# Introduction to Natural Language Processing

Alexandre Rademaker

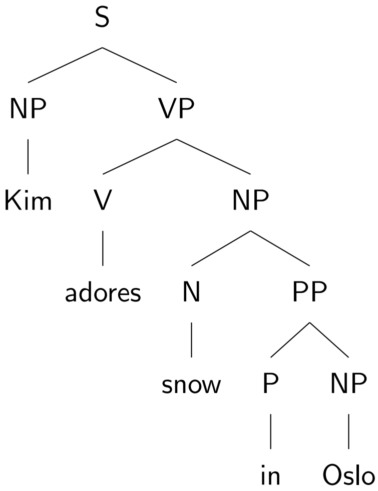
FGV EMAp

October 6, 2021

# Overview

- Formal semantics, FOL, lambda-calculus
- Compositional semantics
- Semantics in computational linguistics
- Semantics in NLP

# Parsing makes explicit inherent structure. So, does this tree represent meaning?



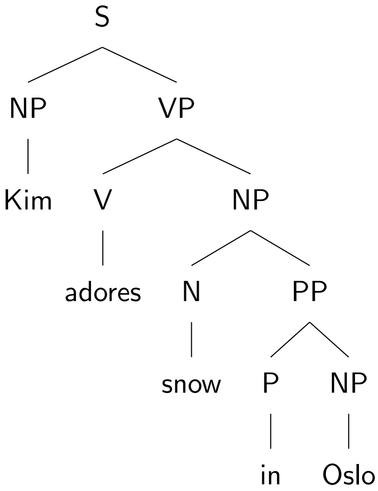
# Why represent meaning computationally?

*I hated this movie!*

- A Dialog system:
  - Parser:
    - Yes, it is grammatical!
    - Here's the structure!
  - System: Great, but what am I supposed to DO?

# Formal semantics question:

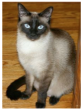
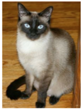
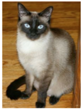
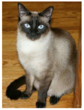
**How could we put this tree in correspondence to a model of the world?**



# Model theoretic semantics

- Create a model of the world consisting of elements, sets of elements, and relations
  - not so much a model of what things **mean** as of **how we reason** about them
- Create an interpretation function which maps linguistic elements (parts of the semantic structure) to parts of the model
- Simple propositions are interpreted by checking their truth in the model
- Define semantics for "logical vocabulary": and, or, not, if, every, some...

# Model theoretic semantics (example)

- Entities: Joey:  Fluffy:  Tiger: 
- Properties: calm: {   }; angry: {  }
- Relations: knows: { <  ,  > , <  ,  > }

# Model theoretic semantics (denotations)

- [[Fluffy]] = 

- [[angry]] = { x | x is angry } = {  }

- [[Fluffy is angry]] = True *iff* the entity denoted by *Fluffy* is in the set denoted by *angry*

- Compositionality: The process of determining the truth conditions of *Fluffy is angry* based on the denotations of its parts and its syntactic structure

# Logical vocabulary gets special treatment

- “First Class and Smile Members here“ (airport)
- Fluffy is angry and Joey is not angry.
  - What does *and* mean?
  - What does *not* mean?
- Every cat is angry.
  - What does *cat* mean?
  - What does *every* mean?
- Is the division into logical and non-logical vocabulary an inherent property of language or an artifact of the system of meaning representation?

# Quantifiers

- The semantic type of a quantifier is a relation between sets, called the restriction and body (or scope) of the quantifier
- $[\![ \textit{every} ]\!]$ $\{ <P,Q> \mid P \subseteq Q \}$
- $[\![$every cat is angry$]\!]$ is True iff
  $\{ x \mid x \text{ is a cat} \} \subseteq \{ y \mid y \text{ is angry} \}$
- $[\![ \textit{some} ]\!]$ $\{ <P,Q> \mid P \cap Q \neq \emptyset \}$
- $[\![$some cat is angry$]\!]$ is True iff
  $\{ x \mid x \text{ is a cat} \} \cap \{ y \mid y \text{ is angry} \} \neq \emptyset$
- $[\![ \textit{many} ]\!]$ ?

