Parsing with Dynamic Continuized CCG

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Introduction
A breakthrough in semantic theory

Indefinites not bothered by scope islands

Example

- if \(<a \text{ relative of mine dies}>\), I’ll inherit a fortune \((\exists \triangleright \text{if})\)
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- if <a relative of mine dies>, I’ll inherit a fortune \((\exists > \text{if})\)
  
i.e., \(\exists x. \text{relative}(x, me) \land [\text{dies}(x) \rightarrow \text{fortune}(me)]\)
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  i.e., \(\exists x. \text{relative}(x, me) \land [\text{dies}(x) \rightarrow \text{fortune}(me)]\)

• if \(<\text{every relative of mine dies}>\), I’ll . . . a fortune \((* \forall > \text{if})\)
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⇒ Explanation in terms of indefinites’ discourse function a long expected result
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⇒ Explanation in terms of indefinites’ discourse function a long expected result — arguably, Charlow (2014) first to show this satisfactorily!

⇒ Can Charlow’s approach be made to work computationally?
Implementing DyC³G

Combinatory Categorial Grammar (CCG; Steedman 2000, 2012)

- Constrained grammar formalism with linguistically motivated treatment of long-distance dependencies and coordination
- Basis for fast & accurate parsers (Hockenmaier & Steedman 2007, Clark & Curran 2007, Lee et al. 2016, . . .)


- Quantifiers are functions on their own continuations
- Order-sensitive phenomena as linguistic side effects

Dynamic Continuized CCG (Charlow 2014)

- Explains exceptional scope of indefinites by treating them as side effects in continuized grammars
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- Explains exceptional scope of indefinites by treating them as side effects in continuized grammars
Why should we care about the scope of indefinites?

As Steedman (2012) observes, computationally implemented approaches to scope taking from Cooper storage (Cooper 1983) to underspecification (e.g. Copestake et al. 2005) and more have not distinguished indefinites from true quantifiers.
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While the scope possibilities for indefinites appear to be unconstrained in general, true quantifiers appear to have a much more limited distribution subject to constraints imposed by scope islands — which is not accounted for even in implementations of DRT (Bos 2003).
Ok — but what about Steedman’s (2012) analysis?

Steedman (2012) accounts for indefinites’ exceptional scope taking by treating them as underspecified Skolem terms in a non-standard static semantics, rather than deriving this behavior from their discourse function.
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...while true quantifiers are restricted by CCG’s surface compositional combinatorics — but does this suffice empirically?
Potential issues for Steedman’s CCG

Steedman’s CCG can’t account for quantifiers taking scope from medial positions (Barker & Shan, 2015)
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**Linear order constraints** on where **negative polarity items** may appear also apparently an issue

⇒ Barker & Shan’s continuized grammars **generalize** Hendrik’s (1993) approach to scope taking while also **enabling order-sensitive analyses**
This paper’s contribution

Open source reference implementation\(^1\) of a shift-reduce parser that

1. extends Barker and Shan (2014) to only invoke Charlow’s (2014) monadic lifting and lowering where necessary
2. integrates Steedman’s (2000) CCG for deriving basic predicate-argument structure and enriches it with a practical method of \textit{lexicalizing scope island constraints} (Barker & Shan 2006)
3. takes advantage of the resulting scope islands in defining \textit{novel normal form constraints} for efficient parsing

\(^1\)https://github.com/mwhite14850/dyc3g
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Continuized CCG
Towers provide a much more intuitive way to understand continuized grammars (Barker & Shan 2015)

\[
\begin{align*}
\text{left phrase} & \quad \text{right phrase} \\
\frac{C | D}{B/A} & \quad \frac{D | E}{A} \\
\frac{g[]}{} & \quad \frac{h[]}{} \\
\frac{f}{x} & \quad \text{Comb, >} \\
\frac{C | E}{B} & \quad \frac{g[h[]]}{f(x)}
\end{align*}
\]
Generalized Type Raising (computationally: \textit{just where necessary})

\[
\begin{array}{c}
\text{any phrase} \\
\hline \\
A \\
\hline \\
\times \\
\hline \\
\text{Lift} \\
B \\
\hline \\
B \\
\hline \\
A \\
\hline \\
[] \\
\hline \\
\times \\
\end{array}
\]

where \[
\frac{[\ ]}{\times} \equiv \lambda k. kx
\]
Needed to complete derivations, and for scope islands

\[
\text{any clause} \\
\begin{array}{c|c}
A & S \\
\hline
\end{array} \\
\frac{A | S}{S} \\
\frac{f[\ ]}{x} \\
\frac{\text{Lower}}{\frac{\text{Lower}}{A}} \\
\frac{\text{Lower}}{f[x]} \\
\text{where } f[x] \equiv \frac{f[\ ]}{x} (\lambda v. v)
\]
Rules are defined recursively

