LANGUAGE AND INFERENCE

Day 1: Types of Inference
Day 2: Designing Meaning Representations
Day 3: Building Meaning Representations
Day 4: Projection and Presupposition
Day 5: Inference in the Real World

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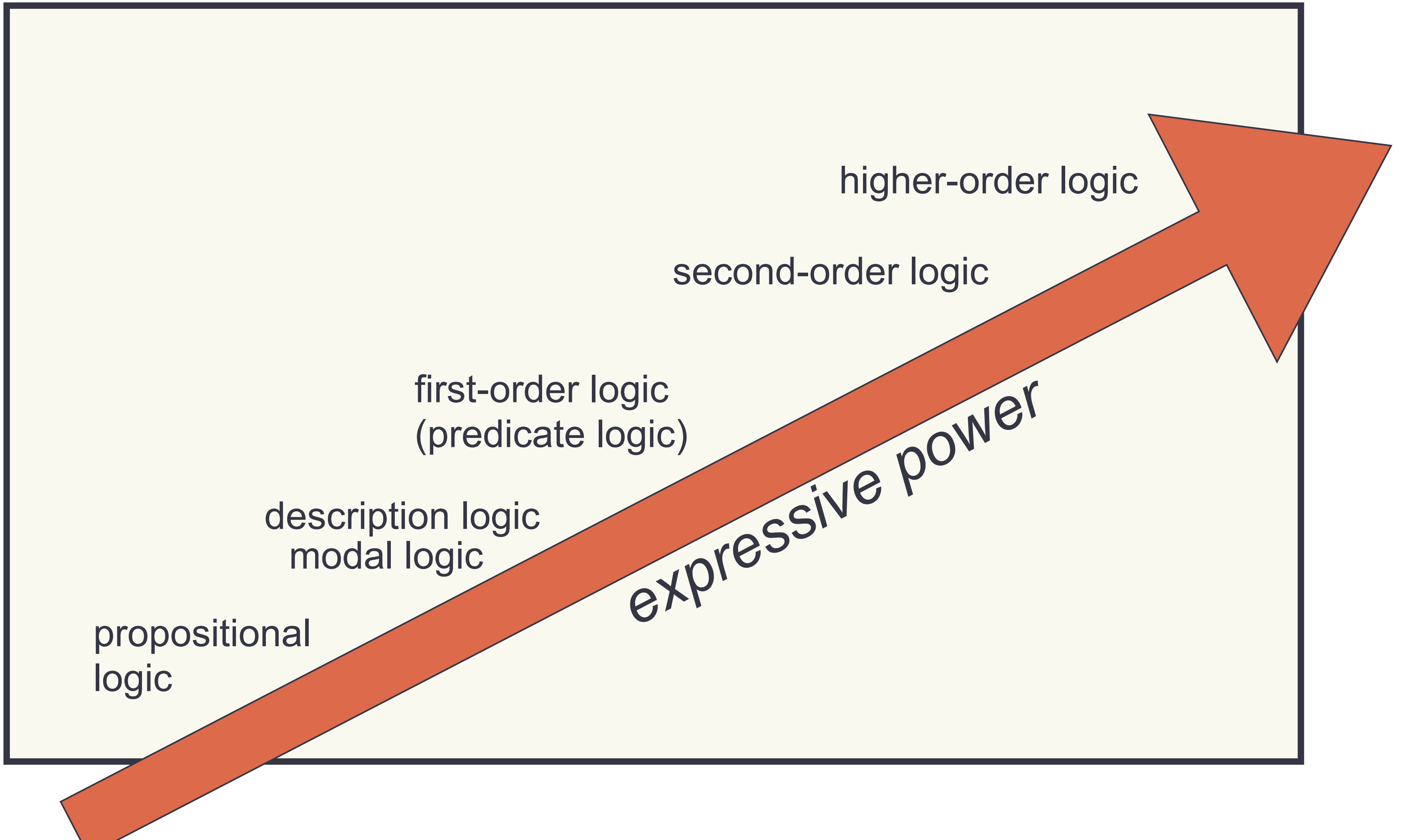
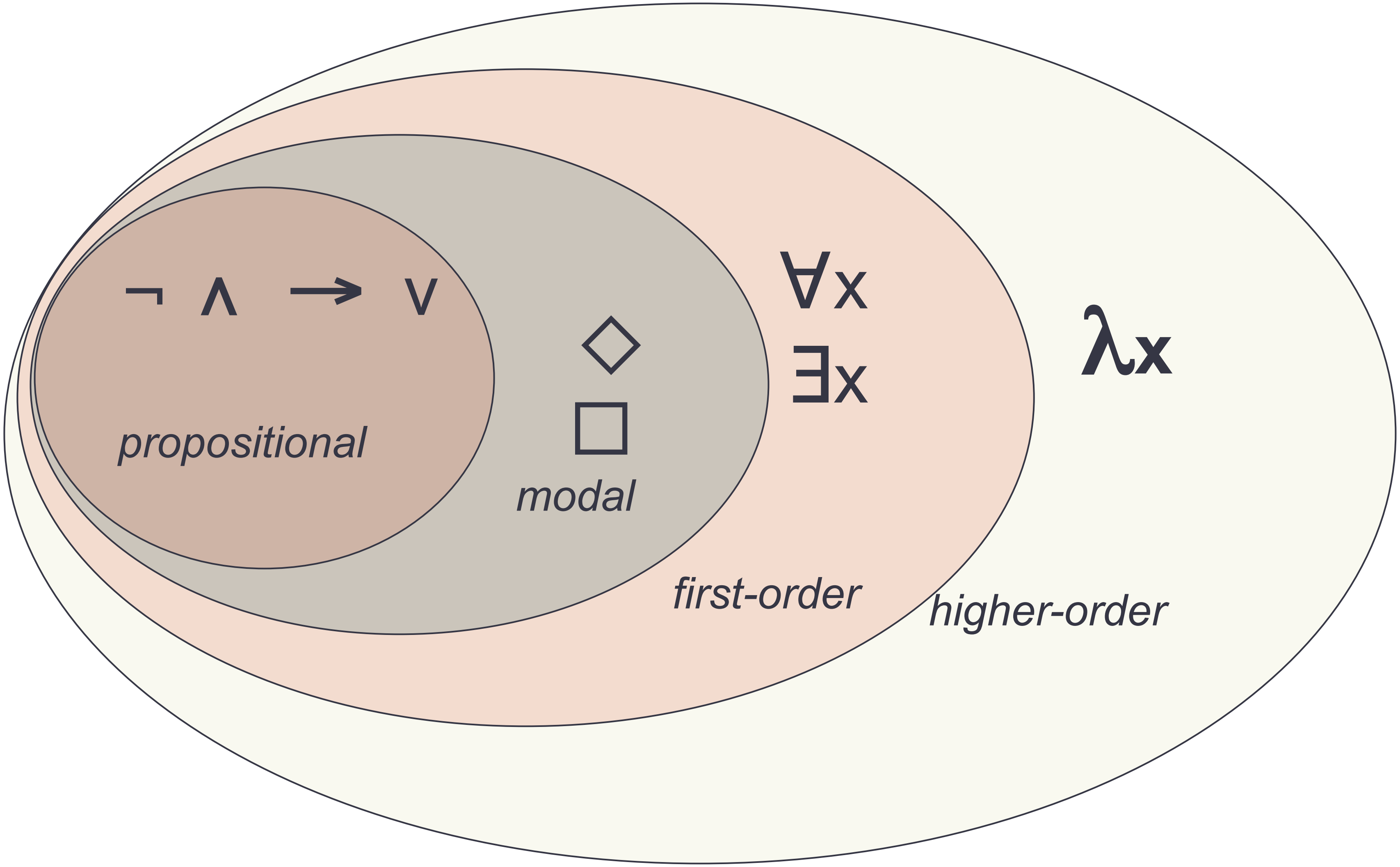
Different Logics for Different Needs



