Knowledge Representation from Text

Lecture Set 4

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Outline

- **Knowledge Representation**
  - Layered approach
    - Logic form
    - Semantic Relations
    - Contexts

Scenario A

(Provided by Steve Maiorano)

The Amtrak train pulled into Union Station Washington D.C. from New York City at 10 AM on March 15, 2005.

It was an Acela Express, number 176, scheduled to depart 30 minutes later on its return trip to the Big Apple.

John took a taxi from his home in Georgetown and arrived at the station 15 minutes before 176's scheduled departure.

He planned to meet his financial adviser, Bill, at CitiBank the same day at 2 PM.

If John's train ran on time, the three-hour trip would get him there on time. If not, John intended to call Bill and push back their appointment two hours.

Scenario B

(Provided by Steve Maiorano)

The train stood at the Amtrak station in Washington DC at 10:00 AM on March 15, 2005.
The name of the station was Union Station.
The train was an Acela Express, number 176.
The number 176 was scheduled to depart for New York City at 10:30 AM and arrive at 1:30 PM on March 15.
John arrived by taxi at Union Station at 10:15 AM.
John boarded the Acela at 10:20 AM and handed the train ticket to the conductor.
The conductor punched the ticket.
John sat by the window.
The train left the station on time.

Motivating Example

- Scenario:

  "…
  The train was an Acela Express, number 176.
  The 176 was scheduled to depart for New York City at 10:30 AM and arrive at 1:30 PM on March 15.
  …
  The train left the station on time."

- Question:

  "What time did the train depart?"

- **How do we represent and reason over this?**

General Approach

- Find a representation for question and candidate answers
  - Must be automatically derivable from text!
  - Expresses the information needed for reasoning
- Feed the question/answer representation into a reasoning system
- Perform post-processing to derive a human-intelligible answer

Layers of the Representation

1. Logic form representation

- Intermediate form between syntactic parse and deeper semantic meaning
- Preserves syntactic links between words in the sentence
  - subject and object
  - prepositional attachment
  - complex nominals
  - adjective and adverb connections

Logic Form Transformation

Advantages of LFT over parsed format:

- LF codification acknowledges syntax-based relationships such as:
  - syntactic subjects
  - syntactic objects
  - prepositional attachments
  - complex nominals
  - adjectival/adverbial adjuncts
- LF is preferred when it comes to reasoning and other logic manipulations in knowledge bases.

Approach to Implement LFT

Criteria:

- Notation be as close as possible to English.
- Notation should be syntactically simple.

Approach:

- Derive LFT directly from the output of the syntactic parser. Parser resolves the structural and syntactic ambiguities.
- Ignore for now:
  - plurals and sets,
  - verb tenses
  - auxiliary verbs
  - quantifiers and modal operators
  - comparatives and negation.
- By relaxing the logic formation we can have an effective representation closer to English.

LFT Definitions 1/6

Predicates:

- A predicate is generated for every noun, verb, adjective or adverb in the sentence. The name of a predicate includes the base form, and part-of-speech.

  Example:

  A learner is enrolled in an educational institution.

  has predicates: (learner:n, enroll:v, educational_institution:n)
- All verb predicates, as well as the nominalizations representing actions, events or states have three arguments: Action/static/event_predicate (e_i,x_1^i,x_2^i), where:
  - $\mathbf{e_i}$ represents the eventuality of the action, state or event i
  - $\mathbf{x_1^i}$ represents the syntactic subject of the action, event or state
  - $\mathbf{x_2^i}$ represents the syntactic direct object of the action, event or state.

LFT Definitions 2/6

A person who backs a politician.
person:n(x_1)& backs:v(e_1,x_1,x_2)& politician:n(x_2)

When the predicate is a bitransitive verb:

- verb(e_i,x_1^i,x_2^i,x_3^i)

  Professor gives student the grades.
  professor:n(x1)& give:v(e_1,x_1,x_2,x_3)&
  grade:v(x_2)& student:n(x_3)

- $\mathbf{x_3^i}$ represents the syntactic indirect object of the action, event, or state.

Slot-allocation representation:

- The arguments of the verb predicates are always in the order: subject, direct object, indirect object.
- The position of the arguments is fixed - for the purpose of simpler notation.
- The arguments for the subject and direct objects are always present even when verb does not have these syntactic roles.
- Argument for indirect object occurs only if necessary.

LFT Definitions 3/6

Modifiers:

- Predicates generated from modifiers share the same arguments with the predicates corresponding to the phrase heads.
  - adjectives have same predicates as nouns

    a man-made object

    object:n(x_1)*& man-made:a*(x_1)

  - adverbial predicate is the eventuality of the verb it modifies.

    run quickly

    run:v(e_1,x_1,x_2)*& quickly:r*(e_1)

LFT Definitions 4/6

Conjunctions:

- Conjunctions are transformed in predicates.
- Conjunction predicates have a variable number of arguments.

  An achievement demonstrating great skill or mastery

  achievement:n(x_1)& demonstrate: v(e_1,x_1,x_2)& or(x_2,x_3,x_4)& skill:n(x_3)& great:a(x_3)& mastery:n(x_4)

  Roll and turn skillfully

  and(e_1,e_2,e_3)& roll:v(e_1,x_1,x_2)& turn:v(e_3,x_1,x_2)& skillfully:r(e_1)

  An unintentional but embarrassing blunder

  blunder:n(x_1)& but(x_1,x_2,x_3)& unintentional:a(x_2)& embarrasing:a(x_3)

LFT Definitions 5/6

Prepositions:

- Every preposition is a predicate with two arguments: the first argument corresponding to the predicate of the head of the phrase, to which PP attaches, and the second argument corresponds to prepositional object.

  Deprive of value for payment

  $deprive{:}v(e_1,x_1,x_2)\&\ of(e_1,x_3)\&\ value{:}n(x_3)\&\ for(x_3,x_4)\&\ payment{:}n(x_4)$

  Playing the position of pitcher on a baseball team

  $playing{:}v(e_1,x_1,x_2)\&\ position{:}n(x_2)\&\ of(x_2,x_3)\&\ pitcher{:}n(x_3)\&\ on(e_1,x_4)$ $\&baseball\_team{:}\ n(x_4)$

LFT Definitions 6/6

- **Complex nominals**:
  - A new predicate nn is introduced to link together the collocating nouns.
  - nn has a variable number of arguments, the first representing the result of aggregation of the nouns, the rest one for each noun.

    An organization created for business ventures.

    organization:n(x_2)& create(e_1,x_1,x_2)& for(e_1,x_3)& nn(x_3,x_4,x_5)& business:n(x_4)& venture:n(x_5)

    Government income credited to taxation.

    nn(x_2,x_3,x_4)& government:n(x_3)& income:n(x_4)& credit:v(e_2,x_1,x_2)& to(e_1,x_5)& taxation:n(x_5)

LFT Inter-Phrase Rulers 1/3

Implementation is done with transformation rules that take the parser output into a LF. Every parser rule translates into a LFT rule. Intra-Phrase transformation rules generate predicates for every noun, verb, adjective or adverb. They assign the variables that describe the local dependencies.