# Partial evaluation for FOL: Lambda calculus

- Basic idea: pass around partially evaluated functions
- feed them to other functions as arguments
- e.g. $f : y = x + 2$
- plug in $x = 3$, evaluate to 5
- or: $f : z = y * (x + 2)$
- plug in $x = 3$, evaluate to $f : z = 3y$
- then can plug in y = 2 and evaluate to 6

# Lambda calculus for semantics

- Used to evaluate FOL expressions in a compositional manner
- e.g. constituent by constituent
- A constituent does not necessarily have a truth value:

$$\lambda x.gave(Kim, book, x)$$

- need to hold on to a partially evaluated constituent
- Converting multi-argument predicates to sequences of single-argument predicates
- Incrementally accumulates multiple arguments spread over different parts of the tree

# Lambda calculus

- Form: $\lambda$ + Variable + FOL expression
- $\lambda x.P(x)$ (evaluating the expression with respect to $x$)
- $\lambda x.P(x)(A) \rightarrow P(A)$ ($\lambda$-reduction; binding a formal parameter to a concrete term)
- $\lambda x.\lambda y.Near(x, y)$
- $\lambda x.\lambda y.Near(x, y)(Moscow)$
- $\lambda y.Near(Moscow, y)$
- $\lambda y.Near(Moscow, y)(Center)$
- $Near(Moscow, Center)$

# Lambda calculus and composition

- One semantic composition rule per syntax rule.
- `S -> NP VP`
  VP′(NP′)
- Rover barks:
  VP *bark* is $\lambda x[\text{bark}'(x)]$
  NP *Rover* is $r$
  $\lambda x[\text{bark}'(x)](r) = \text{bark}'(r)$

# Transitive verbs

Kitty chases Rover

- Transitive verbs: two arguments (NOTE the order)
  $\lambda x[\lambda y[\text{chase}'(y, x)]]$
- `VP -> Vtrans NP`
  $\text{Vtrans}'(\text{NP}')$
- $\lambda x \lambda y[\text{chase}'(y, x)](r) = \lambda y[\text{chase}'(y, r)]$
- `S -> NP VP`
  $\text{VP}'(\text{NP}')$
- $\lambda y[\text{chase}'(y, r)](k) = \text{chase}'(k, r)]$

# Grammar fragment using lambda calculus

| | |
|---|---|
| `S -> NP VP` | $\mathrm{VP}'(\mathrm{NP}')$ |
| `VP -> Vtrans NP` | $\mathrm{Vtrans}'(\mathrm{NP}')$ |
| `VP -> Vintrans` | $\mathrm{Vintrans}'$ |
| `Vtrans -> chases` | $\lambda x \lambda y[\mathrm{chase}'(y, x)]$ |
| `Vintrans -> barks` | $\lambda z[\mathrm{bark}'(z)]$ |
| `Vintrans -> sleeps` | $\lambda w[\mathrm{sleep}'(w)]$ |
| `NP -> Kitty` | $k$ |

# Beyond toy examples . . .

- Use first order logic where possible (e.g., event variables, next slide).
- However, First Order Predicate Calculus (FOPC) is sometimes inadequate: e.g., *most*, *may*, *believe*.
- Quantifier scoping multiplies analyses:
  *Every cat chased some dog*:
  $\forall x[\mathrm{cat}'(x) \implies \exists y[\mathrm{dog}'(y) \wedge \mathrm{chase}'(x,y)]]$
  $\exists y[\mathrm{dog}'(y) \wedge \forall x[\mathrm{cat}'(x) \implies \mathrm{chase}'(x,y)]]$
- Often no straightforward logical analysis
  e.g., Bare plurals such as *Ducks lay eggs*.
- Non-compositional phrases (multiword expressions): e.g., *red tape* meaning bureaucracy.

# Event variables

- Allow first order treatment of adverbs and PPs modifying verbs by reifying the event.
- Rover barked
- instead of $\text{bark}'(r)$ we have $\exists e[\text{bark}'(e, r)]$
- Rover barked loudly
- $\exists e[\text{bark}'(e, r) \wedge \text{loud}'(e)]$
- There was an event of Rover barking and that event was loud.

