Semantic Theory
Week 11 – Incremental Meaning Construction

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Distributional Formal Semantics

- A set of logical models $\mathcal{M}$ that **truth-conditionally** and **probabilistically** capture the state of the world
- A set of **atomic** propositions $\mathcal{P}$ — e.g., **order(beth,cola)**, **enter(thom,bar)**
- The meaning of a (complex) proposition **p** is defined by a vector **v(p)** in $S_{\mathcal{M}\times\mathcal{P}}$, reflecting its truth/falsehood relative to each model in $\mathcal{M}$
- Fully compositional at the propositional level

Q: What about sub-propositional meaning? — e.g., '**beth**', '**ordered**'

Distributional Formal Semantics (ct'd)

- Vectors representing (combinations of) propositions are binary, reflecting truth/falsehood relative to each model

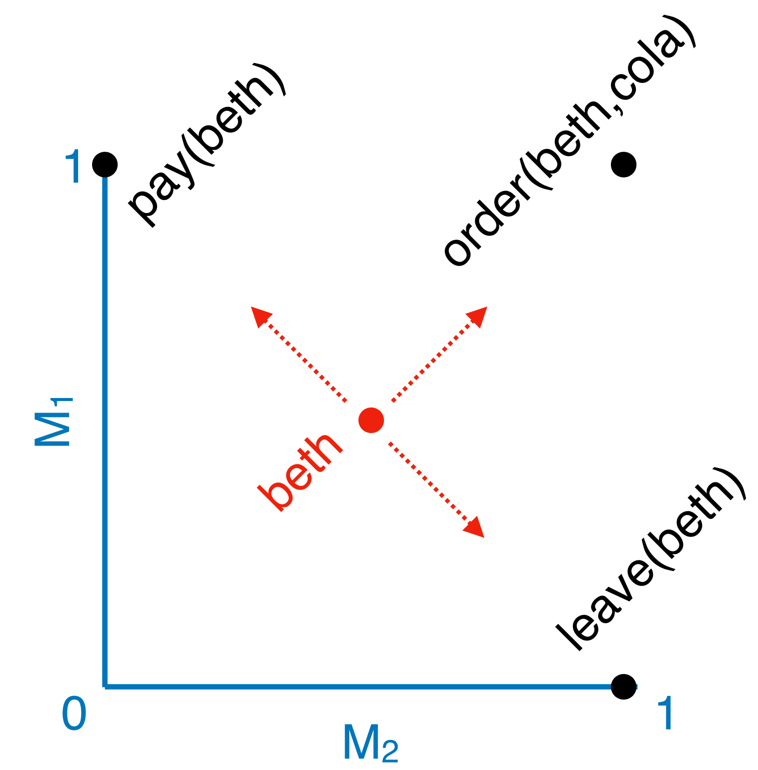
- But the meaning space $S_{\mathcal{M}\times\mathcal{P}}$ is itself **continuous**

- The sub-propositional meaning of an expression **e** is a real-valued vector defining a point in $S_{\mathcal{M}\times\mathcal{P}}$ lying in between the propositions that **e** pertains to

→ The derivation of the meaning of an expression $w_1 \ldots w_i$ is a trajectory through $S_{\mathcal{M}\times\mathcal{P}}$

→ **We can model this derivation using a Simple Recurrent artificial neural Network (SRN)**

Next: A primer on Artificial Neural Networks



Biological Neurons

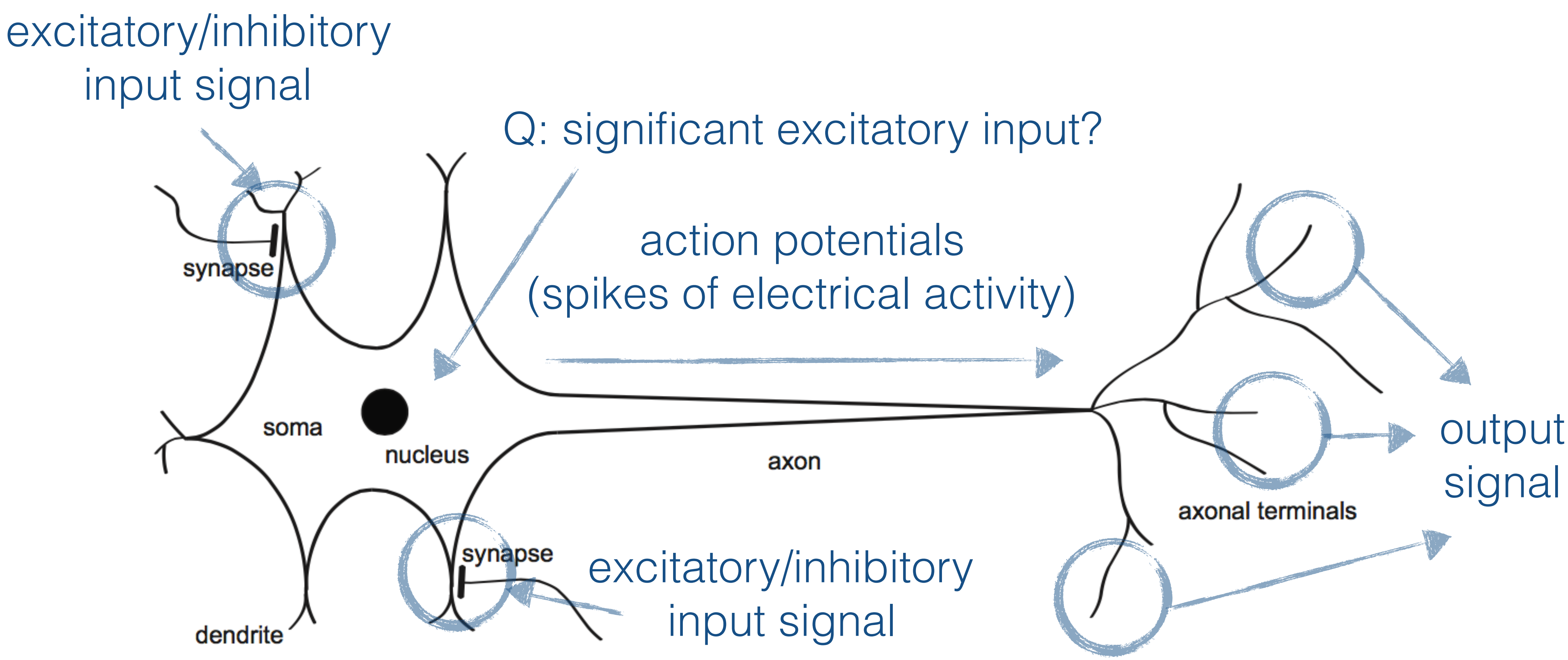


Figure A.1 | *Schematic overview of a biological neuron (or nerve cell).*

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

Artificial "Model" Neurons

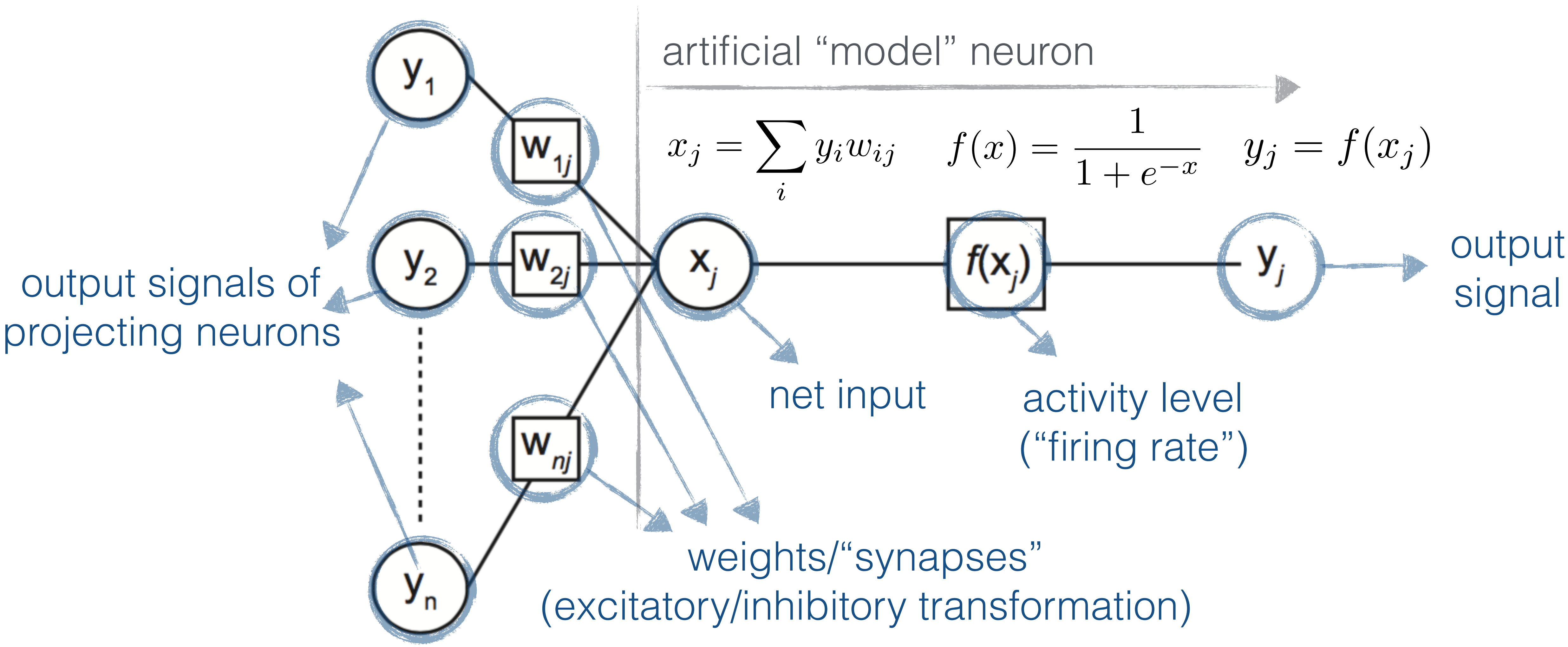


Figure A.2 | *Schematic overview of a unit (or model neuron). The activation level of the unit is a non-linear combination of its net input. The unit's net input, in turn, is the weighted sum of the activation levels of all units that signal to this unit.*