$ART\ N \rightarrow n(x_1)$

a human being $human\_being{:}n(x_1)$

$ART\ ADJ_1 ADJ_2 N \rightarrow n(x_1)\ \&\ adj_1(x_1)\ \&\ adj_2(x_1)$

A hard straight return

$return{:}n(x_1)\ \&\ hard{:}a(x_1)\ \&\ straight{:}a(x_1)$

$ART\ ADJ_1 AND\ ADJ_2 N \rightarrow n(x_1)\ \&\ adj_1(x_1)\ \&\ adj_2(x_1)$

A week and tremulous light

$Light{:}n(x_1)\ \&\ weak{:}a(x_1)\ \&\ tremulous{:}a(x_1)$

$V\ ADV \rightarrow v(e_1,x_1,x_2)\ \&\ adv(e_1)$

Cut open $cut{:}v(e_1,x_1,x_2)\ \&\ open{:}r(e_1)$

$ART\ N_1{}^{'s} N_2 \rightarrow n_2(x_1)\ \&\ n_1(x_2)\ \&\ pos(x_1,x_2)$

A person's body

$body{:}n(x_1)\ \&\ person{:}n(x_2)\ \&\ pos(x_1,x_2)$

LFT Inter-Phrase Rulers 2/3

- Inter-Phrase transformation rules provide the arguments of the verb predicates, preposition predicates and inter-phrasal conjunctions.
- Both intra and inter-phrase transformation rules are produced from the parser.

$NP_1 VP\ NP_2 \rightarrow LFT(NP_1(x_1))\ \&\ LFT(VP(e_1,x_1,x_2))$

$\&\ LFT(NP2(x2))$

a deliberate coordinated movement requiring

dexterity and skill

$movement{:}n(x_1)\ \&\ deliberated{:}a(x_1)\ \&\ coordinated{:}a(x_1)\ \&$

$require{:}v(e_1,x_1,x_2)\ \&\ and\ (x_2,x_3,x_4)\ \&\ dexterity{:}n(x_3)\ \&\ skill{:}n(x_4)$

$VP_1 CONJ\ VP_2 PREP\ NP \rightarrow conj(e_1,e_2,e_3)\ \&$

$LFT(VP_1(e_2,x_1,x_2))\ \&\ LFT(VP_1(e_2,x_1,x_2))\ \&$

$LFT(VP_2(e_3,x_1,x_2))\ \&\ prep(e_1,x_3)\ \&\ LFT(NP)$

keep or maintain in unaltered condition

$or(e_1,e_2,e_3)\ \&\ keep{:}v(e_2,x_1,x_2)\ \&\ maintain{:}v(e_3,x_1,x_2)\ \&$

$in(e_1,x_3)\ \&\ condition{:}n(x_3)\ \&\ unaltered{:}a(x_3)$

LFT Inter-Phrase Rulers 3/3

$NP_1 VP$ *by* $NP_2 PREP\ NP_3 \rightarrow LFT(NP_1(x_2))$ &

$LFT(VP)(e_1,x_1,x_2))$ & $LFT(NP_2(x_1))$ & $prep(x_1,x_3)$ & $LFT(NP_3(x_3))$

A garmet closure *concealed by a fold of cloth*

$nn(x_2,x_4,x_5)$ & $garmet{:}n(x_4)$ & $closure{:}n(x_5)$ &

$conceal{:}v(e_1,x_1,x_2)$ & $fold{:}n(x_1)$ & $of\ (x_1,x_3)$ & $cloth{:}n(x_3)$

$V\ of\ NP_1 CONJ\ NP_2 \rightarrow v(e_1,x_1,x_2)$ &

$conj(x_2,x_3,x_4))$ & $LFT(NP_1(x_3))$ & $LFT(NP_2(x_4))$

Rent of goods and services

$rent{:}v(e_1,x_1,x_2)$ & $and(x_2,x_3,x_4)$ &

$goods{:}n(x_3)$ & $services{:}n(x_4)$

An Example

A game played with rackets by two or four players who hit a ball back and forth over a net that divides a tennis court

$game{:}n(x_2)$ & $play{:}v(e_1,x_1,x_2)$ & $with(e_1,x_3)$ &

$racket{:}n(x_3)$ & $by(e_1,x_1)$ & $or(x_1,x_3,x_4)$ & $two{:}n(x_3)$ &

$four{:}n(x_4)$ & $player{:}n(x_1)$ & $hit{:}v(e_2,x_1,x_5)$ &

$ball{:}n(x_5)$ & $back\_and\_forth{:}r(e_2)$ & $over(e_2,x_6)$ &

$net{:}n(x_6)$ & $divide{:}v(e_3,x_6,x_7)$ & $tennis\_court{:}n(x_7)$

Logic Form Example

- Scenario:

  "…

  The train was an Acela Express, number 176.

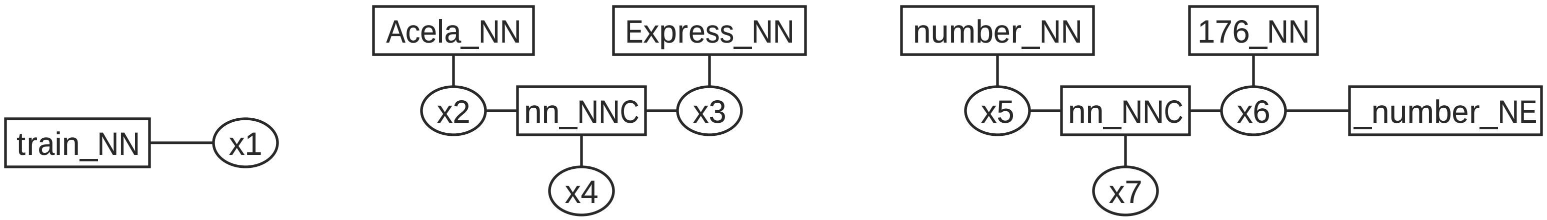
  The 176 was scheduled to depart for New York City at 10:30 AM and arrive at 1:30 PM on March 15.

  …

  ➡ The train left the station on time."

- Logic Form Representation:

  train_NN(x1) & Acela_NN(x2) & Express_NN(x3) & nn_NNC(x4,x2,x3) & number_NN(x5) & 176_NN(x6) & _number_NE(x6) & nn_NNC(x7,x5,x6).



Logic Form Example

- Scenario:

  "…

  The train was an Acela Express, number 176.

  The 176 was scheduled to depart for New York City at 10:30 AM and arrive at 1:30 PM on March 15.

  …

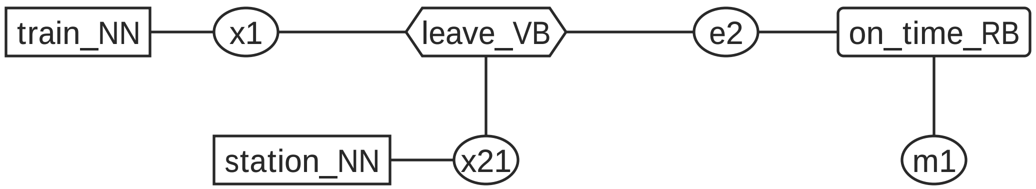
  ⇨ The train left the station on time."