# Computational semantics desiderata (J&M)

- Verifiability: We must be able to compare the representation to a knowledge base
- Lack of ambiguity: A semantic representation should have just one interpretation
- Canonical form: A given interpretation should have just one representation
- Expressiveness: Must be able to adequately represent a wide range of expressions

# Computational semantics desiderata (Copestake)

- Expressive Adequacy: The framework must allow linguistic meanings to be expressed correctly
- Grammatical Compatibility: clear link to other kinds of grammatical information (most notably syntax)
- Computational Tractability: Process meanings, check semantic equivalence, express relationships between semantic representations straightforwardly
- Underspecifiability: Allow resolution of partial semantic representations

# Computational semantics

- Semantic parsing: mapping surface sentence to a semantic representation
- Should this representation be a structure?
  - Sentence meaning: probably yes
  - Speaker meaning: unclear

(But sentence meaning is usually directly involved in speaker meaning)

# Sentence vs. Speaker meaning (Grice 1968)

- Through experience within our speech communities, we learn (and help create) shared linguistic conventions.
- These conventions support fairly consistent calculation of **sentence meaning** by different speakers in the same community.
- The sentence meaning of an utterance (together with its form) serves as a clue which a listener can use to construct his/her representation of the speaker's **speaker meaning**

# Sentence vs. Speaker meaning

*Could you pass me the salt? – No, I couldn't pass you the salt!*

- Sentence meaning, but not speaker meaning, is compositional
- Systems attempting to understand speaker meaning directly from surface: resolve the same problems around grammatical structure for each task unlikely to scale

# Semantic compositionality

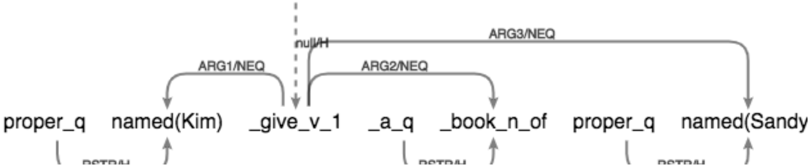
- The meaning of the whole must be directly assembled from its parts
- E.g. *Agent/patient* information comes from the *subject/object constituents*
- The syntactico-semantic formalism must explicitly ensure such connections and assembly

# Compositional layer and syntax-semantics interface

- Predicate-argument structure
- Scope of negation and other operators
- Restriction of quantifiers
- Modality
- Tense/aspect/mood
- Information structure
- Discourse status of referents of NPs
- Politeness

# Minimal Recursion Semantics (MRS)

- An example of a compositional computational semantics approach
- Copestake et al. (2005)
- A semantic formalism (not a semantic theory)