Artificial Neural Networks

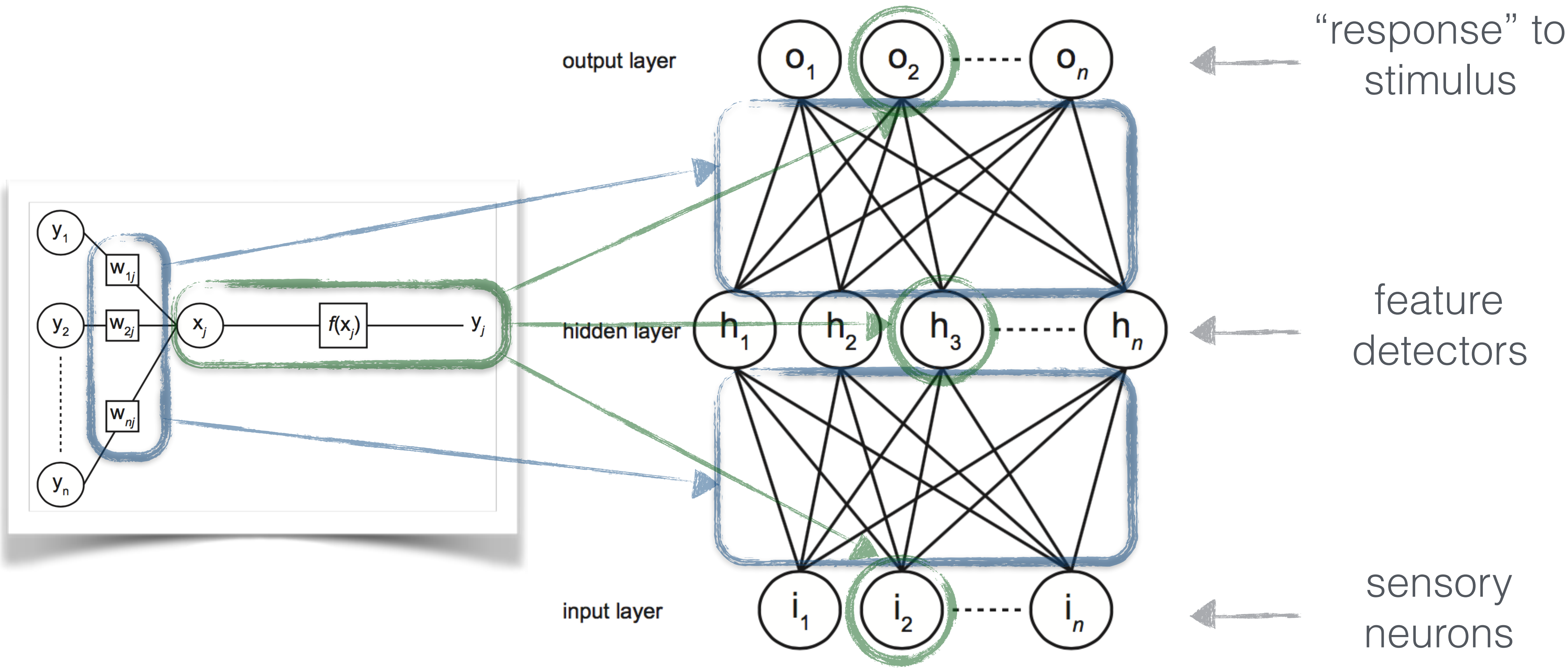


Figure A.3 | *A Feed Forward neural Network (FFN). Units in successive layers are fully connected, whereas units within layers are not.*

Recurrence—Modeling Memory

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

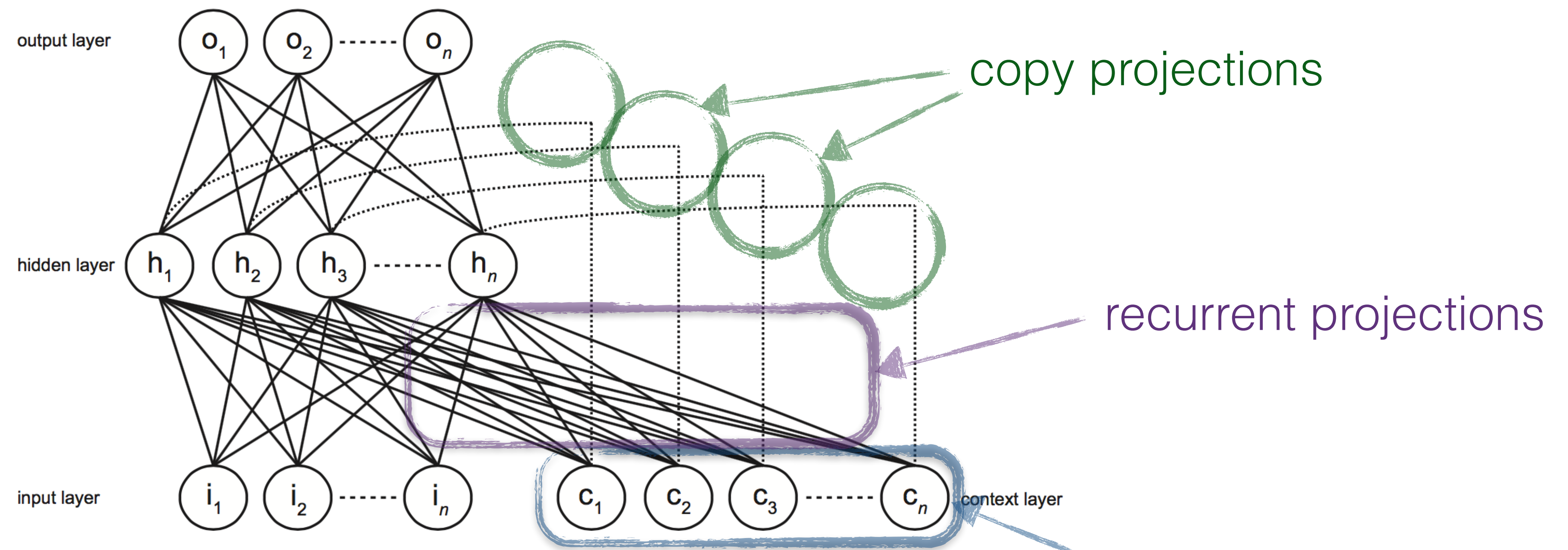


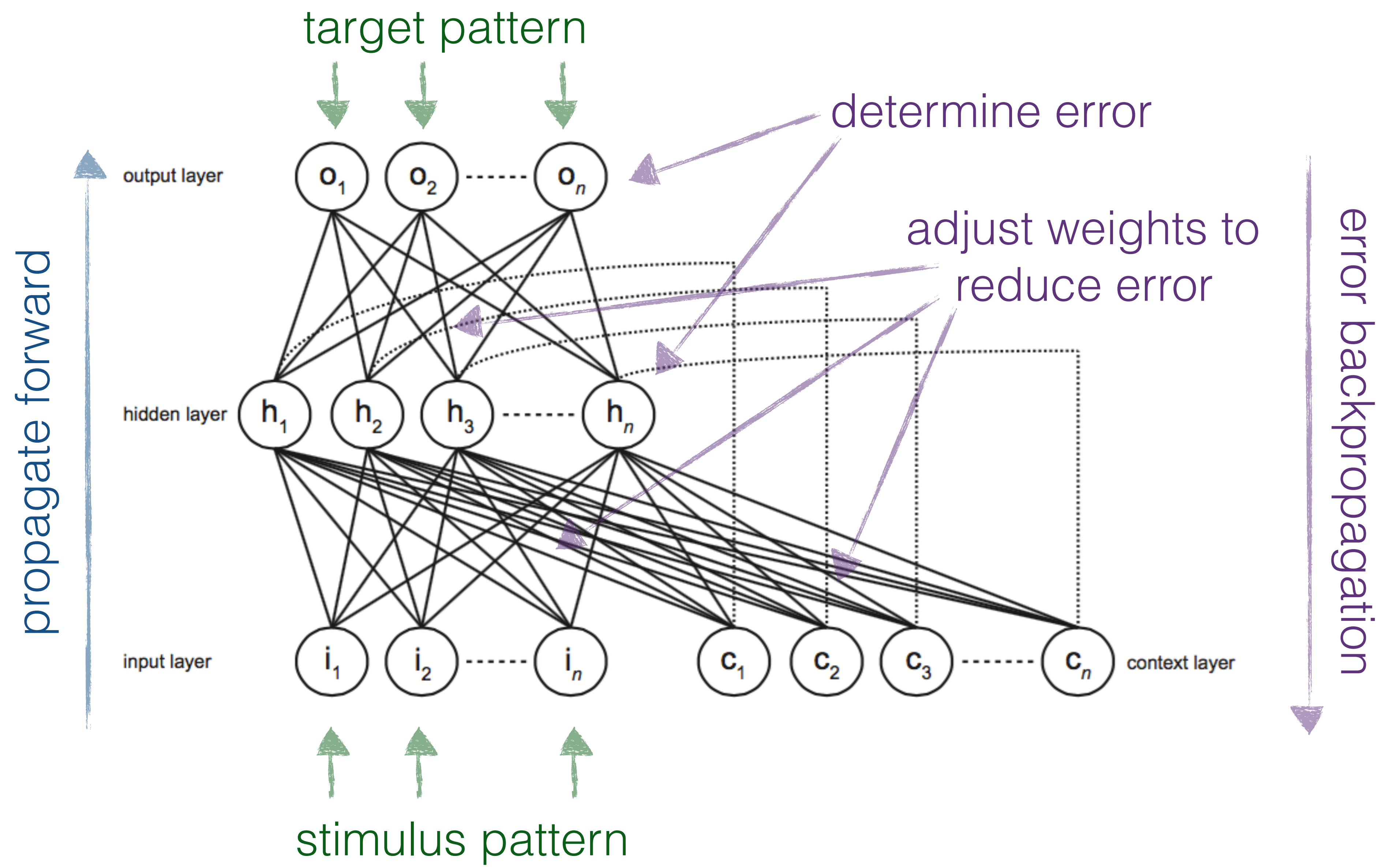
Figure A.5 | *A Simple Recurrent Network (SRN). Before being updated, the activation values of the units in the hidden layer are copied to their corresponding unit in the context layer (the fine dotted lines represent copy connections).*

