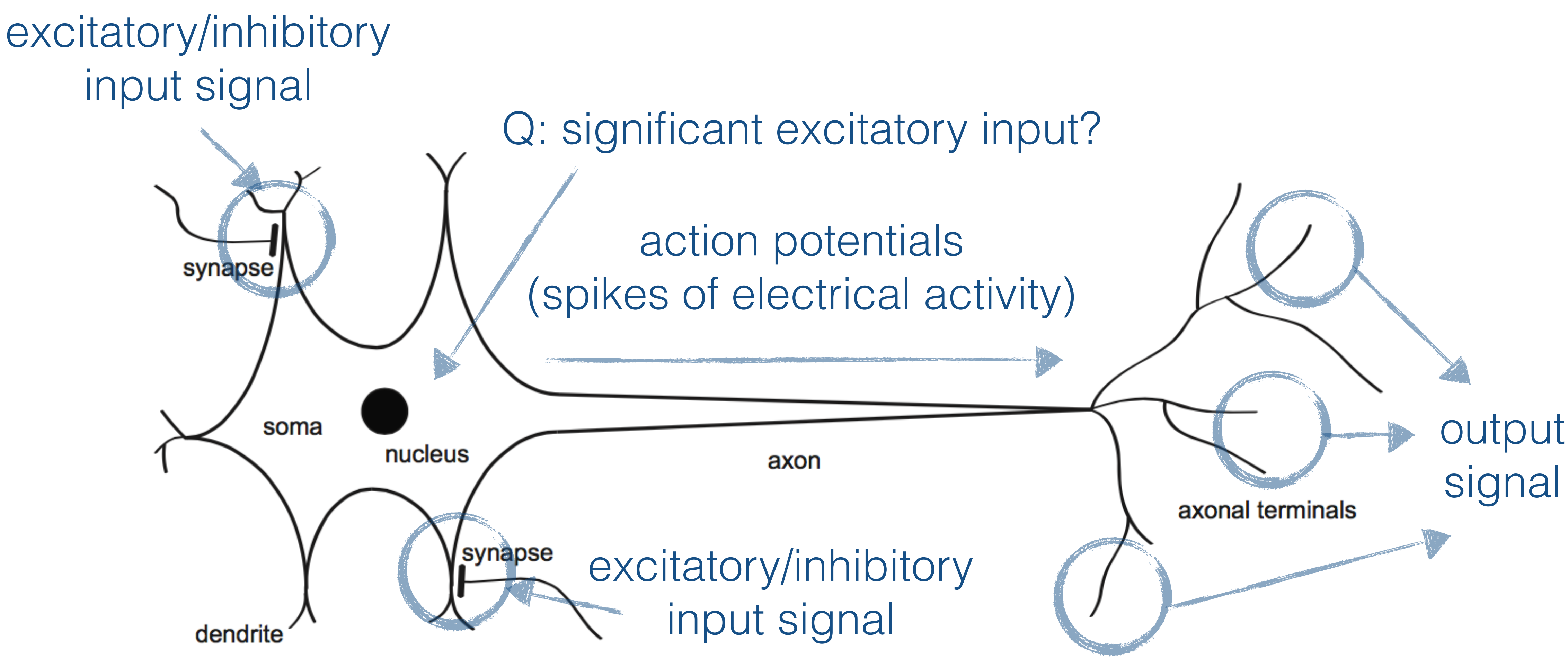


Figure A.1 | *Schematic overview of a biological neuron (or nerve cell).*

> synapses transform action potentials into an excitatory or inhibitory chemical signal

Artificial "Model" Neurons

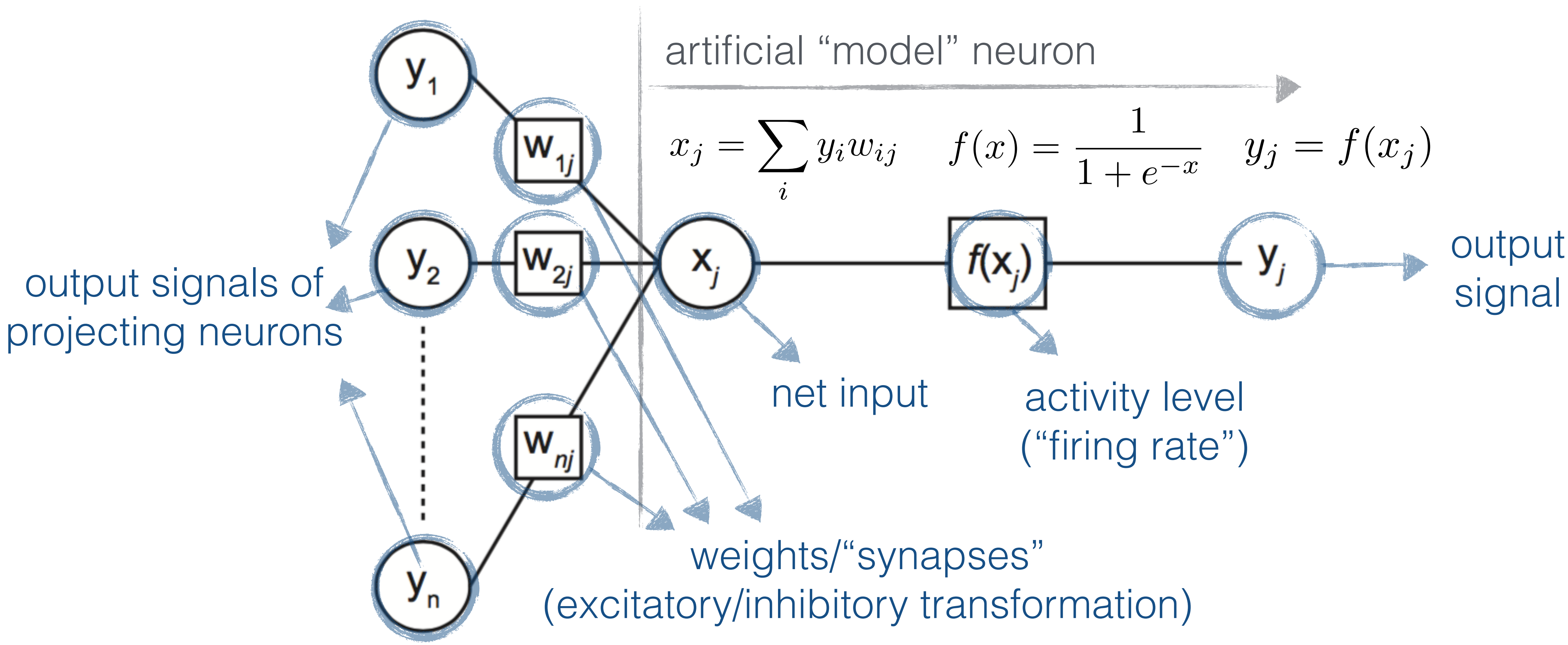


Figure A.2 | *Schematic overview of a unit (or model neuron). The activation level of the unit is a non-linear combination of its net input. The unit's net input, in turn, is the weighted sum of the activation levels of all units that signal to this unit.*

Artificial Neural Networks

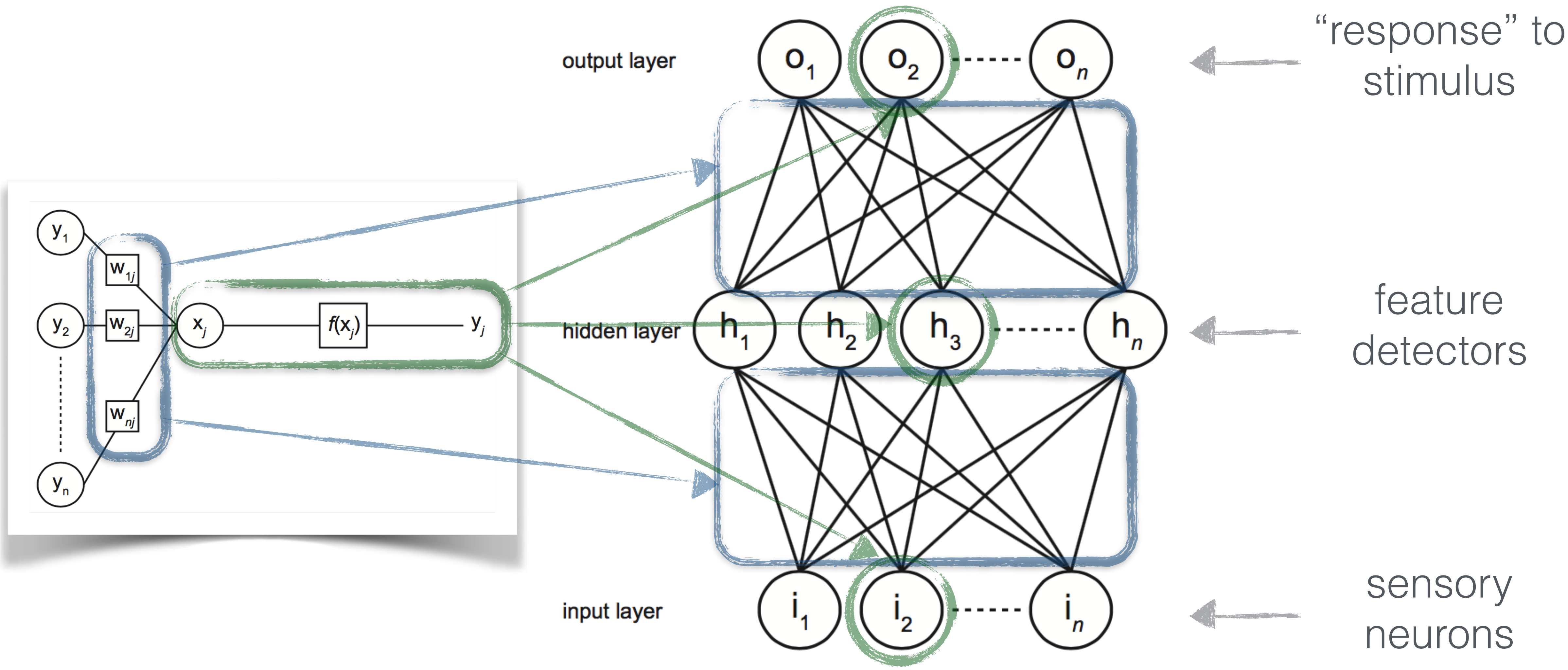


Figure A.3 | *A Feed Forward neural Network (FFN). Units in successive layers are fully connected, whereas units within layers are not.*

Recurrence—Modeling Memory

Q: What about **temporally extended stimuli** (e.g., sentences)?

