Computational Issues in the Parsing of Natural Language

Part 1: Selected Background Material (60%)

- The reason why generative parsing methods for programming languages are inadequate for natural languages.

- Modern techniques for parsing natural languages.

➢ This part is background; it is not about my research.

➢ It assumes knowledge of parsing in computer science (*i.e.,* CFG's), but no knowledge of computational linguistics.

Part 2: Current Research Topics (40%)

- Declarative specification of HPSG-style grammars.

- Computational management of partially specified type hierarchies.

Natural Language Processing and Computational Linguistics

A terminological distinction:

Natural Language Processing (NLP):

- Typically a component of a larger application.
- Restricted domain of linguistic discourse.
- Embodiment of linguistic principles secondary.

➢ Example: Natural-language interface to a help system for UNIX.

Computational Linguistics (CL):

- Study of formal models of language which are amenable to computation.
- Often involves stand-alone or demonstration implementation projects.
- Fairly general domain of linguistic discourse.
- Embodiment of linguistic principles essential.

Some major theories within computational linguistics:

- Lexical Functional Grammar (LFG).
- Head-Driven Phrase Structure Grammar (HPSG).
- Categorial Grammar.

➢ Example parsing systems : PATR, ALE, CUF, Troll, TFS, [Meurers'].

➢ Example projects within CL: Verbmobil.

Parsing

Parsing refers to the process of determining the syntactic and possibly semantic structure of a string.

In programming languages:

- We design the language (usually) to have certain properties, among them that of being amenable to parsing.
  - Notable exceptions: Ada, SQL

- Parsing base:
  - *Unambiguous* context-free grammar (BNF)
  - Semantic constraints to eliminate unwanted parses

- A given string has at most one parse (programs have unique derivations).

In natural language:

- We have to parse the language as it is.
- There are many strategies for parsing; some are based upon context-free grammars, some are not.
- A given sentence may have several parses.
  - Time flies like an arrow.
  - I saw the woman on the hill with a telescope.
- Correct parses may be strongly context dependent.
  - How do I print a file on the laser printer with the lines numbered?
- Parses may be rejected on purely semantic grounds.
  - John gave the book to Mary.
  - * John gave the book from Mary.
  - John gave the book from Mary to Marie.

Apparently similar constructions may be legal or illegal based upon fairly subtle rules.

- John hit the ball to Mary.
- John hit Mary the ball.
- John hit the ball to the wall.
- * John hit the wall the ball.

Pure Generative Parsing of NL

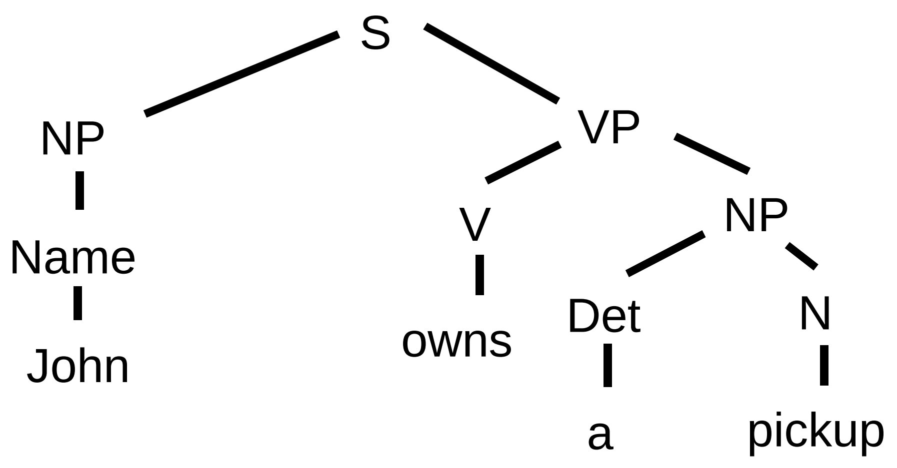
A context-free grammar (CFG) for a tiny fragment of English:

Syntactic Rules:
S → NP VP
VP → V | V NP
NP → Name | Det N

Lexical Rules:
Name → John | Mary | I | We | You
N → car | cars | truck | trucks | pickup | pickups
Det → a | an | the | two
V → own | owns | sleep | sleeps

A parse tree for the sentence:

"John owns a pickup."



The Problem with Pure Generative Parsing

Many ungrammatical sentences can also be generated.

- * John own an pickup.
- * We owns two pickup.
- * John owns.
- * Mary sleeps a truck.

These problems can be remedied by forcing number and verb-type distinction within the grammar.

To fix the verb-type distinction:

$VP \rightarrow V_I \mid V_T\ NP$
$V_I \rightarrow \text{sleep} \mid \text{sleeps}$
$V_T \rightarrow \text{own} \mid \text{owns}$

The number distinction on noun phrases:

$N_s \rightarrow \text{car} \mid \text{truck} \mid \text{pickup}$
$N_P \rightarrow \text{cars} \mid \text{trucks} \mid \text{pickups}$
$Det_S \rightarrow \text{a} \mid \text{an} \mid \text{the}$
$Det_P \rightarrow \text{two}$
$NP \rightarrow Det_S\ N_s \mid Det_P\ N_P$

Why This Is Not a Good Solution

- These types of "fixes" result in a combinatorial explosion in the number of rules of the grammar.

