Synthetic logic characterizations of meanings extracted from large corpora

Alex Djalali and Christopher Potts
Stanford Linguistics

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Overview

Goals

- Establish new connections between Bill MacCartney's NatLog system and linguistic theory
- Understand Natlog's logical underpinnings
- Use the logic to systematize the heterogenous information we have about word meanings

Plan

1. Rethinking NatLog as a logical system (a sequent calculus)
2. Completeness via representation (answering the question, What models does the logic characterize?)
3. Instantiate the semantics using large corpora
4. Evaluate on a novel corpus of indirect question–answer pairs

Two conceptions of semantic theory

- Meaning as model-theoretic denotation
- Meaning as relations between forms

Two conceptions of semantic theory

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Two conceptions of semantic theory

Jerrold Katz, *Semantic Theory*: Meaning as relations between forms

- “The arbitrariness of the distinction between form and matter reveals itself [. . .]”
- “makes no distinction between what is logical and what is not”
- What is meaning? broken down:
    - What is synonymy?
    - What is antonymy?
    - What is superordination?
    - What is semantic ambiguity?
    - What is semantic truth (analyticity, metalinguistic truth, etc.)?
    - What is a possible answer to a question?
    - . . .

Two conceptions of semantic theory

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Bill MacCartney's natural logic

Bill MacCartney and Christopher D. Manning. 2007. Natural logic for textual inference. In Proceedings of the ACL-PASCAL Workshop on Textual Entailment and Paraphrasing.

Bill MacCartney and Christopher D. Manning. 2008. Modeling semantic containment and exclusion in natural language inference. Proceedings COLING 2008.

Bill MacCartney. 2009. *Natural Language Inference*. PhD thesis, Stanford University.

Bill MacCartney and Christopher D. Manning. 2009. An extended model of natural logic. In Proceedings of ACL.

Bill MacCartney's natural logic

1. Ask not what a phrase means, but how it relates to others.

   dog
   - is entailed by *poodle*
   - excludes *tree*
   - is consistent with *hungry*
   - ...

   dance without pants
   - entails *move without jeans*
   - excludes *tango in chinos*
   - is consistent with *tango*
   - ...

2. Seamless blending of logical and non-logical operators: everything appears synthetic (as opposed to analytic).

3. Following Popper: "synthetic statements in general are placed, by the entailment relation, in the open interval between self-contradiction and tautology".

IBM's Watson

"so you're associating words with other words, and then you can associate those with other words . . . "

Propositional Synthetic Logic

- Propositional Synthetic Logic (PSL) is a singly-typed version of MacCartney's natural logic.
- The logic is a theory of the lexicon.
- We will shortly extend the logic with types and composition rules, but our meta-logical results are only for PSL.

Example (A simple PSL proof)

$$\dfrac{\Gamma \vdash \text{short} \mid \text{tall} \qquad \dfrac{}{\Gamma \vdash \text{tall} \wedge \overline{\text{tall}}}\,\wedge_1}{\Gamma \vdash \text{short} \sqsubset \overline{\text{tall}}}\,\mid,\wedge$$

Syntax

Definition (Syntax of $\mathcal{L}$)

Let Φ be a countable set of proposition letters, which we refer to as the set of proper terms. Then,

1. If φ is a proper term, then so is $\overline{\varphi}$;
2. If φ and ψ are proper terms, then

$$\begin{array}{lll} \varphi \equiv \psi, & \varphi \sqsubset \psi, & \varphi \sqsupset \psi, \\ \varphi \,^\wedge\, \psi, & \varphi \mid \psi, & \varphi \smile \psi \end{array}$$

are synthetic terms. Nothing else is a term of $\mathcal{L}$.

Examples

- Frenchman | Dutchman
- run $\sqsubset$ move
- tall $^\wedge$ $\overline{\text{tall}}$

Models

Definition (Synthetic models)

Let a synthetic model $\mathbb{M}$ be the pair $\langle D, [\![\cdot]\!]\rangle$, where

1. D is a non-empty set
2. $[\![\cdot]\!]$ is an interpretation function taking proper terms φ to their denotations in D such that
   a. $[\![\overline{\varphi}]\!] = D - [\![\varphi]\!]$ such that
   b.

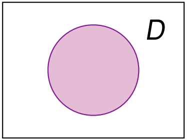
$$[\![\varphi]\!] \neq \begin{cases} \varnothing & \text{or} \\ D & \end{cases}$$

Semantics

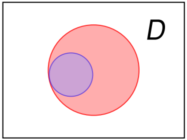
Definition (Tarski-style truth conditions)

$$
\begin{array}{lcl}
\mathbb{M} \models \varphi \equiv \psi & \Leftrightarrow & [\![\varphi]\!] = [\![\psi]\!] \\
\mathbb{M} \models \varphi \sqsubset \psi & \Leftrightarrow & [\![\varphi]\!] \subset [\![\psi]\!] \\
\mathbb{M} \models \varphi \sqsupset \psi & \Leftrightarrow & [\![\varphi]\!] \supset [\![\psi]\!] \\
\mathbb{M} \models \varphi \mathbin{^\wedge} \psi & \Leftrightarrow & ([\![\varphi]\!] \cap [\![\psi]\!] = \emptyset) \wedge ([\![\varphi]\!] \cup [\![\psi]\!] = D) \\
\mathbb{M} \models \varphi \mid \psi & \Leftrightarrow & ([\![\varphi]\!] \cap [\![\psi]\!] = \emptyset) \wedge ([\![\varphi]\!] \cup [\![\psi]\!] \neq D) \\
\mathbb{M} \models \varphi \smile \psi & \Leftrightarrow & ([\![\varphi]\!] \cap [\![\psi]\!] \neq \emptyset) \wedge ([\![\varphi]\!] \cup [\![\psi]\!] = D)
\end{array}
$$