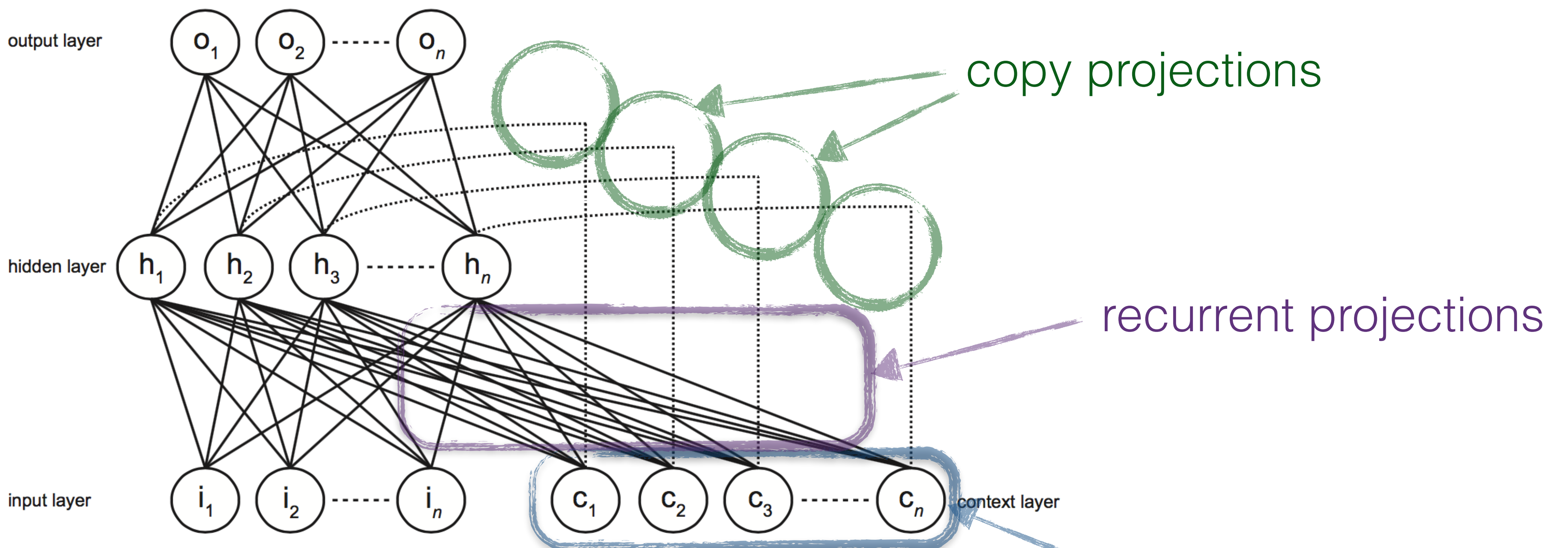


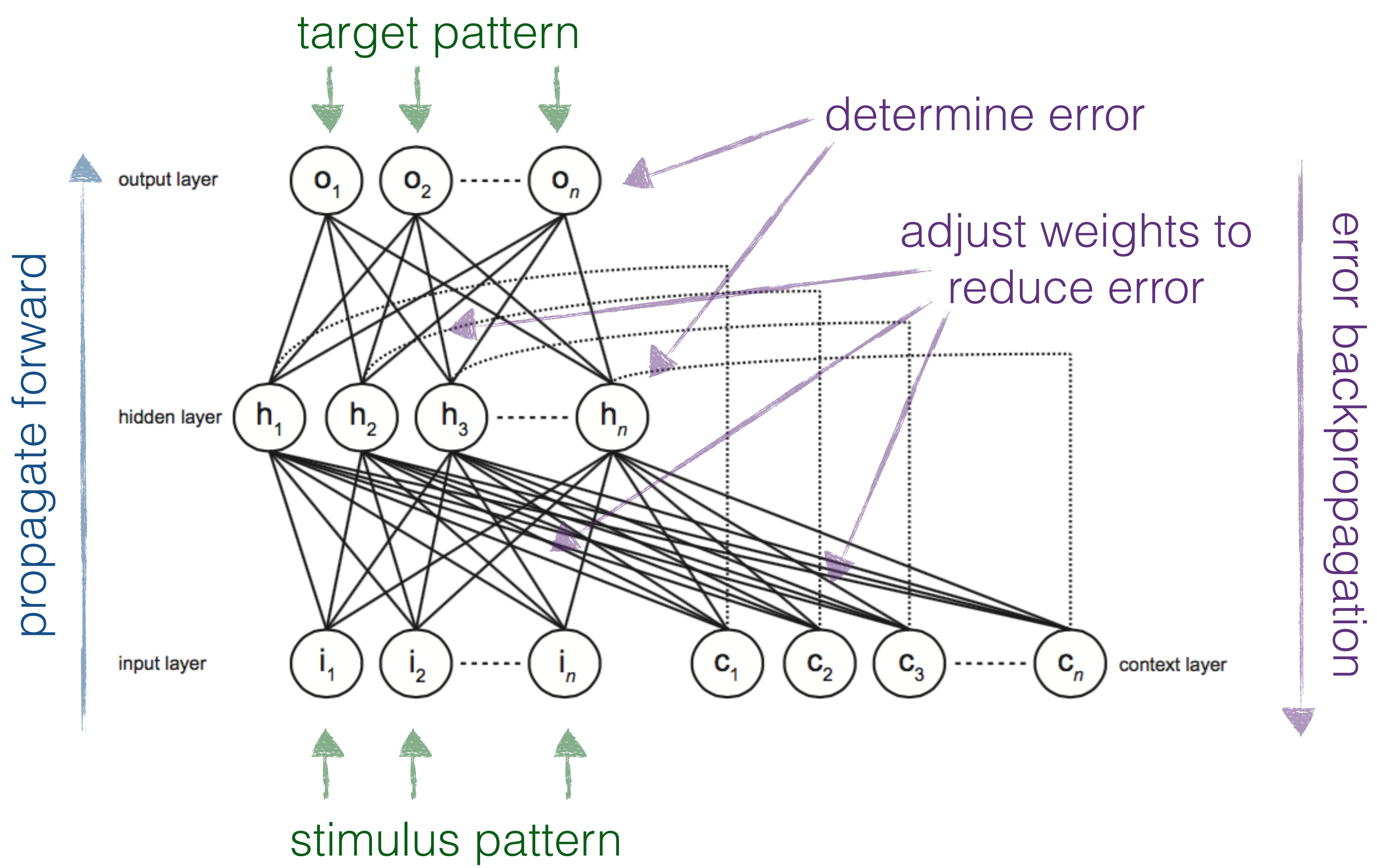
Figure A.5 | *A Simple Recurrent Network (SRN). Before being updated, the activation values of the units in the hidden layer are copied to their corresponding unit in the context layer (the fine dotted lines represent copy connections).*

> a **Simple Recurrent Network (SRN)** is a very powerful tool for cognitive modeling

Elman (1990), *Cogn. Sci.*

Learning in Neural Networks

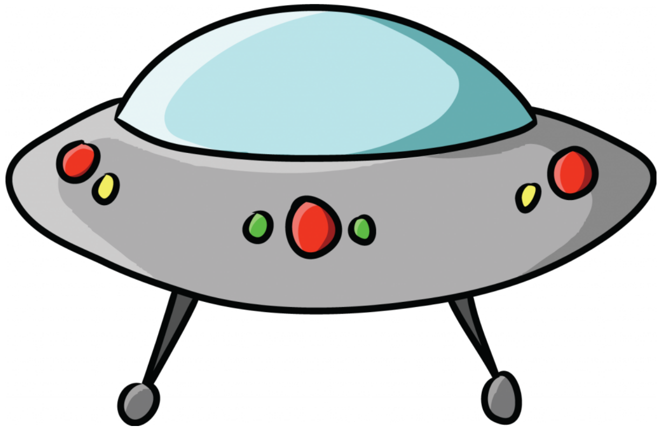
> Neural Networks learn from experience (**training**)



> challenge in neural network modeling is to **minimize error** for a set of stimuli