- Representation of other languages will result in much more serious explosions in size:
  - Multiple genders on nouns which require agreement with determiners and adjectives: French, Swedish: 2; German, Norwegian: 3
  - Complex verb conjugation depending upon both number and person:
    German: 4; French: 5 or 6

Conclusion: CFG, by itself, is not an adequate tool for describing natural language.

Remarks:

- It is a debatable theoretical question as to whether languages such as English can be represented by CFG, in the *weak sense* of being able to generate exactly the legal sentences strings.

- It is easy to show that English cannot be generated by a CFG in the *strong sense*, in which the parse trees reflect the grammatical structure.

The Hybrid
Generative + Constraint Solution

- Approach:
  - CFG (the *context-free skeleton / backbone)* +
  - constraint set
- LFG (Lexical-Functional Grammar) uses this approach.

A simple example: The objects in the lexicon are augmented with types:

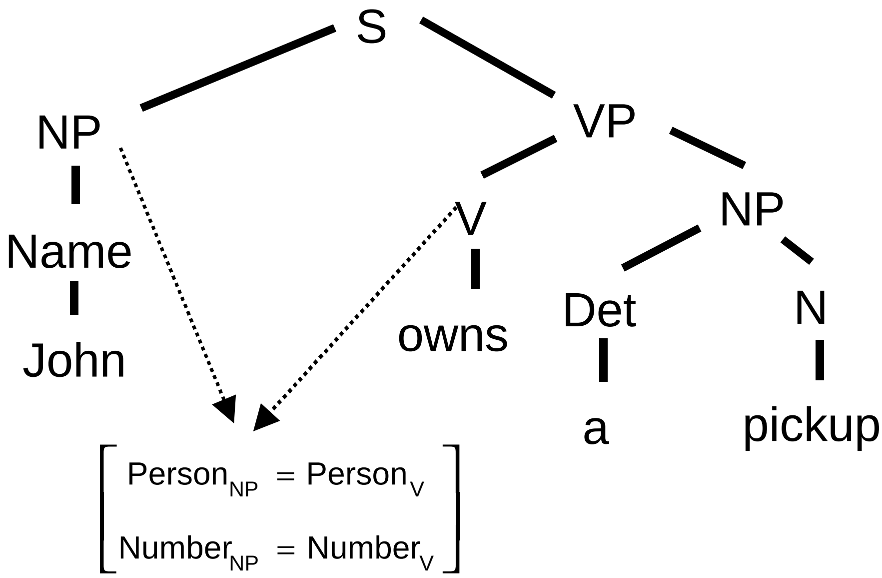
Some Names:

$$\begin{bmatrix} \text{Name}: & \text{John} \\ \text{Person}: & 3 \\ \text{Number}: & \text{Singular} \end{bmatrix} \quad \begin{bmatrix} \text{Name}: & \text{We} \\ \text{Person}: & 1 \\ \text{Number}: & \text{Plural} \end{bmatrix}$$

A verb:

$$\begin{bmatrix} \text{Name}: & \text{owns} \\ \text{Person}: & 3 \\ \text{Number}: & \text{sing} \end{bmatrix} \quad \begin{bmatrix} \text{Name}: & \text{own} \\ \left.\begin{matrix} \text{Person}: \\ \text{Number}: \end{matrix}\right\} & \text{any but sing} + 3\ \text{pers} \end{bmatrix}$$

- The grammatical productions now have these constraints attached to them.
- Similar in idea to *indexed grammars* for programming languages.



The main idea of this approach thus consists of two steps:

- **Generate**: Find the candidate parses for the underlying CFG.
- **Constrain**: Use the feature constraints to eliminate undesired parses.

Decision properties:

- In general, the problem of deciding whether a sentence has a parse tree which satisfies the given constraints is undedicable.
  - ... because there can be infinitely many parse trees for a given string.

- However, it is decidable if we can find all parse trees algorithmically *(off-line parsing condition).*
  - ... in which case the number of parse trees is provably finite and identifiable.

Pure Constraint-Based Parsing

- In pure constraint based parsing (as exemplified by HPSG), there is no underlying context-free grammar.
- The entire parsing process is one of finding *models* of constraints, which are expressed in a *typed feature logic.*
- The main operation is *unification*; hence the techniques is also called unification-based parsing.

The following examples illustrate the idea of typed feature logic, but do **not** represent the HPSG model.

Feature Structures

Typed Feature structures are simply record-like entities.

Example:

Pascal Notation	Feature-Structure Notation
type Person = record Name: Name_type; ID_number: ID_type; Income: Integer end record; {Person}	$\tau_{Person} \begin{bmatrix} \text{Name:} & \tau_{\text{Name-type}} \\ \text{ID\_number:} & \tau_{\text{ID\_type}} \\ \text{Income:} & \tau_{\text{Integer}} \end{bmatrix}$
var P Person; P.Name := Smith; P.ID_number := 123456; P.Income := 100000;	$\begin{bmatrix} \text{Name:} & \text{Smith} \\ \text{ID\_number:} & 123456 \\ \text{Income:} & 100000 \end{bmatrix}$

- Feature structures also admit direct and indirect recursion on types.