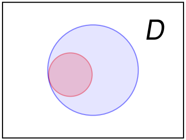
Graphical representation of the semantics



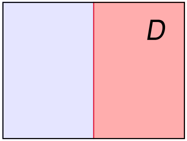
$\varphi \equiv \psi$
equivalence
couch $\equiv$ sofa



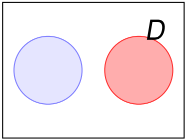
$\varphi \sqsubset \psi$
forward entailment
crow $\sqsubset$ bird



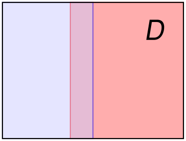
$\varphi \sqsupset \psi$
reverse entailment
bird $\sqsupset$ crow



$\varphi \,^\wedge\, \psi$
negation
man $^\wedge$ non-man



$\varphi \mid \psi$
alternation
cat | dog



$\varphi \smile \psi$
cover
animal $\smile$ non-human

Mutual exclusivity of the relations

Theorem

If $\mathbb{M}$ is a synthetic model then

$$\mathbb{M} \models \varphi \mathcal{R} \psi \Rightarrow \mathbb{M} \not\models \varphi \mathcal{S} \psi$$

for $\mathcal{R} \neq \mathcal{S}$.

Entailment

Definition (Synthetic entailment)

Let Γ be a set of synthetic terms. Γ **entails** $\varphi\mathcal{R}\psi$ written, $\Gamma \models \varphi\mathcal{R}\psi$, if, and only if

$$\mathbb{M} \models \Gamma \Rightarrow \mathbb{M} \models \varphi\mathcal{R}\psi$$

Propositional Synthetic Logic proof calculus

- A sequent calculus for reasoning with PSL
- A logical perspective on (the lexical parts of) MacCartney's procedural, matrix-based reasoning

MacCartney rules

$\mathcal{R},\mathcal{S}$	$\equiv$	$\sqsubset$	$\sqsupset$	$\wedge$	$\mid$	$\smile$
$\equiv$	$\equiv$	$\sqsubset$	$\sqsupset$	$\wedge$	$\mid$	$\smile$
$\sqsubset$	$\sqsubset$	$\sqsubset$	$\cdot$	$\mid$	$\mid$	$\cdot$
$\sqsupset$	$\sqsupset$	$\cdot$	$\sqsupset$	$\smile$	$\cdot$	$\smile$
$\wedge$	$\wedge$	$\smile$	$\mid$	$\equiv$	$\sqsupset$	$\sqsubset$
$\mid$	$\mid$	$\cdot$	$\mid$	$\sqsubset$	$\cdot$	$\sqsubset$
$\smile$	$\smile$	$\smile$	$\cdot$	$\sqsupset$	$\sqsupset$	$\cdot$

M-rules

$$\frac{\Gamma \vdash \varphi \mathcal{R} \psi \qquad \Gamma \vdash \psi \mathcal{S} \chi}{\Gamma \vdash \varphi \mathcal{T} \chi}\ \mathcal{R},\mathcal{S}$$

MacCartney rules

$\mathcal{R}, \mathcal{S}$	$\equiv$	$\sqsubset$	$\sqsupset$	$\wedge$	$\mid$	$\smile$
$\equiv$	$\equiv$	$\sqsubset$	$\sqsupset$	$\wedge$	$\mid$	$\smile$
$\sqsubset$	$\sqsubset$	$\sqsubset$	$\cdot$	$\mid$	$\mid$	$\cdot$
$\sqsupset$	$\sqsupset$	$\cdot$	$\sqsupset$	$\smile$	$\cdot$	$\smile$
$\wedge$	$\wedge$	$\smile$	$\mid$	$\equiv$	$\sqsupset$	$\sqsubset$
$\mid$	$\mid$	$\cdot$	$\mid$	$\sqsubset$	$\cdot$	$\sqsubset$
$\smile$	$\smile$	$\smile$	$\cdot$	$\sqsupset$	$\sqsupset$	$\cdot$

M-rules: Instantiated with $\sqsubset, \sqsubset$

$$\frac{\Gamma \vdash \varphi \sqsubset \psi \qquad \Gamma \vdash \psi \sqsubset \chi}{\Gamma \vdash \varphi \sqsubset \chi}\ {\sqsubset, \sqsubset}$$

MacCartney rules

$\mathcal{R}, \mathcal{S}$	$\equiv$	$\sqsubset$	$\sqsupset$	$\wedge$	$\mid$	$\smile$
$\equiv$	$\equiv$	$\sqsubset$	$\sqsupset$	$\wedge$	$\mid$	$\smile$
$\sqsubset$	$\sqsubset$	$\sqsubset$	$\cdot$	$\mid$	$\mid$	$\cdot$
$\sqsupset$	$\sqsupset$	$\cdot$	$\sqsupset$	$\smile$	$\cdot$	$\smile$
$\wedge$	$\wedge$	$\smile$	$\mid$	$\equiv$	$\sqsupset$	$\sqsubset$
$\mid$	$\mid$	$\cdot$	$\mid$	$\sqsubset$	$\cdot$	$\sqsubset$
$\smile$	$\smile$	$\smile$	$\cdot$	$\sqsupset$	$\sqsupset$	$\cdot$

***M*-rules: Instantiated with $\sqsubset, \wedge$**

$$\frac{\Gamma \vdash \varphi \sqsubset \psi \qquad \Gamma \vdash \psi \wedge \chi}{\Gamma \vdash \varphi \mid \chi}\ {\scriptstyle \sqsubset, \wedge}$$