- Logic Form Representation:

  176_NN(x9) & _number_NE(x9) & schedule_VB(e1,x50,x9) & to_TO(e1,e4) & depart_VB(e2,x9,x51) & for_IN(e2,x13) & New_NN(x10) & York_NN(x11) & City_NN(x12) & nn_NNC(x13,x10,x11,x12) & _town_NE(x13) & at_IN(e2,x16) & 10_30_NN(x14) & AM_NN(x15) & nn_NNC(x16,x14,x15) & _time_NE(x16) & and_CC(e4,e2,e3) & arrive_VB(e3,x9,x52) & at_IN(e3,x19) & 1_30_NN(x17) & PM_NN(x18) & nn_NNC(x19,x17,x18) & _time_NE(x19) & on_IN(e3,x20) & march_15_NN(x20) & _date_NE(x20).

Logic Form Example

- Scenario:
  "…
  The train was an Acela Express, number 176.
  The 176 was scheduled to depart for New York City at 10:30 AM and arrive at 1:30 PM on March 15.
  …
- ➡ The train left the station on time."
- Logic Form Representation:
  train_NN(x1) & leave_VB(e2,x1,x21) & station_NN(x21) & on_time_RB(m1,e2).



Semantically Enhanced LF

Quantifications:

All cats eat mice.

Current System:

all_JJ_1(x1) & cat_NN_1(x1) & eat_VB_1(e1,x1,x2) & Mouse_NN_1(x2)

Semantically- enhanced:

all x1 exists e1 x2 { cat_NN_1(x1) → eat_VB_1(e1,x1,x2) & mouse_NN_1(x2) }

Semantically Enhanced LF

Negation:

The man did not go to the market.

Currently:

man_NN_1(x1) & not_RB_1(e1) & go_VB_1(e1,x1,x3) & to_IN(e1,x2) & market_NN_1(x2)

Semantically-enhanced:

man_NN_1(x1) & - { go_VB_1(e1,x1,x3) & to_IN(e1,x2) }& market_NN_1(x2)

Conditionals

If it rains, John will go to the market.

If_IN(e2,e1) & rain_VB_1(e1,x3,x4) &john_NN_1(x1)&go_VB_1(e2,x1,x5)&to_IN(e2,x2) &market_NN_1(x2)

The LF above says (John goes (to the market) (if it rains)).

The enhanced First-Order Logic representation of the same is given as follows:

All e1 x3 x4 exists e2 x1 x2 x5{ rain_VB_1(e1,x3,x4) ->

John_NN_1(x1) & go_VB_(e2,x1,x5) & to_IN(e2,x2) & market_NN_1(x2) }

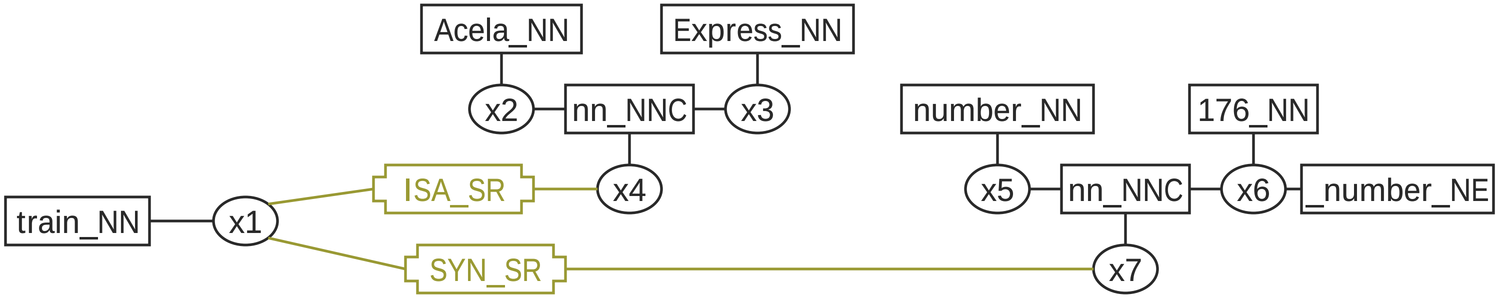
Layers of the Representation

2. Semantic Relations

- Relations between two words or concepts
- Represent a certain meaning type
  - LOCATION, TIME, AGENT, THEME, PART-WHOLE, IS-A, MANNER, PURPOSE, CAUSE, MEASURE, …
- Provide a way to access the deeper semantics of a text
- Allow more abstract reasoning over the concepts

Semantic Relations Example

- Scenario:
  "…
  The train was an Acela Express, number 176.
  The 176 was scheduled to depart for New York City at 10:30 AM and arrive at 1:30 PM on March 15.
  …
  The train left the station on time."
- Logic Form + Semantic Relations:
  train_NN(x1) & Acela_NN(x2) & Express_NN(x3) & nn_NNC(x4,x2,x3) & number_NN(x5) & 176_NN(x6) & _number_NE(x6) & nn_NNC(x7,x5,x6) & ISA_SR(x1,x4) & SYN_SR(x7,x1).



Semantic Relations Example

- Scenario:

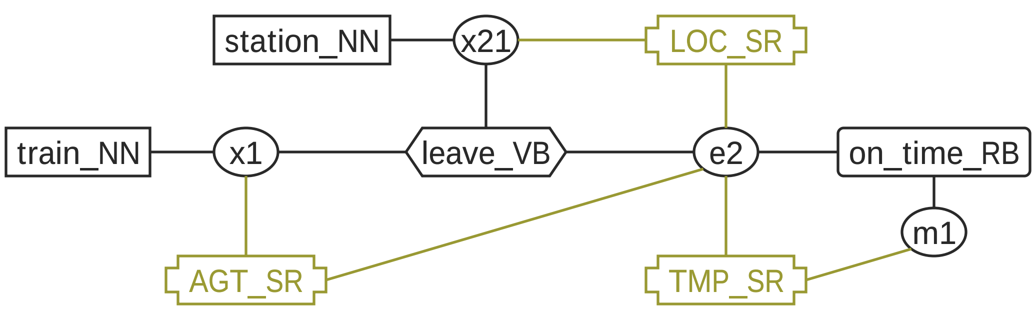
  "…
  The train was an Acela Express, number 176.
  The 176 was scheduled to depart for New York City at 10:30 AM and arrive at 1:30 PM on March 15.
  …
  The train left the station on time."

- Logic Form + Semantic Relations:

  176_NN(x9) & _number_NE(x9) & schedule_VB(e1,x50,x9) & to_TO(e1,e4) & depart_VB(e2,x9,x51) & for_IN(e2,x13) & New_NN(x10) & York_NN(x11) & City_NN(x12) & nn_NNC(x13,x10,x11,x12) & _town_NE(x13) & at_IN(e2,x16) & 10_30_NN(x14) & AM_NN(x15) & nn_NNC(x16,x14,x15) & _time_NE(x16) & and_CC(e4,e2,e3) & arrive_VB(e3,x9,x52) & at_IN(e3,x19) & 1_30_NN(x17) & PM_NN(x18) & nn_NNC(x19,x17,x18) & _time_NE(x19) & on_IN(e3,x20) & march_15_NN(x20) & _date_NE(x20) & THM_SR(x9,e1) & PRP_SR(e2,e4) & AGT_SR(x9,e4) & LOC_SR(x13,e2) & TMP_SR(x16,e2) & TMP_SR(x19,e3) & TMP_SR(x20,e3).