Rumelhart et al. (1986), *Nature*

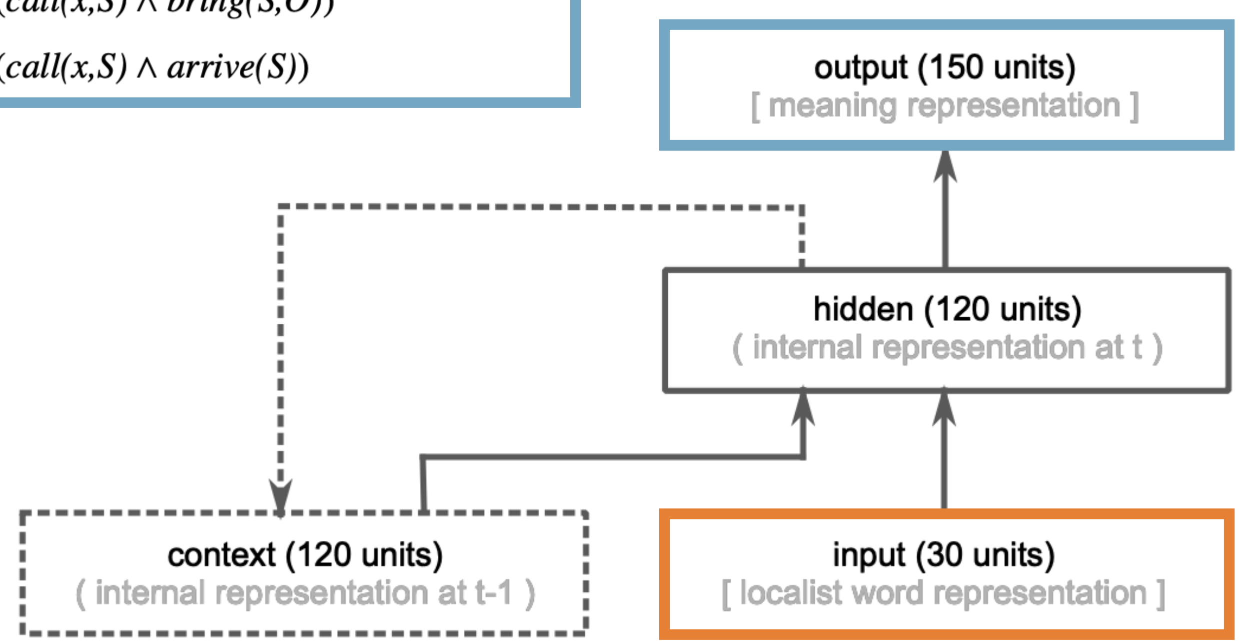
INCREMENTAL MEANING CONSTRUCTION



CONSTRUCTING THE MODEL: LANGUAGE

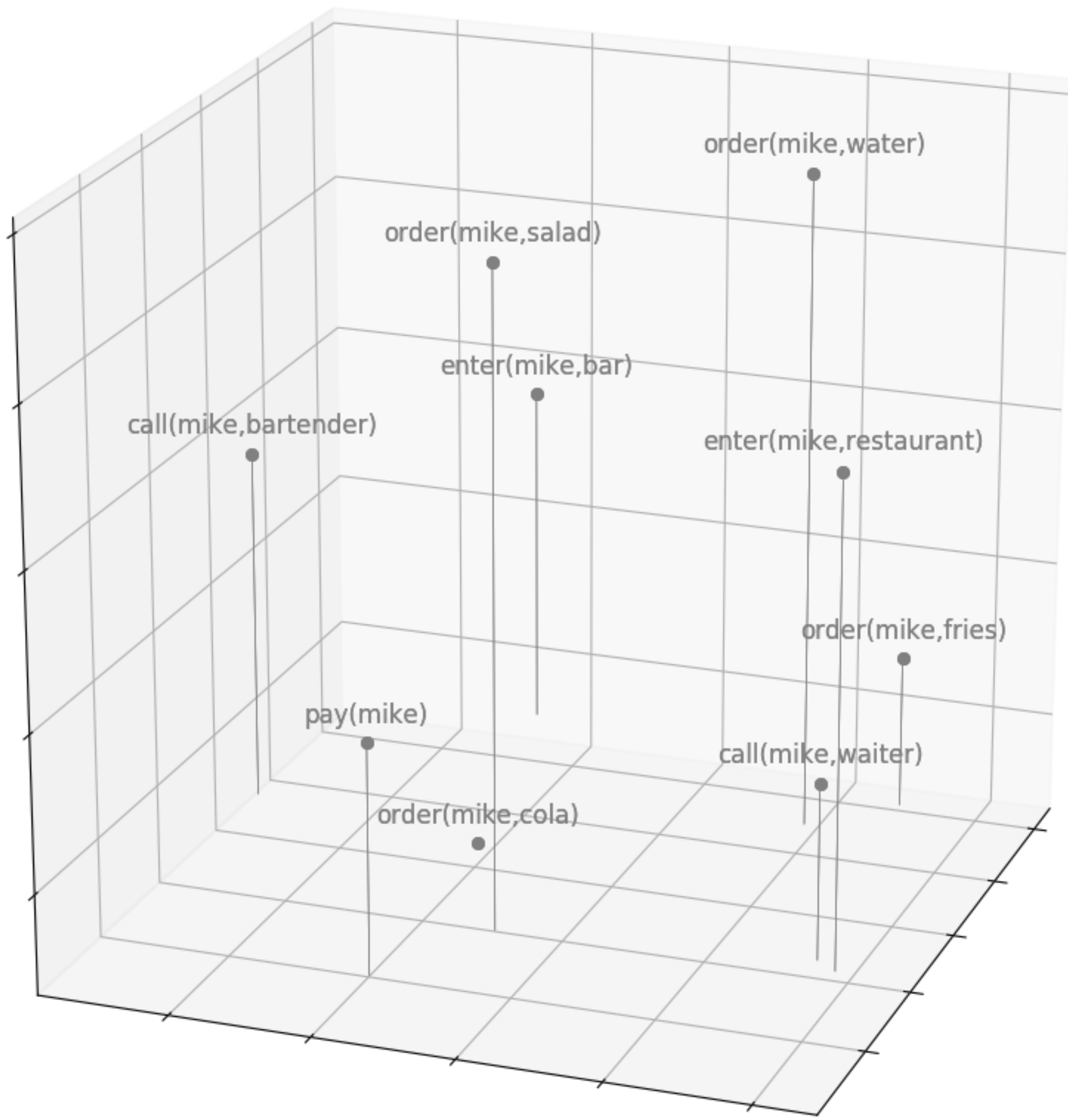
Utterance$_{[a/b]}$
P [entered/didn't enter] a *L*
P [entered/didn't enter] the *L*
P [called/didn't call] the *S*
P [ordered/didn't order] *O*
P [paid/didn't pay]
the *S* [arrived/didn't arrive]
the *S* [brought/didn't bring] *O*
[*P*/someone] entered the *L* he/she ordered *O*
[*P*/someone] entered the *L* he/she called the *S*
[*P*/someone] called the *S* he/she ordered *O*
[*P*/someone] called the *S* he/she paid
[*P*/someone] called the *S* he brought *O*
[*P*/someone] called the *S* he arrived

Semantics$_a$	Semantics$_b$
$enter(P,L)$	$\neg(enter(P,L)) \wedge referent(P)$
$enter(P,L)$	$\neg(enter(P,L)) \wedge referent(P) \wedge referent(L)$
$call(P,S)$	$\neg(call(P,S)) \wedge referent(P) \wedge referent(S)$
$order(P,O)$	$\neg(order(P,O)) \wedge referent(P)$
$pay(P)$	$\neg(pay(P)) \wedge referent(P)$
$arrive(S)$	$\neg(arrive(S)) \wedge referent(S)$
$bring(S,O)$	$\neg(bring(S,O)) \wedge referent(S)$
$enter(P,L) \wedge order(P,O)$	$\exists x_{m/f}(enter(x,L) \wedge order(x,O))$
$enter(P,L) \wedge call(P,S)$	$\exists x_{m/f}(enter(x,L) \wedge call(x,S))$
$call(P,S) \wedge order(P,O)$	$\exists x_{m/f}(call(x,S) \wedge order(x,O))$
$call(P,S) \wedge pay(P)$	$\exists x_{m/f}(call(x,S) \wedge pay(x))$
$call(P,S) \wedge bring(S,O)$	$\exists x(call(x,S) \wedge bring(S,O))$
$call(P,S) \wedge arrive(S)$	$\exists x(call(x,S) \wedge arrive(S))$



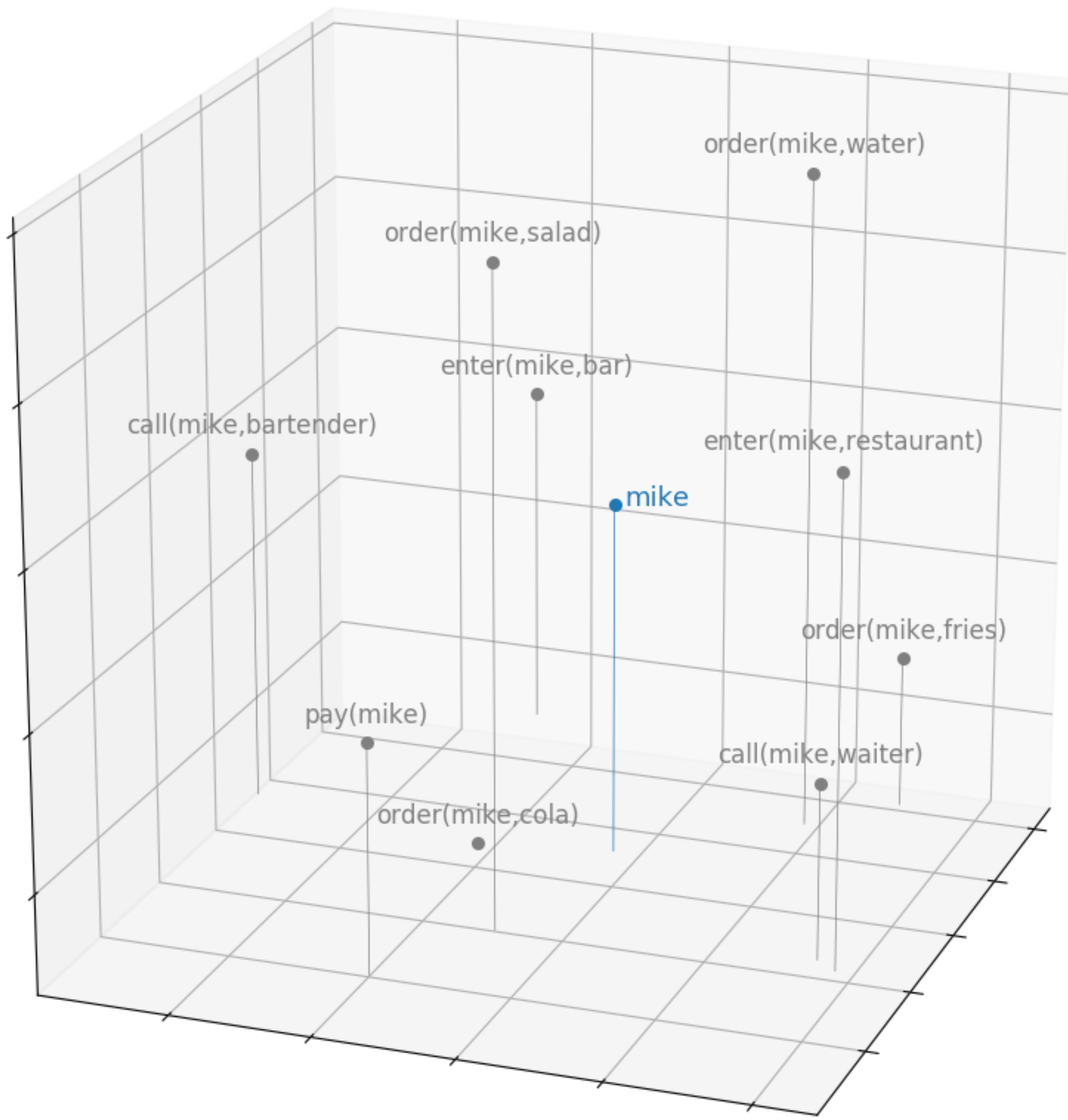
Venhuizen, Hendriks, Crocker, Brouwer (2019, WoLLIC; 2022, Inf. Comp)