Additional proof rules

Definition (*D*-rules)

$$\frac{}{\Gamma \vdash \varphi \equiv \varphi}\equiv_1 \qquad \frac{\Gamma \vdash \varphi \equiv \psi}{\Gamma \vdash \psi \equiv \varphi}\equiv_2 \qquad \frac{}{\Gamma \vdash \varphi \,{}^\wedge\, \overline{\varphi}}{}^\wedge{}_1 \qquad \frac{\Gamma \vdash \varphi \,{}^\wedge\, \psi}{\Gamma \vdash \psi \,{}^\wedge\, \varphi}{}^\wedge{}_2$$

$$\frac{\Gamma \vdash \varphi \sqsubset \psi}{\Gamma \vdash \psi \sqsubset \varphi}\sqsubset_1 \qquad \frac{\Gamma \vdash \varphi \sqsupset \psi}{\Gamma \vdash \psi \sqsubset \varphi}\sqsupset_1 \qquad \frac{\Gamma \vdash \varphi \mid \psi}{\Gamma \vdash \psi \mid \varphi}|_1 \qquad \frac{\Gamma \vdash \varphi \smile \psi}{\Gamma \vdash \psi \smile \varphi}\smile_1$$

Definition (Reflexivity)

$$\frac{\varphi \mathcal{R} \psi \in \Gamma}{\Gamma \vdash \varphi \mathcal{R} \psi}\text{Refl}$$

Proofs involving complementation

Theorem (Complementation)

1. $\Gamma \vdash \varphi \equiv \psi \Leftrightarrow \Gamma \vdash \varphi \wedge \overline{\psi}$
2. $\Gamma \vdash \varphi \wedge \psi \Leftrightarrow \Gamma \vdash \varphi \equiv \overline{\psi}$
3. $\Gamma \vdash \varphi \equiv \overline{\overline{\varphi}}$ *(double negation)*
4. $\Gamma \vdash \varphi \sqsubset \psi \Leftrightarrow \Gamma \vdash \overline{\psi} \sqsubset \overline{\varphi}$ *(contraposition)*
5. $\Gamma \vdash \varphi \sqsupset \psi \Leftrightarrow \Gamma \vdash \overline{\varphi} \sqsubset \overline{\psi}$
6. $\Gamma \vdash \varphi \mid \psi \Leftrightarrow \Gamma \vdash \varphi \sqsubset \overline{\psi}$
7. $\Gamma \vdash \varphi \smile \psi \Leftrightarrow \Gamma \vdash \varphi \sqsupset \overline{\psi}$

Natural language inference

Definition (M-rule: $|, ^\wedge$)

$$\frac{\Gamma \vdash \varphi \mid \psi \qquad \Gamma \vdash \psi \,^\wedge\, \chi}{\Gamma \vdash \varphi \sqsubset \chi}\ |,^\wedge$$

Theorem

$\Gamma \vdash \varphi \mid \psi \Rightarrow \Gamma \vdash \varphi \sqsubset \overline{\psi}$

Proof.

$$\frac{\Gamma \vdash \varphi \mid \psi \qquad \dfrac{}{\Gamma \vdash \psi \,^\wedge\, \overline{\psi}}\ {}^\wedge{}_1}{\Gamma \vdash \varphi \sqsubset \overline{\psi}}\ |,^\wedge$$

$\square$

Natural language inference

Definition (M-rule: $|, ^\wedge$)

$$\frac{\Gamma \vdash \varphi \mid \psi \qquad \Gamma \vdash \psi \mathbin{^\wedge} \chi}{\Gamma \vdash \varphi \sqsubset \chi}\;|,^\wedge$$

Theorem

$\Gamma \vdash \mathit{cat} \mid \mathit{dog} \Rightarrow \Gamma \vdash \mathit{cat} \sqsubset \overline{\mathit{dog}}$

Proof.

$$\frac{\Gamma \vdash \text{cat} \mid \text{dog} \qquad \dfrac{}{\Gamma \vdash \text{dog} \mathbin{^\wedge} \overline{\text{dog}}}\;^\wedge 1}{\Gamma \vdash \text{cat} \sqsubset \overline{\text{dog}}}\;|,^\wedge$$

□

Final proof rule

Definition (Explosion)

$$\frac{\Gamma \vdash \varphi \mathcal{R} \psi \qquad \Gamma \vdash \varphi \mathcal{S} \psi \qquad \text{for } \mathcal{R} \neq \mathcal{S}}{\Gamma \vdash \varphi' \mathcal{T} \psi' \text{ for all synthetic terms } \varphi' \mathcal{T} \psi'} \text{Exp}$$

Consistency

Definition (Consistency)

Γ is consistent if, and only if $\Gamma \nvdash \varphi \mathcal{R} \psi$ for some synthetic term $\varphi \mathcal{R} \psi$.

Inconsistency

Theorem (Inconsistent set)

$\Gamma = \{\varphi \sqsubset \psi, \psi \sqsupset \vartheta, \varphi \smile \vartheta\}$ *is inconsistent*

Proof.

$$\dfrac{\dfrac{\dfrac{\dfrac{\varphi \sqsubset \psi \in \Gamma}{\Gamma \vdash \varphi \sqsubset \psi}\,\text{Refl}}{\Gamma \vdash \psi \sqsupset \varphi}\,\sqsubset_1 \qquad \dfrac{\varphi \smile \vartheta \in \Gamma}{\Gamma \vdash \varphi \smile \vartheta}\,\text{Refl}}{\Gamma \vdash \psi \smile \vartheta}\,\sqsupset,\smile \qquad \dfrac{\psi \sqsupset \vartheta \in \Gamma}{\Gamma \vdash \psi \sqsupset \vartheta}\,\text{Refl}}{\text{☹}}\,\text{Exp}$$

□

Propositional Synthetic Logic completeness

Completeness

$$\Gamma \vdash \varphi \mathcal{R} \psi \Leftrightarrow \Gamma \models \varphi \mathcal{R} \psi$$

Soundness proof sketch

Soundness (if provable, then true)

$$\Gamma \vdash \varphi \mathcal{R} \psi \Rightarrow \Gamma \models \varphi \mathcal{R} \psi$$

1. By induction on the height of the derivation.
2. Basic set-theoretic observations.

Example

$$\frac{\Gamma \vdash \varphi \sqsubset \psi \qquad \Gamma \vdash \psi \sqsubset \chi}{\Gamma \vdash \varphi \sqsubset \chi}\ {\sqsubset,\sqsubset}$$

The semantics of $\sqsubset$ is strict set-theoretic containment, which is transitive.