Semantic Relations Example

- Scenario:
  "…
  The train was an Acela Express, number 176.
  The 176 was scheduled to depart for New York City at 10:30 AM and arrive at 1:30 PM on March 15.
  …
  ➡ The train left the station on time."
- Logic Form + Semantic Relations:
  train_NN(x1) & leave_VB(e2,x1,x21) & station_NN(x21) & on_time_RB(m1,e2) & AGT_SR(x1,e2) & LOC_SR(x21,e2) & TMP_SR(m1,e2).



Towards Automatic Extraction of Text Semantics

Problem Definition

Develop methods for automatic labelling of semantic relations in open text.

Our Approach

1. Identify *syntactic patterns* that occur in parse trees
2. Extract features specific to each syntactic pattern
3. Use machine learning to classify any *semantic relations* applicable to the pattern

Semantic Relations Example

The islamists sent letter bombs a few years ago to newspaper offices in New York City and Washington, D.C. in connection with the earlier bombing of the World Trade Center and the imprisonment of the blind sheik, Sheik Abdel Rahman.

AGENT (send, islamists)	IS-A (newspaper office, office)	TEMPORAL (bombing, earlier)
THEME (send, letter bombs)	LOCATION (newspaper offices, New York)	LOCATION (bombing, World Trade Center)
TEMPORAL (send, a few years ago)	LOCATION (newspaper offices, Washington, D.C.)	RECIPIENT (sheik, imprisonment)
MEASURE (years, few)	PART-WHOLE (Washington, D.C.) LOCATION (Washington, D.C.)	PROPERTY (sheik, blind)
LOCATION (send, to newspaper offices)	ASSOCIATED-WITH (send letter bomb, earlier bombing)	SYNONYMY (sheik, Sheik Abdel Rahman)
MAKE-PRODUCE (offices, newspaper)	ASSOCIATED-WITH (send letter bomb, imprisonment)	ISA (Sheik Abdel Rahman, Sheik)

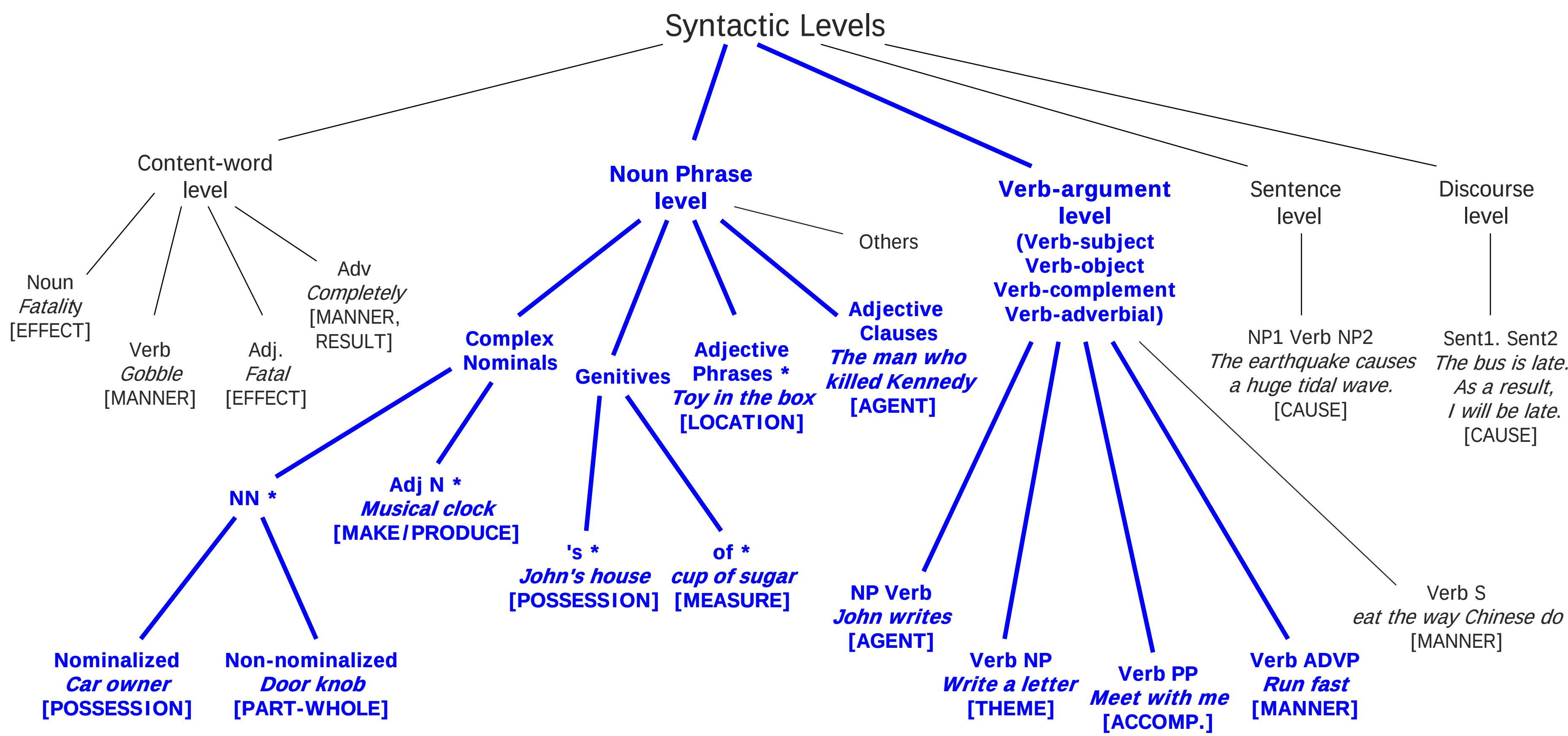
List of Semantic Relations

#	Semantic Relation	Abbr
1	POSSESSION	POS
2	KINSHIP	KIN
3	PROPERTY-ATTRIBUTE HOLDER	PAH
4	AGENT	AGT
5	TEMPORAL	TMP
6	DEPICTION	DPC
7	PART-WHOLE	PW
8	HYPONYMY	ISA
9	ENTAIL	ENT
10	CAUSE	CAU
11	MAKE-PRODUCE	MAK
12	INSTRUMENT	INS
13	LOCATION-SPACE	LOC
14	PURPOSE	PRP
15	SOURCE-FROM	SRC
16	TOPIC	TPC
17	MANNER	MNR
18	MEANS	MNS
19	ACCOMPANIMENT-COMPANION	ACC
20	EXPERIENCER	EXP

#	Semantic Relation	Abbr
21	RECIPIENT	REC
22	FREQUENCY	FRQ
23	INFLUENCE	IFL
24	ASSOCIATED-WITH / OTHER	OTH
25	MEASURE	MEA
26	SYNONYMY-NAME	SYN
27	ANTONYMY	ANT
28	PROBABILITY-OF-EXISTENCE	PRB
29	POSSIBILITY	PSB
30	CERTAINTY	CRT
31	THEME-PATIENT	THM
32	RESULT	RSL
33	STIMULUS	STI
34	EXTENT	EXT
35	PREDICATE	PRD

Other Tags of Interest	
SUBJECT	SBJ
OBJECT	OBJ

Taxonomy of Syntactic Structures



Implemented

Not yet implemented

* Each of these nodes is further subdivided into Nominalized and Non-nominalized (verbal and non-verbal) syntactic patterns, just as illustrated under the NN node. Space does not allow showing them all here.