Pseudo Pascal	Feature Structure
type Node = record Value: Integer; Next: Node end record {Node}	$\tau_{Node} \begin{bmatrix} \text{Value:} & \tau_{\text{Integer}} \\ \text{Next:} & \tau_{\text{Node}} \end{bmatrix}$

Feature structures also admit *coalescing* of values.

Name:	John	Name:	Mary
Salary:	100000	Salary:	100000
Child:	James	Child:	James

Here James is the same person in each case.

This type of construction is critical in modelling linguistic situations in which the same object is referenced in two ways.

Gap-filler constructions:

- Jan$_j$ is easy to talk to ___$_j$ about problems of this sort.

- [Problems of this sort]$_i$, Jan$_j$ is easy to talk to ___$_j$ about ___$_i$.

Example from Norwegian:

- Han vasket sin bil.
- Han vasket hans bil.

Unification-Based Parsing

Recapture: $S \rightarrow NP\ VP$

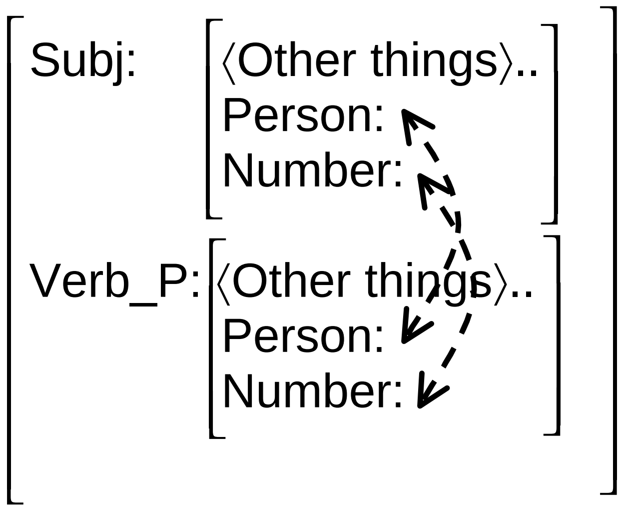
$$\tau_S \begin{bmatrix} \text{Subj:} & \tau_{NP} \\ \text{Verb\_P:} & \tau_{VP} \end{bmatrix}$$

The corresponding logical constraint:

$$(\forall x)(\exists y)(\exists z)$$
$$(\tau_S(x) \Rightarrow x{:}\text{Subj}{:}\tau_{NP}(y) \wedge x{:}\text{Verb\_P}{:}\tau_{VP}(z))$$

To recapture agreement:

$$\tau_{NP} \begin{bmatrix} \langle\text{Other things}\rangle.. & \\ \text{Person:} & \tau_{Pers} \\ \text{Number:} & \tau_{Num} \end{bmatrix} \qquad \tau_{VP} \begin{bmatrix} \langle\text{Other things}\rangle.. & \\ \text{Person:} & \tau_{Pers} \\ \text{Number:} & \tau_{Num} \end{bmatrix}$$



$$(\forall x)\ (\tau_S(x) \Rightarrow (x{:}\text{Subj}\cdot\text{Person} \asymp x.\text{Verb\_P}\cdot\text{Person} \wedge$$
$$x{:}\text{Subj}\cdot\text{Number} \asymp x.\text{Verb\_P}\cdot\text{Number}))$$

VP $\rightarrow$ V | V NP

$$(\forall x)(\tau_{VP}(x) \Leftrightarrow \tau_{VP1}(x) \vee \tau_{VP2}(x))$$

Schema for V:

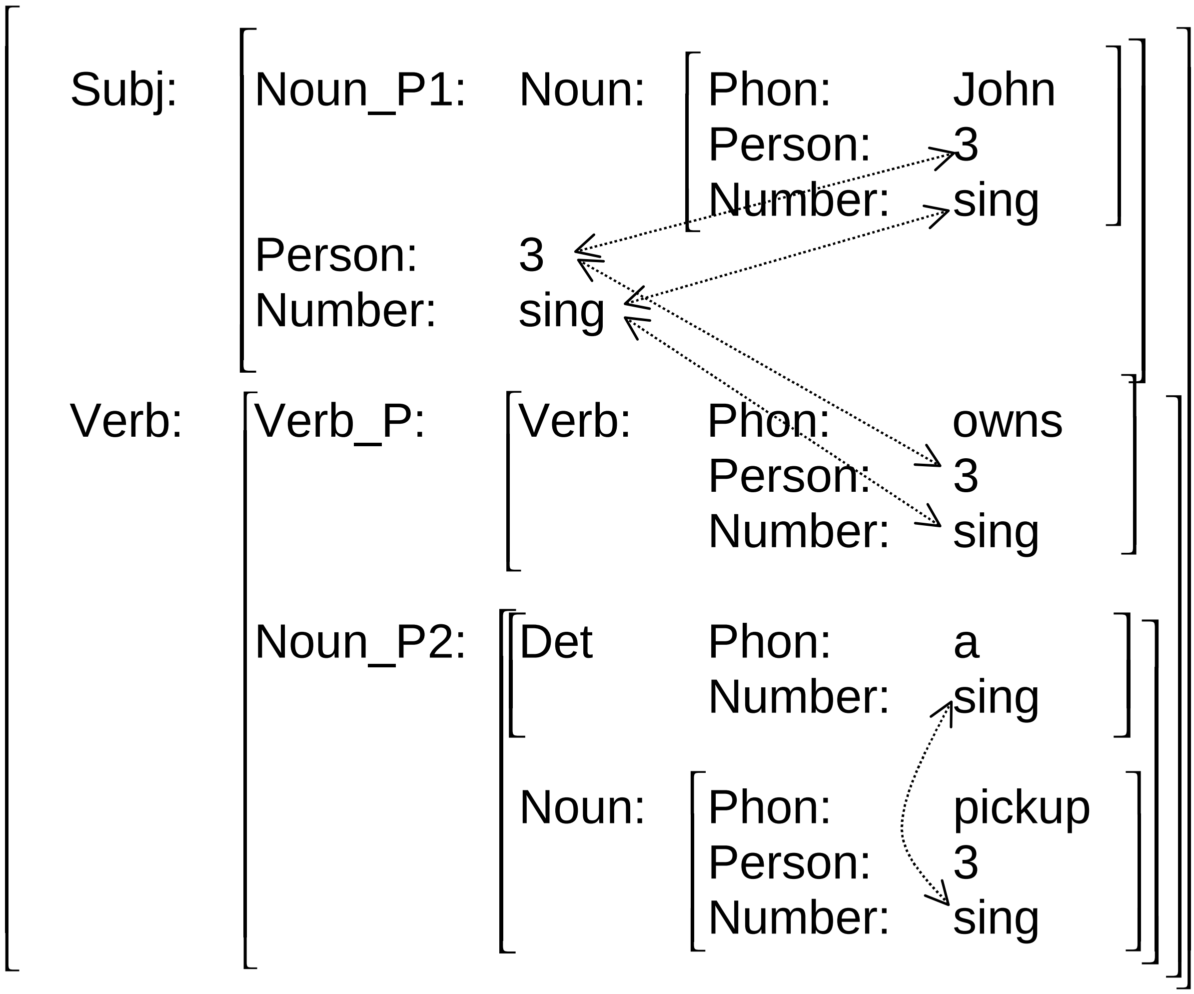
$$\tau_{VP1}\begin{bmatrix} \text{Phon:} & \tau_{V\_Lex} \\ \text{Person:} & \tau_{Pers} \\ \text{Number:} & \tau_{Num} \end{bmatrix}$$

Instances from the lexicon would contain the following information:

$$\begin{bmatrix} \text{Phon:} & \text{own} \\ \text{Person:} & \left.\right\} \text{any but} \\ \text{Number:} & \text{3p+sing} \end{bmatrix} \vee \begin{bmatrix} \text{Phon:} & \text{owns} \\ \text{Person:} & 3 \\ \text{Number:} & \text{sing} \end{bmatrix} \vee ..$$

This process goes on and on..

This is what the final parse might look like:



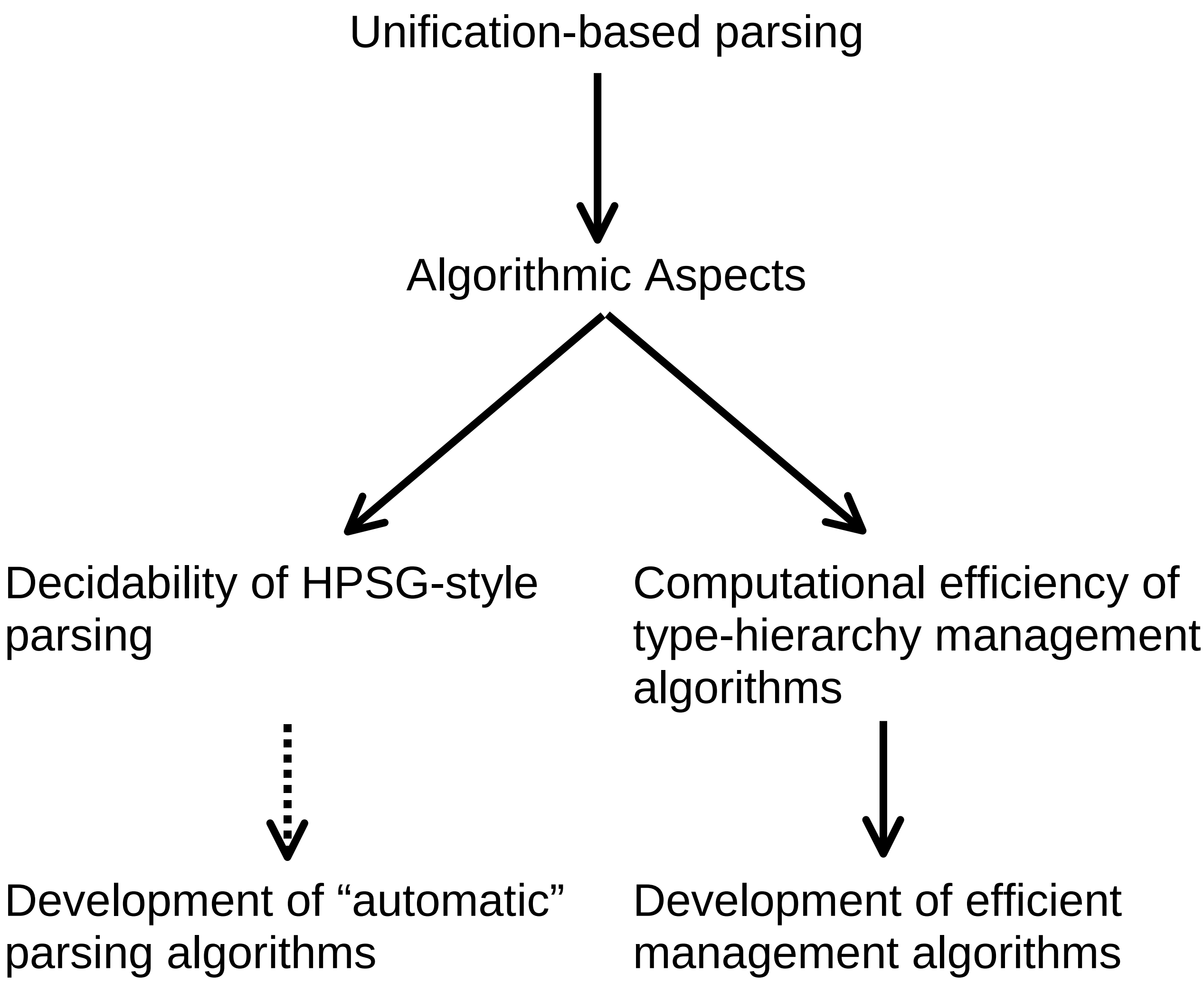
Notes:

- Such a structure is a model of the appropriate constraints in the underlying logic:
  - Framework constraints;
  - Input specific constraints.

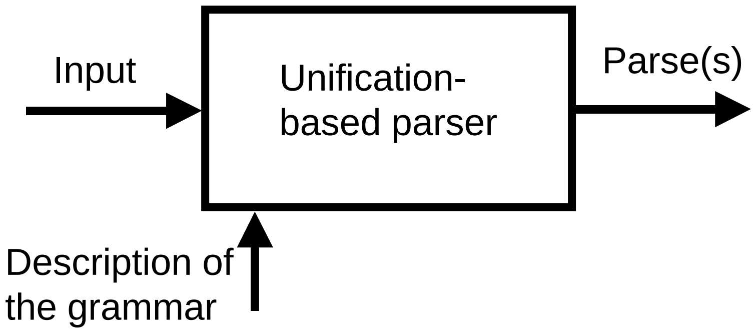
- If there were more than one legal parse, each such parse would be represented by a structure of this form.

- This is **not** HPSG.

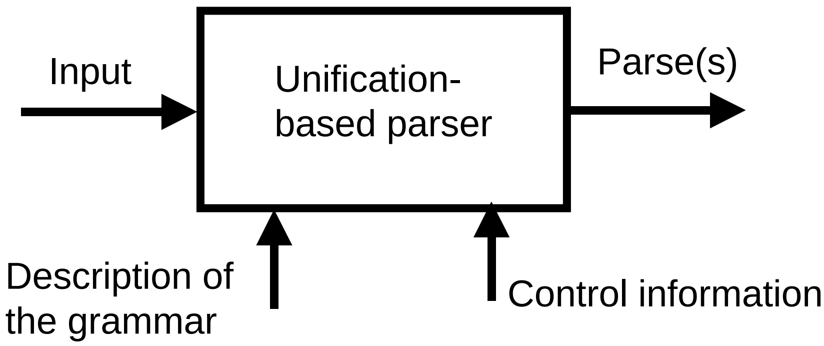
Current Research Directions



Research Problem 1: The Decidability of Parsing within HPSG-style Formalisms



The *ideal* world of constraint-based parsing
(Similar to the *real* world of PL parsing.)



The *real* world of constraint-based parsing

- Question: Is it *possible* to render the process of constraint-based parsing decidable, so that the grammar writer / user need not supply control information?

- This is a nontrivial question...

Motivation:

- The process of understanding natural language appears to be decidable. (Humans do it all the time.)
- Generative frameworks such as LFG render large fragments of natural languages decidable. The user need not supply control information.
- Existing tools for unification-based grammatical formalisms (such as HPSG) require the user to supply control information.

General approach:

- Formalize to an appropriate logic.
- Show the logic, or significant fragments thereof, to be decidable.

My approach:

- Develop a custom logic, and then embedded this logic into first-order predicate logic.
- Show that this fragment is decidable.
- Rationale:
  - A great deal is known about decidable and undecidable classes of formulas within first order logic. This approach makes use of that knowledge.