Logics and how they relate



Summary of Yesterday

inconsistent	*contradictory* true in **no** models	informative
consistent	*synthetic* true in **some** (but not all) models	
	analytic true in **all** models	tautology

An example model

M=<D,F>
D={d1,d2,d3,d4,d5,d6,d7,d8}
F(man)={d1}
F(woman)={d2}
F(house)={d3,d4}
F(dog)={d5}
F(bird)={d6}
F(tree)={d7}
F(car)={d8}
F(happy)={d1,d2}
F(near)={(d5,d2),(d2,d5)}
F(at)={(d6,d3)}

Today

Inference Methods:

Model Building
and **Theorem Proving**

Meaning Representation:

Design
and **Evaluation**

Ways of Inference

- Model Checking
- Model Building (informative, consistent)
- Theorem Proving (non-informative, inconsistent)

Model Checking

- The task of the determining whether a given model satisfies a formula (or a set of formulas)

Input: **model + formula**
Output: true or false

Model Checking

M=<D,F>
D={d1,d2,d3,d4}
F(mia)=d1
F(honey-bunny)=d2
F(vincent)=d3
F(yolanda)=d4
F(customer)={d1,d3}
F(robber)={d2,d4}
F(love)={(d4,d2),(d3,d1)}

Q1: Does M satisfy: $\exists x(customer(x) \wedge \exists y(customer(y) \wedge love(x,y)))$

Q2: Does M satisfy: $\exists x(robber(x) \wedge love(x,x))$

Model Building

- The task of checking whether a formula (or a set of formulas) is satisfiable, or put differently, checking whether there exists a model that satisfies that formula

  Input: **formula**
  Output: **model** (if you're lucky)

- Model building serves to check whether input is consistent and informative!

Model Building

M=<D,F>
D={............}
F(robber)={.........}
F(love)={...............}

Q3: Build a model that satisfies:

$\exists x(robber(x) \wedge love(x,x))$

A robber loves himself

Model Building

M=<D,F>
D={d8}
F(robber)={d8}
F(love)={(d8,d8)}

Q3: Build a model that satisfies:

$\exists x(robber(x) \wedge love(x,x))$

A robber loves himself

Model Building

M=<D,F>
D={d7,d8,d9}
F(robber)={d8,d9}
F(love)={(d7,d8),(d8,d8)}

Q3: Build a model that satisfies:

$\exists x(\text{robber}(x) \wedge \text{love}(x,x))$

A robber loves himself

Model Building

M=<D,F>
D={...}
F(j)=...
F(bkb)={...}
F(eats)={...}

Q4: Build a model that satisfies:

$$\exists x(bkb(x) \wedge eats(j,x))$$

Jules eats a big kahuna burger

Model Building

M=<D,F>
D={d8}
F(j)=d8
F(bkb)={d8}
F(eats)={(d8,d8)}

Q4: Build a model that satisfies:

$$\exists x(bkb(x) \wedge eats(j,x))$$

Jules eats a big kahuna burger

Model Building

M=<D,F>
D={d1,..........}
F(butch)=d1
F(person)={d1,........}
F(parent)={........}

Q5: Build a model that satisfies:

person(butch)
∀x(person(x) → ∃y(person(y) & parent(x,y)))
∀x∀y∀z(parent(x,y)&parent(y,z)→parent(x,z))
¬∃x parent(x,x)

Infinitely large models

The following theory (set of formulas) doesn't have a finite model:

$$\mathrm{person}(\mathrm{butch})$$
$$\forall x(\mathrm{person}(x) \rightarrow \exists y(\mathrm{person}(y) \;\&\; \mathrm{parent}(x,y)))$$
$$\forall x \forall y \forall z(\mathrm{parent}(x,y) \& \mathrm{parent}(y,z) \rightarrow \mathrm{parent}(x,z))$$
$$\neg \exists x \; \mathrm{parent}(x,x)$$

"Everyone has a parent"

Theorem Proving

- The task of checking whether a formula (or a set of formulas) is a validity (a theorem), or put differently, checking whether that formula is true in all models

  Input: **formula**
  Output: **proof** (if you're lucky)

- Theorem proving serves to check whether input is inconsistent and uninformative!

From Models to Proofs

- Problem with checking whether a formula is a validity (satisfied by all models) is that there are many models...
- Proof theory investigates validity from a purely syntactic perspective (formula manipulation, models play no role)
- Various methods exist – we look briefly at just one of them:

tableaux

Tableaux

- Refutation proof method: show that F is valid by showing that all attempts to falsify it must fail

$$\frac{\mathbf{f} : A \vee B}{\begin{array}{c}\mathbf{f} : A \\ \mathbf{f} : B\end{array}} \qquad \frac{\mathbf{t} : A \vee B}{\mathbf{t} : A \mid \mathbf{t} : B} \qquad \frac{\mathbf{f} : A \wedge B}{\mathbf{f} : A \mid \mathbf{f} : B} \qquad \frac{\mathbf{t} : A \wedge B}{\begin{array}{c}\mathbf{t} : A \\ \mathbf{t} : B\end{array}}$$

$$\frac{\mathbf{f} : A \supset B}{\begin{array}{c}\mathbf{t} : A \\ \mathbf{f} : B\end{array}} \qquad \frac{\mathbf{t} : A \supset B}{\mathbf{f} : A \mid \mathbf{t} : B} \qquad \frac{\mathbf{f} : \neg A}{\mathbf{t} : A} \qquad \frac{\mathbf{t} : \neg A}{\mathbf{f} : A}$$

Combining model building with theorem proving

- We have a method for building models
- We have a method for proving theorems

Let's put these together!