*Kim gave a book to Sandy*

# Minimal Recursion Semantics (MRS)

$$
\left[\begin{array}{ll}
\text{TOP} & h0 \\
\text{INDEX} & e2 \\
\text{RELS} & \left\langle
\begin{bmatrix} \textit{proper\_q}\langle 0{:}3\rangle & \\ \text{LBL} & h4 \\ \text{RSTR} & h5 \\ \text{ARG0} & x3 \\ \text{BODY} & h6 \end{bmatrix},
\begin{bmatrix} \textit{named}\langle 0{:}3\rangle & \\ \text{LBL} & h7 \\ \text{ARG0} & x3 \\ \text{CARG} & \textit{Kim} \end{bmatrix},
\begin{bmatrix} \textit{\_give\_v\_1}\langle 4{:}8\rangle & \\ \text{LBL} & h1 \\ \text{ARG3} & x10 \\ \text{ARG2} & x9 \\ \text{ARG1} & x3 \\ \text{ARG0} & e2 \end{bmatrix},
\begin{bmatrix} \textit{\_a\_q}\langle 9{:}10\rangle & \\ \text{LBL} & h11 \\ \text{RSTR} & h12 \\ \text{ARG0} & x9 \\ \text{BODY} & h13 \end{bmatrix},
\begin{bmatrix} \textit{\_book\_n\_of}\langle 11{:}15\rangle & \\ \text{LBL} & h14 \\ \text{ARG1} & i15 \\ \text{ARG0} & x9 \end{bmatrix},
\begin{bmatrix} \textit{proper\_q}\langle 19{:}24\rangle & \\ \text{LBL} & h16 \\ \text{RSTR} & h17 \\ \text{ARG0} & x10 \\ \text{BODY} & h18 \end{bmatrix},
\begin{bmatrix} \textit{named}\langle 19{:}24\rangle & \\ \text{LBL} & h19 \\ \text{ARG0} & x10 \\ \text{CARG} & \textit{Sandy} \end{bmatrix}
\right\rangle \\
\text{HCONS} & \left\langle
\begin{bmatrix} \textit{qeq} & \\ \text{HARG} & h17 \\ \text{LARG} & h19 \end{bmatrix},
\begin{bmatrix} \textit{qeq} & \\ \text{HARG} & h12 \\ \text{LARG} & h14 \end{bmatrix},
\begin{bmatrix} \textit{qeq} & \\ \text{HARG} & h0 \\ \text{LARG} & h1 \end{bmatrix},
\begin{bmatrix} \textit{qeq} & \\ \text{HARG} & h5 \\ \text{LARG} & h7 \end{bmatrix}
\right\rangle
\end{array}\right.
$$

*Kim gave a book to Sandy*

# Machine translation by transfer

- Assuming a canonical form for semantic structure, we can generate sentences in one language given a semantic structure which was obtained by parsing a sentence in another language
- A **symbolic** approach to MT
- Requires **grammars** for both languages
- Ensures **precision and grammaticality** of the translations
- Disadvantage: lack of **robustness**: not every sentence will be translated.

```
ace -g grammar.dat -Tf1 | ace -g grammar.dat -e
```

# MRS: MINIMAL recursion semantics

- Syntactic structure may sometimes be irrelevant to the truth conditions
- *fierce black cat* vs *gato negro y feroz*
- with syntax insufficiently abstracted away, hard to do transfer
- the LFs produced by the two grammars will look different:

a. $\lambda x[\text{fierce}(x) \wedge (\text{black}(x) \wedge \text{cat}(x))]$

b. $\lambda x[\text{gato}(x) \wedge (\text{negro}(x) \wedge \text{feroz}(x))]$

c. $\lambda x[\text{cat}(x) \wedge (\text{black}(x) \wedge \text{fierce}(x))]$

- $\mathit{fierce}(x) \wedge \mathit{black}(x) \wedge \mathit{cat}(x)$ – solution?

# Flat semantics: quantifier problem

- *Every white horse is old*
- every (x, white (x) $\wedge$ horse (x), old (x))
- Flat: every(x), horse(x), old(x), white(x)
- problem?

# Flat semantics: quantifier problem

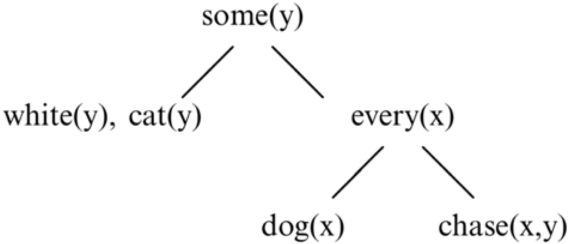
- *Every white horse is old*
- every (x, white (x) $\wedge$ horse (x), old (x))
- Flat: every(x), horse(x), old(x), white(x)
- problem?
- *Every old horse is white*?

# Quantifier scope

*Every dog chases some white cat*

a. some($y$, white($y$) $\wedge$ cat($y$), every($x$, dog($x$), chase($x$, $y$)))

b.