Adequacy proof sketch

Adequacy of the Proof Calculus

$$\Gamma \models \varphi \mathcal{R} \psi \Rightarrow \Gamma \vdash \varphi \mathcal{R} \psi \Leftrightarrow \underbrace{\Gamma \nvdash \varphi \mathcal{R} \psi \Rightarrow \Gamma \not\models \varphi \mathcal{R} \psi}_{\text{contraposition}}$$

The strategy

The proof is built around a model existence lemma: we show that every consistent Γ has a synthetic model $\mathbb{M}$ such that

$$\Gamma \vdash \varphi \mathcal{R} \psi \Leftrightarrow \mathbb{M} \models \varphi \mathcal{R} \psi \qquad \text{for all } \varphi, \mathcal{R}, \psi$$

Model construction via representation

1. Every consistent Γ induces an order on the set of proper terms Φ.
2. That ordered set can be transformed into an orthoposet.
3. Every orthoposet can be represented as a system of sets.
4. The system of sets will function as a synthetic model for Γ.

Cristian Calude, Peter Hertling, and Karl Svozil. 1999. Embedding quantum universes in classical ones. *Foundations of Physics* 29: 349–379.

Lawrence S. Moss. 2007. Syllogistic logic with complements. Manuscript, Indiana University.

Nel Zierler and Michael Schlessinger. 1965. Boolean embeddings of orthomodular sets and quantum and logic. *Duke Math Journal* 32: 251–262.

From premise sets to orthoposets

Definition (Orthposets)

An *orthoposet* is a tuple $(P, \leq, 0, -)$ such that

1. $(P, \leq)$ is a partial order;
2. 0 is a minimal element, i.e., $0 \leq x$ for all $x \in P$;
3. $x \leq y$ if, and only if $\overline{y} \leq \overline{x}$;
4. $\overline{\overline{x}} = x$
5. If $x \leq y$ and $x \leq \overline{y}$, then $x = 0$.

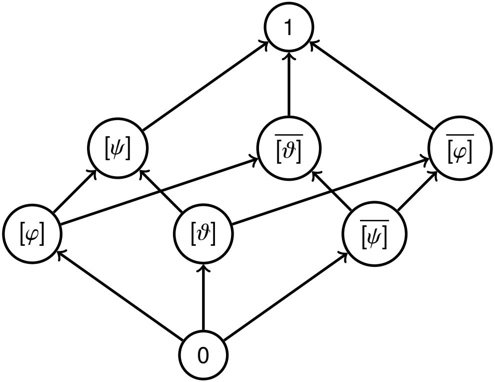
From arbitrary consistent Γ to orthoposet $(\Phi^*, \leq_\Gamma, 0, -)$

- Φ^* is a set of equivalence classes under $\equiv$;
- $\varphi \leq_\Gamma \psi \;\Leftrightarrow\; \Gamma \vdash \varphi \equiv \psi$ or $\Gamma \vdash \varphi \sqsubset \psi$
- 0 is a fresh element added not in the original language;
- $-$ is the complementation operator.

Example of orthoposet construction

1. Define the relation $\leq_\Gamma$: $\varphi \leq_\Gamma \psi \iff \Gamma \vdash \varphi \equiv \psi$ or $\Gamma \vdash \varphi \sqsubset \psi$
2. $\leq_\Gamma$ induces an equivalence relation under $\equiv$
3. Let the elements of the orthoposet be those equivalence classes
4. Let the equivalence class for φ, written $[\overline{\varphi}]$, be $\overline{[\varphi]}$
5. Add elements $0, 1$ to Φ, setting $\overline{0} = 1$ and $0 < x < 1$:

$$\Gamma = \{\varphi \sqsubset \psi, \vartheta \sqsubset \psi, \varphi \mid \vartheta\}$$



From orthopsets to systems of sets (models)

Definition (Points)

A *point* of an orthoposet P is a subset $S \subseteq P$ such that:

1. If $x \in S$ and $x \leq y$, then $y \in S$ (S is *upward-closed*);
2. For all x, either $x \in S$ or $\overline{x} \in S$ (S is *complete*), but not both (S is *consistent*).

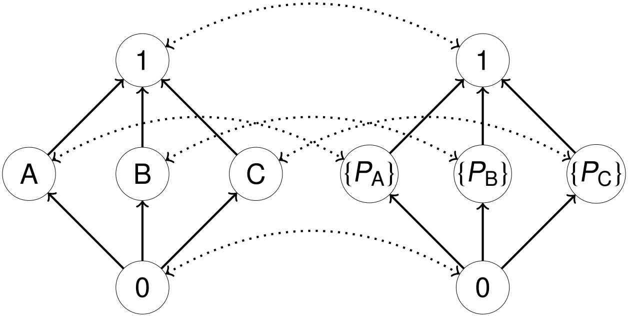
From orthopsets to systems of sets (models)

Theorem (Representation)

Let $P = (P, \leq, 0, -)$ be an orthoposet. There is a set $points(P)$ and a strict morphism f such that

$$f : P \to \mathcal{P}(points(P))$$

by setting $f(x) = \{S \in points(P) \mid x \in S\}$



Model construction (putting the pieces together)

Recall, $(\Phi^*, \leq, 0, -)$ is an orthoposet. So,

1. Define $g : \Phi \to \Phi^*$ such that
$$\varphi \mapsto [\varphi]_{=_\Gamma}$$
2. Set $f : \Phi^* \to \mathcal{P}(\text{points}(\Phi^*))$ such that
$$f(x) = \{S \in \text{points}(\Phi^*) \mid x \in S\}$$
3. Let $[\![\cdot]\!]$ be defined as the *composition* of f and g $(f \cdot g)$.