Other approaches:

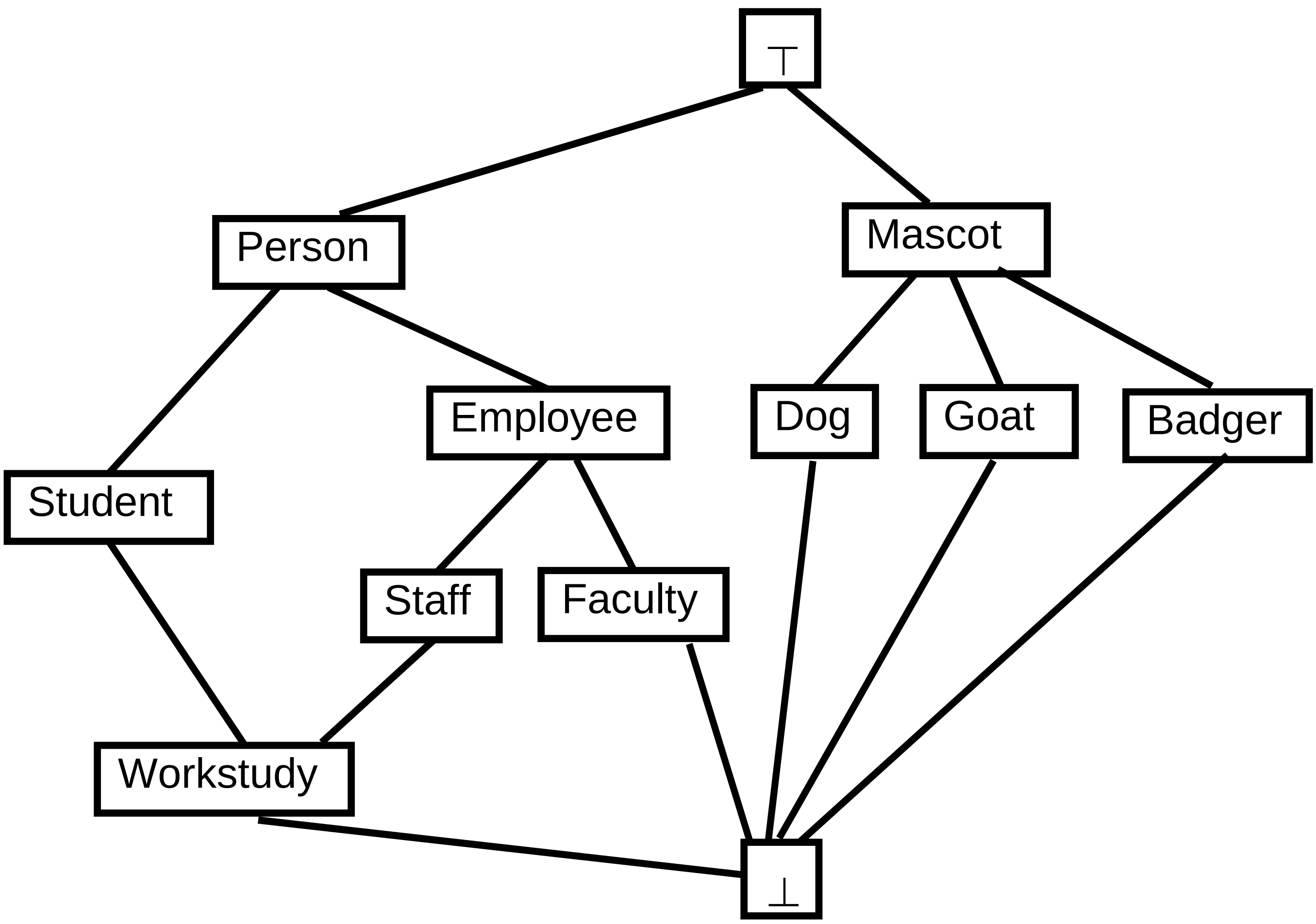
- Custom logics:
  - Tübingen (King, Kepser)
  - Edinburgh (Manandhar)

Research Problem 2: Efficient Computational Management of Partially Specified Type Hierarchies

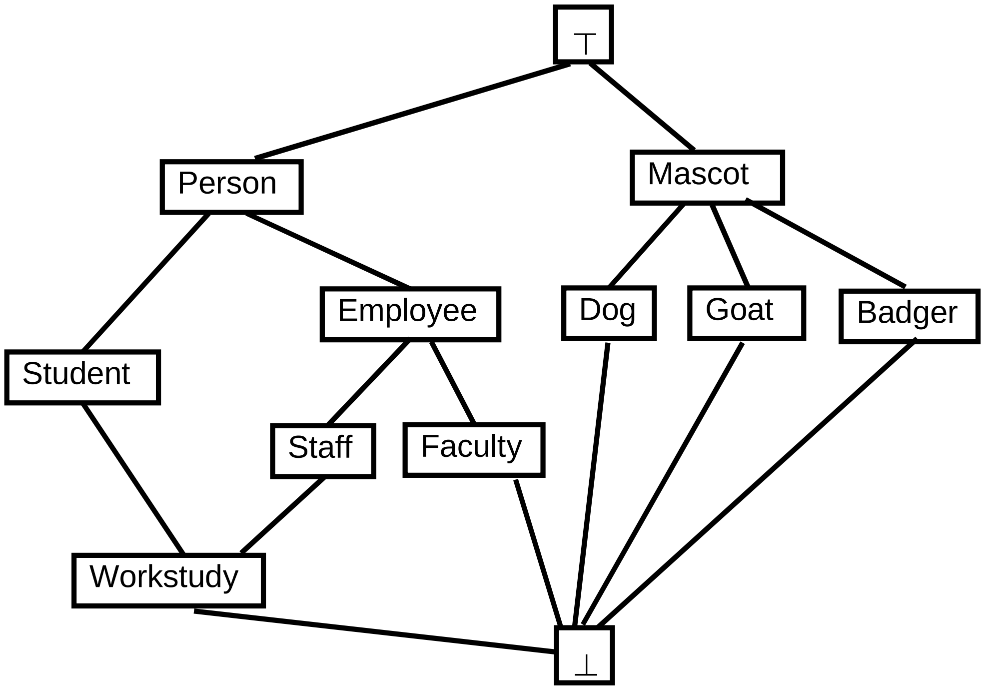
- Feature logic, as applied to formalisms such as HPSG, depends critically upon the concept of a type hierarchy.

