Machine Translation, Type Theory, Dependent Types

Aarne Ranta

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Plan

Machine Translation

Grammatical Framework

Dependent Types
Machine Translation
Important research problems

(From Hamming, "You and your research")

What are the important problems in your field?

Are you working on one of them?

If not, why?

http://www.paulgraham.com/hamming.html
The important problems in computational linguistics

type-theoretical semantics
The important problems in computational linguistics

- type-theoretical semantics
- anaphora resolution
The important problems in computational linguistics

- type-theoretical semantics
- anaphora resolution
- multilingual syntax editing
The important problems in computational linguistics

type-theoretical semantics

anaphora resolution

multilingual syntax editing

machine translation
Beginnings of machine translation

Weaver 1947, encouraged by cryptography in WW II

Word lookup $\rightarrow$ n-gram models (Shannon’s "noisy channel")

$$\hat{e} = \arg\max_e P(f|e)P(e)$$

$P(w_1 \ldots w_n)$ approximated by e.g. $P(w_1w_2)P(w_2w_3)\ldots P(w(n-1)w_n)$ (2-grams)

Modern version: Google translate translate.google.com
Word sense disambiguation

Eng. even $\rightarrow$ Fre égal, équitable, pair, plat ; même, ...

Eng. even number $\rightarrow$ Fre nombre pair

Eng. not even $\rightarrow$ Fre même pas

Eng. 7 is not even $\rightarrow$ Fre 7 n’est pas pair

Eng. 7 is not even even $\rightarrow$ Fre 7 n’est même pas pair
Long-distance dependencies

Ger. *er bringt mich um* $\rightarrow$ Eng. *he kills me*

Ger. *er bringt seinen besten Freund um* $\rightarrow$ Eng. *he kills his best friend*
Type theory and machine translation

Bar-Hillel (1953): MT should aim at rendering meaning, not words.

Method: Ajdukiewicz syntactic calculus (1935) for syntax and semantics.

Directional types (prefix and postfix functions)

\[
\text{loves} : (n \backslash s)n \quad \text{Mary} : n
\]

\[
\begin{array}{c}
\text{John} : n \\
\text{loves Mary} : n \backslash s
\end{array}
\]

\[
\begin{array}{c}
\text{John loves Mary} : s
\end{array}
\]

Categorial grammar, developed further by Lambek (1958), Curry (1961)
Bar-Hillel’s criticism

1963: FAHQT (Fully Automatic High-Quality Translation) is impossible - not only in foreseeable future but in principle.

Example: word sense disambiguation for *pen*:

*the pen is in the box* vs. *the box is in the pen*

Requires unlimited intelligence, universal encyclopedia.
1970’s and 1980’s

Trade-off: coverage vs. precision

Precision-oriented systems: Curry → Montague → Rosetta

Interactive systems (Kay 1979/1996)

- ask for disambiguation if necessary
- text editor + translation memory
Present day

IBM system (Brown, Jelinek, & al. 1990): back to Shannon’s model

Google translate 2007- (Och, Ney, Koehn, ...)

- 57 languages
- models built automatically from text data

*Browsing quality* rather than *publication quality*

Systran/Babelfish: rule-based, since 1960’s

Apertium (2005-): rule-based, closely related languages
MOLTO's mission is to develop a set of tools for translating texts between multiple languages in real time with high quality. MOLTO will use multilingual grammars based on semantic interlinguas.

FP7-ICT-247914, Strep, www.molto-project.eu

U Gothenburg, U Helsinki, UPC Barcelona, Ontotext (Sofia)

March 2010 - February 2013
What’s new?