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

Elman (1990), *Cogn. Sci.*

Learning in Neural Networks

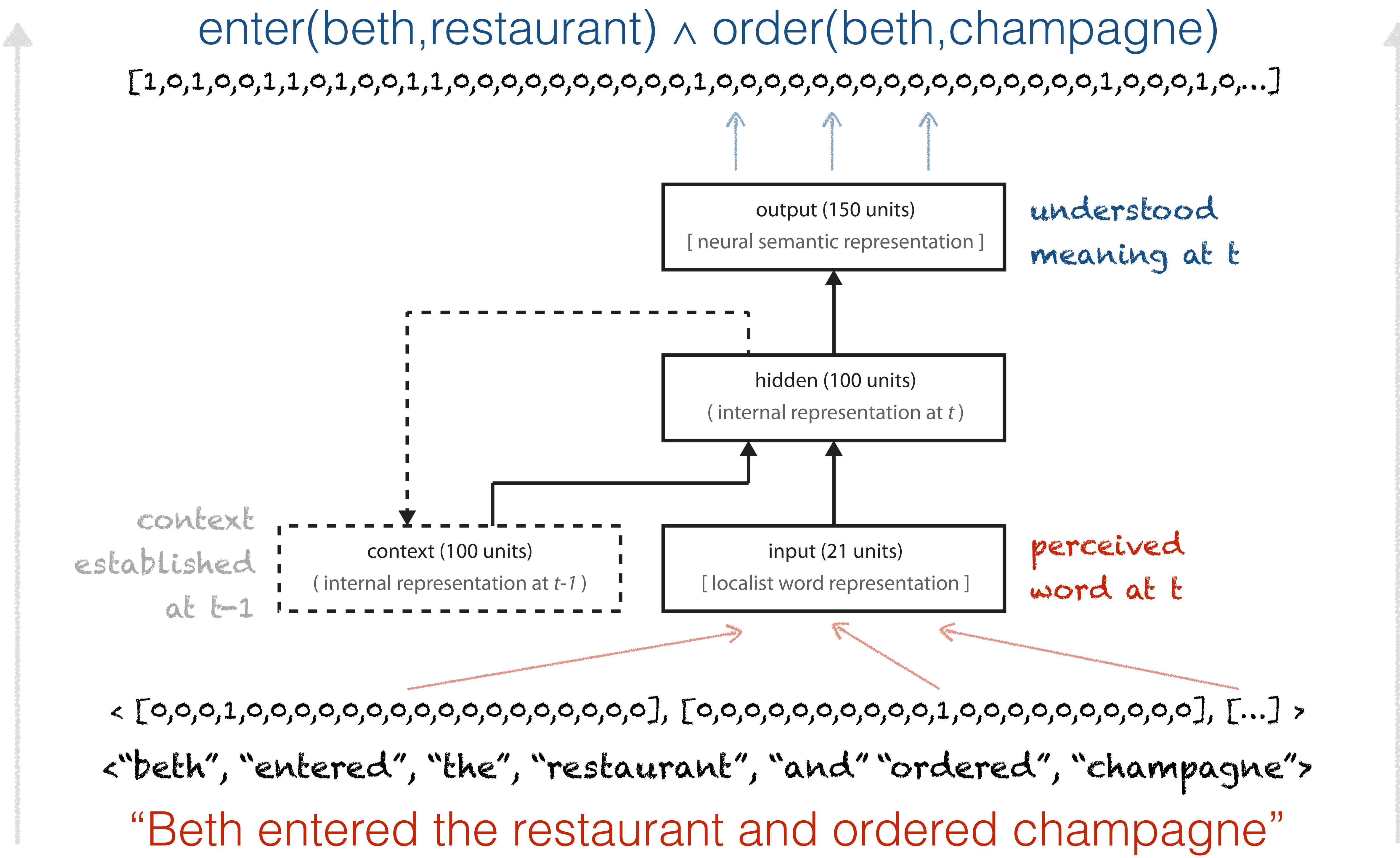
> Neural Networks learn from experience (**training**)



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

Rumelhart et al. (1986), *Nature*

A Neural Model of Comprehension



Elman (1990)
Cognitive Sci.

Venhuizen, Crocker & Brouwer (2019)
Discourse Process.

DP Model — Atomic propositions

Table 1. Microworld concepts.

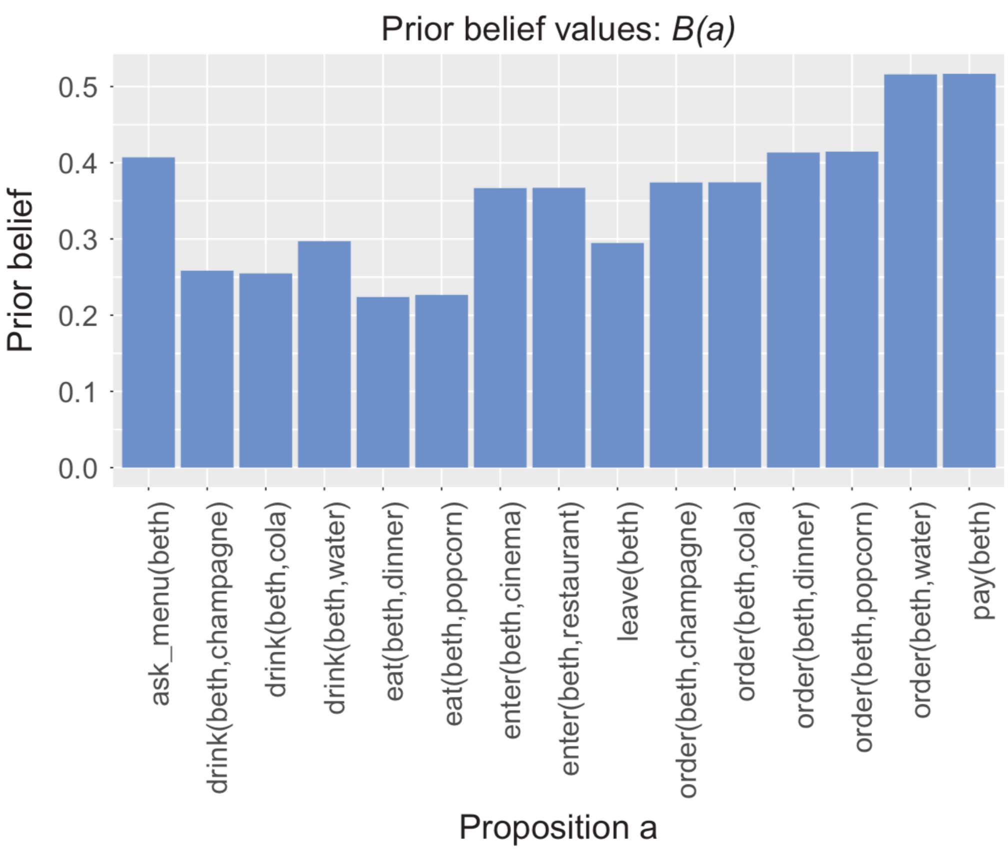
Class	Variable	Class members
Persons	*x*	beth, dave, thom
Places	*p*	cinema, restaurant
Foods	*f*	dinner, popcorn
Drinks	*d*	champagne, cola, water
Predicates	-	enter, ask menu, order, eat, drink, pay, leave

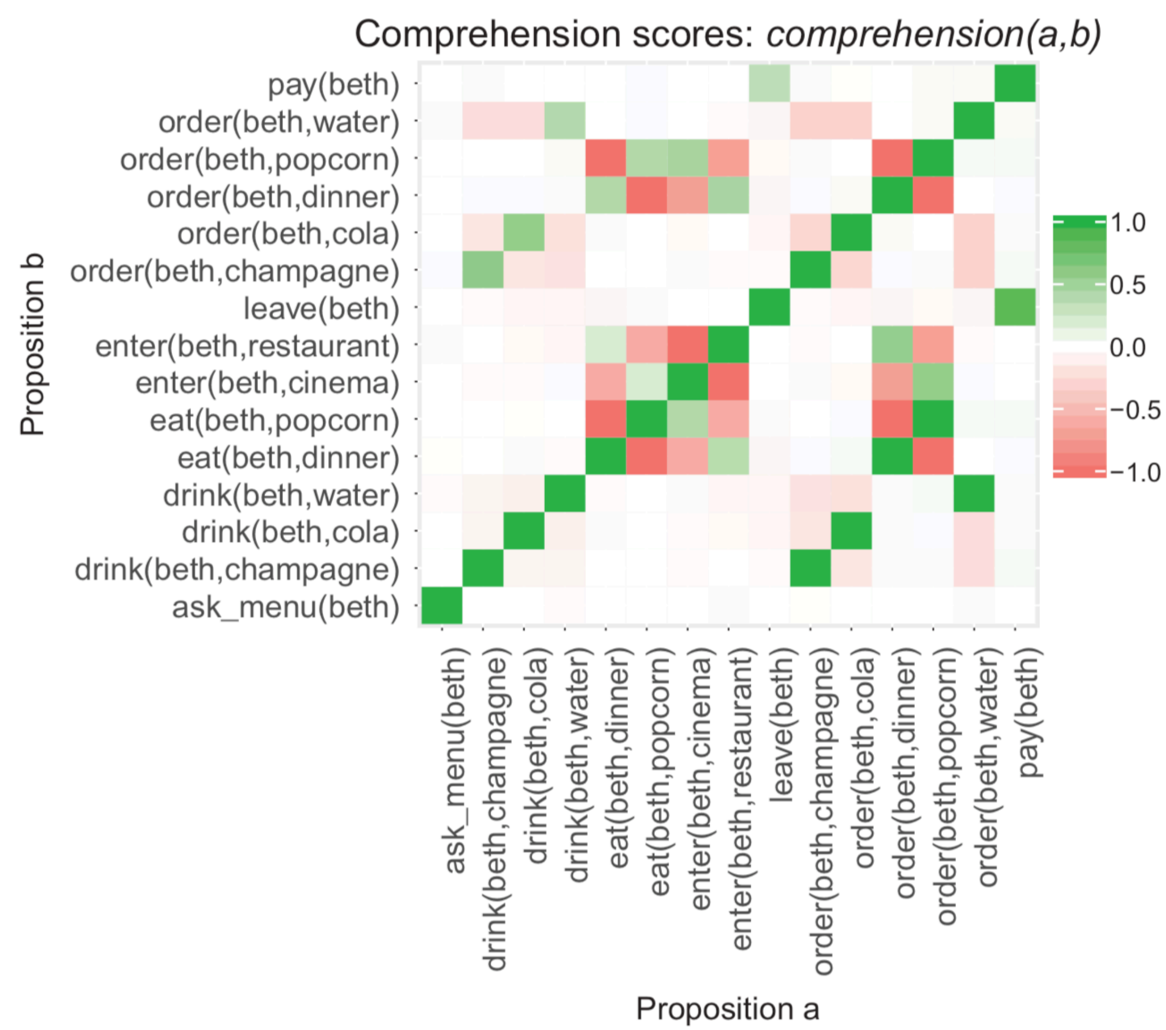
Table 2. Basic propositions.