Consistency checking:

1. give F to a model builder; if it finds a model then F consistent
2. give ¬F to a theorem prover; it it finds a proof then F inconsistent

Combining model building with theorem proving

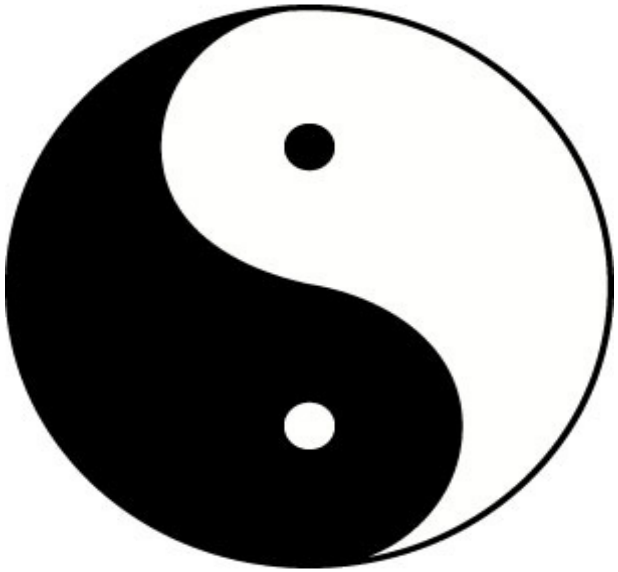
- We have a method for building models
- We have a method for proving theorems

Let's put these together!

Informativeness checking:

1. give ¬F to a model builder; if it finds a model then F informative
2. give F to a theorem prover; it it finds a proof then F uninformative

The Yin and Yang of Inference



Theorem Proving and **Model Building**
function as opposite forces

Good and bad news

(Very) Bad News

- First-order logic is undecidable
- There is no algorithm capable of determining whether an input formula is a theorem or not

(Reasonably) Good News

- First-order logic is actually semi-decidable
- If the input is a theorem, then there is a way to show so (given enough time and memory) – if it’s not then all bets are off
- Finding a finite model for a given domain size is decidable

Moving on...

- What are adequate meaning representations?
- How can we judge whether they are adequate?

What is an adequate meaning representation formalism?

1. Mia smokes → a woman smokes
2. Every woman smokes and Mia is a woman → Mia smokes
3. A tall woman smokes → a woman smokes
4. Mia smokes silently → Mia smokes
5. Mia smokes a cigarette → Mia smokes
6. Mia smokes a cigarette at a table → Mia smokes at a table
7. Mia smiles and smokes → Mia smiles
8. Mia met Vincent → Vincent met Mia
9. Mia is taller than Vincent → Vincent is not taller than Mia.
10. Mia is the tallest woman → Mia is taller than Yolanda.
11. Mia is taller than Vincent and Vincent is tall → Mia is tall.
12. Vincent saw a woman. She smokes. → a woman smokes.

Case Study 1: ....

Translation

Background Knowledge (aka Meaning Postulates)

Critical Reflection

Case Study 1: Mia smokes → a woman smokes

Translation

Mia smokes: p121

A woman smokes: p247

Background Knowledge

p121 → p247

Critical Reflection

- silly: doesn't scale
- need a new propositional variable for every sentence

Case Study 1: Mia smokes → a woman smokes

Translation

Mia smokes: mia(smokes)

A woman smokes: a-woman(smokes)

Background Knowledge

$\forall x(\text{mia}(x) \rightarrow \text{a-woman}(x))$

Critical Reflection

- bad choice predicate/argument
- doesn't scale to transitive verbs

Case Study 1: Mia smokes → a woman smokes

Translation

Mia smokes: smokes(mia)

A woman smokes: smokes(a-woman)

Background Knowledge

$\forall x(x=mia \rightarrow x=a\text{-}woman)$

Critical Reflection

- better predicate/argument choice
- noun phrases don't scale
- need a different constant for each noun phrase (silly)

Case Study 1: Mia smokes → a woman smokes

Translation

Mia smokes: $smokes(mia)$

A woman smokes: $\exists x(woman(x) \wedge smokes(x))$

Background Knowledge

$woman(mia)$

Critical Reflection

- this is promising

Case Study 2: Every woman smokes and Mia is a woman → Mia smokes

Translation

Every woman smokes: $\exists x(woman(x) \wedge smokes(x))$

Mia is a woman: woman(mia)