What is a type hierarchy?

- The concept of inheritance via a hierarchy should be familiar from object-oriented languages.



The Semantics of Type Hierarchies:



- Every class has a set of instances:
  - Inst(Student) = the class of students, etc.
  - Inst($\top$) = universe;   Inst($\bot$) = $\emptyset$.

ISA semantics:

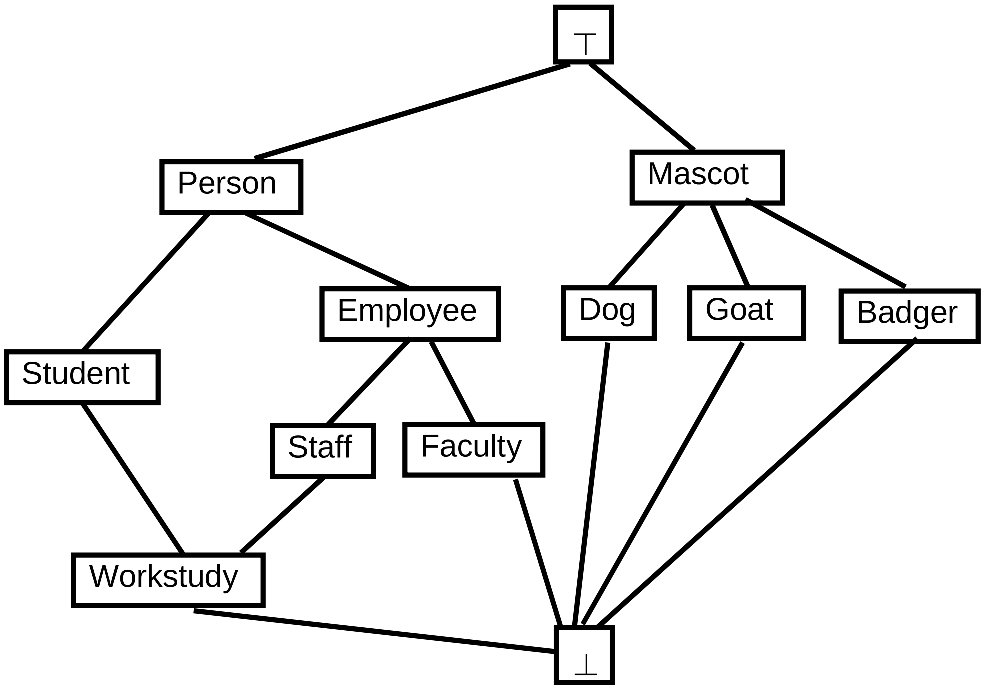
- $X \leq Y \Rightarrow$ Inst(Y) $\subseteq$ Inst(X).
  - Workstudy(x) $\Rightarrow$ Student(x)

Natural semantics:

($\wedge$ = infimum ; $\vee$ = supremum)

- $Z = X \wedge Y \Rightarrow$ Inst(Z) = Inst(X) $\cap$ Inst(Y)
- $Z = X \vee Y \Rightarrow$ Inst(Z) = Inst(X) $\cup$ Inst(Y)
  - Student(x) $\wedge$ Staff(x) $\Leftrightarrow$ Workstudy(x)
  - Student(x) $\vee$ Staff(x) $\Leftrightarrow$ Person(x)

Are these semantics always consistent?



The natural semantics is valid if and only if the hierarchy does not contain a *pentagon* or a *diamond*.

This is equivalent to satisfaction of either of the *distributive laws* (Birkhoff"s representation):

- $(X \wedge Y) \vee Z = (X \vee Z) \wedge (Y \vee Z)$
- $(X \vee Y) \wedge Z = (X \wedge Z) \vee (Y \wedge Z)$