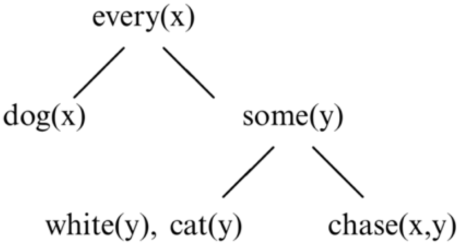

c. $h1$: every($x$, $h3$, $h4$), $h3$: dog($x$), $h7$: white($y$), $h7$: cat($y$), $h5$: some($y$, $h7$, $h1$), $h4$: chase($x$, $y$)

# Quantifier scope

*Every dog chases some white cat*

a. $\text{every}(x, \text{dog}(x), \text{some}(y, \text{white}(y) \wedge \text{cat}(y), \text{chase}(x, y)))$

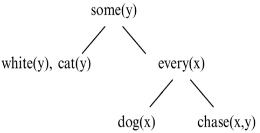
b.




c. $h1: \text{every}(x, h3, h5), h3: \text{dog}(x), h7: \text{white}(y), h7: \text{cat}(y),$
$h5: \text{some}(y, h7, h4), h4: \text{chase}(x, y)$

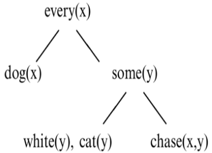
# Scope underspecification

a. $\text{some}(y, \text{white}(y) \wedge \text{cat}(y), \text{every}(x, \text{dog}(x), \text{chase}(x, y)))$
b.




c. $h1\colon \text{every}(x, h3, h4), h3\colon \text{dog}(x), h7\colon \text{white}(y), h7\colon \text{cat}(y),$
$h5\colon \text{some}(y, h7, h1), h4\colon \text{chase}(x, y)$

a. $\text{every}(x, \text{dog}(x), \text{some}(y, \text{white}(y) \wedge \text{cat}(y), \text{chase}(x, y)))$
b.




c. $h1\colon \text{every}(x, h3, h5), h3\colon \text{dog}(x), h7\colon \text{white}(y), h7\colon \text{cat}(y),$
$h5\colon \text{some}(y, h7, h4), h4\colon \text{chase}(x, y)$

$$h1\colon \text{every}(x, h3, h8), h3\colon \text{dog}(x), h7\colon \text{white}(y), h7\colon \text{cat}(y),$$
$$h5\colon \text{some}(y, h7, h9), h4\colon \text{chase}(x, y)$$

- *Every dog chases some white cat*
- Can say EITHER $h9 = h1$ or $h8 = h5$

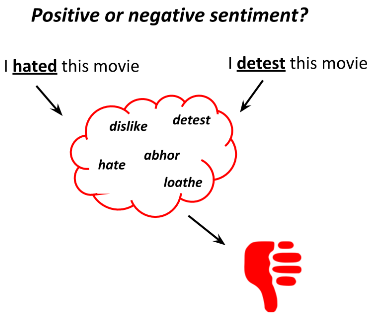
# NLP business with semantics

- Construct knowledge base or model of the world
  - wikidata, DbPedia, ConceptNet
  - TBOX vs ABOX
- Extract meaning representations from linguistic input
- Match input to world knowledge
- Produce replies/take action (or queries) on the basis of the results

# Semantics in NLP

- The hottest area in NLP right now
- all kinds of NLU tasks are associated with semantic annotation and semantic parsing
  - sentiment analysis
  - dialog systems
  - news/ads ranking etc.
- NLP semantics today is usually task-oriented and domain-tailored e.g. a grammar/semantic system for cooking recipes often have nothing to do with theoretical semantics ambitions

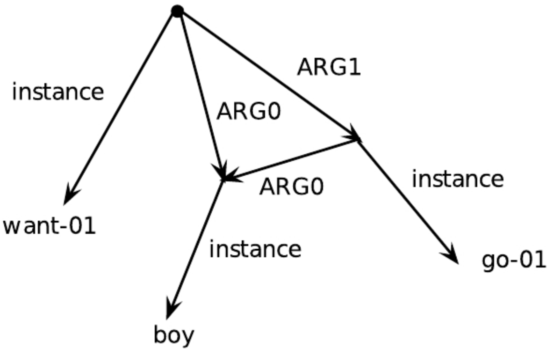
# Semantics in NLP




- Linguistic models, syntactic or semantic (or morphological...) tend to be too unwieldy for today's NLP
- NLP goals: perform well on a task, not necessarily precisely and not necessarily providing explanations
- Tacit expectation to map directly from *surface* to *speaker meaning*