Model existence

Lemma

$$\mathbb{M} \models \varphi \mathcal{R} \psi \Leftrightarrow \Gamma \vdash \varphi \mathcal{R} \psi$$

Proof.

$$\begin{aligned}
\Gamma \vdash \varphi \equiv \psi &\Leftrightarrow g(\varphi) = g(\psi) \\
&\Leftrightarrow f(g(\varphi)) = f(g(\psi)) \\
&\Leftrightarrow [\![\varphi]\!] = [\![\psi]\!] \\
&\Leftrightarrow \mathbb{M} \models \varphi \equiv \psi
\end{aligned}$$

$$\begin{aligned}
\Gamma \vdash \varphi \sqsubset \psi &\Leftrightarrow g(\varphi) <_\Gamma g(\psi) \\
&\Leftrightarrow f(g(\varphi)) \subset f(g(\psi)) \\
&\Leftrightarrow [\![\varphi]\!] \subset [\![\psi]\!] \\
&\Leftrightarrow \mathbb{M} \models \varphi \sqsubset \psi
\end{aligned}$$

$\square$

Semantic composition

- We have so far looked only at lexical reasoning, or reasoning within a single type domain.
- We now extend the system, more informally, with a theory of semantic composition.

Projectivity

Every pair of like-typed lexical items has an associated projectivity signature mapping synthetic logic relations into same.

Example (Negation, both inserted and deleted)

$$\text{Project}(\textbf{not}, \textbf{not}) = \text{Project}(\varepsilon, \textbf{not}) = \begin{bmatrix} \sqsubset & \mapsto & \sqsupset \\ \sqsupset & \mapsto & \sqsubset \\ | & \mapsto & \smile \\ \smile & \mapsto & | \\ \equiv & \mapsto & \equiv \\ \wedge & \mapsto & \wedge \end{bmatrix}$$

$$\text{Project}(\textbf{not}, \varepsilon) = \text{identity}$$

- MacCartney motivates numerous projectivity signatures, for one- and two-place operators, as well as default signatures for inserting and deleting phrases.
- Thomas Icard is currently exploring the formal properties of the linguistically useful signatures.

Semantic compositon rule

Definition (Semantic composition)

The rule for computing the value of the mother based on its daughter:

$\mathcal{R} \bowtie \text{Project}(\alpha,\beta)(\mathcal{S})$ with daughters $\alpha\mathcal{R}\beta$ and $\delta\mathcal{S}\gamma$

or

$\text{Project}(\alpha,\beta)(\mathcal{S}) \bowtie \mathcal{R}$ with daughters $\alpha\mathcal{R}\beta$ and $\delta\mathcal{S}\gamma$

where $\mathcal{A} \bowtie \mathcal{B}$ abbreviates the proof

$$\frac{\Gamma \vdash \varphi\mathcal{A}\psi \qquad \Gamma \vdash \psi\mathcal{B}\chi}{\Gamma \vdash \varphi\mathcal{C}\chi}\ \mathcal{A},\mathcal{B}$$

$\mathcal{R},\mathcal{S}$	$\equiv$	$\sqsubset$	$\sqsupset$	$\wedge$	$\mid$	$\smile$
$\equiv$	$\equiv$	$\sqsubset$	$\sqsupset$	$\wedge$	$\mid$	$\smile$
$\sqsubset$	$\sqsubset$	$\sqsubset$	$\cdot$	$\mid$	$\mid$	$\cdot$
$\sqsupset$	$\sqsupset$	$\cdot$	$\sqsupset$	$\smile$	$\cdot$	$\smile$
$\wedge$	$\wedge$	$\smile$	$\mid$	$\equiv$	$\sqsupset$	$\sqsubset$
$\mid$	$\mid$	$\cdot$	$\mid$	$\sqsubset$	$\cdot$	$\sqsubset$
$\smile$	$\smile$	$\smile$	$\cdot$	$\sqsupset$	$\sqsupset$	$\cdot$

Example: negation

Example (Insertion)

$$\text{Project}(\varepsilon, \textbf{not}) = \begin{bmatrix} \sqsubset & \mapsto & \sqsupset \\ \sqsupset & \mapsto & \sqsubset \\ \mid & \mapsto & \smile \\ \smile & \mapsto & \mid \\ \equiv & \mapsto & \equiv \\ \wedge & \mapsto & \wedge \end{bmatrix}$$

move $\smile$ **not run**

ε $\wedge$ **not**   **move** $\sqsupset$ **run**

Example (Deletion)

$\text{Project}(\textbf{not}, \varepsilon) = \text{identity}$

not move $\mid$ **run**

not $\wedge$ ε **move** $\sqsupset$ **run**

$\mathcal{R}, \mathcal{S}$	$\equiv$	$\sqsubset$	$\sqsupset$	$\wedge$	$\mid$	$\smile$
$\equiv$	$\equiv$	$\sqsubset$	$\sqsupset$	$\wedge$	$\mid$	$\smile$
$\sqsubset$	$\sqsubset$	$\sqsubset$	$\cdot$	$\mid$	$\mid$	$\cdot$
$\sqsupset$	$\sqsupset$	$\cdot$	$\sqsupset$	$\smile$	$\cdot$	$\smile$
$\wedge$	$\wedge$	$\smile$	$\mid$	$\equiv$	$\sqsupset$	$\sqsubset$
$\mid$	$\mid$	$\cdot$	$\mid$	$\sqsubset$	$\cdot$	$\sqsubset$
$\smile$	$\smile$	$\smile$	$\cdot$	$\sqsupset$	$\sqsupset$	$\cdot$

