Ease of learning explains semantic universals

Shane Steinert-Threlkeld Jakub Szymanik

Overview

Universals in Linguistic Theory

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Question

What is the range of variation in human languages? That is: which out of all of the logically possible languages that humans could speak, do they in fact speak?

Explaining Universals

Natural Question

Why do universals hold?

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- The universals greatly restrict the search space that a language learner must explore when learning the meanings of expressions. This makes it easier (possible?) for them to learn such meanings from relatively small input.
  [Compare: Poverty of the Stimulus argument for UG. (Chomsky 1980; Pullum and Scholz 2002)]

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  [Compare: Poverty of the Stimulus argument for UG. (Chomsky 1980; Pullum and Scholz 2002)]
- In a sense must be true, but:
  - May not help much (Piantadosi 2013)
  - Does not explain *which* universals are attested.

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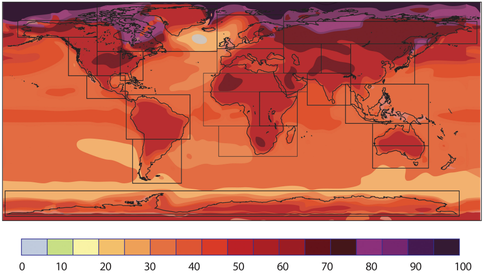
- Our goal: make good on this claim by providing a single model of learning and using it to explain **semantic** universals from several different domains.
- In particular, we train *artificial neural networks* to learn the meanings of different kinds of expressions. Within each kind, we will compare expressions satisfying proposed universals to those that do not.

Heat-map



Overview

1. Main Question
2. (Machine) Learning
3. Color Terms
4. Quantifiers
5. Responsive Verbs
6. Conclusion

Learnability and Semantic Universals

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- An innovation: using *artificial neural networks* as a model of learning.
- Allows us to test many domains quickly, in a roughly biologically plausible fashion.

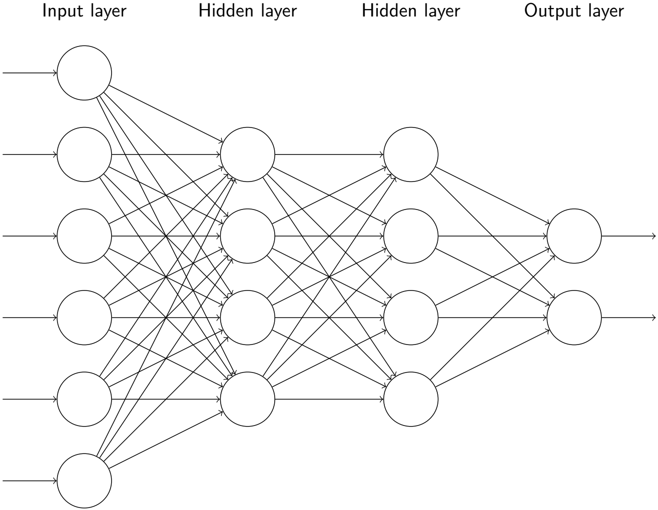
Existing Study with Children


(a)


(b)

From: Hunter and Lidz 2013

Artificial Neural Network



Nielsen 2015; Goodfellow, Bengio, and Courville 2016

http://www.3blue1brown.com/neural-networks

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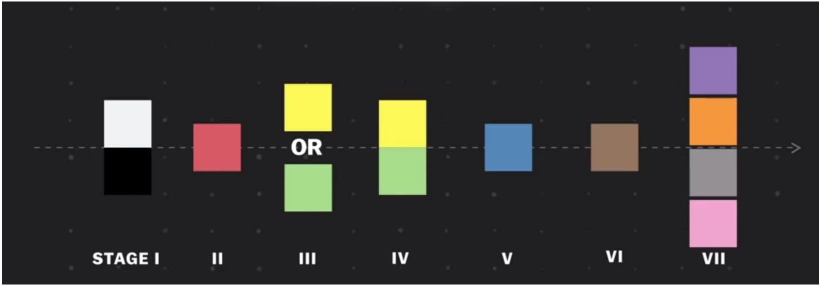
- This is called (stochastic) gradient descent; there are fancier variations now.