# (pre-vector space) semantics in NLP

- e.g. Abstract Meaning Representation (AMR; Banarescu et al., 2013)
- Note similarities with dependency parse
- https://amr.isi.edu



# AMR: a widely adopted formalism

*"We describe Abstract Meaning Representation (AMR), a semantic representation language in which we are writing down the meanings of thousands of English sentences. We hope that a sembank of simple, whole-sentence semantic structures will spur new work in statistical natural language understanding and generation, like the Penn Treebank encouraged work on statistical parsing."* (Banarescu et al., 2013)

**this came true**!! we look at it as an example of a widely adopted formalism!

# AMR: Pros and Cons

- \+ very simple representation
- \+ yields nice immediate results
- \+ wide paraphrase sets
- \- Plateaus: like WJS, AMR-based research keeps reusing the same dataset and ends up overfitting to it
- \- Inconsistent and task-dependent annotation

# Thematic Roles

- describe semantic roles of verbal arguments
- capture commonality across verbs
- e.g. subject *break/open* is AGENT (volitional cause). THEME (things affected by action)
- enables generalization over surface order of arguments
  - John$_{agent}$ broke the window$_{theme}$
  - The rock$_{instrument}$ broke the window$_{theme}$
  - The window$_{theme}$ was broken by John$_{agent}$

# Thematic Role Issues

Hard to produce:

- standard set of roles. Fragmentation: often need to make more specific. E.g. INSTRUMENT can be subject?
- standard definition of roles: most AGENTs (animals, volitional, sentient, causal. . . ) but not all.

strategies:

- generalized semantic roles (proto-agent, proto-patient etc)
- definied heuristically (propbank)
- define roles specific to verbs/nouns: FrameNet

Even if we come up with a standard set of some sort, we will have low inter-annotator agreement. Hard to expect that people will interpret the roles exactly the same

# Sembanks, Propbanks...

- Representations like AMR can be stored in “sembanks”
- Compare to treebanks
- Challenge: **interannotator agreement**
  - ...is a problem with treebanks, too, unless a grammar is used
  - is even a bigger problem in sembanks
  - role-labeling is more vague than syntactic structure
  - e.g. what kind of granularity?
- Familiar issues with overfitting

# PropBank

(22.11) **agree.01**

Arg0: Agreer
Arg1: Proposition
Arg2: Other entity agreeing

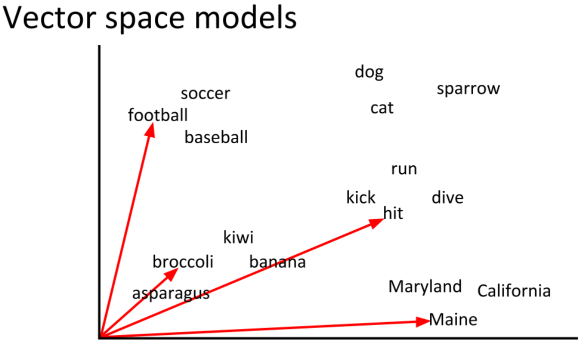
Ex1: [$_{\text{Arg0}}$ The group] *agreed* [$_{\text{Arg1}}$ it wouldn't make an offer].
Ex2: [$_{\text{ArgM-TMP}}$ Usually] [$_{\text{Arg0}}$ John] *agrees* [$_{\text{Arg2}}$ with Mary] [$_{\text{Arg1}}$ on everything].

(22.12) **fall.01**

Arg1: Logical subject, patient, thing falling
Arg2: Extent, amount fallen
Arg3: start point
Arg4: end point, end state of arg1
Ex1: [$_{\text{Arg1}}$ Sales] *fell* [$_{\text{Arg4}}$ to \$25 million] [$_{\text{Arg3}}$ from \$27 million].
Ex2: [$_{\text{Arg1}}$ The average junk bond] *fell* [$_{\text{Arg2}}$ by 4.2%].

http://propbank.github.io

# Vector space semantics




- The core of today's NLP
- Are word vectors semantic representations?
- Yes, but not necessarily compositional

# Word senses and Word sense disambiguation

- A problem from which word vectors arise
- How close/distinct are the senses of two words?
- How to determine this computationally?