Mia smokes: smokes(mia)

Background Knowledge

Critical Reflection

- wrong choice of quantifier
- required entailment not produced

Case Study 2: Every woman smokes and Mia is a woman → Mia smokes

Translation

Every woman smokes: $\forall x(woman(x) \wedge smokes(x))$

Mia is a woman: $woman(mia)$

Mia smokes: $smokes(mia)$

Background Knowledge

Critical Reflection

- better choice of quantifier
- we get the inference
- but true only in a female smoky worlds

Case Study 2: Every woman smokes and Mia is a woman → Mia smokes

Translation

Every woman smokes: $\forall x(woman(x) \rightarrow smokes(x))$

Mia is a woman: $woman(mia)$

Mia smokes: $smokes(mia)$

Background Knowledge

Critical Reflection

- we get the inference
- proper restriction of the universal quantifier

Case Study 3: A tall woman smokes → a woman smokes

Translation

A tall woman smokes: $\exists x(\text{tall-woman}(x) \wedge \text{smokes}(x))$

A woman smokes: $\exists x(\text{woman}(x) \wedge \text{smokes}(x))$

Background Knowledge

$\forall x(\text{tall-woman}(x) \rightarrow \text{woman}(x))$

Critical Reflection

- doesn't scale
- need a lot of BK rules for all adjective-noun combinations

Case Study 3: A tall woman smokes → a woman smokes

Translation

A tall woman smokes: $\exists x(\mathrm{tall}(x) \wedge \mathrm{woman}(x) \wedge \mathrm{smokes}(x))$

A woman smokes: $\exists x(\mathrm{woman}(x) \wedge \mathrm{smokes}(x))$

Background Knowledge

Critical Reflection

- scales
- no BK rules needed
- works for intersective adjectives, but not for subsective ones

Case Study 4: Mia smokes silently → Mia smokes

Translation

Mia smokes silently: smokes-silently(mia)

Mia smokes: smokes(mia)

Background Knowledge

$\forall x(\text{smokes-silently}(x) \rightarrow \text{smokes}(x))$

Critical Reflection

- doesn't scale
- need a lot of BK rules for all adverb-verb combinations
- but what do we do?

Case Study 4: Mia smokes silently → Mia smokes

Translation

Mia smokes silently: $\exists x(\text{smokes}(x,\text{mia}) \wedge \text{silently}(x))$

Mia smokes: $\exists x\ \text{smokes}(x,\text{mia})$

Background Knowledge

Critical Reflection

- scales
- no BK needed
- known as *Davidsonian* analysis

Case Study 5: Mia smokes a cigarette → Mia smokes

Translation

Mia smokes a cigarette: $\exists x(\mathrm{cigarette}(x) \wedge \exists y\ \mathrm{smokes}(y,\mathrm{mia},x))$

Mia smokes: $\exists x\ \mathrm{smokes}(x,\mathrm{mia})$

Background Knowledge

$\forall x \forall y \forall z(\mathrm{smokes}(x,y,z) \rightarrow \mathrm{smokes}(x,y))$

Critical Reflection

- looking promising
- but BK needed to model optional arguments
- alternatives?

Thematic Roles

- Roles of all participants in an event
- The *who* does *what* to *whom*, *where* and *when*

- Example role inventory (subset of VerbNet):

  agent: human or animate volitional participant
  patient: participant undergoing a process
  theme: participant undergoing a change of location
  location: spatial location
  experiencer: participant that is experiencing something
  instrument: objects that come into contact with an object and cause some change in them

Case Study 5: Mia smokes a cigarette → Mia smokes

Translation

Mia smokes a cigarette:

$\exists e \exists x(cigarette(x) \wedge smokes(e) \wedge agent(e,mia) \wedge patient(e,x))$

Mia smokes:

$\exists e(smokes(e) \wedge agent(e,mia))$

Background Knowledge

Critical Reflection

- no BK required
- instead new inventory of thematic roles
- known as *neo-Davidsonian* analysis

Case Study 6:

Mia smokes a cigarette at a table →
Mia smokes at a table

Translation

Mia smokes a cigarette at a table:
$\exists e \exists x \exists y(\text{cigarette}(x) \wedge \text{smokes}(e) \wedge \text{agent}(e,\text{mia}) \wedge \text{patient}(e,x) \wedge \text{at}(e,y) \wedge \text{table}(y))$