MEANING SPACE NAVIGATION



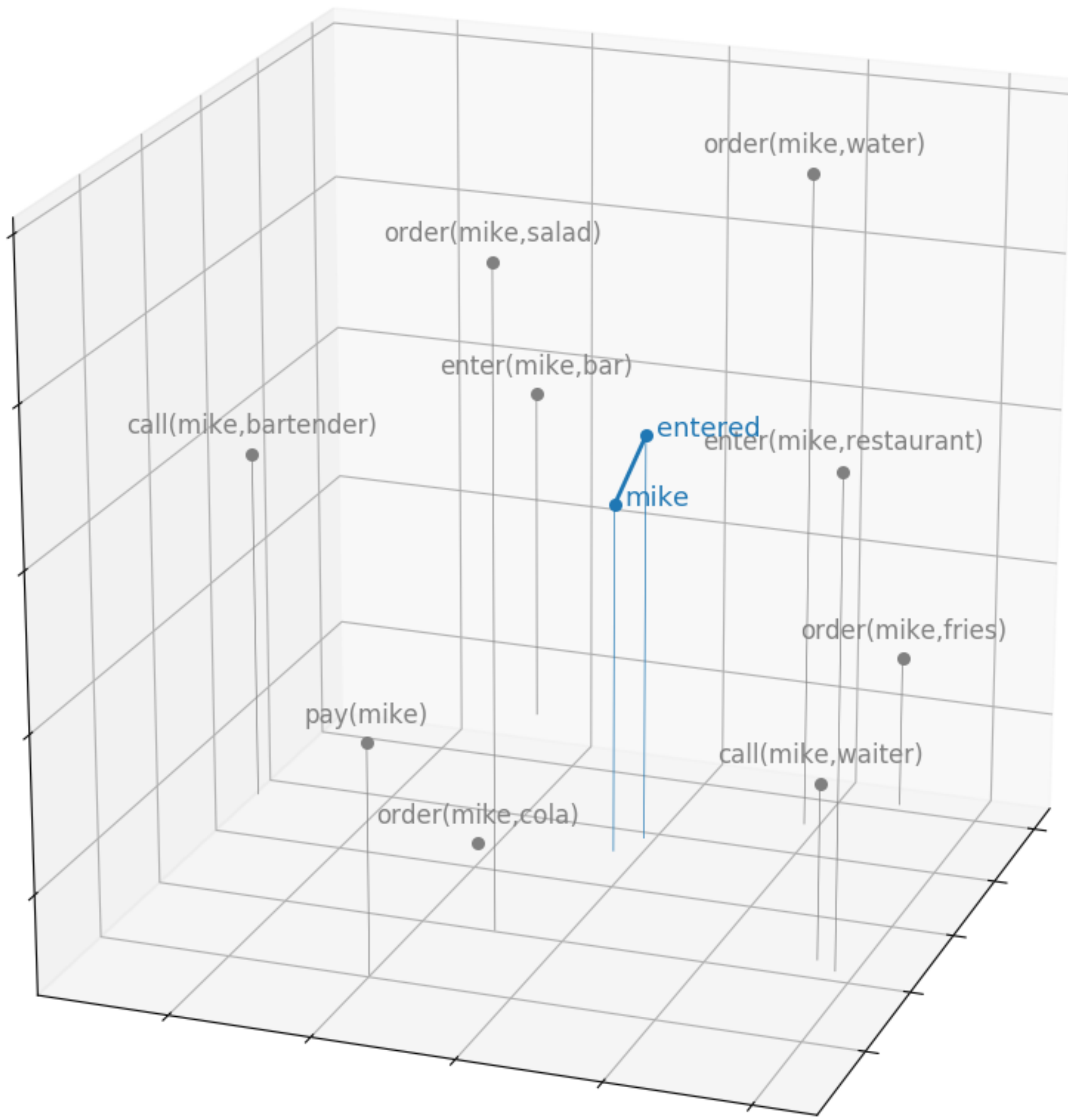
- Propositions that co-occur frequently in $\mathcal{M}$ are positioned close to each other in space

MEANING SPACE NAVIGATION



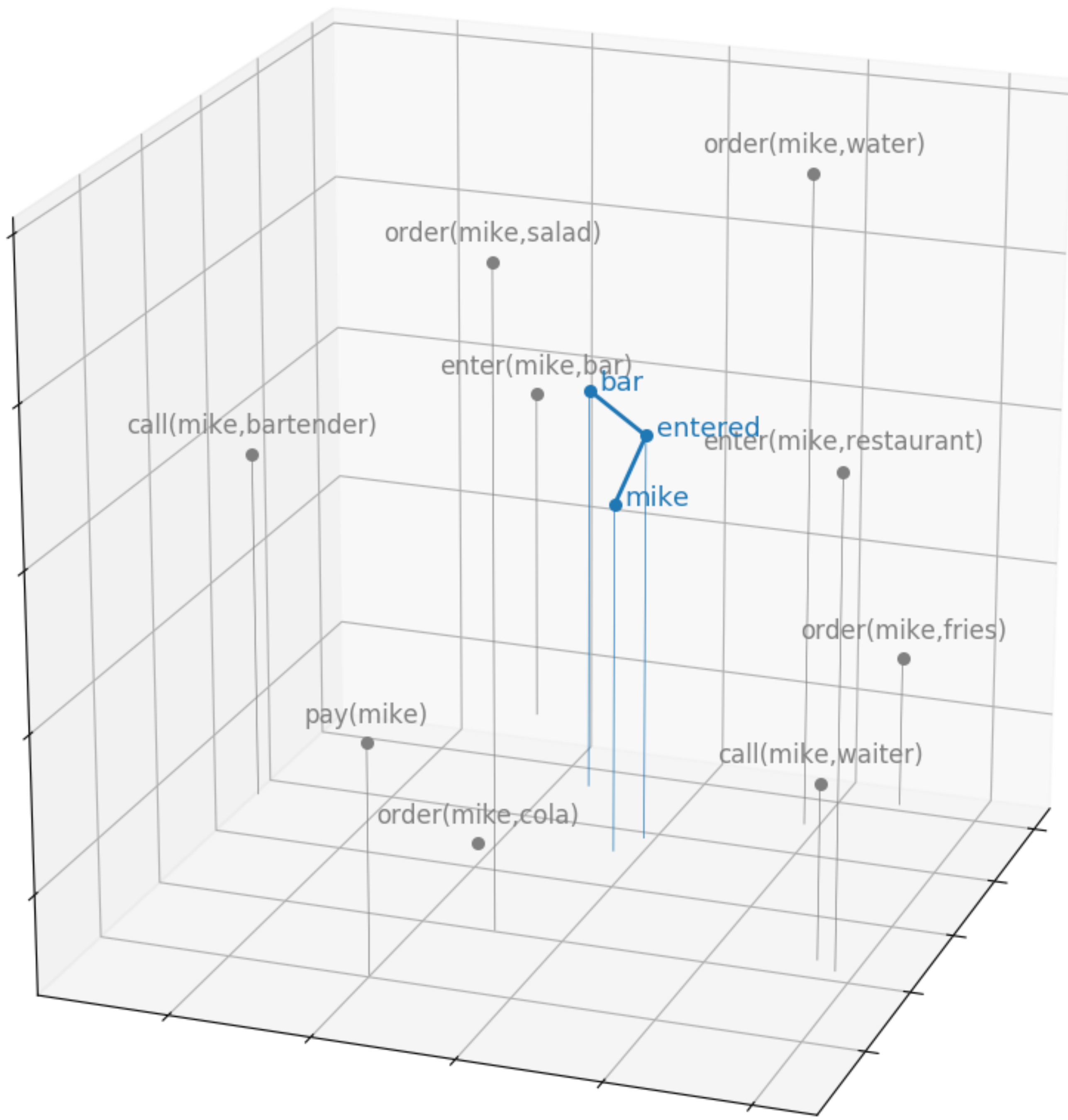
- Model-derived meaning of ‘*mike*’ abstracts over the meanings of all propositions pertaining to *mike*