Proposition	*n*
enter (*x*, *p*)	6
ask menu (*x*)	3
order (*x*, *d*), order (*x*, *f*)	15
eat (*x*, *f*)	6
drink (*x*, *d*)	9
pay (*x*)	3
leave (*x*)	3
Total	45

Venhuizen, Crocker & Brouwer (2019)
Discourse Process.

DP Model — Meaning space





(only propositions for ‘beth’ are shown)

Venhuizen, Crocker & Brouwer (2019)
Discourse Process.

DP Model — Grammar

Table 3. Grammar of the language used for training. Optional arguments are in square brackets, and different instantiations of a rule are separatedusing the pipe symbol. Variable $V \in \{enter, menu, order, eat, drink, pay, leave\}$ denotes verb types.

Head		Body
S	$\rightarrow$	NP_{person} VP_V [$CoordVP_V$]
NP_{person}	$\rightarrow$	beth | dave | thom
NP_{place}	$\rightarrow$	the cinema | the restaurant
NP_{food}	$\rightarrow$	dinner | popcorn
NP_{drink}	$\rightarrow$	champagne | cola | water
VP_{enter}	$\rightarrow$	entered NP_{place}
VP_{menu}	$\rightarrow$	asked for the menu
VP_{order}	$\rightarrow$	ordered NP_{food} | ordered NP_{drink}
VP_{eat}	$\rightarrow$	ate NP_{food}
VP_{drink}	$\rightarrow$	drank NP_{drink}
VP_{pay}	$\rightarrow$	paid
VP_{leave}	$\rightarrow$	left
$CoordVP_{enter}$	$\rightarrow$	and VP_{menu} | and VP_{order} | and VP_{leave}
$CoordVP_{menu}$	$\rightarrow$	and VP_{order} | and VP_{leave}
$CoordVP_{pay}$	$\rightarrow$	and VP_{order} | and VP_{leave}

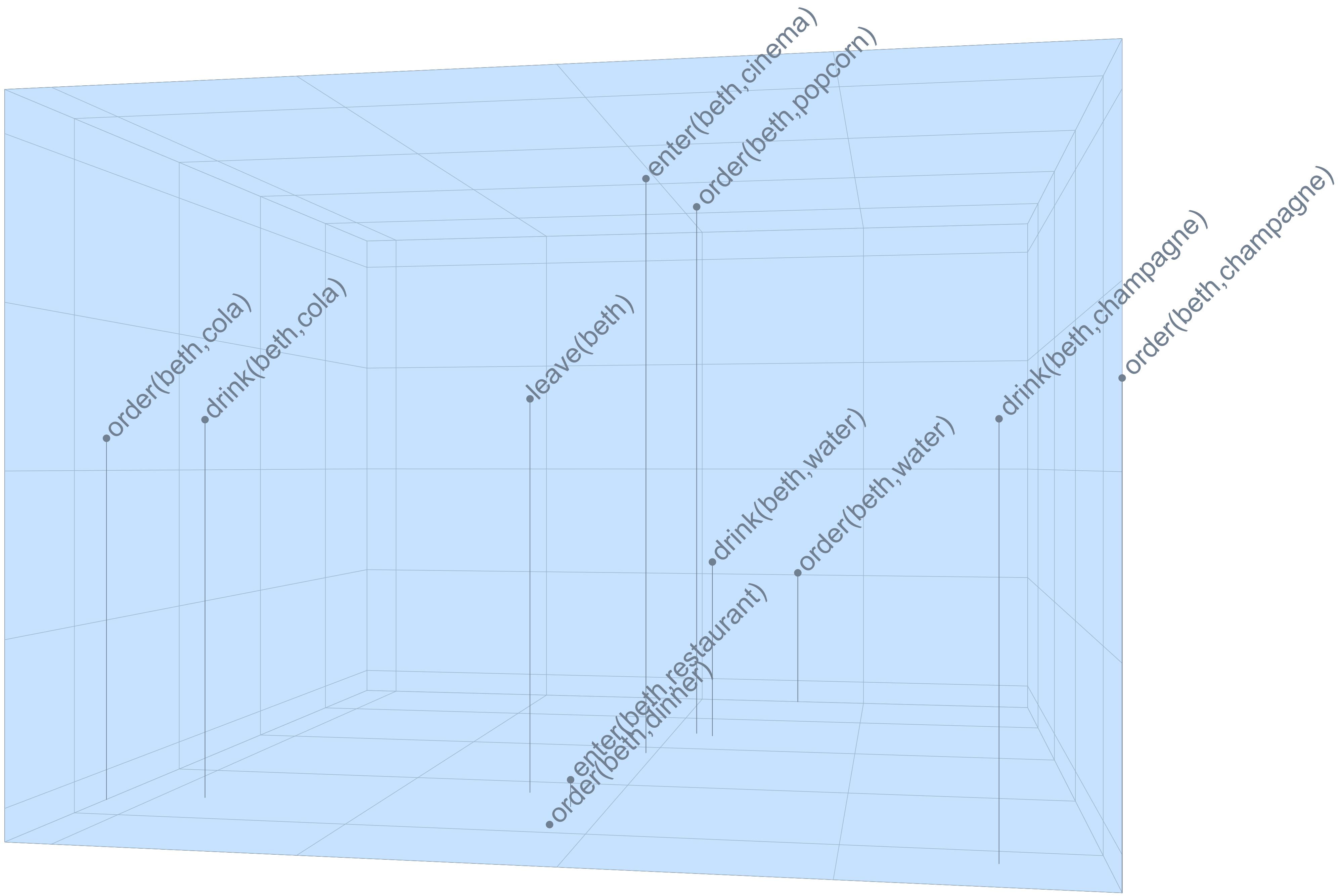
Highly frequent (x9): "NP_{person} ordered dinner," "NP_{person} ate popcorn," "NP_{person} ordered champagne," "NP_{person} drank water";

Relatively frequent (x5): "NP_{person} ordered cola," "NP_{person} drank cola."

Default (x1): All other structures

Venhuizen, Crocker & Brouwer (2019)
Discourse Process.

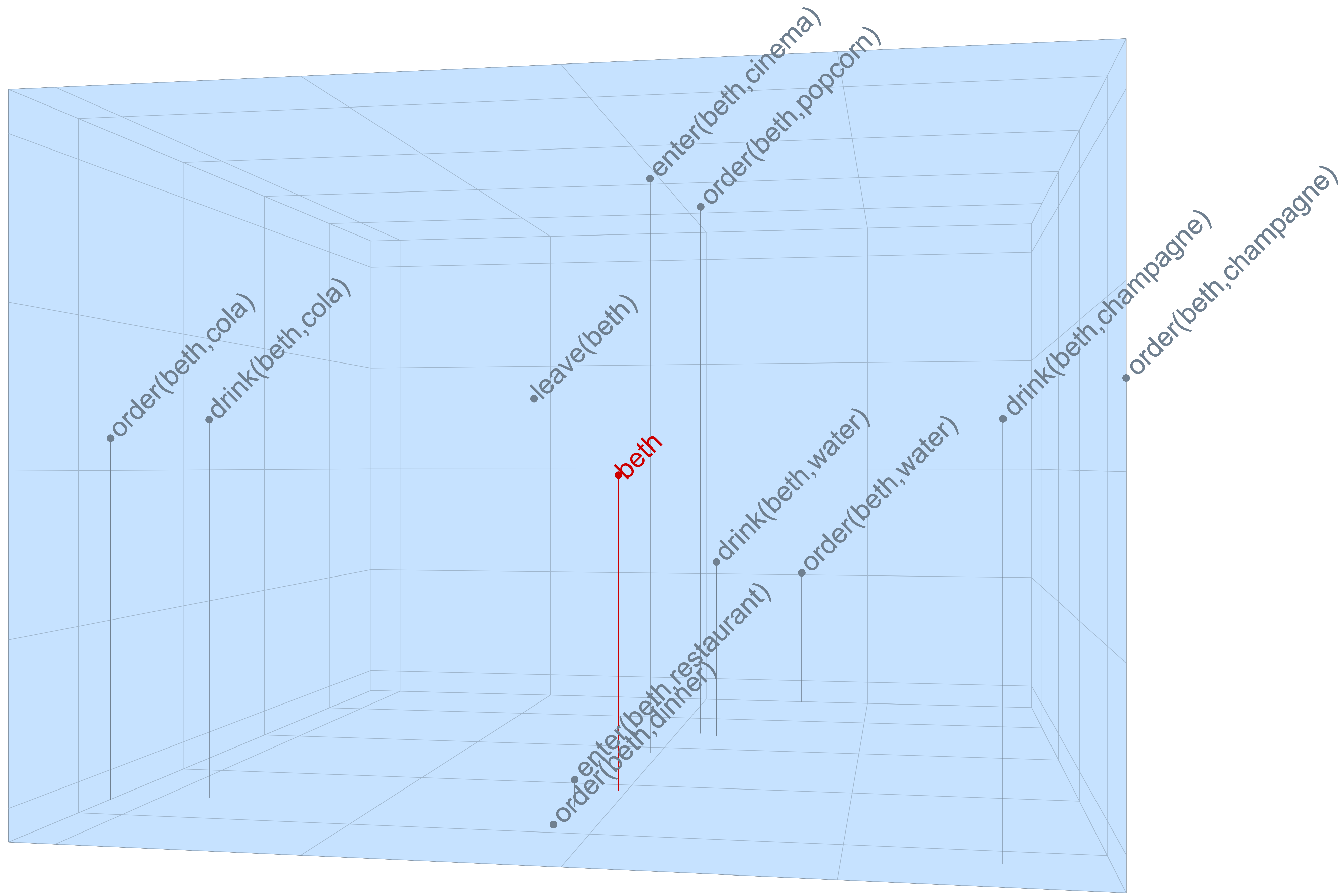
Comprehension is meaning-space navigation