Overview

The Order of Color Terms



Berlin and Kay 1969; Regier, Kay, and Khetarpal 2007; Gibson et al. 2017

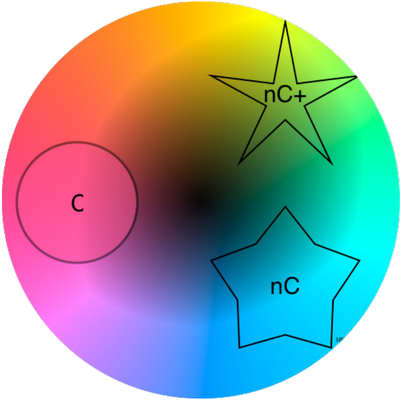
https://www.vox.com/videos/2017/5/16/15646500/color-pattern-language

Convexity

While natural languages vary in how many color terms they have and which specific colors are denoted, it seems that all color terms denote very 'well-behaved' regions of color space.

- X is *convex* just in case if $x, y \in X$, then for every $t \in (0, 1)$,

$$tx + (1 - t)y \in X$$



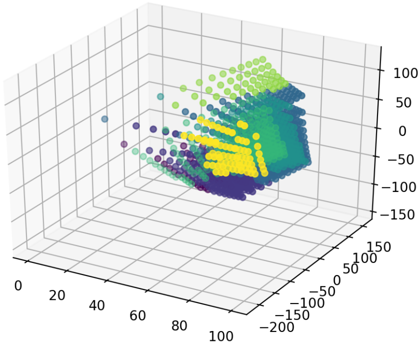
Convexity universal

Convexity Universal (Gärdenfors 2014; Jäger 2010)

All color terms denote convex regions of color space.

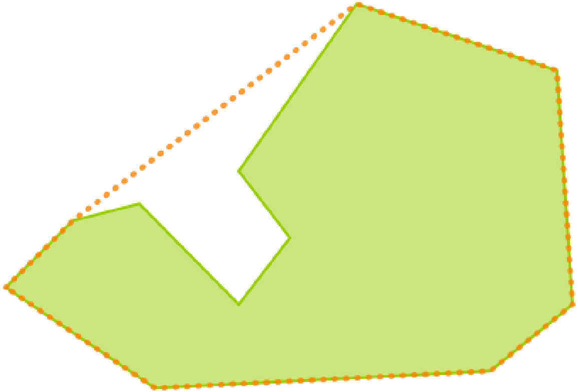
Partitioning CIE-L*a*b* Space

We generated 300 artificial color-naming systems by partitioning the CIELab color space into distinct categories. CIELab approximates human color vision. It is perceptually uniform, meaning that the distance in the space corresponds well with the visually perceived color change.

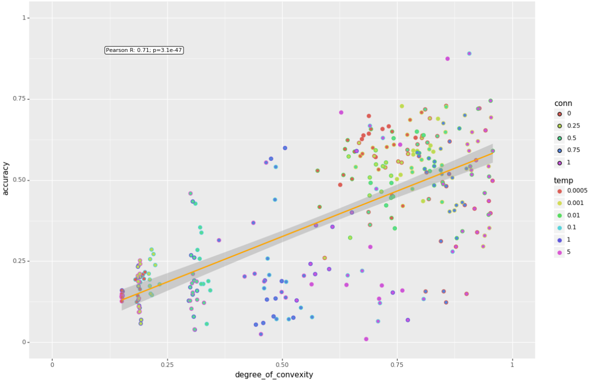


Degree of convexity

We varied the degree of convexity, measured as the average area of the convex hull of each color that is covered by that color.