MEANING SPACE NAVIGATION



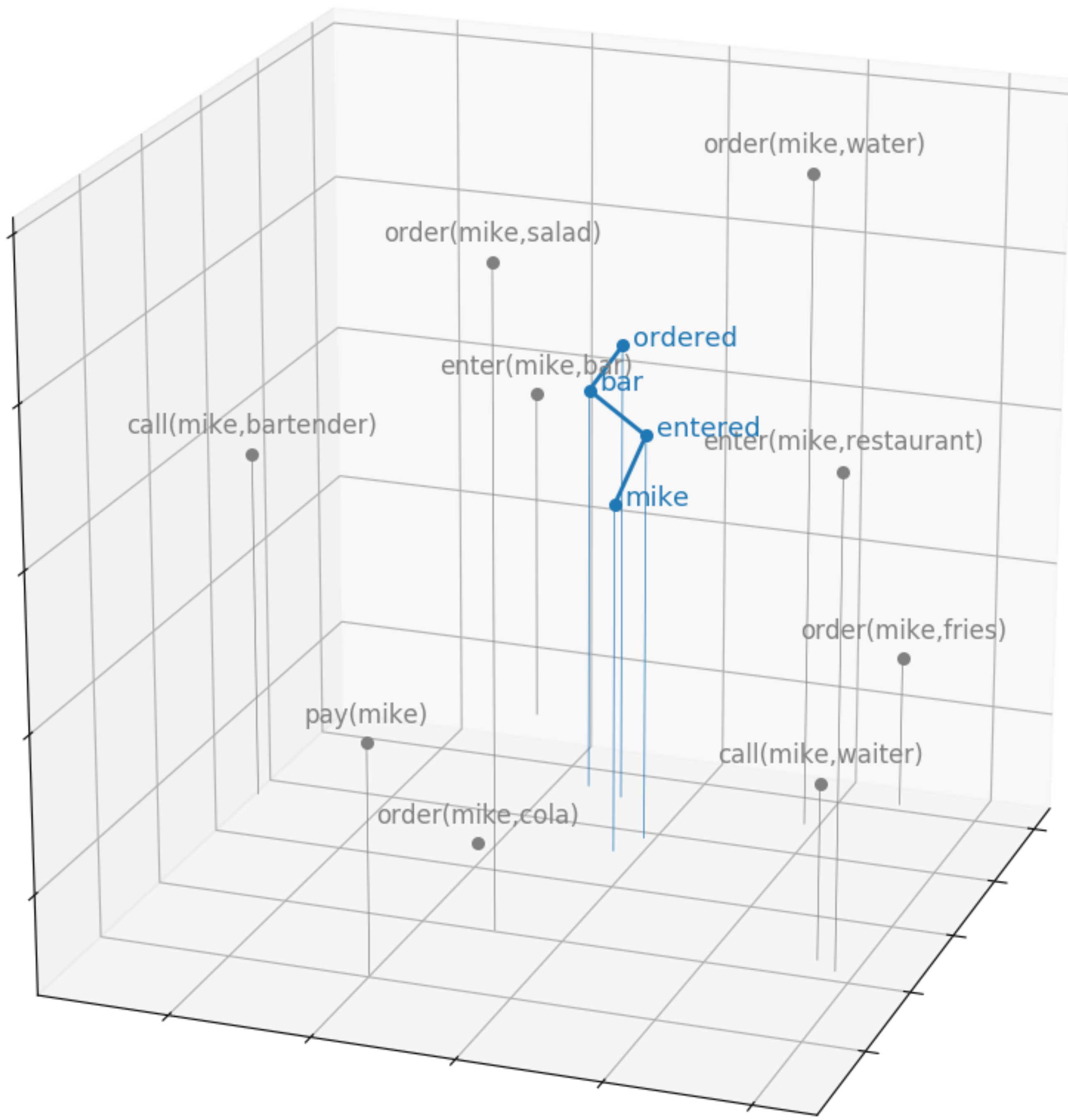
- At the word "entered", the model navigates to a point that represents the contextualised meaning "mike entered"

MEANING SPACE NAVIGATION



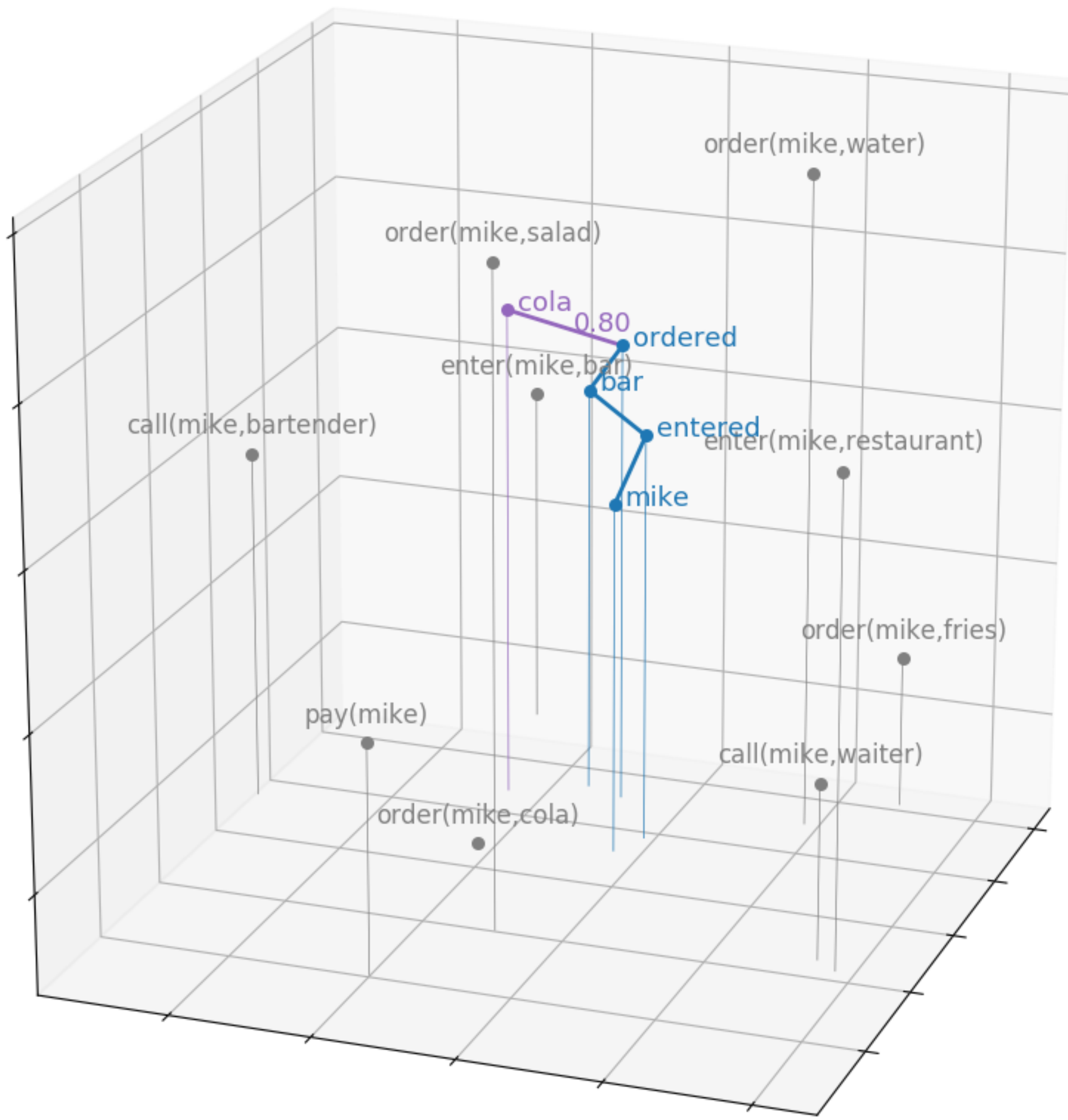
- The utterance "*mike entered the bar*" approximates the propositional meaning vector for *enter(mike,bar)*

MEANING SPACE NAVIGATION



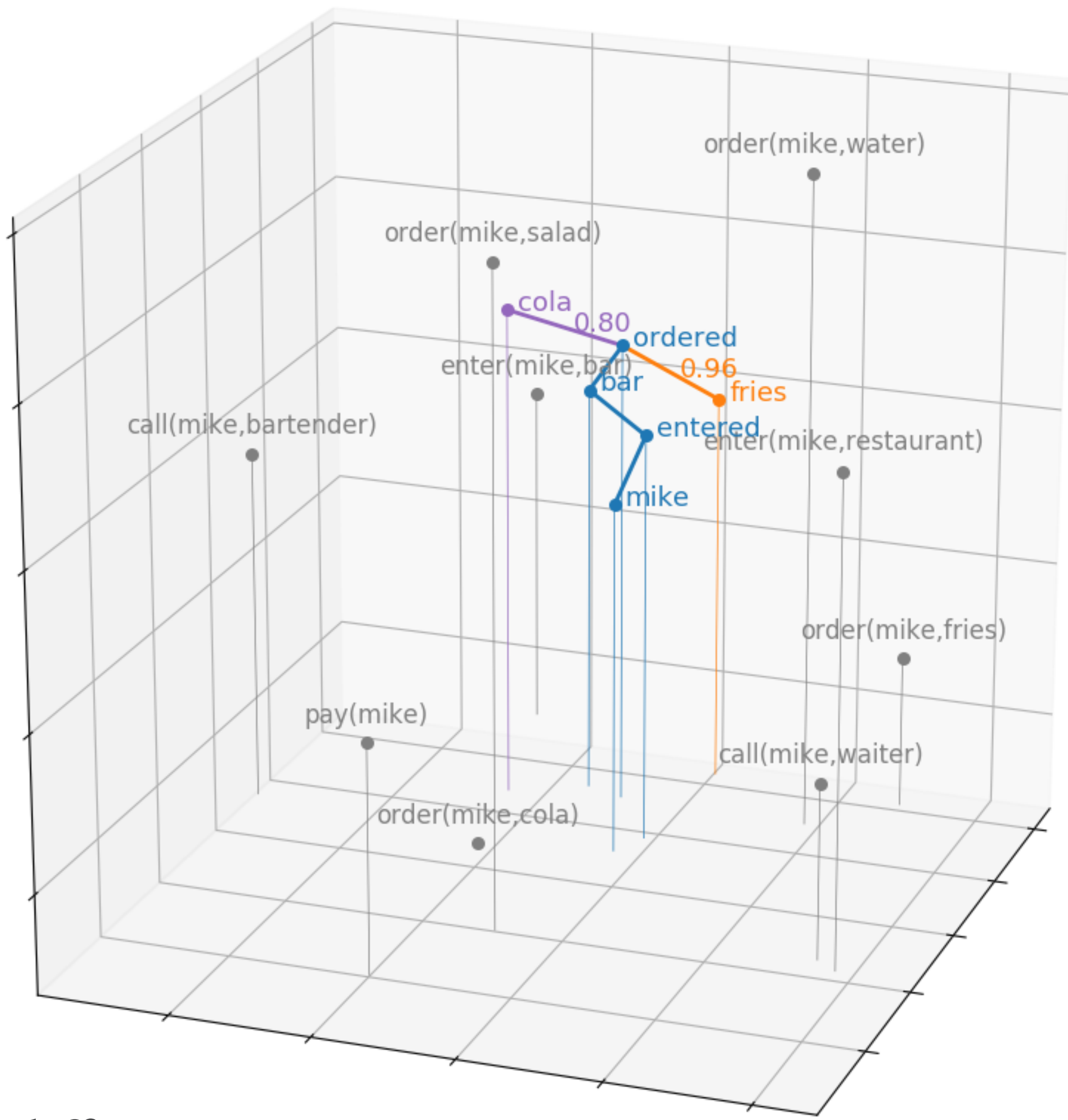
- The meaning vector after processing *"mike entered the bar [.] he ordered"* is close to *order* propositions that are typical given *enter(mike,bar)*