Multi-dimensional scaling: 150D ↦ 3D

Venhuizen, Crocker & Brouwer (2019)
Discourse Process.

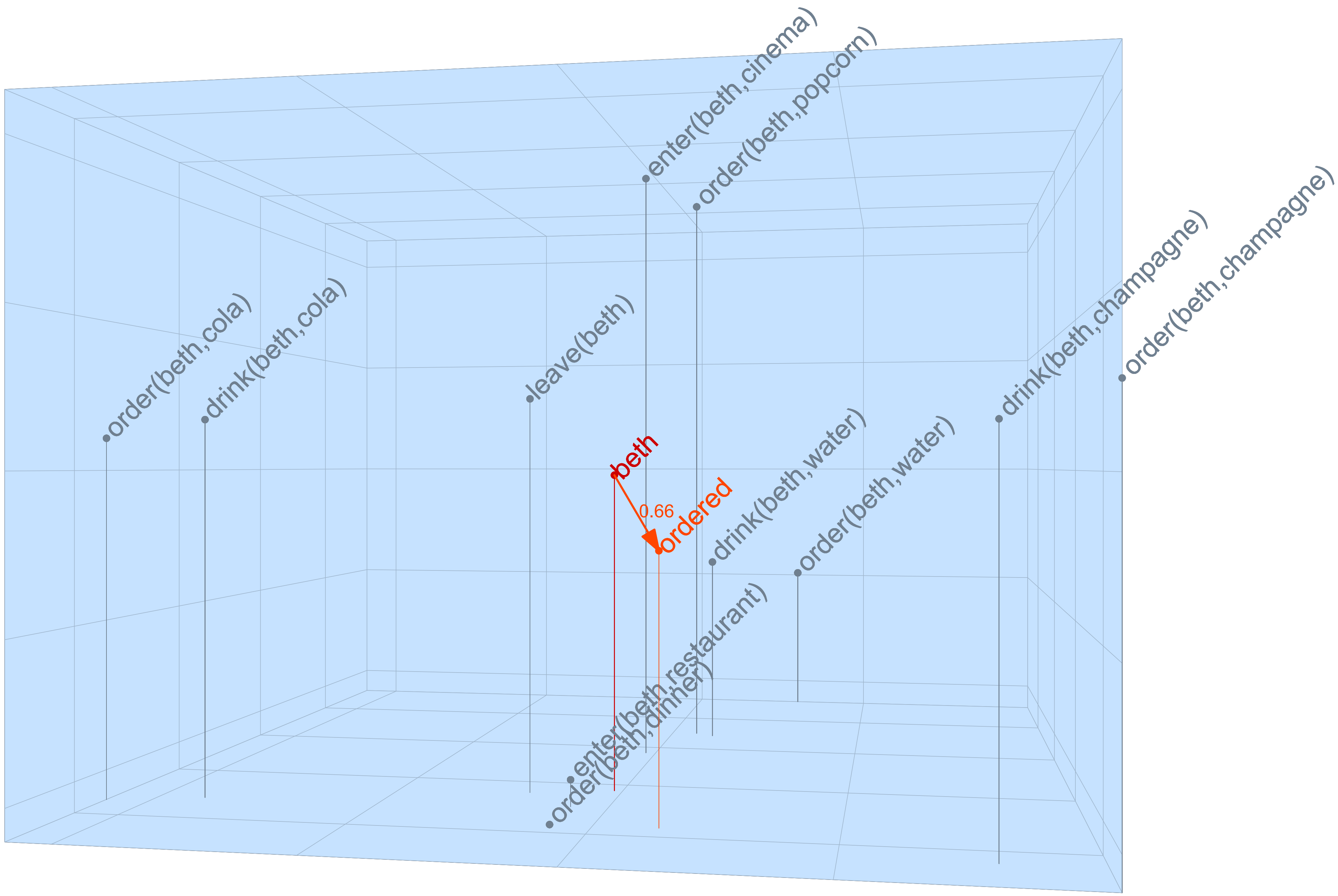
Comprehension is meaning-space navigation



["beth"]

Venhuizen, Crocker & Brouwer (2019)
Discourse Process.

Comprehension is meaning-space navigation

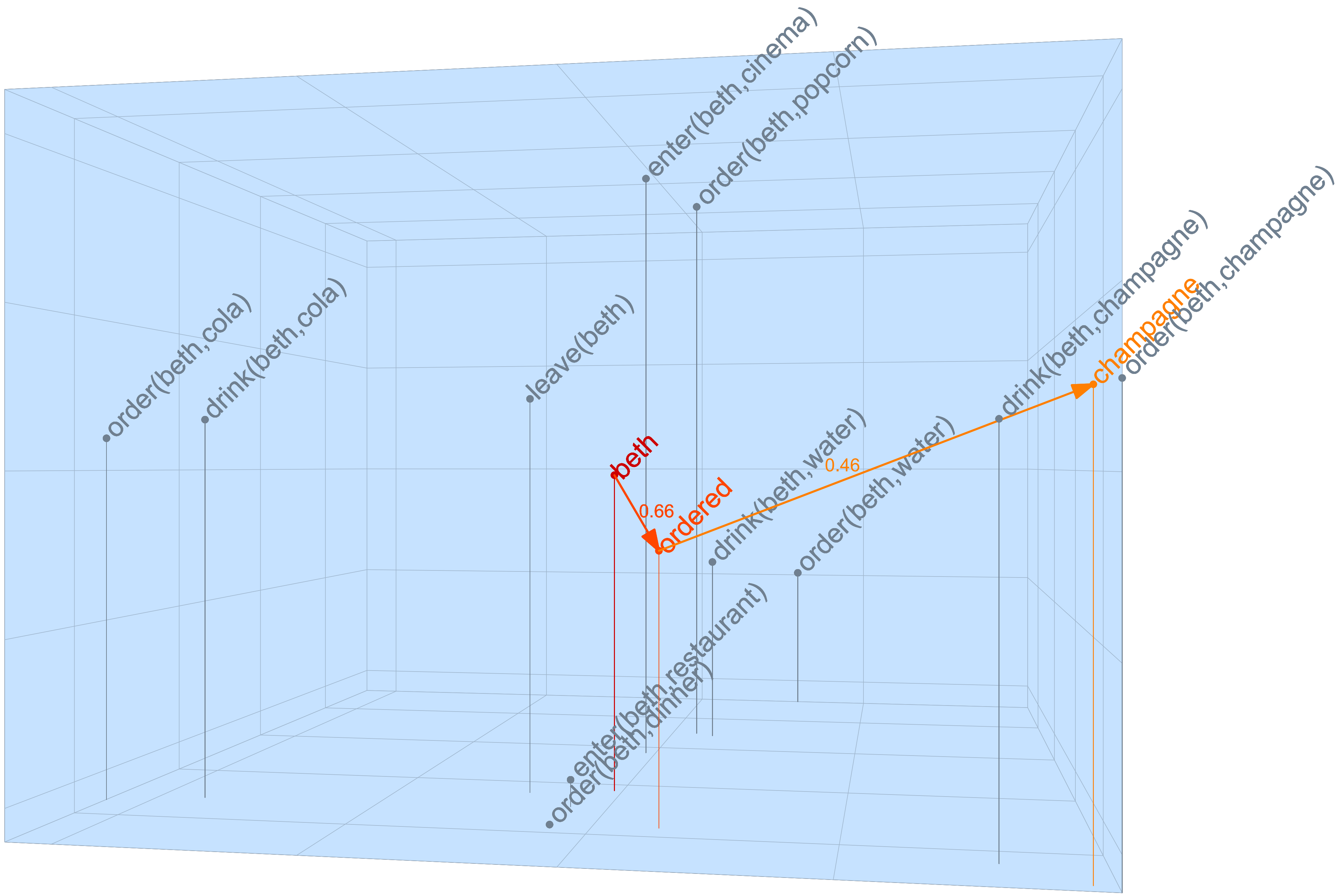


["beth", "ordered"]

(scalars ∝ distance)