# Word senses and Word sense disambiguation

- A problem from which word vectors arise
- How close/distinct are the senses of two words?
- How to determine this computationally?
  - See which contexts they appear in: N-grams! (or, these days, word vectors) $\rightarrow$ Compute distance $\rightarrow$ Closer distance $=$ closer meaning?
- What is one problem with this?

# Word senses and Word sense disambiguation

- A problem from which word vectors arise
- How close/distinct are the senses of two words?
- How to determine this computationally?
  - See which contexts they appear in: N-grams! (or, these days, word vectors) $\rightarrow$ Compute distance $\rightarrow$ Closer distance $=$ closer meaning?
- What is one problem with this?
  - This place is very **loud**
  - This place is very **quiet**
- Antonyms tend to occur in the same context

# Natural language inference

- Inference on a knowledge base: convert natural language expression to KB expression, valid inference according to KB.
  - \+ Precise
  - \+ Formally verifiable
  - \+ Disambiguation using KB state
  - \- Limited domain, requires KB to be formally encodable
- Language-based inference: does one utterance follow from another?
  - \+ Unlimited domain
  - +/- Human judgement
  - -/+ Approximate/imprecise
- Both approaches may use logical form of utterance.

# Lexical meaning and meaning postulates

- Some inferences validated on logical representation directly, most require lexical meaning.
- meaning postulates: e.g.,

$$\forall x[\text{bachelor}'(x) \rightarrow \text{man}'(x) \wedge \text{unmarried}'(x)]$$

- usable with compositional semantics and theorem provers
- e.g. from 'Kim is a bachelor', we can construct the LF $\text{bachelor}'(\text{Kim})$ and then deduce $\text{unmarried}'(\text{Kim})$
- Problematic in general, OK for narrow domains or micro-worlds.

# Recognising Textual Entailment (RTE) shared tasks

T: The girl was found in Drummondville earlier this month.

H: The girl was discovered in Drummondville.

- DATA: pairs of text (T) and hypothesis (H). H may or may not follow from T.
- TASK: label TRUE (if follows) or FALSE (if doesn't follow), according to human judgements.

# Many approaches

- https://aclanthology.org/S14-2125/ and https://aclanthology.org/W15-2205/
- Natural Logic https://aclanthology.org/W09-3714/
- Combining symbolic and ML/DL https://aclanthology.org/2020.coling-demos.9/ and https://aclanthology.org/P16-2079/

# RTE using logical forms

- T sentence has logical form T′, H sentence has logical form H′
- If $\mathrm{T}' \implies \mathrm{H}'$ conclude TRUE, otherwise conclude FALSE.

T The girl was found in Drummondville earlier this month.

T′ $\exists x, u, e[\mathrm{girl}'(x) \wedge \mathrm{find}'(e, u, x) \wedge \mathrm{in}'(e, \mathrm{Drummondville}) \wedge \mathrm{earlier\text{-}this\text{-}month}'(e)]$

H The girl was discovered in Drummondville.

H′ $\exists x, u, e[\mathrm{girl}'(x) \wedge \mathrm{discover}'(e, u, x) \wedge \mathrm{in}'(e, \mathrm{Drummondville})]$

MP $[\mathrm{find}'(x, y, z) \implies \mathrm{discover}'(x, y, z)]$

- So $\mathrm{T}' \implies \mathrm{H}'$ and we conclude TRUE

# More complex examples

T: Four Venezuelan firefighters who were traveling to a training course in Texas were killed when their sport utility vehicle drifted onto the shoulder of a highway and struck a parked truck.

H: Four firefighters were killed in a car accident.

Systems using logical inference are not robust to missing information: simpler techniques can be effective (partly because of choice of hypotheses in RTE).

# More examples

T: Clinton's book is not a big seller here.

H: Clinton's book is a big seller.

T: After the war the city was briefly occupied by the Allies and then was returned to the Dutch.

H: After the war, the city was returned to the Dutch.

T: Lyon is actually the gastronomic capital of France.

H: Lyon is the capital of France.