MEANING SPACE NAVIGATION



- When the utterance is continued with *"cola"*, the model approximates the conjunctive meaning vector *enter(mike,bar)* ∧ *order(mike,cola)*

MEANING SPACE NAVIGATION



- *“fries”* results in different transition in meaning space, approximating the conjunctive meaning *enter(mike,bar)* ∧ *order(mike,fries)*—but is **less expected** after “*mike entered the bar [.] he ordered*”

INFORMATION THEORY IN DFS

Probabilistic nature of meaning space allows for defining formal notion of information (Shannon, 1948)

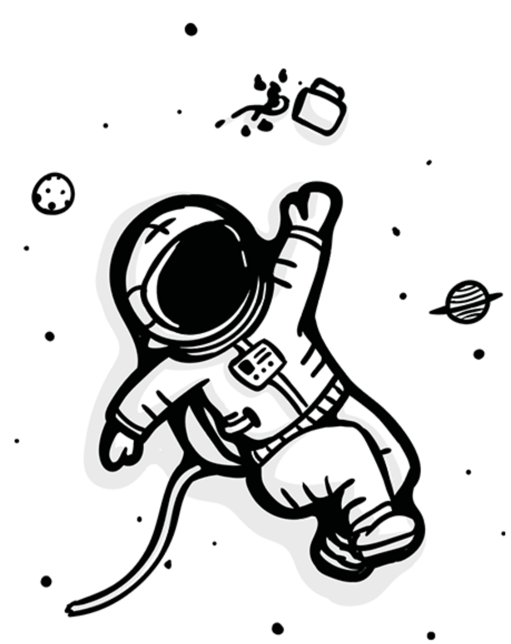
- **Surprisal** quantifies the expectancy of words in context
- Higher Surprisal ⇔ increased processing cost (Hale, 2001; Levy, 2008)
- In DFS, Surprisal quantifies expectancy of transition in meaning space, triggered by message m_{ab}:

$$S(m_{ab}) = -\log P(b|a)$$

➡ Word-by-word information effects of semantic constructions

Venhuizen, Crocker, Brouwer (2019, Discourse Proc; 2019, Entropy)

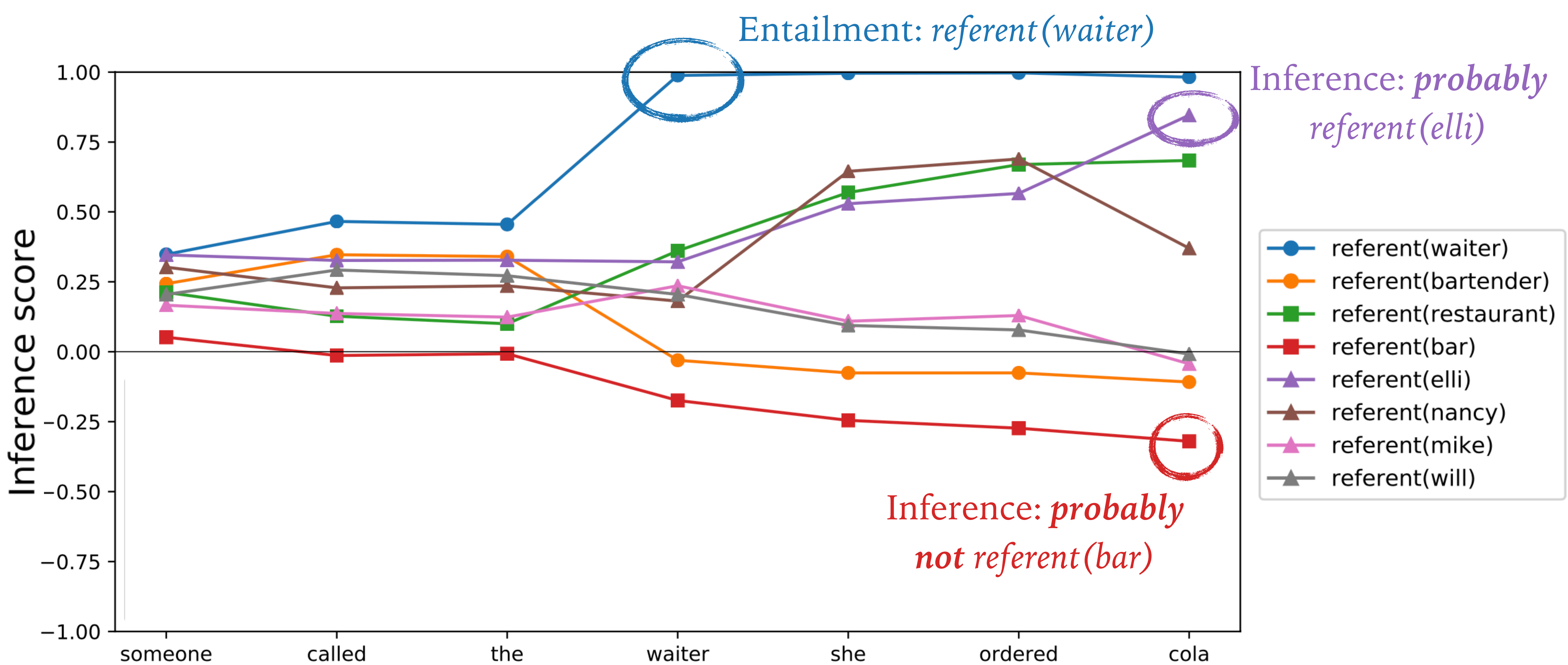
SEMANTIC PROCESSING IN THE MEANING SPACE



ENTAILMENT AND INFERENCE

Incremental meaning construction in the model is driven by:

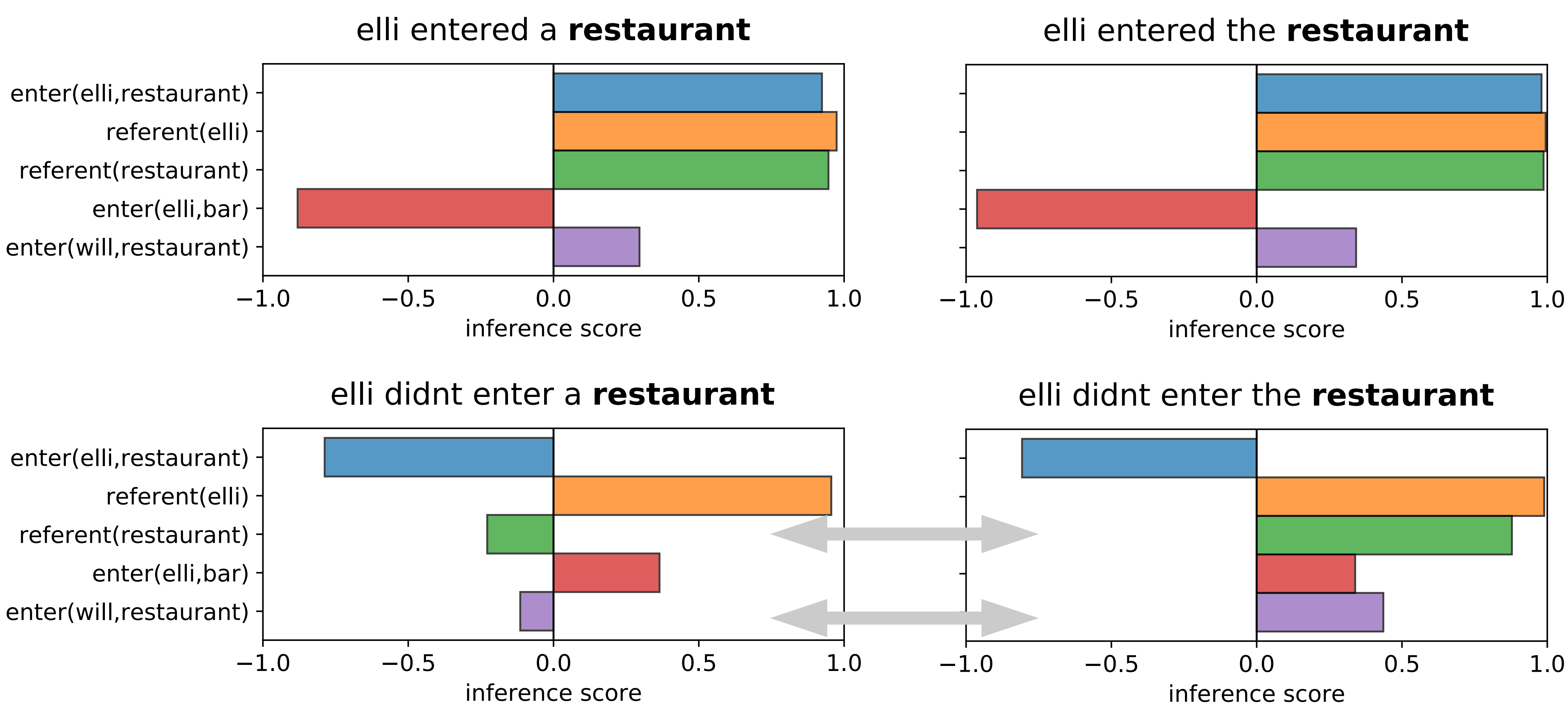
- ➤ Sentence-semantics mappings (literal utterance meaning)
- ➤ Structure of the meaning space (probabilistic inferences)



Venhuizen, Hendriks, Crocker, Brouwer (2022, Inf. Comp)