Combined Semantic Relation Axioms

- CAUSE(x,y) & CAUSE(y,z) → CAUSE(x,z)
- ACCOMPANIMENT(x,y) → ACCOMPANIMENT(y,x)
- ACCOMPANIMENT(x,y) & LOCATION(y,z) → LOCATION(x,z)
- INFLUENCE(x,y) & CAUSE(y,z) → INFLUENCE(x,z)
- ISA(x,y) & PURPOSE(y,z) → PURPOSE(x,z)
- LOCATION(x,y) & MAKEPRODUCE(y,z) → PURPOSE(x,z)

Layers of the Representation

3. Contexts

- Place boundaries around knowledge that is not universal
- Enable more precise time and space reasoning
- Enable reasoning with uncertainty and subjectivity
- Provide for more specific queries

- New idea under development!
  - Currently only time contexts have been implemented and used
  - We want to transfer their success to other types of contexts

Requirements for a Context Representation

- Enable filtering of candidate answers by their contexts
- Improve the reasoning done by the theorem prover
- Capture information about contexts
  - Boundaries in text
  - Constraints (such as signals and time values; spatial location; subjective type and/or strength)
- Represent contexts explicitly and in human-readable form
- Layer on top of logic form and semantic relations
- Be practical and useful from an engineering standpoint

Applying Context to Natural Language

- [CA [CA-a As America slouches toward the year 2000], [CA-b Wendy Kaminer suggests [CA-c in her new book], reason is on the run, and superstition, pseudoscience and spiritual mumbo jumbo are on the rise].]
  - CA: Global context - Wendy Kaminer's opinion
  - CA-a : Temporal Context - indicates a time just before the beginning of the year 2000
  - CA-b: Opinion Context (This is a sub context of the global context) -Wendy Kaminers opinion : pseudoscience and spiritual mumbo jumbo are on the rise
  - CA-c : Spatial Context - the opinion is expressed in her new book

Applying Context to Natural Language

[CA1 Mandelson said that he hoped [CA1-a the review, launched by Mitchell at the request of the Irish and British governments to try to build trust between the feuding parties, would enable all sides to offer "clarity and certainty."]

[CA1-b "That's what we're looking for and that will require a bit of give and take from everyone. [CA1-c Like David (Andrews), I remain hopeful.] The possibility of implementing it (the Good Friday agreement) in full remains within our grasp," he was quoted as saying [CA1-d by a Reuters report from Dublin].]

Mandelson insisted that [CA1-e there be no alternative to the Good Friday peace agreement and said he was hopeful [CA1-f the review would make progress this week]]. The Dublin visit marks Mandelson's first talks with Irish government ministers [CA1-g since he succeeded Mo Mowlam as Northern Ireland secretary].]

Applying Context to Natural Language

- CA1: Global Context - Mandelson's visit
  - CA1-a, CA1-b, CA1-e: Opinion Context - Mandelson's opinion on the review launched by Mitchell
  - CA1-c: Opinion Context - Andrews' opinion
  - CA1-d: Spatial Context - Reuters report
  - CA1-f: Temporal Context - This week refers to the week of 10/19/1999 (from the Document date)
  - CA1-g: Temporal Context – the Dublin visit is after Mandelson succeeded Mo Mowlam

Types of Contexts

- Taxonomy of contexts, by content type:
  - Physical
    - Temporal
    - Spatial
  - Possible-Worlds
    - Subjective
      - Statements
      - Beliefs
      - Fictive (dreams, desires)
    - Necessity (if-then)
    - Planning
    - Situational
    - Possibility, probability, uncertainty
  - Domain

Types of Contexts

- Objective contexts (describing "real" world)
  "The Sun rises every morning." - this is true in general
- Subjective contexts (describing beliefs, opinions, etc.) "John thinks Mary is gorgeous." - the statement is true in the context of John's opinions.
- Probability/possibility/uncertainty contexts (describing possible situations) "The stock market may go up this year."
- Time/space contexts (describing situations in a limited space/time) “Jack was sick yesterday. He stayed in bed the whole day." - the second sentence is true in the context of today; it would probably be false in the context of the whole year .

Types of Contexts

- Necessity contexts (describing necessary facts for something to happen) “The iron must be hot to bend."
- Consequence contexts (describing consequences of something) "If the pipe breaks, the engine will stop and the aircraft will lose altitude."
- Planning context (describes an agent's plan or intent) “The plane is scheduled to depart at noon."

Types of Contexts

The class of subjective contexts can be further divided in subclasses:

- Statement-type contexts - the speaker states some facts; more likely to be true
- Belief-type contexts - the speaker states his beliefs, opinions about reality
- Fictious contexts - reveal products of fiction (dream, movie, book, etc.) - less likely to be true in the real world

Physical Contexts Example

- Scenario:
  "The 176 was scheduled to depart for New York City at 10:30 AM and arrive at 1:30 PM on March 15."
- Logic Form + Semantic Relations:
  176_NN(x9) & _number_NE(x9) & schedule_VB(e1,x50,x9) & to_TO(e1,e4) & depart_VB(e2,x9,x51) & for_IN(e2,x13) & New_NN(x10) & York_NN(x11) & City_NN(x12) & nn_NNC(x13,x10,x11,x12) & _town_NE(x13) & at_IN(e2,x16) & 10_30_NN(x14) & AM_NN(x15) & nn_NNC(x16,x14,x15) & _time_NE(x16) & and_CC(e4,e2,e3) & arrive_VB(e3,x9,x52) & at_IN(e3,x19) & 1_30_NN(x17) & PM_NN(x18) & nn_NNC(x19,x17,x18) & _time_NE(x19) & on_IN(e3,x20) & march_15_NN(x20) & _date_NE(x20) & THM_SR(x9,e1) & PRP_SR(e2,e4) & AGT_SR(x9,e4) & LOC_SR(x13,e2) & TMP_SR(x16,e2) & TMP_SR(x19,e3) & TMP_SR(x20,e3).
- Spot the spatial context!

Physical Contexts Example

- Scenario:
  "The 176 was scheduled to depart for New York City at 10:30 AM and arrive at 1:30 PM on March 15."

- Logic Form + Semantic Relations:
  176_NN(x9) & _number_NE(x9) & schedule_VB(e1,x50,x9) & to_TO(e1,e4) & depart_VB(e2,x9,x51) & for_IN(e2,x13) & New_NN(x10) & York_NN(x11) & City_NN(x12) & nn_NNC(x13,x10,x11,x12) & _town_NE(x13) & at_IN(e2,x16) & 10_30_NN(x14) & AM_NN(x15) & nn_NNC(x16,x14,x15) & _time_NE(x16) & and_CC(e4,e2,e3) & arrive_VB(e3,x9,x52) & at_IN(e3,x19) & 1_30_NN(x17) & PM_NN(x18) & nn_NNC(x19,x17,x18) & _time_NE(x19) & on_IN(e3,x20) & march_15_NN(x20) & _date_NE(x20) & THM_SR(x9,e1) & PRP_SR(e2,e4) & AGT_SR(x9,e4) & LOC_SR(x13,e2) & TMP_SR(x16,e2) & TMP_SR(x19,e3) & TMP_SR(x20,e3).