Lexical meanings

- Instantiating the lexicon using multiple resources
- Balancing high precision (WordNet and hand-built lexicons) with broad coverage (data gathered from the Web)
- Using Synthetic Logic to characterize this information and reason in terms of it

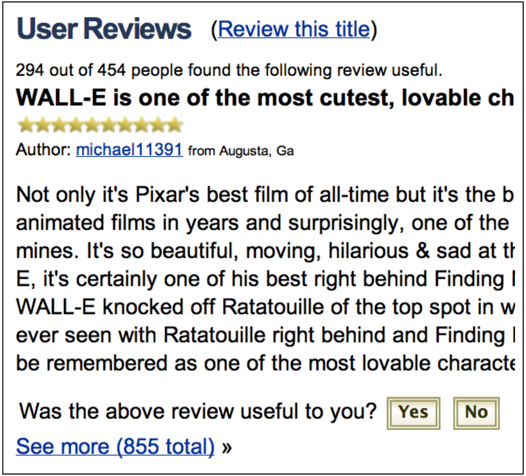
WordNet (roughly as in MacCartney's work)

$$
\begin{array}{rll}
\textbf{if} & \mathrm{WordNet}(\varphi,\psi) = \text{antonym} & \textbf{then } \varphi \mid \psi \\[2ex]
\textbf{else if} & \mathrm{WordNet}(\varphi,\psi) \in \left\{\begin{array}{c}\text{entailment, (instance) hypernym,} \\ \text{member|substance|part meronym}\end{array}\right\} & \textbf{then } \varphi \sqsubset \psi \\[2ex]
\textbf{else if} & \mathrm{WordNet}(\varphi,\psi) \in \left\{\begin{array}{c}\text{cause, (instance) hyponym,} \\ \text{member|substance|part holonym}\end{array}\right\} & \textbf{then } \varphi \sqsupset \psi \\[2ex]
\textbf{else if} & \mathrm{WordNet}(\varphi,\psi) \in \left\{\begin{array}{c}\text{also see, similar to, synonym} \\ \text{derivationally related, pertainym}\end{array}\right\} & \textbf{then } \varphi \equiv \psi \\[2ex]
\textbf{else} & \varphi \# \psi &
\end{array}
$$

Overview of WordNet coverage

	a	n	r	v
hypernyms	0	74389	0	13208
instance hypernyms	0	7730	0	0
hyponyms	0	16693	0	3315
instance hyponyms	0	945	0	0
member holonyms	0	12201	0	0
substance holonyms	0	551	0	0
part holonyms	0	7859	0	0
member meronyms	0	5553	0	0
substance meronyms	0	666	0	0
part meronyms	0	3699	0	0
attributes	620	320	0	0
entailments	0	0	0	390
causes	0	0	0	218
also sees	1333	0	0	325
verb groups	0	0	0	1498
similar tos	13205	0	0	0
antonyms	3872	2120	707	1069
derivationally related	10531	26758	1	13102
pertainyms	4665	0	3220	0

IMDB user-supplied reviews

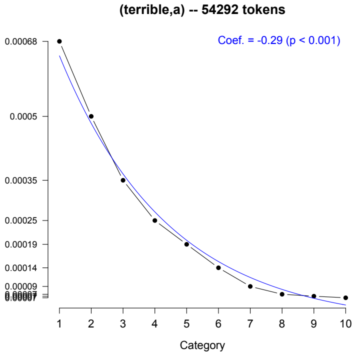


IMDB user-supplied reviews

Rating	Reviews	Words	Vocabulary	Mean words/review
1	124,587 (9%)	25,395,214	172,346	203.84
2	51,390 (4%)	11,755,132	119,245	228.74
3	58,051 (4%)	13,995,838	132,002	241.10
4	59,781 (4%)	14,963,866	138,355	250.31
5	80,487 (6%)	20,390,515	164,476	253.34
6	106,145 (8%)	27,420,036	194,195	258.33
7	157,005 (12%)	40,192,077	240,876	255.99
8	195,378 (14%)	48,723,444	267,901	249.38
9	170,531 (13%)	40,277,743	236,249	236.19
10	358,441 (26%)	73,948,447	330,784	206.31
Total	1,361,796	317,062,312	800,743	232.83

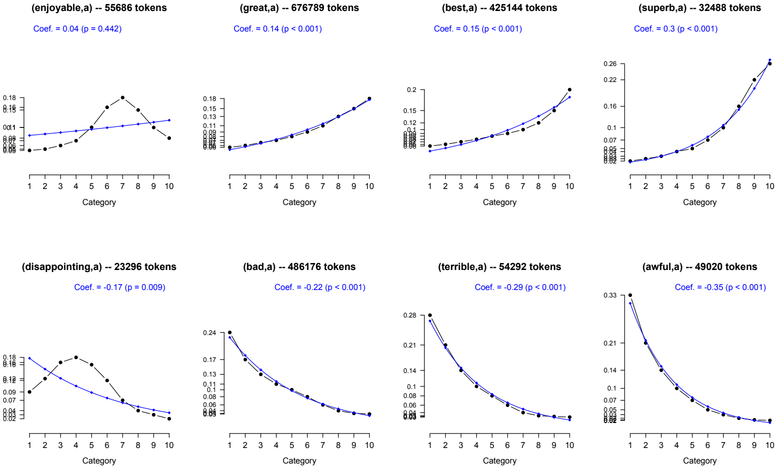
Counting and visualizing: IMDB

A R	B Count	C Total	D $\Pr(w\|c)$
1	17256	25395214	0.00068
2	5875	11755132	0.00050
3	4851	13995838	0.00035
4	3744	14963866	0.00025
5	3938	20390515	0.00019
6	3755	27420036	0.00014
7	3709	40192077	0.00009
8	3581	48723444	0.00007
9	2773	40277743	0.00007
10	4810	73948447	0.00007



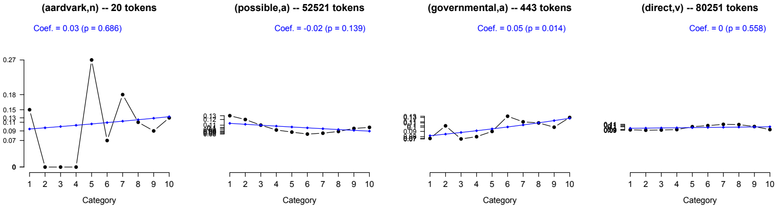
$$Pr(terrible, a) = \text{logit}^{-1}(7.06 + -0.29 * \text{category})$$

Scalars



(Pr$(w|c)$ values rescaled to Pr$(c|w)$ to facilitate comparison.)