Convexity: Results



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Overview

Determiners

- Meaning (semantics):
- If languages have syntactic constituents (NPs), then their semantic function is to express generalized quantifiers. (Barwise and Cooper 1981)
- Determiners:
  - Simple: *every*, *some*, *few*, *most*, *five*, . . .
  - Complex: *all but five*, *fewer than three*, *at least eight or fewer than five*, . . .

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- For example:

$$[\![every]\!] = \{\langle M, A, B\rangle : A \subseteq B\}$$
$$[\![three]\!] = \{\langle M, A, B\rangle : |A \cap B| \geq 3\}$$
$$[\![most]\!] = \{\langle M, A, B\rangle : |A \cap B| > |A \setminus B|\}$$

Monotonicity

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So: 'at least 6 or at most 2' is not monotone.

Monotonicity Universal

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  if $\langle M, A, B \rangle \in \mathsf{Q}$ and $B \subseteq B'$, then $\langle M, A, B' \rangle \in \mathsf{Q}$

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Monotonicity Universal (Barwise and Cooper 1981)

All simple determiners are monotone.

Quantity

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So: 'the first three' is not quantitative.

Quantity Universal

- Q is *quantitative*:
  if $\langle M, A, B, \ldots \rangle \in$ Q and $A \cap B, A \setminus B, B \setminus A, M \setminus (A \cup B)$ have the same cardinality (size) as their primed-counterparts, then $\langle M', A', B', \ldots \rangle \in$ Q

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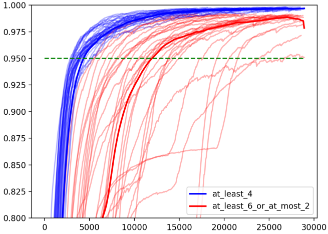
Monotonicity: Results



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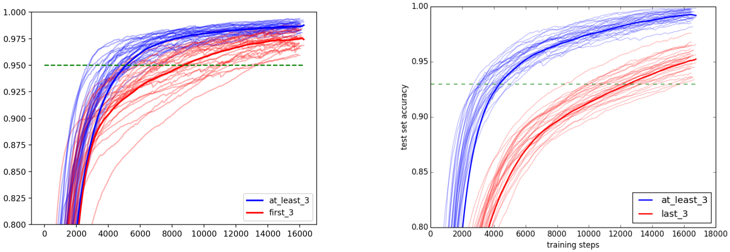

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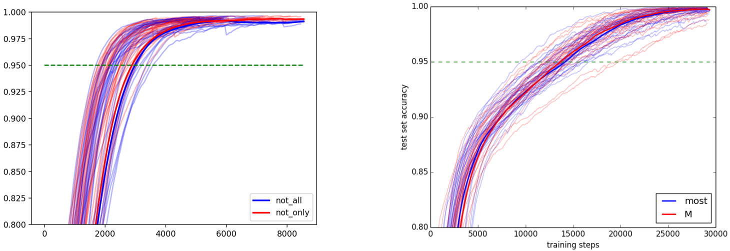

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- Cons as a syntactic/structural constraint, not a semantic universal [See Fox 2002; Sportiche 2005; Romoli 2015]

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Types of Verbs

type	declarative	interrogative	example
rogative	x	✓	‘wonder’
anti-rogative	✓	x	‘believe’
responsive	✓	✓	‘know’

Lahiri 2002; Theiler, Roelofsen, and Aloni 2018; Uegaki 2018

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So: ‘know‘ is *veridically uniform*.

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The Veridical Uniformity Thesis

Veridical Uniformity Universal (Spector and Egré 2015; Theiler, Roelofsen, and Aloni 2018)

All responsive verbs are veridically uniform.