Physical Contexts Example

- Scenario:
  "The 176 was scheduled to depart for New York City at 10:30 AM and arrive at 1:30 PM on March 15."
- Logic Form + Semantic Relations + Spatial Context:
  176_NN(x9) & _number_NE(x9) & schedule_VB(e1,x50,x9) & to_TO(e1,e4) & depart_VB(e2,x9,x51) & for_IN(e2,x13) & New_NN(x10) & York_NN(x11) & City_NN(x12) & nn_NNC(x13,x10,x11,x12) & _town_NE(x13) & at_IN(e2,x16) & 10_30_NN(x14) & AM_NN(x15) & nn_NNC(x16,x14,x15) & _time_NE(x16) & and_CC(e4,e2,e3) & arrive_VB(e3,x9,x52) & at_IN(e3,x19) & 1_30_NN(x17) & PM_NN(x18) & nn_NNC(x19,x17,x18) & _time_NE(x19) & on_IN(e3,x20) & march_15_NN(x20) & _date_NE(x20) & THM_SR(x9,e1) & PRP_SR(e2,e4) & AGT_SR(x9,e4) & LOC_SR(x13,e2) & TMP_SR(x16,e2) & TMP_SR(x19,e3) & TMP_SR(x20,e3) & spatial_CTXT(c1) & toward_LOC(c1,l1) & locationOf_LOC(l1,x13) & in_CTXT(e2,c1).

Physical Contexts Example

- Scenario:
  "The 176 was scheduled to depart for New York City at 10:30 AM and arrive at 1:30 PM on March 15."
- Logic Form + Semantic Relations + Spatial Context:
  176_NN(x9) & _number_NE(x9) & schedule_VB(e1,x50,x9) & to_TO(e1,e4) & depart_VB(e2,x9,x51) & for_IN(e2,x13) & New_NN(x10) & York_NN(x11) & City_NN(x12) & nn_NNC(x13,x10,x11,x12) & _town_NE(x13) & at_IN(e2,x16) & 10_30_NN(x14) & AM_NN(x15) & nn_NNC(x16,x14,x15) & _time_NE(x16) & and_CC(e4,e2,e3) & arrive_VB(e3,x9,x52) & at_IN(e3,x19) & 1_30_NN(x17) & PM_NN(x18) & nn_NNC(x19,x17,x18) & _time_NE(x19) & on_IN(e3,x20) & march_15_NN(x20) & _date_NE(x20) & THM_SR(x9,e1) & PRP_SR(e2,e4) & AGT_SR(x9,e4) & LOC_SR(x13,e2) & TMP_SR(x16,e2) & TMP_SR(x19,e3) & TMP_SR(x20,e3) & spatial_CTXT(c1) & toward_LOC(c1,l1) & locationOf_LOC(l1,x13) & in_CTXT(e2,c1).
- Spot the temporal contexts!

Physical Contexts Example

- Scenario:
  "The 176 was scheduled to depart for New York City at 10:30 AM and arrive at 1:30 PM on March 15."

- Logic Form + Semantic Relations + Spatial Context:
  176_NN(x9) & _number_NE(x9) & schedule_VB(e1,x50,x9) & to_TO(e1,e4) & depart_VB(e2,x9,x51) & for_IN(e2,x13) & New_NN(x10) & York_NN(x11) & City_NN(x12) & nn_NNC(x13,x10,x11,x12) & _town_NE(x13) & at_IN(e2,x16) & 10_30_NN(x14) & AM_NN(x15) & nn_NNC(x16,x14,x15) & _time_NE(x16) & and_CC(e4,e2,e3) & arrive_VB(e3,x9,x52) & at_IN(e3,x19) & 1_30_NN(x17) & PM_NN(x18) & nn_NNC(x19,x17,x18) & _time_NE(x19) & on_IN(e3,x20) & march_15_NN(x20) & _date_NE(x20) & THM_SR(x9,e1) & PRP_SR(e2,e4) & AGT_SR(x9,e4) & LOC_SR(x13,e2) & TMP_SR(x16,e2) & TMP_SR(x19,e3) & TMP_SR(x20,e3) & spatial_CTXT(c1) & toward_LOC(c1,l1) & locationOf_LOC(l1,x13) & in_CTXT(e2,c1).

Physical Contexts Example

- Scenario:
  "The 176 was scheduled to depart for New York City at 10:30 AM and arrive at 1:30 PM on March 15."
- Logic Form + Semantic Relations + Spatial/Temporal Contexts:
  176_NN(x9) & _number_NE(x9) & schedule_VB(e1,x50,x9) & to_TO(e1,e4) & depart_VB(e2,x9,x51) & for_IN(e2,x13) & New_NN(x10) & York_NN(x11) & City_NN(x12) & nn_NNC(x13,x10,x11,x12) & _town_NE(x13) & at_IN(e2,x16) & 10_30_NN(x14) & AM_NN(x15) & nn_NNC(x16,x14,x15) & _time_NE(x16) & and_CC(e4,e2,e3) & arrive_VB(e3,x9,x52) & at_IN(e3,x19) & 1_30_NN(x17) & PM_NN(x18) & nn_NNC(x19,x17,x18) & _time_NE(x19) & on_IN(e3,x20) & march_15_NN(x20) & _date_NE(x20) & THM_SR(x9,e1) & PRP_SR(e2,e4) & AGT_SR(x9,e4) & LOC_SR(x13,e2) & TMP_SR(x16,e2) & TMP_SR(x19,e3) & TMP_SR(x20,e3) & spatial_CTXT(c1) & toward_LOC(c1,l1) & locationOf_LOC(l1,x13) & in_CTXT(e2,c1) &
  Time_CTMP(BeginFn(e6),2005,3,15,10,30,0) &
  Time_CTMP(EndFn(e6),2005,3,15,10,30,59) &
  overlapsTemporally_CTMP(c2,e6) & in_CTXT(e2,c2) &
  Time_CTMP(BeginFn(e7),2005,3,15,13,30,0) &
  Time_CTMP(EndFn(e7),2005,3,15,13,30,59) &
  overlapsTemporally_CTMP(c3,e7) & in_CTXT(e3,c3).

Planning Context Example

- Scenario:
  "The 176 was scheduled to depart for New York City at 10:30 AM and arrive at 1:30 PM on March 15."

- Logic Form + Semantic Relations + Spatial/Temporal Contexts:
  176_NN(x9) & _number_NE(x9) & schedule_VB(e1,x50,x9) & to_TO(e1,e4) & depart_VB(e2,x9,x51) & for_IN(e2,x13) & New_NN(x10) & York_NN(x11) & City_NN(x12) & nn_NNC(x13,x10,x11,x12) & _town_NE(x13) & at_IN(e2,x16) & 10_30_NN(x14) & AM_NN(x15) & nn_NNC(x16,x14,x15) & _time_NE(x16) & and_CC(e4,e2,e3) & arrive_VB(e3,x9,x52) & at_IN(e3,x19) & 1_30_NN(x17) & PM_NN(x18) & nn_NNC(x19,x17,x18) & _time_NE(x19) & on_IN(e3,x20) & march_15_NN(x20) & _date_NE(x20) & THM_SR(x9,e1) & PRP_SR(e2,e4) & AGT_SR(x9,e4) & LOC_SR(x13,e2) & TMP_SR(x16,e2) & TMP_SR(x19,e3) & TMP_SR(x20,e3) & spatial_CTXT(c1) & toward_LOC(c1,l1) & locationOf_LOC(l1,x13) & in_CTXT(e2,c1) & Time_CTMP(BeginFn(e6),2005,3,15,10,30,0) & Time_CTMP(EndFn(e6),2005,3,15,10,30,59) & overlapsTemporally_CTMP(c2,e6) & in_CTXT(e2,c2) & Time_CTMP(BeginFn(e7),2005,3,15,13,30,0) & Time_CTMP(EndFn(e7),2005,3,15,13,30,59) & overlapsTemporally_CTMP(c3,e7) & in_CTXT(e3,c3).