<table>
<thead>
<tr>
<th>Tool</th>
<th>Google, Babelfish</th>
<th>MOLTO</th>
</tr>
</thead>
<tbody>
<tr>
<td>target</td>
<td>consumers</td>
<td>producers</td>
</tr>
<tr>
<td>input</td>
<td>unpredictable</td>
<td>predictable</td>
</tr>
<tr>
<td>coverage</td>
<td>unlimited</td>
<td>limited</td>
</tr>
<tr>
<td>quality</td>
<td>browsing</td>
<td>publishing</td>
</tr>
</tbody>
</table>
Producer’s quality

Cannot afford translating French

• *prix 99 euros*

to Swedish

• *pris 99 kronor*

Typical SMT error due to parallel corpus containing localized texts. (N.B. 99 kronor = 11 euros)
Reliability

German to English

- er bringt mich um -> he is killing me

correct, but

- er bringt meinen besten Freund um -> he brings my best friend for

should be he kills my best friend. (Typical error due to long distance dependencies, causes unpredictability)
Aspects of reliability

Separation of levels (syntax, semantics, pragmatics, localization)

Predictability (generalization for similar constructs, and over time)

Programmability / debugging and fixing bugs (vs. holism)
The translation directions

Statistical methods (e.g. Google translate) work decently to English

- rigid word order
- simple morphology
- originates in projects funded by U.S. defence

Grammar-based methods work equally well for different languages

- Finnish cases
- German word order
Main technologies

GF, grammaticalframework.org

- Domain-specific interlingua + concrete syntaxes
- GF Resource Grammar Library
- Incremental parsing
- Syntax editing

OWL Ontologies: resources for domain semantics

Statistical Machine Translation: robustness, grammar learning
MOLTO languages
Domain-specific interlinguas

The abstract syntax must be formally specified, well-understood

• semantic model for translation
• fixed word senses
• proper idioms

For instance: a mathematical theory, an ontology
Example: social network

Abstract syntax:

```
fun Like : Person -> Item -> Fact
```

Concrete syntax (first approximation):

```
lin Like x y = x ++ "likes" ++ y      -- Eng
lin Like x y = x ++ "tycker om" ++ y -- Swe
lin Like x y = y ++ "piace a" ++ x    -- Ita
```
Complexity of concrete syntax

Italian: agreement, rection, clitics (*il vino piace a Maria* vs. *il vino mi piace*; *tu mi piaci*)

```plaintext
lin Like x y = y.s ! nominative ++ case x.isPron of {
   True  => x.s ! dative ++ piacere_V ! y.agr ;
   False => piacere_V ! y.agr ++ "a" ++ x.s ! accusative
}
oper piacere_V = verbForms "piaccio" "piaci" "piace" ...
```

Moreover: contractions (*tu piaci ai bambini*), tenses, mood, ...
Two things we do better than before

No universal interlingua:

- *The Rosetta stone is not a monolith, but a boulder field.*

Yes universal concrete syntax:

- no hand-crafted *ad hoc* grammars
- but a general-purpose **Resource Grammar Library**
The GF Resource Grammar Library

Currently for 16 languages; 3-6 months for a new language.

Complete morphology, comprehensive syntax, lexicon of irregular words.

Common syntax API:

```
lin Like x y = mkCl x (mkV2 (mkV "like")) y       -- Eng
lin Like x y = mkCl x (mkV2 (mkV "tycker") "om") y -- Swe
lin Like x y = mkCl y (mkV2 piacere_V dative) x    -- Ita
```
Word/phrase alignments via abstract syntax
Domains for case studies

Mathematical exercises (<- WebALT)

Patents in biomedical and pharmaceutical domain

Museum object descriptions

Demo: a tourist phrasebook (web and Android phones)
Other potential uses

Wikipedia articles

E-commerce sites

Medical treatment recommendations

Social media

SMS

Contracts
Challenge: grammar tools

Scale up production of domain interpreters

- from 100’s to 1000’s of words
- from GF experts to domain experts and translators
- from months to days
- writing a grammar $\approx$ translating a set of examples
Example-based grammar writing

Abstract syntax  Like She He
English example  she likes him
German translation er gefällt ihr
resource tree  mkCl he_Pron gefallen_V2 she_Pron
concrete syntax rule  Like x y = mkCl y gefallen_V2 x
first grammarian
first grammarian
human translator
GF parser
variables renamed
Learning GF grammars by statistics