NEGATION AND PRESUPPOSITION

- Negation affects entailments and probabilistic inferences
- Interaction between negation and presupposition (triggered by *"the"*)
  - Presupposition has an effect beyond the literal meaning

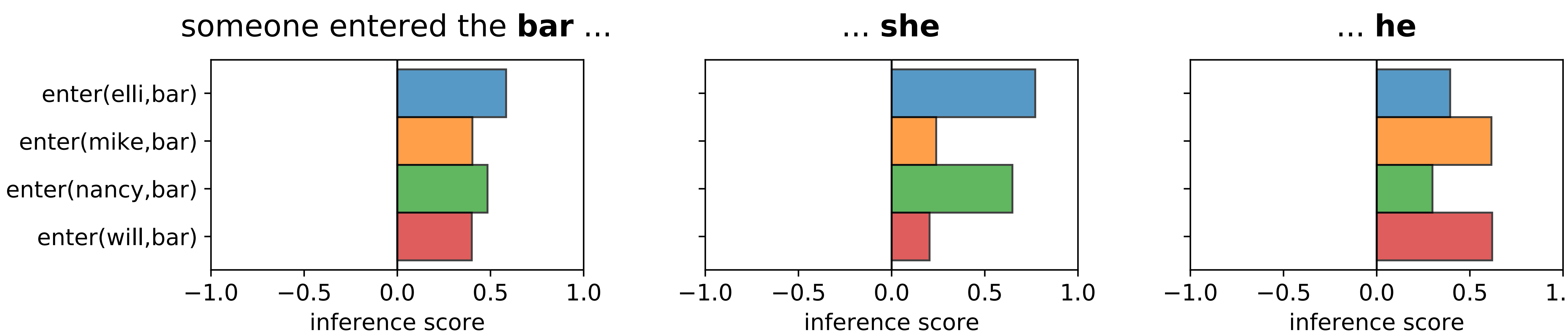


Venhuizen, Hendriks, Crocker, Brouwer (2022, Inf. Comp)

QUANTIFICATION AND REFERENCE

Quantified expressions induce inferential uncertainty

- ➤ Selective expressions (e.g. pronouns) can reduce this uncertainty
- ➤ Confirming initial expectations results in reduced Surprisal



$S(she) = 0.92$

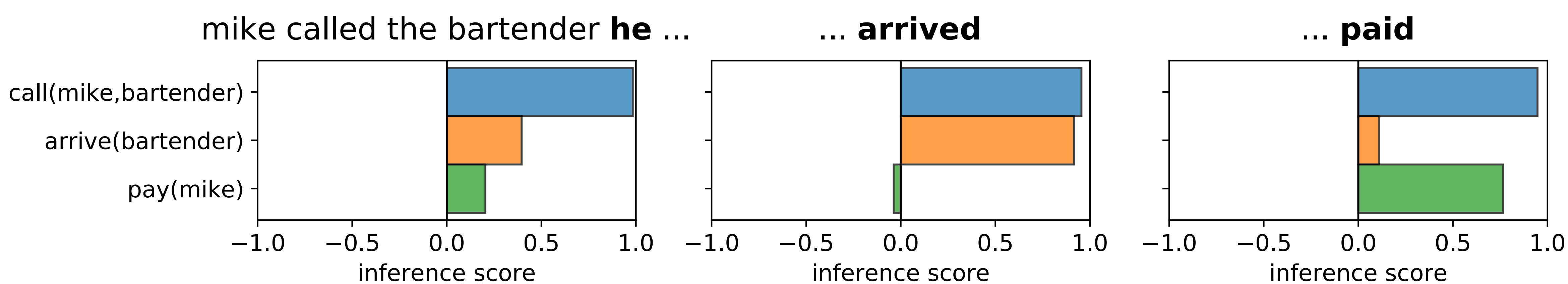
$S(he) = 1.12$

Venhuizen, Hendriks, Crocker, Brouwer (2022, Inf. Comp)

REFERENTIAL AMBIGUITY

In the training data, the anaphoric antecedent of pronouns is always disambiguated by the preceding or the following context

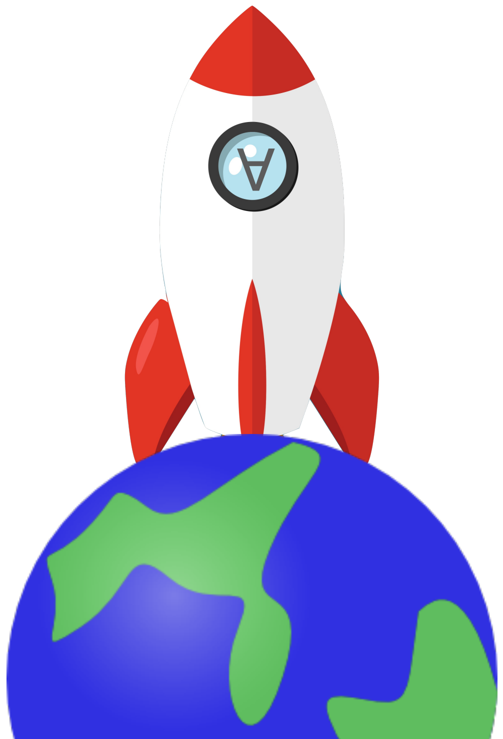
- ➤ Ambiguous pronouns trigger competing hypotheses about the utterance-final interpretation
- ➤ Disambiguating continuations result in utterance-level entailments
- ➤ Surprisal estimates reflect difference between expected and unexpected continuations



$S(arrived) = 0.44$ $S(paid) = 0.66$

Venhuizen, Hendriks, Crocker, Brouwer (2022, Inf. Comp)

BACK FROM SPACE



SUMMARY

Distributional Formal Semantics

- Compositionality
- Entailment and probabilistic inference
- Incremental meaning construction

?

Distributional Semantics

- Semantic similarity
- Empirically driven
- Cognitively inspired

DS VS. DFS: COMPLEMENTARY ASPECTS OF MEANING

- **Semantic similarity:**

lexical similarity	vs.	propositional similarity
beer ~ wine		*order(mike,beer) ~ drink(mike,beer)*

- **Data-driven sampling:**

bottom-up	vs.	top-down
individual linguistic co-occurrences		*high-level description of the world*

- **Cognitive foundation:**

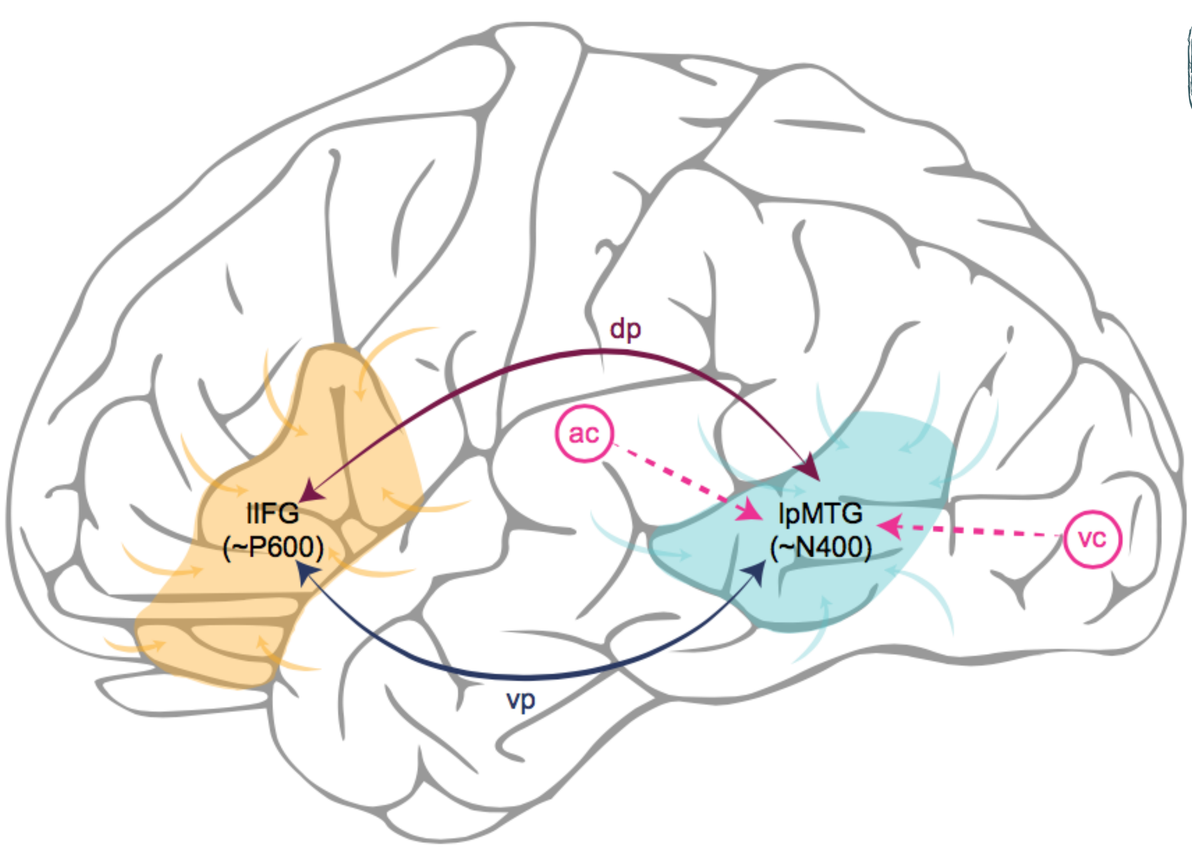
semantic memory	vs.	utterance interpretation
feature-based word meanings		*unfolding discourse-level interpretation*

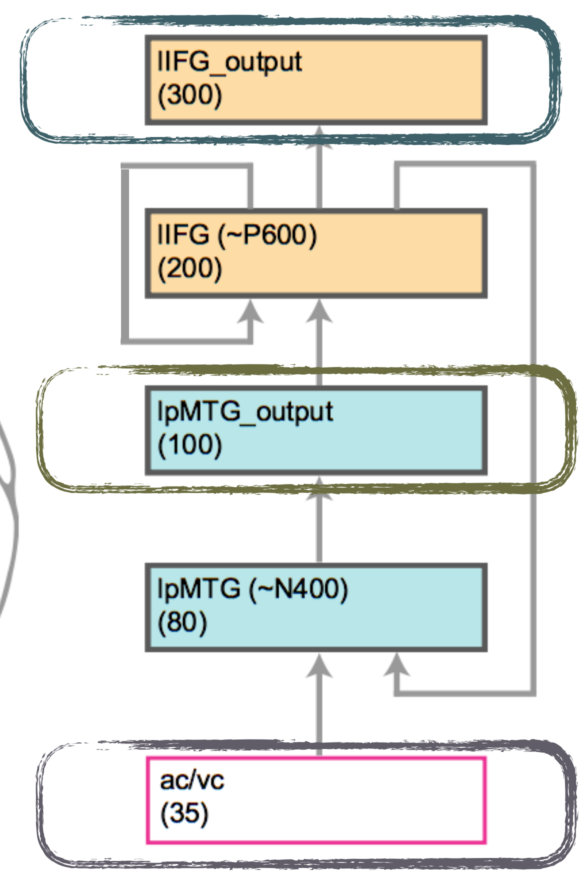
Kutas & Federmeier (2000); McRae et al. (2005); van Berkum (2009); Brouwer et al. (2012, 2017)

DISCUSSION: COGNITIVE FOUNDATION FOR DFS?