Planning Context Example

- Scenario:
  "The 176 was scheduled to depart for New York City at 10:30 AM and arrive at 1:30 PM on March 15."
- Logic Form + Semantic Relations + Multiple Contexts:
  176_NN(x9) & _number_NE(x9) & schedule_VB(e1,x50,x9) & to_TO(e1,e4) & depart_VB(e2,x9,x51) & for_IN(e2,x13) & New_NN(x10) & York_NN(x11) & City_NN(x12) & nn_NNC(x13,x10,x11,x12) & _town_NE(x13) & at_IN(e2,x16) & 10_30_NN(x14) & AM_NN(x15) & nn_NNC(x16,x14,x15) & _time_NE(x16) & and_CC(e4,e2,e3) & arrive_VB(e3,x9,x52) & at_IN(e3,x19) & 1_30_NN(x17) & PM_NN(x18) & nn_NNC(x19,x17,x18) & _time_NE(x19) & on_IN(e3,x20) & march_15_NN(x20) & _date_NE(x20) & THM_SR(x9,e1) & PRP_SR(e2,e4) & AGT_SR(x9,e4) & LOC_SR(x13,e2) & TMP_SR(x16,e2) & TMP_SR(x19,e3) & TMP_SR(x20,e3) & spatial_CTXT(c1) & toward_LOC(c1,l1) & locationOf_LOC(l1,x13) & in_CTXT(e2,c1) & Time_CTMP(BeginFn(e6),2005,3,15,10,30,0) & Time_CTMP(EndFn(e6),2005,3,15,10,30,59) & overlapsTemporally_CTMP(c2,e6) & in_CTXT(e2,c2) & Time_CTMP(BeginFn(e7),2005,3,15,13,30,0) & Time_CTMP(EndFn(e7),2005,3,15,13,30,59) & overlapsTemporally_CTMP(c3,e7) & in_CTXT(e3,c3) & planning_CTXT(c1,e1) & planning_CTXT(c2,e1) & in_CTXT(e2,c1) & in_CTXT(e3,c1).

Three-Level Representation

- Scenario:
  "The 176 was scheduled to depart for New York City at 10:30 AM and arrive at 1:30 PM on March 15."
- Logic Form + Semantic Relations + Contexts:
  176_NN(x9) & _number_NE(x9) & schedule_VB(e1,x50,x9) & to_TO(e1,e4) & depart_VB(e2,x9,x51) & for_IN(e2,x13) & New_NN(x10) & York_NN(x11) & City_NN(x12) & nn_NNC(x13,x10,x11,x12) & _town_NE(x13) & at_IN(e2,x16) & 10_30_NN(x14) & AM_NN(x15) & nn_NNC(x16,x14,x15) & _time_NE(x16) & and_CC(e4,e2,e3) & arrive_VB(e3,x9,x52) & at_IN(e3,x19) & 1_30_NN(x17) & PM_NN(x18) & nn_NNC(x19,x17,x18) & _time_NE(x19) & on_IN(e3,x20) & march_15_NN(x20) & _date_NE(x20) & THM_SR(x9,e1) & PRP_SR(e2,e4) & AGT_SR(x9,e4) & LOC_SR(x13,e2) & TMP_SR(x16,e2) & TMP_SR(x19,e3) & TMP_SR(x20,e3) & spatial_CTXT(c1) & toward_LOC(c1,l1) & locationOf_LOC(l1,x13) & in_CTXT(e2,c1) & Time_CTMP(BeginFn(e6),2005,3,15,10,30,0) & Time_CTMP(EndFn(e6),2005,3,15,10,30,59) & overlapsTemporally_CTMP(c2,e6) & in_CTXT(e2,c2) & Time_CTMP(BeginFn(e7),2005,3,15,13,30,0) & Time_CTMP(EndFn(e7),2005,3,15,13,30,59) & overlapsTemporally_CTMP(c3,e7) & in_CTXT(e3,c3) & planning_CTXT(c1,e1) & planning_CTXT(c2,e1) & in_CTXT(e2,c1) & in_CTXT(e3,c1).

Question Representation

- Question:
  "What time did the train depart?"
- Logic Form + Semantic Relations + Contexts:
  train_NN(x1) & depart_VB(e1,x1,x2) &
  Time_CTMP(BeginFn(e2),t1,t2,t3,t4,t5,t6) &
  Time_CTMP(EndFn(e2),t7,t8,t9,t10,t11,t12) &
  overlapsTemporally_CTMP(c1,e2) & inContext(e1,c1))

Reasoning with Contexts

- Some kinds of reasoning apply to all contexts
  - Containment of objects within the context
  - Possible nesting or overlapping of contexts
- Other special types of reasoning apply only to certain types of contexts
  - Physical contexts: adjacency, span (duration, size), overlapping, containment, relative anchoring, …
  - Possible-Worlds contexts: true/false, probability, uncertainty, truth dependency, epistemic logic, …
  - Domain contexts: subdomains/superdomains, different meaning of a term in different contexts, different rules, …

Reasoning with Possible-Worlds Contexts

- Logic Form, Semantic Relations, Spatial/Temporal Contexts + Planning Context:
  176_NN(x9) & _number_NE(x9) & schedule_VB(e1,x50,x9) & to_TO(e1,e4) &
  depart_VB(e2,x9,x51) & for_IN(e2,x13) & New_NN(x10) & York_NN(x11) & City_NN(x12) & nn_NNC(x13,x10,x11,x12) & _town_NE(x13) & at_IN(e2,x16) & 10_30_NN(x14) & AM_NN(x15) & nn_NNC(x16,x14,x15) & _time_NE(x16) & and_CC(e4,e2,e3) & arrive_VB(e3,x9,x52) & at_IN(e3,x19) & 1_30_NN(x17) & PM_NN(x18) & nn_NNC(x19,x17,x18) & _time_NE(x19) & on_IN(e3,x20) & march_15_NN(x20) & _date_NE(x20) & THM_SR(x9,e1) & PRP_SR(e2,e4) & AGT_SR(x9,e4) & LOC_SR(x13,e2) & TMP_SR(x16,e2) & TMP_SR(x19,e3) & TMP_SR(x20,e3) & spatial_CTXT(c1) & toward_LOC(c1,l1) & locationOf_LOC(l1,x13) & in_CTXT(e2,c1) & Time_CTMP(BeginFn(e6),2005,3,15,10,30,0) & Time_CTMP(EndFn(e6),2005,3,15,10,30,59) & overlapsTemporally_CTMP(c2,e6) & in_CTXT(e2,c2) & Time_CTMP(BeginFn(e7),2005,3,15,13,30,0) & Time_CTMP(EndFn(e7),2005,3,15,13,30,59) & overlapsTemporally_CTMP(c3,e7) & in_CTXT(e3,c3) & planning_CTXT(c1,e1) & planning_CTXT(c2,e1) & in_CTXT(e2,c1) & in_CTXT(e3,c1).
- Possible-worlds contexts require reasoning with uncertainty; the representation above is not enough
  - Extend the theorem prover to handle reasoning with uncertainty, or
  - Pre-process, do the proof, then post-process to handle uncertain cases