Abstract syntax
Like She He

English example
*she likes him*

German translation
*er gefällt ihr*

Resource tree
mkCl he_Pron gefallen_V2 she_Pron

Concrete syntax rule
Like x y = mkCl y gefallen_V2 x

Rationale: SMT is *good* for sentences that are *short* and *frequent*
Improving SMT by grammars

Rationale: SMT is *bad* for sentences that are *long* and involve *word order variations*

*if you like me, I like you*

*If (Like You I) (Like I You)*

*wenn ich dir gefalle, gefällst du mir*
Grammatical Framework
History

Background: type theory, logical frameworks (LF), compilers

GF = LF + concrete syntax

Started at Xerox (XRCE Grenoble) in 1998 for **multilingual document authoring**

Functional language with dependent types, parametrized modules, optimizing compiler

Run-time: Parallel Multiple Context-Free Grammar, polynomial
Factoring out functionalities

GF grammars are declarative programs that define

- parsing
- generation
- translation
- editing

Some of this can also be found in BNF/Yacc, HPSG/LKB, LFG/XLE...
A model for reliable automatic translation: compilers

Translate source code to target code, *preserving meaning*

Method: parsing, semantic analysis, optimization, code generation
Multilingual grammars in compilers

Source and target language related by abstract syntax

\[ 2 \times x + 1 \quad \text{<------>} \quad \text{plus (times 2 x) 1} \quad \text{<------>} \quad \text{imul} \]

\[ \text{iconst}_2 \quad \text{iadd} \]

\[ \text{iload}_0 \quad \text{iconst}_1 \]
A GF grammar for arithmetic expressions

abstract Expr = {
    cat Exp ;
    fun plus : Exp -> Exp -> Exp ;
    fun times : Exp -> Exp -> Exp ;
    fun one, two : Exp ;
}

concrete ExprJava of Expr = {
    lincat Exp = Str ;
    lin plus x y = x ++ "+" ++ y ;
    lin times x y = x ++ "*" ++ y ;
    lin one = "1" ;
    lin two = "2" ;
}

concrete ExprJVM of Expr= {
    lincat Expr = Str ;
    lin plus x y = x ++ y ++ "iadd" ;
    lin times x y = x ++ y ++ "imul" ;
    lin one = "iconst_1" ;
    lin two = "iconst_2" ;
}
Multi-source multi-target compilers

Diagram:
- Fortran
- C
- Java

Abstract Syntax

- Intel
- ARM
- JVM
Multilingual grammars in natural language

Mary loves John
\ /
Pred Mary (Compl Love John)
\ /
Marie aime Jean

Maria Ioannem amat

מריה אָמעט אוּן ג'אן
Natural language structures

Predication:  *John* + *loves Mary*

Complementation:  *love* + *Mary*

Noun phrases:  *John*

Verb phrases:  *love Mary*

2-place verbs:  *love*
Abstract syntax of sentence formation

abstract Zero = {
    cat
        S ; NP ; VP ; V2 ;
    fun
        Pred : NP -> VP -> S ;
        Compl : V2 -> NP -> VP ;
        John, Mary : NP ;
        Love : V2 ;
}
Concrete syntax, English

concrete ZeroEng of Zero = {
    lincat
        S, NP, VP, V2 = Str ;
    lin
        Pred np vp = np ++ vp ;
        Compl v2 np = v2 ++ np ;
        John = "John" ;
        Mary = "Mary" ;
        Love = "loves" ;
}

Multilingual grammar

The same system of trees can be given

- different words
- different word orders
- different linearization types
concrete ZeroFre of Zero = {
    lincat
    S, NP, VP, V2 = Str ;
    lin
    Pred np vp = np ++ vp ;
    Compl v2 np = v2 ++ np ;
    John = "Jean" ;
    Mary = "Marie" ;
    Love = "aime" ;
}

Just use different words
Translation and multilingual generation in GF

Import many grammars with the same abstract syntax

> i ZeroEng.gf ZeroFre.gf
Languages: ZeroEng ZeroFre

Translation: pipe parsing to linearization

> p -lang=ZeroEng "John loves Mary" | l -lang=ZeroFre
Jean aime Marie

Multilingual random generation: linearize into all languages

> gr | l
Pred Mary (Compl Love Mary)
Mary loves Mary
Marie aime Marie
Parameters in linearization

Latin has cases: nominative for subject, accusative for object.