**Combine**

\[
\begin{array}{c|c}
D & E \\
\hline
A & B \\
\hline
g[ ] & h[ ] \\
\hline
a & b \\
\hline
\end{array}
\]

\[
\begin{array}{c|c}
D & F \\
\hline
C \\
\hline
g[h[ ]] \\
\hline
c \\
\end{array}
\]

**Lift Left**

\[
\begin{array}{c|c}
E & F \\
\hline
A & B \\
\hline
h[ ] & \\
\hline
a & b \\
\hline
\end{array}
\]

\[
\begin{array}{c|c}
E & F \\
\hline
C & \\
\hline
h[ ] & \\
\hline
\end{array}
\]

**Lift Right**

\[
\begin{array}{c|c}
D & E \\
\hline
A & B \\
\hline
g[ ] & \\
\hline
a & b \\
\hline
\end{array}
\]

\[
\begin{array}{c|c}
D & E \\
\hline
C & \\
\hline
g[ ] & \\
\hline
\end{array}
\]

if \( A : a \quad B : b \)

\[
\begin{array}{c|c}
C & c \\
\hline
\end{array}
\]
Linear Scope Bias

(With Steedman’s CCG “on the bottom”)

\[ \exists x.[] \quad \forall y.[] \]
\[ \text{love}(z, y) \]
\[ \text{Comb}, < \]
\[ \exists x. \forall y.[] \]
\[ \text{love}(x, y) \]
\[ \exists x. \forall y.\text{love}(x, y) \]
Inverse Scope

External and internal lift integrated into binary step

\[
\begin{align*}
\text{someone} & \quad \text{loves everyone} \\
\exists x.[] & \quad \forall y.[] \\
\lambda z.\text{love}(z, y) & \quad \text{LiftL,LiftR,}< \\
\end{align*}
\]
Using Steedman’s CCG on the bottom tower level enables the CCG analysis of relative clauses, right node raising, etc. — in particular, there’s no need for empty string elements.

Who(m)  Everyone  Loves

\[ \forall x. \text{person}(x) \rightarrow [ ] \]
\[ \lambda p. px \]

\[ \lambda zy. \text{love}(z, y) \]

\[ \forall x. \text{person}(x) \rightarrow [ ] \]
\[ \lambda y. \text{love}(x, y) \]
Monadic Dynamic Semantics
Barker & Shan’s tower system by itself does not adequately account for the exceptional scope of indefinites
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Monads provide a clean way to enrich pure function application in the semantics with side effects — in particular, they provide a way to integrate a dynamic treatment of indefinites (Charlow 2014).
Charlow’s Dynamic Semantics

Translation to FOL similar to DRT

**Example**

*a linguist swims*

\[ \lambda s.\{\langle\text{swim}(x), \hat{s}x\rangle \mid \text{linguist}(x)\} \]

\[ \Downarrow \]

\[ \exists x.\text{linguist}(x) \land \text{swim}(x) \]
Sequencing and Sequence Reduction

Sequencing
“run $m$ to determine $v$ in $\pi$”

\[ m_v \rightarrow \pi \]

Example
a linguist swims

\[
(\lambda s.\{\langle x, \hat{s}x \rangle \mid \text{linguist}(x)\})_y \rightarrow \lambda s.\{\langle \text{swim}(y), s \rangle \}
\]

\[
\Downarrow
\]

\[
\lambda s.\{\langle \text{swim}(x), \hat{s}x \rangle \mid \text{linguist}(x)\}
\]
The State.Set Monad

More formally:

\[ M\alpha = s \to \alpha \times s \to t \]
\[ a^\eta = \lambda s. \{ \langle a, s \rangle \} \]
\[ m_v \circ \pi = \lambda s. \bigcup_{\langle a, s' \rangle \in ms} \pi[a/v]s' \]
States can be left implicit for representational simplicity (cf. implicit assignments with DRT)