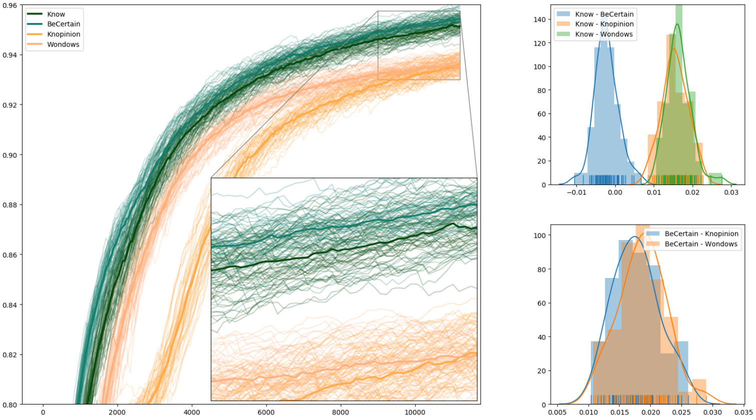
Four Responsive Verbs

Verb	Lexical Entry: $\lambda P_T.\lambda p_{\langle s,t\rangle}.\lambda a_e.\forall w \in p : \ldots$	Veridical Declarative	Veridical Interrogative
know	$w \in \text{DOX}^a_w \in P$	✓	✓
wondows	$w \in \text{DOX}^a_w \subseteq \text{info}(P)$ and $\text{DOX}^a_w \cap q \neq \emptyset\, \forall q \in \text{alt}(P)$	✓	x
knopinion	$w \in \text{DOX}^a_w$ and $(\text{DOX}^a_w \in P$ or $\text{DOX}^a_w \in \neg P)$	x	✓
be-certain	$\text{DOX}^a_w \in P$	x	x

Table : Four verbs, exemplifying the possible profiles of veridicality.

The semantics are given in terms of *inquisitive semantics* Ciardelli, Groenendijk, and Roelofsen 2018

Veridical Uniformity: Results



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In each, a general purpose and biologically-inspired model of learning made good on this answer. We take this as strong evidence that learnability does indeed explain semantic universals.

Future Directions

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- . . . and more!

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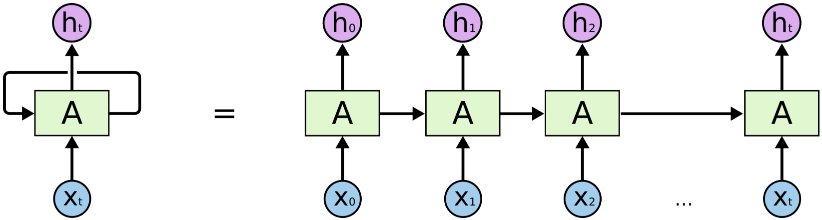
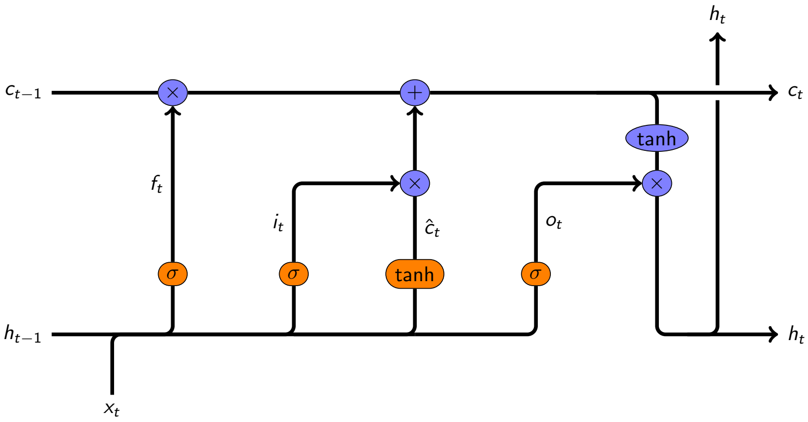
Overview

RNNs



Long Short-Term Memory Network



Hochreiter and Schmidhuber 1997