- Ioannes Mariam amat "John-Nom loves Mary-Acc"
- Maria Ioannem amat "Mary-Nom loves John-Acc"

Parameter type for case (just 2 of Latin’s 6 cases):

    param Case = Nom | Acc
Concrete syntax, Latin

concrete ZeroLat of Zero = {
    lincat
        S, VP, V2 = Str ;
        NP = Case => Str ;
    lin
        Pred np vp = np ! Nom ++ vp ;
        Compl v2 np = np ! Acc ++ v2 ;
        John = table {Nom => "Ioannes" ; Acc => "Ioannem"} ;
        Mary = table {Nom => "Maria" ; Acc => "Mariam"} ;
        Love = "amat" ;
    param
        Case = Nom | Acc ;
}

Different word order (SOV), different linearization type, parameters.
Table types and tables

The linearization type of NP is a **table type**: from Case to Str,

\[
\text{lincat } \text{NP} = \text{Case} \Rightarrow \text{Str}
\]

The linearization of John is an **inflection table**,

\[
\text{lin John} = \text{table} \{\text{Nom} \Rightarrow "Ioannes" ; \text{Acc} \Rightarrow "Ioannem"\}
\]

When using an NP, **select** (!) the appropriate case from the table,

\[
\text{Pred np vp} = \text{np} ! \text{Nom} ++ \text{vp} \\
\text{Compl v2 np} = \text{np} ! \text{Acc} ++ \text{v2}
\]
Love in Dutch

John loves Mary

Jan heeft Marie lief
Concrete syntax, Dutch

concrete ZeroDut of Zero = {

    lincat
        S, NP, VP = Str ;
        V2 = {v : Str ; p : Str} ;

    lin
        Pred np vp = np ++ vp ;
        Compl v2 np = v2.v ++ np ++ v2.p ;
        John = "Jan" ;
        Mary = "Marie" ;
        Love = {v = "heeft" ; p = "lief"} ;

}

The verb *heeft lief* is a discontinuous constituent.
Record types and records

The linearization type of \( V2 \) is a record type

\[
\text{lincat } V2 = \{v : \text{Str} ; p : \text{Str}\}
\]

The linearization of \( \text{Love} \) is a record

\[
\text{lin Love} = \{v = "\text{heeft}" ; p = "\text{lief}"\}
\]

The values of fields are picked by projection (.)

\[
\text{lin Compl } v2 \text{ np } = v2.v ++ \text{np} ++ v2.p
\]
Concrete syntax, Hebrew

```concrete
concrete ZeroHeb of Zero = {
    flags coding=utf8 ;
    lincat
    S = Str ;
    NP = {s : Str ; g : Gender} ;
    VP , V2 = Gender => Str ;
    lin
    Pred np vp = np.s ++ vp ! np.g ;
    Compl v2 np = table {g => v2 ! g ++ "ה" ++ np.s} ;
    John = {s = "יון" ; g = Masc} ;
    Mary = {s = "מר" ; g = Fem} ;
    Love = table {Masc => "אהבה" ; Fem => "אהבה"} ;
    param
    Gender = Masc | Fem ;
}
```

The verb agrees to the gender of the subject.
Abstract trees vs. parse trees

Abstract trees

- nodes: constructor functions
- leaves: constructor functions

Parse trees

- nodes: categories
- leaves: words
Abstract is more abstract

```
                   S
                   \  /  \\
                    NP VP
                         \   /  \\
                          V2 NP

                   NP
                   \  /  \\
                    John loves Mary
```

```
Pred
   \  /  \\
John Compl
     \  /  \\
Love Mary
```
Abstract is more abstract
Abstract is more abstract
From trees to words
From words to trees to words
From words to words
Generating word alignment: summary

In L1 and L2: link every word with its smallest spanning subtree

Delete the intervening tree, combining links directly from L1 to L2

Notice: in general, this gives phrase alignment

Notice: links can be crossing, phrases can be discontinuous
Complexity of grammar writing

To implement a translation system, we need

- domain expertise: technical and idiomatic expression
- linguistic expertise: how to inflect words and build phrases
The GF Resource Grammar Library

Morphology and basic syntax

Common API for different languages

Currently (June 2011) 19 languages: Afrikaans, Bulgarian, Catalan, Danish, Dutch, English, Finnish, French, German, Italian, Norwegian, Persian, Polish, Punjabi, Romanian, Russian, Spanish, Swedish, Urdu.

