Abductive Reasoning for Natural Language Semantics

Johannes Dellert

Seminar für Sprachwissenschaft, Universität Tübingen

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What is abduction?

Abduction

- inference to the best explanation ("guessing why")
- from $A \rightarrow B$ and B conclude A, contrary to classical logic
- introduced to modern logic by Charles Sanders Peirce
- prior to induction and deduction in scientific reasoning:
  abduction: hypothesis building (the DETECTIVE)
  induction: rule inference (the SCIENTIST)
  deduction: theorem proving (the MATHEMATICIAN)

Example

I know that the streets become wet when it rains. I observe that the streets are wet, so (I guess) it must be raining.

Abduction in Artificial Intelligence

Fault diagnosis

Given a (weighted) map from issues to the symptoms they cause, infer from a symptom the problem that might have caused it.

Automated Planning

Given a logical theory relating action occurrences with their effects, finding a plan for achieving a desired state amounts to abducing a set of literals implying that the final state is the goal state.

Belief revision

Avoid generating inconsistency when enlarging a set of beliefs by only considering explanations, and in a fuzzy logic, prefer the most explanatory model for encountered facts.

Abduction in Natural Language Processing

Interpretation via Abduction

View the interpretation process as seeking to provide the best explanation of why a sentence would be true.

Concept of Communication

Communication constitutes a bid to extend the area of mutual beliefs of speaker and hearer by some beliefs of the speaker.

Classical and Abductive Reasoning Combined

- for beliefs stated explicitly, classical reasoning can be used
- abductive reasoning on top can explain accomodation, disambiguation and reference resolution effects

Hobbs et al. 1993: Interpretation as Abduction

Ideas

- **weighted abduction** assigns costs to building hypotheses
- interpret a sentence by
  - trying to prove it from **mutual knowledge**
  - allowing for **coercion**
  - **merging redundancies** where possible
  - making **assumptions where necessary**

Claims

- abduction allows for very simple conceptualization of meaning
- making the minimal necessary assumptions predicted by weighted abduction accounts for local pragmatics phenomena
- interpretation as abduction and parsing as deduction allow for an elegant integration of syntax, semantics and pragmatics

Solving Local Pragmatics Problems

Notational Convention (Davidsonian Reification of Eventualities)

- $p(x)$ means that p is true of x
- $p'(e, x)$ means that e is **the eventuality of** p being true of x
- axiom schema: $\forall x\ p(x) \Leftrightarrow \exists e(p'(e, x) \wedge \mathit{Rexists}(e))$
- $\mathit{Rexists}(e)$ states true existence, $\exists e$ platonic existence of e

Example of Axiom Eventualization

intuitive form: $\forall x(p(x) \longrightarrow q(x))$
will be written: $\forall e_1 \forall x(p'(e_1, x) \longrightarrow \exists e_2\ q'(e_2, x))$
stronger variant: $\forall e_1 \forall x(p'(e_1, x) \longrightarrow \exists e_2\ (q'(e_2, x) \wedge \mathit{gen}(e_1, e_2)))$
iff the eventuality e_1 exists **by virtue of the fact that** e_2 exists

Solving Local Pragmatics Problems

Example report

(1) Disengaged compressor after lube-oil alarm.

Problem 1: Reference Resolution

We must detect that the alarm was activated by the compressor. For this we need background knowledge or previous context.

Problem 2: Compound Nominals

The **implicit relation** between “lube-oil” and “alarm” is $\lambda x \lambda y[y \textit{ sounds when the pressure of } x \textit{ drops too low}]$; approximate this using $\exists o \exists a \exists nn(loil(o) \wedge alarm(a) \wedge nn(o, a))$ and axioms such as $\forall x \forall y(part(x, y) \rightarrow nn(x, y))$.

Solving Local Pragmatics Problems

Example report

(1) Disengaged compressor after lube-oil alarm.

Problem 3: Syntactic Ambiguity

Does "after" refer to the compressor or the disengaging event?
$\ldots\ \exists e \exists c \exists y \exists a\ \ldots \wedge \mathit{after}(y, a) \wedge y \in \{c, e\} \wedge \ldots$

Problem 4: Metonymy

Predicates impose **constraints on arguments**; violation requires coercion into something that fulfills the constraints.
Example: $\mathit{after}(e_1, e_2) : \mathit{event}(e_1) \wedge \mathit{event}(e_2)$
Express similarity notion using *rel* predicate: $\ldots\ \exists k_1 \exists k_2 \exists y \exists a\ \ldots$
$\ldots\ \wedge \mathit{after}(k_1, k_2) \wedge \mathit{event}(k_1) \wedge \mathit{rel}(k_1, y) \wedge \mathit{event}(k_2) \wedge \mathit{rel}(k_2, a)\ \ldots$
Possible coercions: $\forall x\ \mathit{rel}(x, x)$, $\forall x \forall y (\mathit{part}(x, y) \rightarrow \mathit{rel}(x, y))$, etc.