Duds


(aardvark,n) -- 20 tokens
Coef. = 0.03 (p = 0.686)
0.27
0.18
0.15
0.13
0.11
0.09
0.07
0
1 2 3 4 5 6 7 8 9 10
Category
(possible,a) -- 52521 tokens
Coef. = -0.02 (p = 0.139)
1 2 3 4 5 6 7 8 9 10
Category
(governmental,a) -- 443 tokens
Coef. = 0.05 (p = 0.014)
1 2 3 4 5 6 7 8 9 10
Category
(direct,v) -- 80251 tokens
Coef. = 0 (p = 0.558)
1 2 3 4 5 6 7 8 9 10
Category

Scalar semantics

Definition (coef)

$\text{coef}(\varphi) \overset{def}{=}$ the coeffecient estimate for Category

Definition (imdb_x)

$$\text{imdb}_x(\varphi) \overset{def}{=} \begin{cases} \text{coef}(\varphi) & \text{if } p \leqslant x \\ \text{undefined otherwise} \end{cases}$$

Definition (Scalar relations)

$$\begin{array}{rrcll}
\textbf{if} & \text{sign}(\text{imdb}_x(\varphi)) & \neq & \text{sign}(\text{imdb}_x(\psi)) & \textbf{then } \varphi \mid \psi \\
\textbf{else if} & \text{imdb}_x(\varphi) & \approx & \text{imdb}_x(\psi) & \textbf{then } \varphi \equiv \psi \\
\textbf{else if} & \text{abs}(\text{imdb}_x(\varphi)) & > & \text{abs}(\text{imdb}_x(\psi)) & \textbf{then } \varphi \sqsubset \psi \\
\textbf{else if} & \text{abs}(\text{imdb}_x(\varphi)) & < & \text{abs}(\text{imdb}_x(\psi)) & \textbf{then } \varphi \sqsupset \psi
\end{array}$$

Lexical semantics

if WordNet(φ, ψ) = antonym **then** $\varphi \mid \psi$

else if WordNet$(\varphi, \psi) \in \left\{ \begin{array}{c} \text{entailment, (instance) hypernym,} \\ \text{member|substance|part meronym} \end{array} \right\}$ **then** $\varphi \sqsubset \psi$

else if WordNet$(\varphi, \psi) \in \left\{ \begin{array}{c} \text{cause, (instance) hyponym,} \\ \text{member|substance|part holonym} \end{array} \right\}$ **then** $\varphi \sqsupset \psi$

else if WordNet$(\varphi, \psi) \in \left\{ \begin{array}{c} \text{also see, similar to, synonym} \\ \text{derivationally related, pertainym} \end{array} \right\}$ **then** $\varphi \equiv \psi$

else if coef(φ) and coef(ψ) are defined **then**

- **if** sign(imdb$_x(\varphi)$) $\neq$ sign(imdb$_x(\psi)$) **then** $\varphi \mid \psi$
- **else if** imdb$_x(\varphi) \approx$ imdb$_x(\psi)$ **then** $\varphi \equiv \psi$
- **else if** abs(imdb$_x(\varphi)$) $>$ abs(imdb$_x(\psi)$) **then** $\varphi \sqsubset \psi$
- **else if** abs(imdb$_x(\varphi)$) $<$ abs(imdb$_x(\psi)$) **then** $\varphi \sqsupset \psi$

else $\varphi \# \psi$

(implementation: compprag.christopherpotts.net/iqap-experiments.html)

Hand-built supplementary lexicon

- Our method doesn't learn sensible meanings for most pairs of closed-class lexical items, so we specify those relations by hand.
- Our method doesn't learn projectivity signatures, so we write those by hand (mostly taking them from MacCartney's work).

Indirect question–answer pairs experiment

- A new corpus
- A new experiment, akin to MacCartney's but with more intermingling of semantics and pragmatics
- A: Does the system work?
  B: It's instructive.

Answers and inferences

Jerrold Katz, *Semantic Theory*: Meaning as relations between forms

- What is meaning? broken down:
  - What is synonymy?
  - What is antonymy?
  - What is superordination?
  - What is semantic ambiguity?
  - What is semantic truth (analyticity, metalinguistic truth, etc.)?
  - What is a possible answer to a question?
  - ...

Example

A: Was the vacation enjoyable?

B: It was memorable.

Collaborators

Marie-Catherine de Marneffe

Scott Grimm

Chris Manning

Marie-Catherine de Marneffe, Scott Grimm & Christopher Potts. 2009. Not a simple yes or no: Uncertainty in indirect answers. Proceedings of SIGDIAL 10.

Marie-Catherine de Marneffe, Christopher D. Manning & Christopher Potts. 2010. Was it good? It was provocative. Learning the meaning of scalar adjectives. Proceedings of ACL 48.