Venhuizen, Crocker & Brouwer (2019) *Discourse Process.*

Comprehension is meaning-space navigation

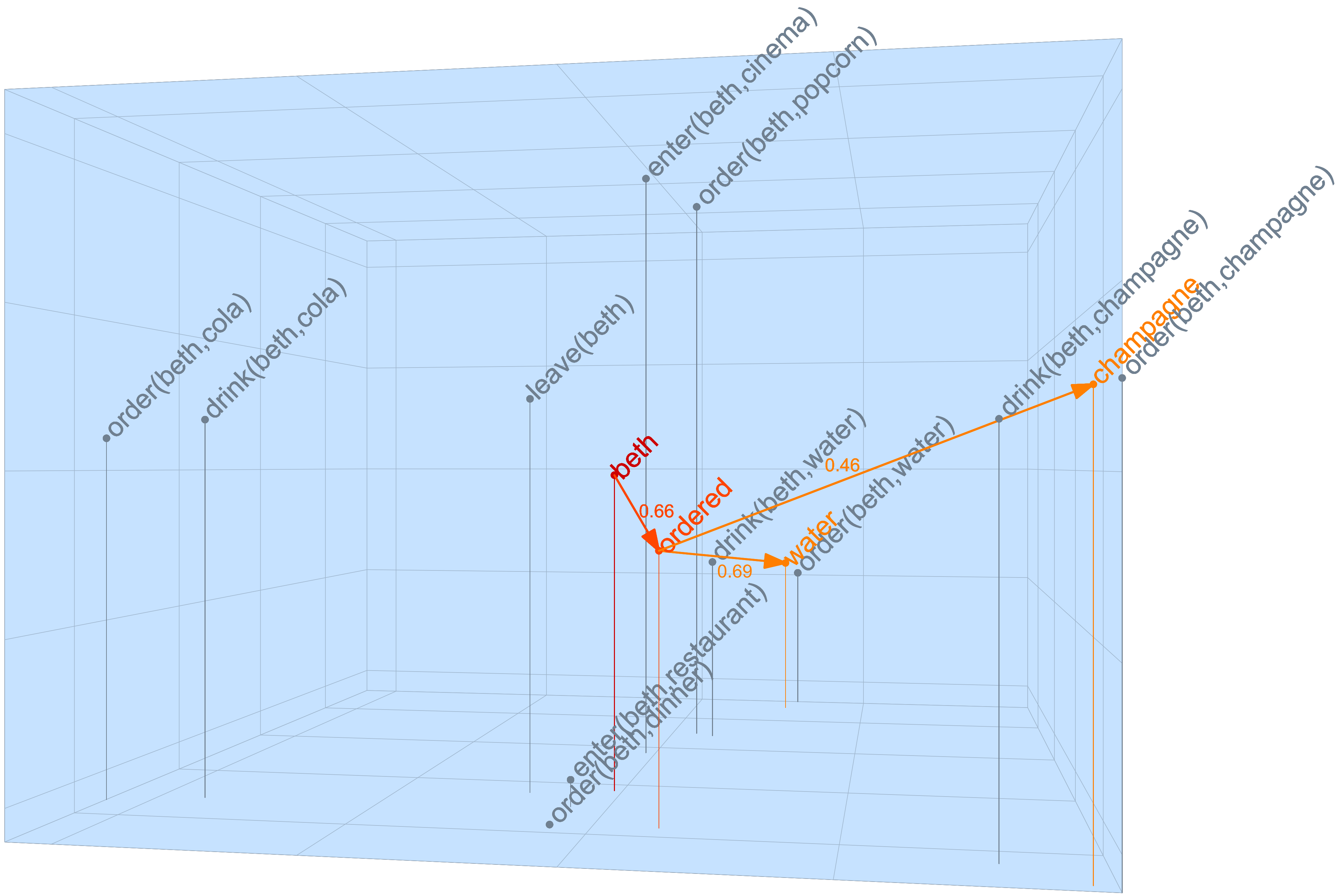


["beth", "ordered", "champagne"]

(scalars ∝ distance)

Venhuizen, Crocker & Brouwer (2019)
Discourse Process.

Comprehension is meaning-space navigation

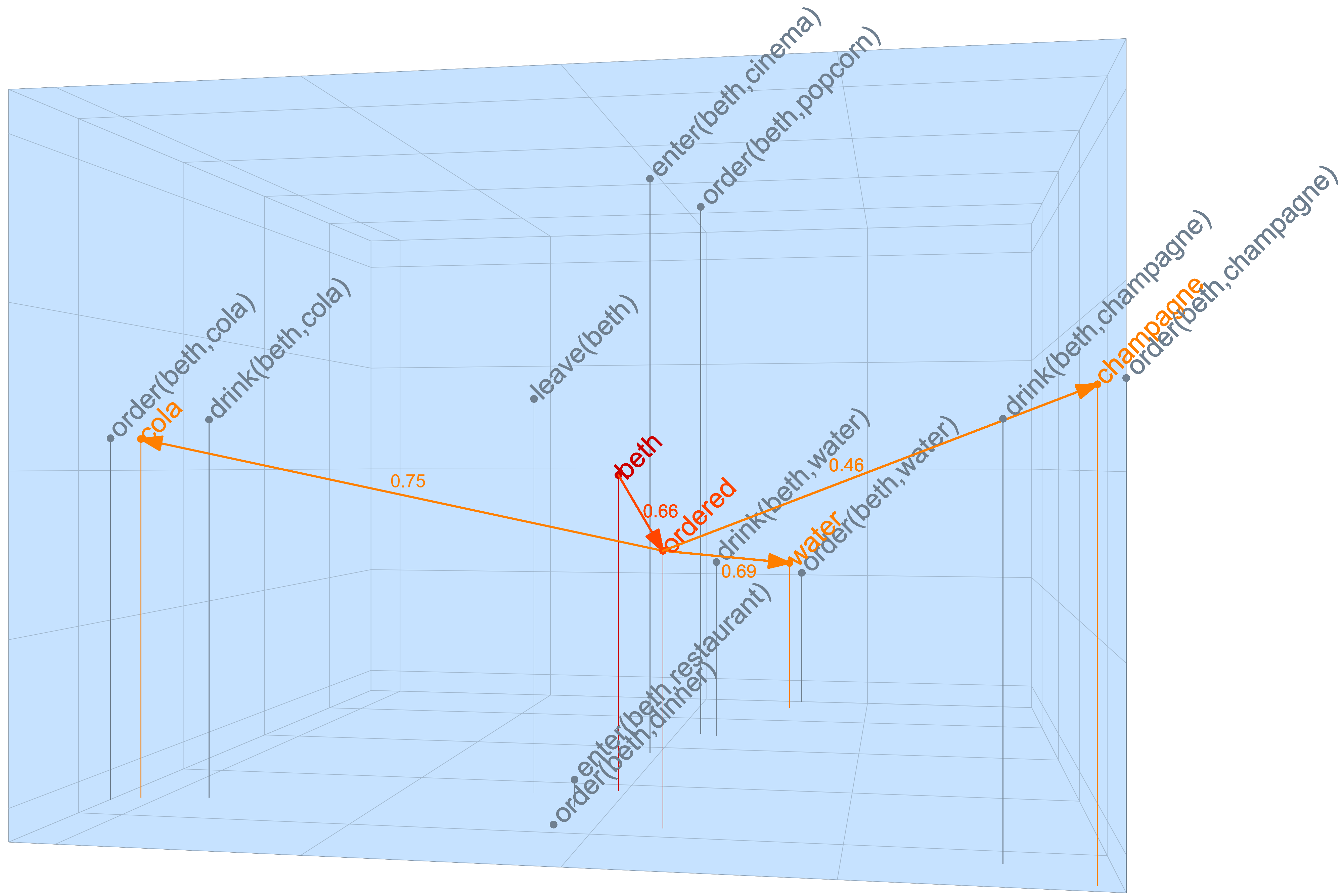


["beth", "ordered", "water"]

(scalars ∝ distance)

Venhuizen, Crocker & Brouwer (2019)
Discourse Process.

Comprehension is meaning-space navigation

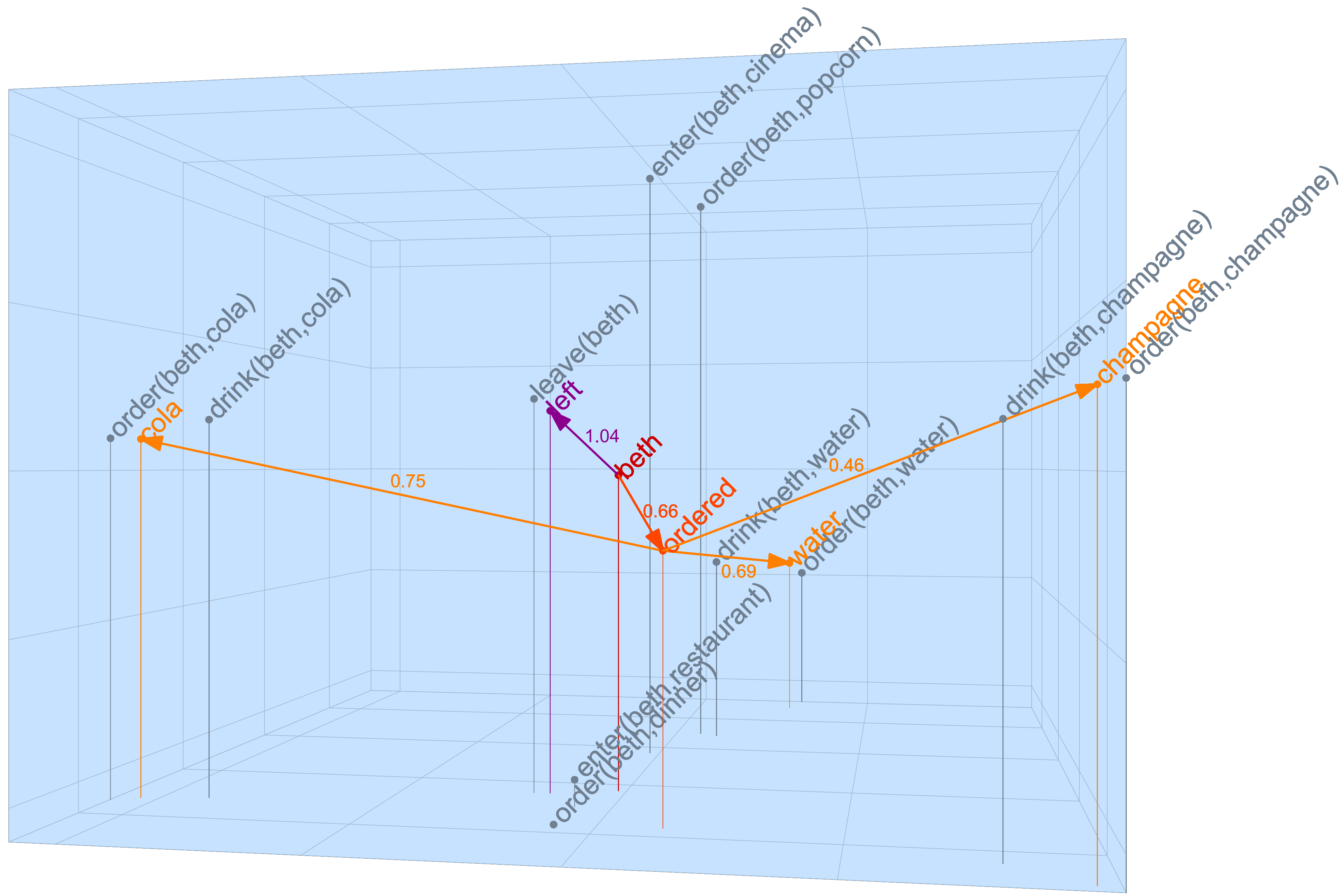


["beth", "ordered", "cola"]

(scalars ∝ distance)

Venhuizen, Crocker & Brouwer (2019)
Discourse Process.