Weighted Abduction

Problem: Selecting the Right Explanation

- from $\forall x(p(x) \rightarrow q(x))$ and $q(A)$ we want to infer $p(A)$
- we may have to select from many such $p(A)$

Selection Criteria

- $p(A)$ must be consistent with the rest of what one knows
- simplicity, parsimony: $p(A)$ should be as small as possible
- consilience: $q(A)$ should be as big as possible (explain a lot)

Problem: Informativeness-Correctness Tradeoff

- we usually want the least specific assumption (correctness)
- but sometimes we could be more specific (informativeness)

Weighted Abduction

Requirements for an Inference Scheme

- goal expressions should be assumable (at varying costs)
- assumptions at various levels of specificity should be possible
- allow more economic proofs by exploiting natural redundancy

Weighted Abduction

- give an assumability cost to every conjunct in the LF
- pass back costs to antecedents in clauses by assigning weights: $P_1^{w_1} \wedge P_2^{w_2} \rightarrow Q;\ c(Q) = c \Rightarrow c(P_1) = w_1 c \wedge c(P_2) = w_2 c$
- allow synthesis with minimal cost assignment: $\exists x \exists y (q(x) \wedge q(y)) \Rightarrow \exists z q(z)$ if not inconsistent, and $c(q(z)) = \min\{c(q(x)), c(q(y))\}$ to favour minimality.

Weighted Abduction

Guiding Specificity by Antecedent Weights

- more specific abduction if antecedent weights sum up to < 1
- less specific abduction if antecedent weights sum up to > 1
- assign weights according to “semantic contribution”

Examples

- $P_1^{0.6} \wedge P_2^{0.6} \rightarrow Q$: only assume Q, total cost: 1.0
- $P_1^{0.6} \wedge P_2^{0.6} \rightarrow Q, P_1$: only assume P_2, total cost: 0.6
- $P_1^{0.6} \wedge P_2^{0.6} \rightarrow Q_1, P_2^{0.6} \wedge P_3^{0.6} \rightarrow Q_2$, derive $Q_1 \wedge Q_2$: only assume $P_1 \wedge P_2 \wedge P_3$, total cost: 1.8
- $\forall x(car(x)^{0.8} \wedge notop(x)^{0.4} \rightarrow convertible(x))$

"Et cetera" Propositions

Circumscriptive axioms

- while back-chaining, keep information as specific as possible
- introducing axioms $\forall x(\mathit{species}(x) \rightarrow \mathit{genus}(x))$ is wrong
- replacing by a biconditional helps:
  $\forall x(\mathit{genus}(x) \wedge \mathit{differentiae}(x) \leftrightarrow \mathit{species}(x))$
- weights allow to quantify the precision degree of axioms

Examples

- $\forall x(\mathit{fluid}(x)^{0.6} \wedge \mathit{etc}(x)^{0.6} \leftrightarrow \mathit{lube} - \mathit{oil}(x)$
  "if we talk about a fluid, we possibly refer to lube oil"
- $\forall x(\mathit{mammal}(x)^{0.2} \wedge \mathit{etc}(x)^{0.9} \leftrightarrow \mathit{elephant}(x)$
  "one specific way of being a mammal is being an elephant"

Definite Reference

Example sentences

I bought a new car last week.

- (2) *The vehicle* is already giving me trouble.
- (3) *The engine* is already giving me trouble

In both cases, we use an axiom relating concepts for abduction.

- (2) $\forall x(car(x) \rightarrow vehicle(x))$
- (3) $\forall x(car(x) \rightarrow \exists y\ engine(y, x))$

Interpret the article by giving high assumption costs to $vehicle(x)$ and $\exists y\ engine(y, x)$, thus force resolution and and use the minimal cost proof to find the most salient appropriate entity.

Distinguishing the Given and the New

Example

(4) John walked into the room. The chandelier shone brightly.

- LF contains $\exists x\ \mathit{chandelier}(x)$, which we want to prove
- Assume that in the knowledge database, we have $\forall l(\mathit{light}(l) \wedge \mathit{has\text{-}branches}(l) \rightarrow \mathit{chandelier}(l))$
- We can prove the first antecedent with the following axiom: $\forall r(\mathit{room}(r) \rightarrow \exists l(\mathit{light}(l) \wedge \mathit{in}(l, r)))$
- $\mathit{room}(R)$ is part of the logical form, we can prove it at no cost
- for second antecedent, we must pay because we cannot explain it with the given information
- new information: the light in the room John walks into has several branches (and shone brightly)
- just assuming $\exists x\ \mathit{chandelier}(x)$ would have been more costly

Lexical Ambiguity

Example

(5) John wanted a loan. He went to a bank.