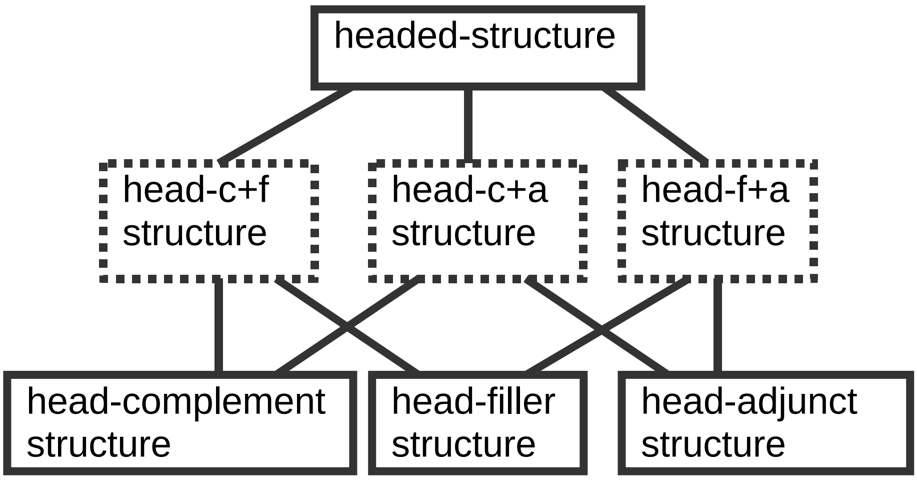
- These tests may be performed in time $O(n^3)$, with n the number of classes in the hierarchy.

Partial Specification

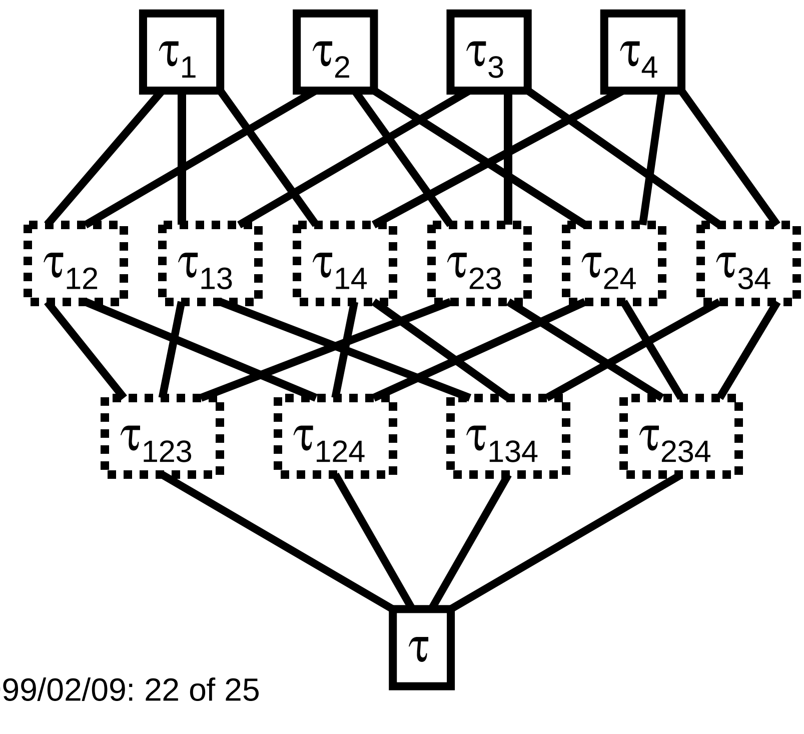
The need:

- In large systems, complete explicit specification of the type hierarchy is impractical.

headed-structure = head-complement-structure
$\vee$ head-filler-structure
$\vee$ head-adjunct-structure



$\tau = \tau_1 \wedge \tau_2 \wedge \tau_3 \wedge \tau_4$



Formal Open Specification

In a formal *open specification*, declarations of the following forms are allowed.

Order constraints:

(a) $\tau_1 \leq \tau_2$

(b) $\tau = \tau_1 \vee \tau_2 \vee .. \vee \tau_n$

(c) $\tau = \tau_1 \wedge \tau_2 \wedge .. \wedge \tau_n$

Note: Supremum is not $\vee$, by default.
Infimum is not $\wedge$, by default.

Position constraints:

(d) $\tau_1 \neq \tau_2$

(e) $\mathsf{Atom}(\tau)$ ($\tau \notin \{\top, \bot\}$.)

- The interpretation of these constraints is in accordance with the natural semantics, and is inherently partial:
  - A collection of such rules characterizes not a single hierarchy; such a collection is a set of constraints defining a set of hierarchies.

Goal:

- Find effective algorithms for characterizing the distributive hierarchies which are consistent with such a collection of rules.

Result:

- Does a given open specification have an extension to a complete distributive type hierarchy?
  - This problem is *NP-complete* [Hegner, 1995].
    ⇒ The best known algorithm is $O(2^n)$.

Special aspects making this problem unique:

- NP-complete problems must be dealt with, and are dealt with, all the time.

- Existing techniques (approximation) apply to optimization problems, and are not applicable to this problem.

- This problem belongs to a class including satisfiability problems in logic, in which approximation makes no sense.

- In addition, *all* solutions are sought, rather than just a single solution.

Current Directions:

- Development of techniques which make use of the special properties of the solution space (it forms a complete lattice) to reduce greatly the amount of searching which needs to be done.

- Experimental measurement of algorithm performance.

- Incremental modification:

  - Linguistic databases, particularly lexicons, undergo frequent modification.

  - Rather than rebuild the entire hierarchy every time a modification is to be performed, it would be simpler to modify the existing hierarchy.

  - Current research includes investigation of determining whether an update of a legal formal specification is also legal.