Comprehension is meaning-space navigation

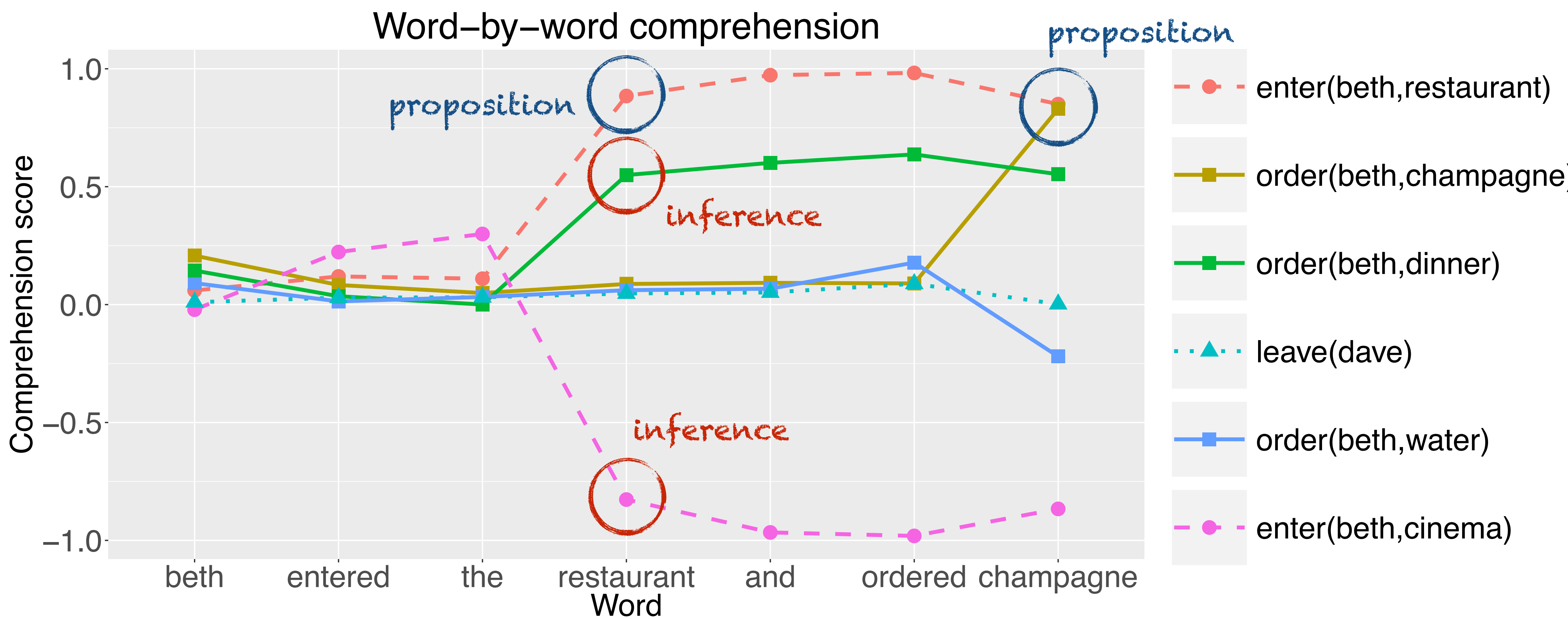


["beth", "left"]

(scalars ∝ distance)

Venhuizen, Crocker & Brouwer (2019)
Discourse Process.

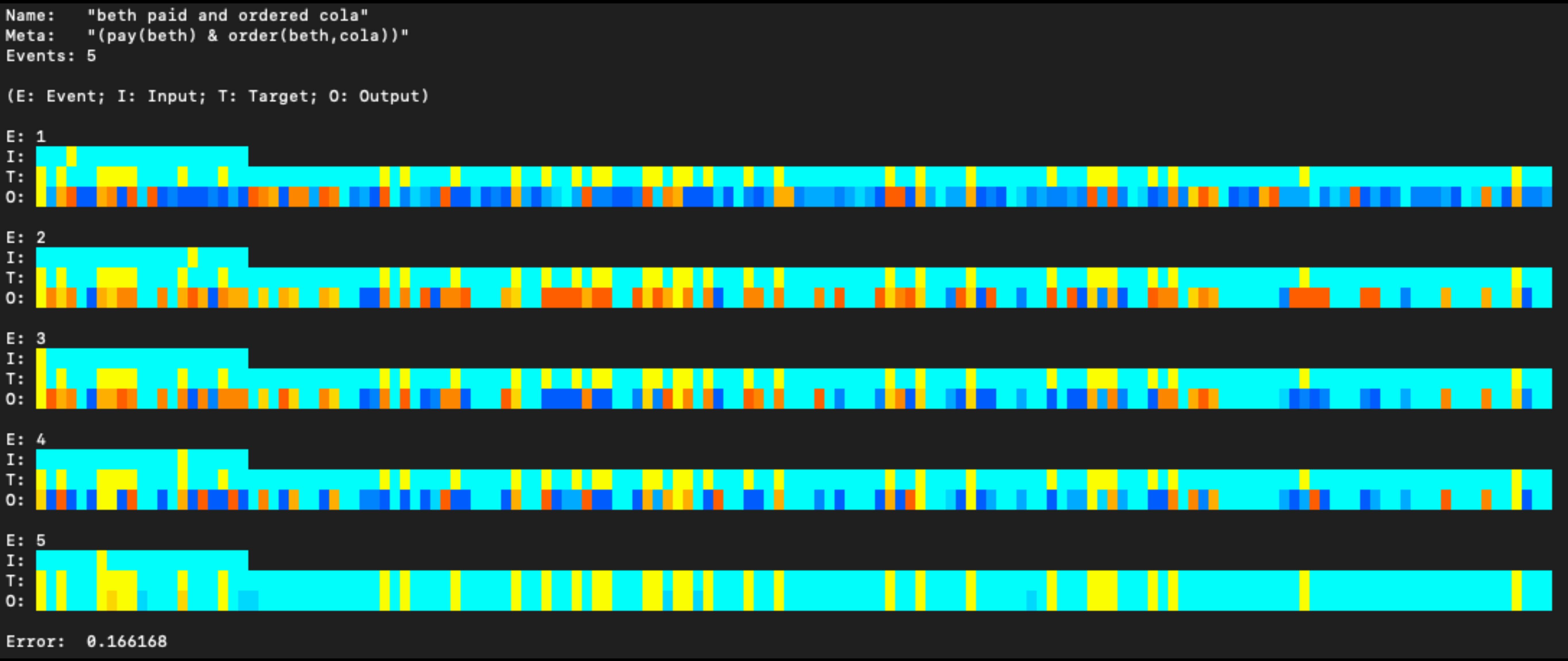
What does the model 'understand'?



> Points in meaning-space capture meaning beyond literal propositional content; i.e., model engages in **direct knowledge-driven inferencing**

Venhuizen, Crocker & Brouwer (2019)
Discourse Process.

Processing in the model



What does the model ‘understand’?

```
Sentence:  "beth entered the restaurant and ordered champagne"
Semantics: "(enter(beth,restaurant) & order(beth,champagne))"
```