- LF contains $\exists x \; bank(x)$, which we want to disambiguate
- We use two bank predicates, where $bank_1$ is true of financial institutions, and $bank_2$ is true of river banks, with $\forall x(bank_1(x) \rightarrow bank(x))$ and $\forall x(bank_2(x) \rightarrow bank(x))$
- Axioms about banks are stated with either $bank_1$ or $bank_2$:
  $\forall x(\mathit{financial\text{-}institution}(x) \wedge etc(x) \rightarrow bank_1(x))$
  $\forall z(river(z) \rightarrow bank_2(z) \wedge borders(x, z))$
- we additionally need the following axiom:
  $\forall y(loan(y) \rightarrow \exists x \mathit{financial\text{-}institution}(x) \wedge issue(x, y))$
- for the minimum-cost proof, back-chaining will select $bank_1$

Compound Nominals

Example

(6) the turpentine jar

- LF: $turpentine(y) \wedge nn(y, x) \wedge jar(x)$
- we want to find the relation between turpentine and jar
- assume the following axioms are in our knowledge base: $\forall y(liquid(y) \wedge etc_1(y) \rightarrow turpentine(y))$, $\forall e_1, x, y(function(e_1, x) \wedge cont'(e_1, x, y) \wedge liquid(y) \wedge etc_2(e_1, x, y) \rightarrow jar(x))$, $\forall e_1, x, y(cont'(e_1, x, y) \rightarrow nn(y, x))$
- minimal proof will identify the liquid *turpentine* with the liquid implicit in *jar*, and it will take the *nn* relation to be the *cont* relation, resulting in a correct compound analysis

Integration with Prolog-Style Parsing as Deduction

Example

(7) The Boston office called.

- will be interpreted correctly via the following rules:
  $\forall w_1, w_2, y, p, e, x(np(w_1, y) \wedge verb(w_2, p) \wedge p'(e, x) \wedge rel(x, y) \wedge Req(p, x) \rightarrow s(w_1, w_2, e))$
  $\forall w_1, w_2, q, r, y, z(det(the) \wedge noun(w_1, r) \wedge noun(w_2, q) \wedge r(z) \wedge q(y) \wedge nn(z, y) \rightarrow np(the\ w_1\ w_2, y))$,
  $\forall x(person(x) \rightarrow Req(call, x))$
- we simultaneously prove that we have an interpretable sentence and that the eventuality e is its interpretation
- as a result, we get a logical form that makes sense:
  $\exists x, y, z, e(call'(e, x) \wedge person(x) \wedge rel(x, y) \wedge office(y) \wedge Boston(z) \wedge nn(z, y))$

Raina et al. 2005: Robust Textual Inference via Learning and Abductive Reasoning

Ideas

- assumption costs can be inferred by machine learning
- WordNet as source for theorems used in abduction
- if one sentence follows from the other using only low-cost leaps of faith, it is likely that entailment holds

Results

- their inferencing system took part in PASCAL RTE 2005
- achieved the highest confidence weighted score
- better linguistic modelling led to even better results in subareas, can actually make use of more elaborate resources

Assumption Cost Model

Concept of Assumption

- assumptions are unifications of two terms
- assumption cost function determined by similarity measures

Components of the cost function

- **predicate "similarity"** based on WordNet proximity
- **predicate compatibility**: identity of pos, word stem, NE tag of the words represented by the predicates
- **argument compatibility**: use features from dependency structure and penalize e.g. matching a subject with an object
- **constant unification**: sum up **constant distances**
- **word frequency**: inversely proportional to relative word frequency of hypothesis predicate in English text

Learning Assumption Costs

What do we learn?

- the weighting factors for components in the cost function

What is the idea?

- take a training set of desired proofs
- determine weighting that leads to minimal costs over all proofs

How can we compute this?

- exact optimization is intractable because of recursion
- use an iterative approximation scheme that starts out with a fixed proof and gradually explores other weightings
- in each iteration, lower the costs for successful assumptions and increase the costs for misleading assumptions by manipulating the weights

Results

Confidence Weighted Score (CWS)

- sort all confidence values and compute average precision
- assigns higher values to better calibrated predictions

Performance of the overall best theorem prover

In total: CWS of 0.651, which was competitive

Class	CD	IE	IR	MT	PP	QA	RC
Acc.	79.3	49.2	50.0	58.3	46.0	50.0	53.6
CWS	0.906	0.577	0.559	0.608	0.453	0.485	0.567

Hallmark of the Approach

- can produce short and human-readable justifications
- this might be useful for applications such as QA

Summary

Abduction in NLP

- abduction is inference to the best explanation
- can explain accomodation and reference resolution effects
- use in RTE allows production of human-readable justifications

Weighted Abduction

- model best explanations by imposing assumption costs
- costs can also be used to steer specificity

Learning Assumption Costs

- abductive theorems can be inferred from WordNet
- training with a set of desired proofs to learn costs
- better assumption cost models measurably improve results

References

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The End

Thank you!