Mia smokes at a table:
$\exists e \exists x(\text{smokes}(e) \wedge \text{agent}(e,\text{mia}) \wedge \text{at}(e,x) \wedge \text{table}(x))$

Background Knowledge

Critical Reflection

- no BK required
- neo-Davidsonian approach naturally extends to other verb modifiers

Case Study 7: Mia smiles and smokes → Mia smiles

Translation

Mia smiles and smokes: $\exists e(\text{smiles-and-smokes}(e) \wedge \text{agent}(e,\text{mia}))$

Mia smiles: $\exists e(\text{smiles}(e) \wedge \text{agent}(e,\text{mia}))$

Background Knowledge

$\forall x(\text{smiles-and-smokes}(x) \rightarrow \text{smokes}(x))$

$\forall x(\text{smokes-and-smiles}(x) \rightarrow \text{smokes}(x))$

Critical Reflection

- silly again...
- make use of boolean connectives

Case Study 7: Mia smiles and smokes → Mia smiles

Translation

Mia smiles and smokes:

$\exists e \exists e'(smiles(e) \wedge agent(e,mia) \wedge smokes(e') \wedge agent(e',mia))$

Mia smiles: $\exists e(smiles(e) \wedge agent(e,mia))$

Background Knowledge

Critical Reflection

- much better

Case Study 8: Mia met Vincent → Vincent met Mia

Translation

Mia met Vincent: $\exists e(meet(e) \wedge agent(e,mia) \wedge co\text{-}agent(e,vincent))$

Vincent met Mia: $\exists e(meet(e) \wedge agent(e,vincent) \wedge co\text{-}agent(e,mia))$

Background Knowledge

$\forall e \forall x(meet(e) \wedge agent(e,x) \rightarrow co\text{-}agent(e,x))$

$\forall e \forall x(meet(e) \wedge co\text{-}agent(e,x) \rightarrow agent(e,x))$

Critical Reflection

- can we do without BK?

Case Study 9: Mia is taller than Vincent → Vincent is not taller than Mia.

Translation

Mia is taller than Vincent:

$\exists e(\text{be-taller}(e) \wedge \text{theme}(e,\text{mia}) \wedge \text{than}(e,\text{vincent}))$

Vincent is not taller than Vincent:

$\neg\exists e(\text{be-taller}(e) \wedge \text{theme}(e,\text{vincent}) \wedge \text{than}(e,\text{mia}))$

Background Knowledge

$\forall e\forall x\forall y(\text{be-taller}(e) \wedge \text{theme}(e,x) \wedge \text{than}(e,y) \rightarrow \text{taller}(x,y))$

$\forall x\forall y\forall z((\text{taller}(x,y) \wedge \text{taller}(y,z)) \rightarrow \text{taller}(x,z))$

$\neg\exists x\ \text{taller}(x,x)$

Critical Reflection

- can we do without BK?

Case Study 10: Mia is the tallest woman → Mia is taller than Yolanda

Translation

Mia is the tallest woman:
$\exists e(\text{be-tallest}(e) \wedge \text{theme}(e,\text{mia}) \wedge \text{woman}(\text{mia}))$

Mia is taller than Yolanda:
$\exists e(\text{be-taller}(e) \wedge \text{theme}(e,\text{mia}) \wedge \text{than}(e,\text{yolanda}))$

Background Knowledge

$\forall e \forall x(\text{be-tallest}(e) \wedge \text{theme}(e,x)) \rightarrow \forall y(\neg x{=}y \rightarrow \text{taller}(x,y))$

$\forall e \forall x \forall y((\text{be-taller}(e) \wedge \text{theme}(e,x) \wedge \text{than}(e,y)) \rightarrow \text{taller}(x,y))$

$\forall x \forall y \forall y((\text{taller}(x,y) \wedge \text{taller}(y,z)) \rightarrow \text{taller}(x,z))$

$\neg \exists x\ \text{taller}(x,x)$

Critical Reflection

- restriction

Powerful but Limited

Many things that we haven't considered can be modeled or approximated with first-order logic

- modalities
- plurals
- tense and aspect

However, several natural language phenomena can't be handled by first-order logic

- relational quantifiers: most, few, many
- cardinal expressions (clumsy in FOL)
- intersective adjectives
- generics

Moving from sentences to text

- First-order Logic
- Discourse Representation Theory (DRT)

Discourse Representation Theory

- DRT is a formal semantic theory of text
- Predicts difference in acceptability of pronouns
- It employs box-like representations (DRS)