Under construction for more languages: Amharic, Arabic, Hindi, Irish, Latin, Latvian, Nepali, Swahili, Thai, Turkish.

Contributions welcome!
The scope of resource grammars

Morphology: all inflectional forms and paradigms

Syntax: basic syntax, ”complete in expressive power” (cf. CLE)

Lexicon:

- multilingual test lexicon of 500 words (structural and irregular; Swadesh)
- comprehensive monolingual for Bulgarian, English, Finnish, Swedish, Turkish
Inflectional morphology

Goal: a complete system of inflection paradigms

Paradigm: a function from "basic form" to full inflection table

GF morphology is inspired by

- Zen (Huet 2005): typeful functional programming
- XFST (Beesley and Karttunen 2003): regular expressions
regV : Str -> V = \v -> case v of {
  fi + ("s"|"z"|"x"|"ch"|"sh") => mkV v (v + "es") (v + "ed") (v + "ing") ;
  d + "ie" => mkV v (v + "s") (v + "d") (d + "ying") ;
  fr + "ee" => mkV v (v + "s") (v + "d") (v + "ing") ;
  us + "e" => mkV v (v + "s") (v + "d") (us + "ing") ;
  pl + ("a"|"e"|"o"|"u") + "y" => mkV v (v + "s") (v + "d") (v + "ing") ;
  cr + "y" => mkV v (cr + "ies") (cr + "ied") (v + "ing") ;
  dr + o@(#vowel) + p@(#cons) => mkV v (v + "s") (v + p + "ed") (v + p + "ing") ;
  _ => mkV v (v + "s") (v + "ed") (v + "ing") ;
} ;
Morphology API

Overloaded function, heuristic variables for arguments

\[
\text{mkV} : (\text{fix} : \text{Str}) \rightarrow \text{V} \\
\text{mkV} : (\text{sing}, \text{sang}, \text{sung} : \text{Str}) \rightarrow \text{V}
\]

\[
\text{mkN} : (\text{bunch} : \text{Str}) \rightarrow \text{N} \\
\text{mkN} : (\text{man}, \text{men} : \text{Str}) \rightarrow \text{N}
\]
This is how the lexicon looks

Principle: just the minimum of information given (POS, characteristic forms)

mkN "boy"
mkV "cut" "cut" "cut"
mkV "drop"
mkA "happy"
mkN "mouse" "mice"
mkV "munch"
mkV "sing" "sang" "sung"
mkV "try"
This scales up

In Finnish, nouns have 30 forms.

- 85% need only one form
- 1.42 is the average

Finnish verbs with hundreds of forms need an average of 1.2 forms.
Syntax API

Combination rules

\[ \text{mkCl} : \text{NP} \rightarrow \text{V2} \rightarrow \text{NP} \rightarrow \text{Cl} \quad -- \quad \text{John loves Mary} \]
\[ \text{mkNP} : \text{Numeral} \rightarrow \text{CN} \rightarrow \text{NP} \quad -- \quad \text{five houses} \]

Structural words

\[ \text{the_Det} : \text{Det} \]
\[ \text{youSg_NP} : \text{NP} \]
Meaning-preserving translation

Translation must preserve meaning.

It need not preserve syntactic structure.

Sometimes this is even impossible:

- *John likes Mary* in Italian is *Maria piace a Giovanni*

The abstract syntax in the semantic grammar is a logical predicate:

```plaintext
fun Like : Person -> Item -> Fact
lin Like x y = x ++ "likes" ++ y -- English
lin Like x y = y ++ "piace" ++ "a" ++ x -- Italian
```
Translation and resource grammar

To get all grammatical details right, we use resource grammar and not strings

```
lin cat Person, Item = NP ; Fact = Cl ;

lin Like x y = mkCl x like_V2 y -- English
lin Like x y = mkCl y piacere_V2 x -- Italian
```

From syntactic point of view, we perform transfer, i.e. structure change.