The Retrieval-Integration account of the electrophysiology of language comprehension

- Word meaning retrieval~N400
- Integration in utterance meaning~P600





Utterance meaning:
DFS vectors

Word meaning:
DS vectors

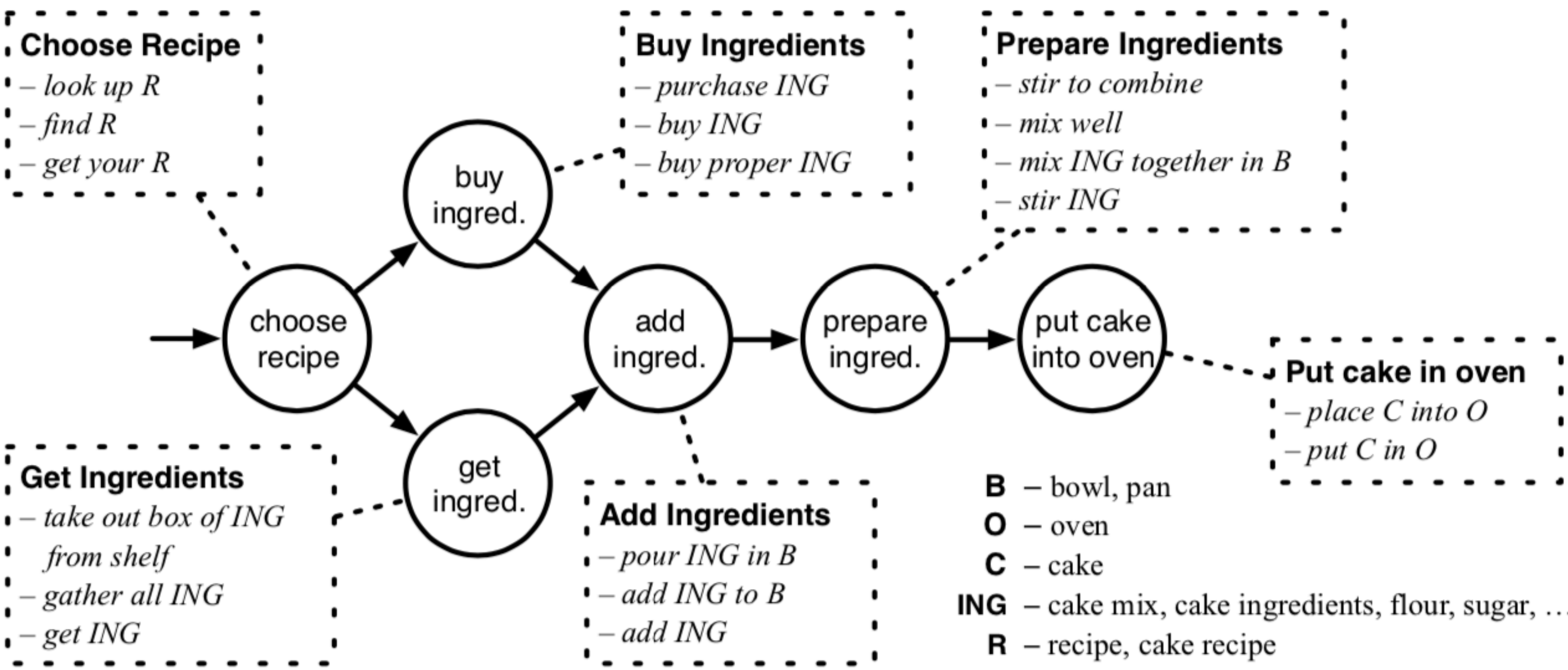
Word form:
Localist vectors

Brouwer et al. (2012, Brain Res.; 2017, Cogn. Sci.; 2021, Frontiers Psych.);

DISCUSSION: DATA-DRIVEN DFS?

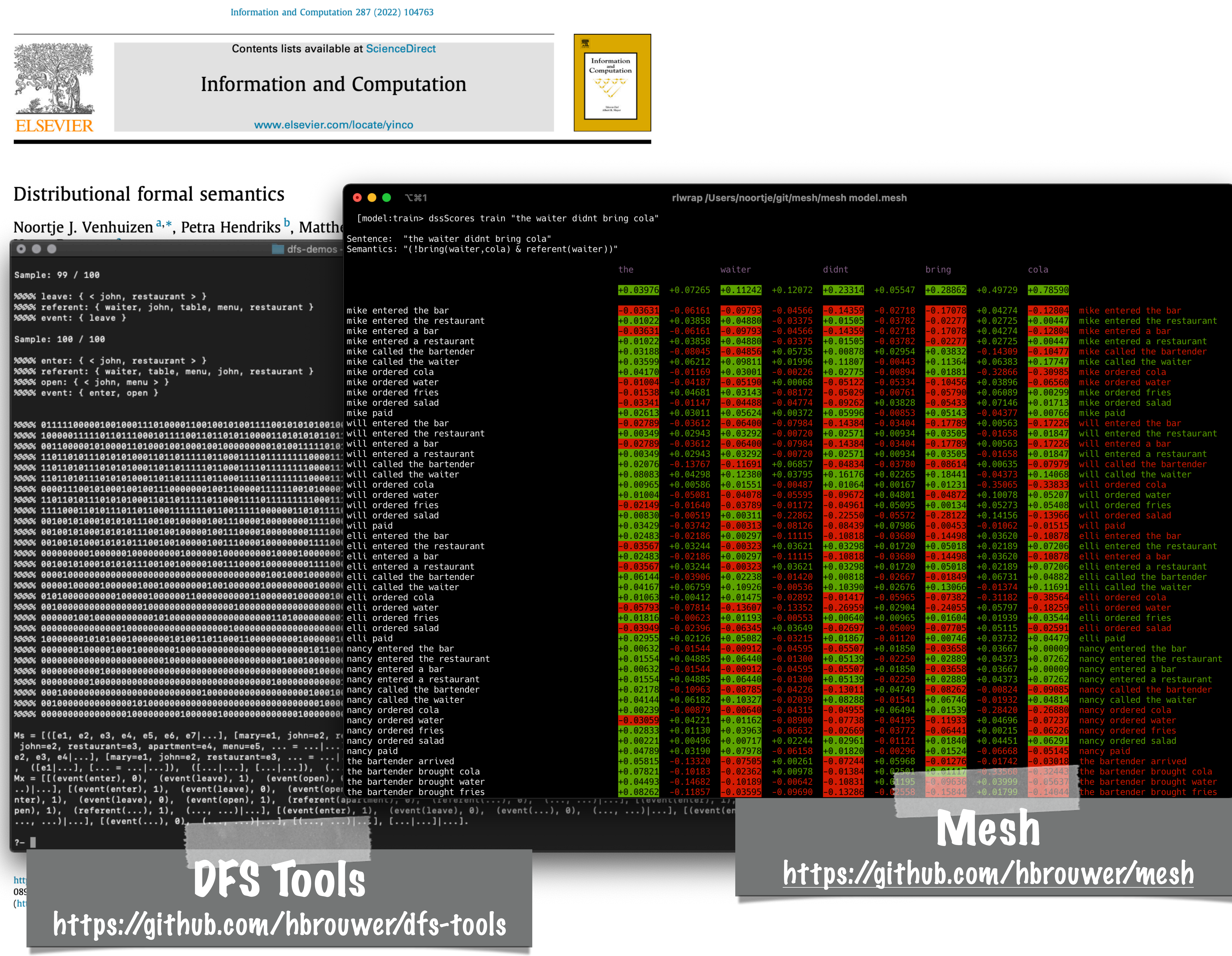
Meaning space reflects world knowledge about propositional co-occurrence, rather than linguistic co-occurrence

- DeScript corpus (Wanzare et al., 2016)



DISTRIBUTIONAL FORMAL SEMANTICS

- The meaning space $S_{\mathcal{M} \times \mathcal{P}}$ captures the structure of the world **truth-conditionally** and **probabilistically**
- Meaning vectors are **compositional** at the propositional level
- **Sub-propositional meaning** derived by incrementally navigating $S_{\mathcal{M} \times \mathcal{P}}$ (using a Simple Recurrent neural Network)
- Semantic phenomena—*negation, presupposition, quantification & reference*—affect **incremental entailments and inferences** during meaning space navigation



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Distributional formal semantics
Noortje J. Venhuizen a,*, Petra Hendriks b, Matthe
dfs-demos
Sample: 99 / 100
Sample: 100 / 100
rlwrap /Users/noortje/git/mesh/mesh model.mesh
[model:train> dssScores train "the waiter didnt bring cola"
Sentence: "the waiter didnt bring cola"
Semantics: "(!bring(waiter,cola) & referent(waiter))"
the
waiter
didnt
bring
cola
DFS Tools
https://github.com/hbrouwer/dfs-tools
Mesh
https://github.com/hbrouwer/mesh