Pre-processing Example

- Logic Form, Semantic Relations, Spatial/Temporal Contexts + Planning Context:
  176_NN(x9) & _number_NE(x9) & schedule_VB(e1,x50,x9) & to_TO(e1,e4) & for_IN(e2,x13) & New_NN(x10) & York_NN(x11) &
  City_NN(x12) & nn_NNC(x13,x10,x11,x12) & _town_NE(x13) & at_IN(e2,x16) &
  10_30_NN(x14) & AM_NN(x15) & nn_NNC(x16,x14,x15) & _time_NE(x16) &
  and_CC(e4,e2,e3) & at_IN(e3,x19) & 1_30_NN(x17) &
  PM_NN(x18) & nn_NNC(x19,x17,x18) & _time_NE(x19) & on_IN(e3,x20) &
  march_15_NN(x20) & _date_NE(x20) & THM_SR(x9,e1) & PRP_SR(e2,e4) &
  AGT_SR(x9,e4) & LOC_SR(x13,e2) & TMP_SR(x16,e2) & TMP_SR(x19,e3) &
  TMP_SR(x20,e3) & spatial_CTXT(c1) & toward_LOC(c1,l1) &
  locationOf_LOC(l1,x13) & in_CTXT(e2,c1) &
  Time_CTMP(BeginFn(e6),2005,3,15,10,30,0) &
  Time_CTMP(EndFn(e6),2005,3,15,10,30,59) &
  overlapsTemporally_CTMP(c2,e6) & in_CTXT(e2,c2) &
  Time_CTMP(BeginFn(e7),2005,3,15,13,30,0) &
  Time_CTMP(EndFn(e7),2005,3,15,13,30,59) &
  overlapsTemporally_CTMP(c3,e7) & in_CTXT(e3,c3) & planning_CTXT(c1,e1)
  & planning_CTXT(c2,e1) & in_CTXT(e2,c1) & in_CTXT(e3,c1).

  (context_assumed(c1) | context_true(c1)) -> depart_VB(e2,x9,x51).
  (context_assumed(c2) | context_true(c2)) -> arrive_VB(e3,x9,x52).

Pre-processing Example

- Logic Form, Semantic Relations, Spatial/Temporal Contexts + Planning Context:
  176_NN(x9) & _number_NE(x9) & schedule_VB(e1,x50,x9) & to_TO(e1,e4) & for_IN(e2,x13) & New_NN(x10) & York_NN(x11) &
  City_NN(x12) & nn_NNC(x13,x10,x11,x12) & _town_NE(x13) & at_IN(e2,x16) &
  10_30_NN(x14) & AM_NN(x15) & nn_NNC(x16,x14,x15) & _time_NE(x16) &
  and_CC(e4,e2,e3) & at_IN(e3,x19) & 1_30_NN(x17) &
  PM_NN(x18) & nn_NNC(x19,x17,x18) & _time_NE(x19) & on_IN(e3,x20) &
  march_15_NN(x20) & _date_NE(x20) & THM_SR(x9,e1) & PRP_SR(e2,e4) &
  AGT_SR(x9,e4) & LOC_SR(x13,e2) & TMP_SR(x16,e2) & TMP_SR(x19,e3) &
  TMP_SR(x20,e3) & spatial_CTXT(c1) & toward_LOC(c1,l1) &
  locationOf_LOC(l1,x13) & in_CTXT(e2,c1) &
  Time_CTMP(BeginFn(e6),2005,3,15,10,30,0) &
  Time_CTMP(EndFn(e6),2005,3,15,10,30,59) &
  overlapsTemporally_CTMP(c2,e6) & in_CTXT(e2,c2) &
  Time_CTMP(BeginFn(e7),2005,3,15,13,30,0) &
  Time_CTMP(EndFn(e7),2005,3,15,13,30,59) &
  overlapsTemporally_CTMP(c3,e7) & in_CTXT(e3,c3) & planning_CTXT(c1,e1)
  & planning_CTXT(c2,e1) & in_CTXT(e2,c1) & in_CTXT(e3,c1).

  (context_assumed(c1) | context_true(c1)) -> depart_VB(e2,x9,x51).
  (context_assumed(c2) | context_true(c2)) -> arrive_VB(e3,x9,x52).
  on_IN(x9,x90) & schedule_NN(x90) -> context_true(c1) & context_true(c2).

Pre-processing Example

- Logic Form, Semantic Relations, Spatial/Temporal Contexts + Planning Context:
176_NN(x9) & _number_NE(x9) & schedule_VB(e1,x50,x9) & to_TO(e1,e4) & for_IN(e2,x13) & New_NN(x10) & York_NN(x11) & City_NN(x12) & nn_NNC(x13,x10,x11,x12) & _town_NE(x13) & at_IN(e2,x16) & 10_30_NN(x14) & AM_NN(x15) & nn_NNC(x16,x14,x15) & _time_NE(x16) & and_CC(e4,e2,e3) & at_IN(e3,x19) & 1_30_NN(x17) & PM_NN(x18) & nn_NNC(x19,x17,x18) & _time_NE(x19) & on_IN(e3,x20) & march_15_NN(x20) & _date_NE(x20) & THM_SR(x9,e1) & PRP_SR(e2,e4) & AGT_SR(x9,e4) & LOC_SR(x13,e2) & TMP_SR(x16,e2) & TMP_SR(x19,e3) & TMP_SR(x20,e3) & spatial_CTXT(c1) & toward_LOC(c1,l1) & locationOf_LOC(l1,x13) & in_CTXT(e2,c1) & Time_CTMP(BeginFn(e6),2005,3,15,10,30,0) & Time_CTMP(EndFn(e6),2005,3,15,10,30,59) & overlapsTemporally_CTMP(c2,e6) & in_CTXT(e2,c2) & Time_CTMP(BeginFn(e7),2005,3,15,13,30,0) & Time_CTMP(EndFn(e7),2005,3,15,13,30,59) & overlapsTemporally_CTMP(c3,e7) & in_CTXT(e3,c3) & planning_CTXT(c1,e1) & planning_CTXT(c2,e1) & in_CTXT(e2,c1) & in_CTXT(e3,c1).

(context_assumed(c1) | context_true(c1)) -> depart_VB(e2,x9,x51).
(context_assumed(c2) | context_true(c2)) -> arrive_VB(e3,x9,x52).
on_IN(x9,x90) & schedule_NN(x90) -> context_true(c1) & context_true(c2).

context_assumed(c1).
context_assumed(c2).

← These two statements are given a heavy "pick weight" (the prover will use them only after all other paths are exhausted.)