GF has compile-time transfer, and uses interlingua (semantic abstract syntax) at run time.
More on GF

GF homepage, http://grammaticalframework.org
Registration open till 30 June:  http://school.grammaticalframework.org
Dependent Types
Semantics: well-typedness

Domain-dependent categories

\[
\text{cat Dom} ; \text{NP Dom} ; \text{VP Dom} ; S
\]

\[
\text{fun Pred : (d : Dom) -> NP d -> VP d -> S}
\]

Uses

- word sense disambiguation
- better generation of synthetic corpora
Generalization of well-typedness: type classes

Proof objects establish class membership

cat Dom ; Animate Dom

fun
  Sleep : (d : Dom) -> Animate d -> VP d
  Man, Donkey : Dom
  ManIsAnimate : Animate Man
  DonkeyIsAnimate : Animate Donkey

Notice: this may well be language dependent, e.g. German essen - fressen "eat"
Another generalization of well-typedness: coercive sub-typing

Proof objects establish subtype relation

cat Dom ; Subtype Dom Dom

fun
  Pred : (d,e : Dom) -> Subtype d e -> NP d -> VP e -> S
  Human, Teacher : Dom
  TeacherIsHuman : Subtype Teacher Human
Semantics: anaphora

the monkey ate the banana because it was hungry - er war hungrig

the monkey ate the banana because it was ripe - sie war reif

the monkey ate the banana because it was tea-time - es war Teezeit
The grammar of pronouns

Simplified German:

fun Pron : (t : Typ) -> Ref t -> Exp t

lin Pron t _ = case (gender t) of {
  Masc => "er" ;
  Fem => "sie" ;
  Neutr => "es"
  }

Parsing English *it* creates the tree Pron ?1 ?2.
Algorithm

1. Analyse the context to form the referent space \{r_1 : R_1, \ldots, r_n : R_n\}.
2. Collect all types \{T_1, \ldots, T_m\} that an object may have in the position of the pronoun.
3. Consider the set of those elements \{r_i : R_i\} whose type \(R_i\) matches some of the types \(T_j\).
   (a) If the set is singleton \{r_i : R_i\}, then \(r_i\) is the referent and its type is \(R_i\).
   (b) If the set is empty, then report an anaphora resolution error (or widen the referent space).
   (c) If the set has many elements, then ask the user to disambiguate (or look for more constraints).
Syntax: agreement

Agreement *could* be modelled by

    fun Pred : (a : Agr) -> NP a -> VP a -> S

However, we find it better to model agreement in *concrete syntax*
Syntax: subcategorization

Instead of

\[
\begin{align*}
\text{ComplV1} : V1 & \rightarrow VP \quad -- \text{sleep} \\
\text{ComplV2} : V2 & \rightarrow NP \rightarrow VP \quad -- \text{love} \\
\text{ComplVS} : VS & \rightarrow S \rightarrow VP \quad -- \text{believe}
\end{align*}
\]

one could have

\[
\text{Compl} : (s : \text{Subcat}) \rightarrow V \ s \rightarrow \text{Comps} \ s \rightarrow VP
\]

However, the saving is marginal, since one has to define \text{Subcat} and \text{Comps} with as many rules.
Syntax: coordination

Rule: V2 coordination requires common complement case/preposition

ConjV2 : Conj -> (c : Case) -> V2 c -> V2 c -> V2 c

This is the only rule known to us that requires the use of language-specific features in concrete syntax.
Conclusion

You shouldn’t expect

• general-purpose translation ("Google competitor")

You can expect

• high quality multilingual translation
• portability to limited domains (up to 1000’s of words)
• productivity (days, weeks, months)
• ease of use (no training for authoring, a few days for grammarians)

Dependent types: used minimally so far, mostly for disambiguation.