IQAP corpus

Source	Dev. set	Eval. set
CNN show transcripts	40	17
From Julia Hirschberg's (1985) thesis	26	12
The Switchboard Dialog Act Corpus	26	11
Yahoo Answers Corpus	58	25
Total	150	65

Available at compprag.christopherpotts.net/iqap.html

Annotations

Indirect Answers to Yes/No Questions

In the following dialogue, speaker A asks a simple Yes/No question, but speaker B answers with something more indirect and complicated:

A: ${Question}

B: ${Answer}

Which of the following best captures what speaker B meant here?

- B definitely meant to convey "Yes".
- B probably meant to convey "Yes".
- B definitely meant to convey "No".
- B probably meant to convey "No".

30 annotations per IQAP:

A: Have you mailed that letter yet?

B: I haven't proofread it.

$$\begin{bmatrix} \text{definite yes} & 0 \\ \text{probable yes} & 0 \\ \text{probable no} & 5 \\ \text{definite no} & 25 \end{bmatrix} \Rightarrow \begin{bmatrix} \text{yes} & 0 \\ \boxed{\text{no} \quad 30} \end{bmatrix}$$

Entailment cases

The answer is stronger than the question radical:		def. Y	prob. Y	prob. N	def. N
Did he do a good job?	He did a great job.	30	0	0	0
Is it a comedy?	I think it's a black comedy.	14	16	0	0
Is Cadillac an American company?	It's a division of General Motors.	7	22	1	0
Have you finished the third grade?	I've finished the fourth.	20	9	1	0

The answer is stronger than the negation of the question radical:

Do you think that's a good idea?	It's a terrible idea.	0	0	1	29
Is Santa an only child?	He has a brother named Fred.	1	0	5	24

The question radical is stronger than the negation of the answer:

Have you mailed that letter yet?	I haven't proofread it.	0	0	5	25
Did you buy a house?	We haven't gotten a mortgage yet.	0	2	12	16

Implicature cases

The question radical is stronger than the answer:		def. Y	prob. Y	prob. N	def. N
Have you mailed that letter yet?	I've typed it.	0	0	15	15
Did you buy a house?	We haven't gotten a mortgage yet.	0	2	16	12
Did you ever get any information on it?	I sent off for stuff on it.	0	4	3	23
Is it a sin to get drunk?	It is a sin to drink to excess.	13	14	2	1
Do you need this?	I want it.	2	15	13	0

The question radical and the answer seem to be independent:					
Do you know how to spell it?	It starts with a K.	0	6	20	4
Have you made fondue in this pot yet?	Not chocolate fondue.	1	19	9	1
Do you speak Ladino?	I speak Spanish.	1	9	16	4
Do you have paste?	We have rubber cement.	0	8	18	4
Was he cute?	He wasn't stunning.	2	2	7	19
Have you read the third chapter?	I read the fourth.	3	16	9	2

Answerhood

$$
\begin{array}{rcll}
\text{Question} \equiv \text{Answer} & \Rightarrow & \text{`Yes'} & \text{(entailed)} \\
\text{Question} \sqsupset \text{Answer} & \Rightarrow & \text{`Yes'} & \text{(entailed)} \\[6pt]
\text{Question} \mid \text{Answer} & \Rightarrow & \text{`No'} & \text{(entailed)} \\
\text{Question} \wedge \text{Answer} & \Rightarrow & \text{`No'} & \text{(entailed)} \\[6pt]
\text{Question} \smile \text{Answer} & \Rightarrow & \text{`No'} & \text{(implicated)} \\
\text{Question} \sqsubset \text{Answer} & \Rightarrow & \text{`No'} & \text{(implicated)} \\
\text{Question} \# \text{Answer} & \Rightarrow & \text{`No'} & \text{(implicated)}
\end{array}
$$

Examples

A: Is Kenya a continent?

B: It's a country in eastern Africa.
[Yes: 1, No: 29]

‘No’
continent | country in-ea

continent | country $\quad$ $\varepsilon \sqsupset$ **in-ea**

A: Was he cute?

B: He wasn't stunning.
[Yes: 4, No: 26]

‘No’
cute $\smile$ **not stunning**

ε ^ **not** $\quad$ **cute** $\sqsupset$ **stunning**

A: Do you need this?

B: I want it.
[Yes: 17, No: 13]

‘No’
need this $\sqsubset$ **want it**

need $\sqsubset$ **want** $\quad$ **this** $\equiv$ **it**

Experiment

Limited to the development set. Hand-alignment of 'contrast' subtrees.
Experiment code: code.google.com/p/pynatlog/

	precision	recall
'Yes'	0.63	0.73
'No'	0.82	0.74

Table: Effectiveness results for our approach. Accuracy: 0.74.

	precision	recall
'Yes'	0.71	0.44
'No'	0.66	0.86

Table: Deterministic approach, no semantic composition. Accuracy: 0.67.

micro-averaged precision	micro-averaged recall
0.8	0.76

Table: MaxEnt, no composition, 10 random train/test splits. Average accuracy: 0.77. (0.8 on training data.)

Discussion

1. WordNet is high precision but low coverage: just 22% of the examples rely on WordNet, but accuracy is around 88% for them.
2. The IMDB is lower precision, but high coverage: 43% of the examples rely on IMDB, and accuracy is around 71%.
3. 82/150 examples involve comparing just one word. For these, accuracy is 68%.
4. We get a performance boost from the fact that where our algorithm fails to predict a relationship, we infer independence, i.e., a ‘No’.
5. Implicature inferences correlate with higher variability in the annotations and more use of the ‘probable’ categories. We should find a way to bring this into the model.

Conclusion

Summary

1. Developed Propositional Synthetic Logic and proved completeness
2. Extended PSL with a theory of composition (inspired by MacCarntney's NatLog procedure)
3. Instantiated a broad-coverage lexicon using multiple sources
4. Reported on an initial experiment using a new corpus of indirect question–answer pairs

Looking ahead

- Meta-logical results for the theory of composition
- Methods for automatic alignment
- Extend the corpus to include a wider range of examples
- Bring in contextual information