	beth		entered		the		restaurant		and		ordered		champagne	
	+0.07039	+0.00133	+0.07172	-0.01075	+0.06097	+0.29321	+0.35418	+0.03641	+0.39059	+0.00066	+0.39125	+0.38655	+0.77780	
enter(beth,cinema)	-0.02148	+0.24441	+0.22293	+0.07659	+0.29951	-1.12625	-0.82674	-0.13942	-0.96616	-0.01477	-0.98093	+0.11462	-0.86631	enter(beth,cinema)
enter(beth,restaurant)	+0.05997	+0.05947	+0.11943	-0.00959	+0.10984	+0.77479	+0.88463	+0.08838	+0.97301	+0.00947	+0.98248	-0.13230	+0.85018	enter(beth,restaurant)
enter(dave,cinema)	-0.02625	-0.01673	-0.04299	-0.01351	-0.05649	-0.13095	-0.18745	+0.01112	-0.17633	+0.00439	-0.17194	-0.39679	-0.56873	enter(dave,cinema)
enter(dave,restaurant)	-0.04534	+0.03629	-0.00905	-0.00655	-0.01560	-0.07485	-0.09046	-0.01653	-0.10699	+0.00971	-0.09729	-0.06977	-0.16706	enter(dave,restaurant)
enter(thom,cinema)	-0.00525	-0.03060	-0.03585	-0.02386	-0.05971	-0.04328	-0.10299	+0.01426	-0.08873	-0.03386	-0.12259	-0.00894	-0.13153	enter(thom,cinema)
enter(thom,restaurant)	-0.03036	+0.03124	+0.00087	-0.05578	-0.05490	+0.12838	+0.07348	-0.00730	+0.06618	-0.00237	+0.06381	+0.04208	+0.10589	enter(thom,restaurant)
ask_menu(beth)	+0.05057	+0.11973	+0.17030	+0.01159	+0.18189	-0.18738	-0.00549	+0.00811	+0.00261	-0.18110	-0.17849	+0.17818	-0.00031	ask_menu(beth)
ask_menu(dave)	-0.04209	+0.02578	-0.01631	-0.01432	-0.03063	+0.12555	+0.09492	+0.01173	+0.10664	+0.01758	+0.12423	-0.17724	-0.05301	ask_menu(dave)
ask_menu(thom)	+0.01846	+0.03027	+0.04873	+0.02419	+0.07292	-0.10789	-0.03497	-0.04742	-0.08239	-0.09128	-0.17368	-0.00405	-0.17772	ask_menu(thom)
order(beth,dinner)	+0.14434	-0.10891	+0.03543	-0.03510	+0.00034	+0.54904	+0.54937	+0.05165	+0.60102	+0.03589	+0.63691	-0.08404	+0.55286	order(beth,dinner)
order(beth,popcorn)	-0.02546	+0.12098	+0.09552	+0.03812	+0.13364	-0.80028	-0.66664	-0.07155	-0.73819	+0.01270	-0.72550	+0.08943	-0.63607	order(beth,popcorn)
order(dave,dinner)	+0.01596	+0.04722	+0.06318	-0.00278	+0.06040	-0.12641	-0.06601	-0.00295	-0.06897	+0.02697	-0.04200	+0.07955	+0.03754	order(dave,dinner)
order(dave,popcorn)	-0.03225	-0.03485	-0.06710	-0.01343	-0.08053	+0.09368	+0.01315	-0.00292	+0.01024	+0.01403	+0.02426	-0.28394	-0.25968	order(dave,popcorn)
order(thom,dinner)	-0.03628	+0.02388	-0.01240	-0.02644	-0.03884	+0.01253	-0.02631	-0.01203	-0.03834	+0.04019	+0.00184	-0.04016	-0.03832	order(thom,dinner)
order(thom,popcorn)	+0.01154	-0.07262	-0.06107	+0.01155	-0.04952	+0.11567	+0.06615	+0.01977	+0.08592	-0.01373	+0.07219	+0.05639	+0.12859	order(thom,popcorn)
order(beth,water)	+0.09100	-0.07737	+0.01364	+0.01873	+0.03236	+0.02871	+0.06107	+0.00627	+0.06735	+0.11077	+0.17812	-0.39810	-0.21998	order(beth,water)
order(beth,cola)	+0.13845	-0.05860	+0.07985	+0.00329	+0.08313	+0.02980	+0.11293	-0.01142	+0.10151	+0.00440	+0.10591	-0.26652	-0.16062	order(beth,cola)
order(beth,champagne)	+0.20763	-0.12451	+0.08312	-0.03408	+0.04904	+0.03848	+0.08752	+0.00478	+0.09229	-0.00253	+0.08976	+0.74019	+0.82995	order(beth,champagne)
order(dave,water)	+0.01068	-0.03213	-0.02145	-0.00894	-0.03039	+0.15632	+0.12593	+0.00546	+0.13139	-0.00865	+0.12273	+0.06657	+0.18930	order(dave,water)
order(dave,cola)	-0.05614	-0.02260	-0.07874	+0.00407	-0.07466	-0.13882	-0.21349	-0.03048	-0.24397	+0.03365	-0.21032	-0.07418	-0.28450	order(dave,cola)
order(dave,champagne)	+0.05206	-0.03239	+0.01966	-0.00447	+0.01520	+0.12534	+0.14054	+0.00292	+0.14346	+0.05018	+0.19364	+0.26044	+0.45408	order(dave,champagne)
order(thom,water)	-0.05171	-0.02807	-0.07978	-0.03525	-0.11503	+0.07721	-0.03782	+0.02320	-0.01463	-0.04257	-0.05720	+0.05179	-0.00541	order(thom,water)
order(thom,cola)	+0.01398	-0.02959	-0.01561	+0.01692	+0.00131	-0.01943	-0.01812	+0.00263	-0.01548	+0.02882	+0.01334	+0.03148	+0.04482	order(thom,cola)
order(thom,champagne)	+0.06160	+0.02403	+0.08562	+0.02497	+0.11059	-0.03093	+0.07966	-0.00539	+0.07427	-0.03965	+0.03462	+0.04474	+0.07935	order(thom,champagne)
eat(beth,dinner)	+0.05633	-0.07578	-0.01946	-0.06135	-0.08080	+0.26135	+0.18055	+0.00860	+0.18915	+0.02788	+0.21704	-0.01073	+0.20630	eat(beth,dinner)
eat(beth,popcorn)	+0.03360	-0.00791	+0.02568	+0.00981	+0.03550	-0.58427	-0.54878	-0.05601	-0.60478	+0.10527	-0.49951	+0.19868	-0.30083	eat(beth,popcorn)
eat(dave,dinner)	-0.00731	+0.04919	+0.04188	+0.00258	+0.04446	-0.22841	-0.18395	-0.01299	-0.19694	+0.11421	-0.08273	+0.06631	-0.01641	eat(dave,dinner)
eat(dave,popcorn)	-0.00597	-0.01517	-0.02113	-0.01303	-0.03417	+0.11036	+0.07619	+0.00741	+0.08360	+0.00302	+0.08663	-0.32592	-0.23930	eat(dave,popcorn)
eat(thom,dinner)	-0.12249	-0.07249	-0.19498	-0.07000	-0.26498	+0.12073	-0.14425	+0.01676	-0.12749	+0.00643	-0.12106	+0.10552	-0.01554	eat(thom,dinner)
eat(thom,popcorn)	+0.01243	-0.09506	-0.08263	+0.02377	-0.05886	+0.09268	+0.03382	+0.01292	+0.04674	+0.00033	+0.04707	+0.00069	+0.04777	eat(thom,popcorn)
drink(beth,water)	+0.15517	-0.13449	+0.02068	-0.00969	+0.01100	+0.10176	+0.11276	+0.00355	+0.11631	+0.06561	+0.18192	-0.13573	+0.04619	drink(beth,water)
drink(beth,cola)	+0.12933	-0.05569	+0.07363	+0.00240	+0.07604	+0.00048	+0.07652	-0.00911	+0.06741	+0.01188	+0.07929	-0.16304	-0.08375	drink(beth,cola)
drink(beth,champagne)	+0.13052	-0.07613	+0.05440	-0.02212	+0.03227	+0.05866	+0.09093	+0.00803	+0.09896	-0.01220	+0.08676	+0.46996	+0.55672	drink(beth,champagne)
drink(dave,water)	-0.02234	-0.08484	-0.10718	+0.00913	-0.09805	+0.10459	+0.00653	+0.00410	+0.01063	+0.02124	+0.03187	+0.12517	+0.15704	drink(dave,water)
drink(dave,cola)	-0.02153	-0.02252	-0.04405	+0.02316	-0.02089	-0.20839	-0.22928	-0.03643	-0.26571	+0.10335	-0.16236	+0.04278	-0.11958	drink(dave,cola)
drink(dave,champagne)	+0.01509	-0.01130	+0.00379	+0.00610	+0.00989	-0.00919	+0.00069	-0.01031	-0.00962	+0.01910	+0.00948	+0.15540	+0.16488	drink(dave,champagne)
drink(thom,water)	-0.05061	-0.02465	-0.07525	-0.01961	-0.09486	-0.08131	-0.17618	-0.00217	-0.17834	+0.00132	-0.17702	-0.20149	-0.37851	drink(thom,water)
drink(thom,cola)	+0.00930	-0.01481	-0.00551	+0.00614	+0.00064	-0.11499	-0.11435	-0.02679	-0.14114	+0.03246	-0.10868	+0.03576	-0.07292	drink(thom,cola)
drink(thom,champagne)	+0.02685	+0.01670	+0.04355	+0.01531	+0.05886	-0.05493	+0.00393	-0.00401	-0.00007	-0.13066	-0.13074	+0.13525	+0.00451	drink(thom,champagne)
pay(beth)	+0.15462	+0.05596	+0.21058	+0.02684	+0.23742	+0.04137	+0.27879	-0.00146	+0.27733	-0.10862	+0.16871	-0.03894	+0.12977	pay(beth)
pay(dave)	+0.01319	+0.02897	+0.04217	+0.00715	+0.04932	+0.02936	+0.07868	+0.00097	+0.07965	+0.08539	+0.16505	-0.20711	-0.04206	pay(dave)
pay(thom)	-0.00686	+0.12125	+0.11439	+0.00955	+0.12394	+0.00018	+0.12412	+0.00689	+0.13100	+0.05886	+0.18986	-0.05526	+0.13460	pay(thom)
leave(beth)	+0.05375	+0.06625	+0.12000	-0.00191	+0.11809	+0.02816	+0.14625	+0.00750	+0.15375	-0.17314	-0.01939	+0.08081	+0.06142	leave(beth)
leave(dave)	+0.01022	+0.01904	+0.02927	+0.00185	+0.03111	+0.01600	+0.04711	+0.00440	+0.05151	+0.03667	+0.08818	-0.08615	+0.00203	leave(dave)
leave(thom)	+0.01520	+0.07592	+0.09112	+0.00861	+0.09974	-0.06078	+0.03896	-0.01819	+0.02076	+0.01631	+0.03707	-0.22917	-0.19209	leave(thom)

Discussion

- The meaning space $S_{\mathcal{M}\times\mathcal{P}}$ is continuous
- The sub-propositional meaning of an expression **e** is a real-valued vector defining a point in $S_{\mathcal{M}\times\mathcal{P}}$ lying in between the propositions that **e** pertains to
- The derivation of the meaning of a multiword expression $w_1 \ldots w_i$ is a trajectory through $S_{\mathcal{M}\times\mathcal{P}}$
- This derivation can be modeled using an SRN that incrementally maps words in context onto (complex) propositional meanings
- This synergy between DFS and neural networks paves way towards novel investigations into formal meaning representation and construction

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