**Example**

*a linguist swims*

\[
(\{\langle x, x \rangle \mid \text{linguist}(x)\})_y \rightarrow \{\langle \text{swim}(y), \epsilon \rangle \}
\]

\[\Downarrow\]

\[
\{\langle \text{swim}(x), x \rangle \mid \text{linguist}(x)\}
\]
Dynamic Combinatory Rules
Continuized grammars can be reconceptualized as operating over an underlying monad.
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- Lift identified with sequencing (→ο)
- Lower identified with monadic injection (η)
Sequences a continuation

\[
\begin{align*}
\text{any phrase} & \\
A & \\
m & \\
\text{Lift} & \\
S & S \\
\text{Lift} & \\
A & \\
m_v & \circ [ ] \\
\nu & 
\end{align*}
\]
Injests meaning on tower bottom into monad

\[
\text{any clause} \\
\quad \frac{A | S}{S} \\
\quad \frac{f[[]]}{a} \\
\quad \frac{\text{Lower}}{f[a^n]}
\]
Lexically-Triggered Reset

Delimit Right

\[
\begin{array}{c}
\text{if} \\
\begin{array}{c}
\frac{X/\langle Y \rangle}{a} \\
\frac{Y}{b} \\
\frac{\text{DR}}{} \\
\frac{X}{c}
\end{array}
\end{array}
\]

and

\[
\begin{array}{c}
\frac{X/Y}{a} \\
\frac{Y}{b} \\
\frac{\uparrow, \downarrow}{b'} \\
\frac{X}{c}
\end{array}
\]
Universal forced to have narrow scope

\[
\begin{align*}
\text{if} & \quad \text{everyone complains} & \quad \ldots \\
S/\langle S \rangle/\langle S \rangle & \quad \frac{S}{S} & \\
\lambda xy.(x \to y)^\eta & \quad \frac{(\forall x[\ ])^\eta}{\text{complain}(x)} & \quad \ldots \\
\end{align*}
\]
Reset closes off scope

\[
\frac{(\forall x[\ ])^\eta}{\text{complain}(x)} \downarrow
\]

\[
(\forall x \text{complain}(x)^\eta)^\eta \uparrow
\]

\[
[\ ] \downarrow
\]

\[
\forall x \text{complain}(x)^\eta
\]
Reset applied as before

\[
\begin{align*}
\text{if } & \quad \text{someone complains} \
S/\langle S \rangle/\langle S \rangle & \quad \text{...} \\
S & \quad S \\
\downarrow & \\
S & \quad S \\
\downarrow & \\
\text{complain}(u) & \quad \text{...} \\
\{\langle x, x \rangle\}_u & \rightarrow \emptyset \\
\downarrow & \\
\text{complain}(x) & \quad \text{...} \\
\{\langle \text{complain}(x), x \rangle\}_p & \rightarrow \emptyset \\
\downarrow & \\
\lambda y. (p^n \rightarrow y)^\eta & \\
& \\
& \\
\end{align*}
\]
Resetting an Indefinite

No real scope to close off, result is equivalent

\[
\begin{align*}
\{\langle x, x \rangle \}_{u} \xrightarrow{\circ} & \left[ \right] \\
\text{complain}(u) & \\
\{\langle x, x \rangle \}_{u} \xrightarrow{\circ} & \{\langle \text{complain}(u), \epsilon \rangle \}
\end{align*}
\]

\[
\equiv
\]

\[
\{\langle \text{complain}(x), x \rangle \}
\]

\[
\uparrow
\]

\[
\{\langle \text{complain}(x), x \rangle \}_{p} \xrightarrow{\circ} \left[ \right]
\]

\[
p
\]
Normal Form Constraints
Normal Form Constraints

- Normal form constraints can play an important role in practical CCG parsing by eliminating derivations leading to spurious ambiguities without requiring expensive pairwise equivalence checks (Eisner, 1996; Clark and Curran, 2007; Hockenmaier and Bisk, 2010; Lewis and Steedman, 2014)
Normal Form Constraints

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- The lowering operations triggered by scope islands or sentence boundaries provide an opportunity to recursively detect and eliminate non–normal form derivations beyond the base level.
Non–Normal Form Derivation

Superfluous three-level tower

\[
\begin{array}{c|c}
A & B \\
\hline
C \\
\end{array} & \quad \begin{array}{c|c}
D & E \\
\hline
F \\
\end{array} \quad H
\]

\[\text{***} \quad \uparrow R, \uparrow L, \ldots\]

\[
\begin{array}{c|c}
A & B \\
\hline
D & E \\
\hline
G \\
\end{array}
\]

\[\uparrow R, \ldots\]

\[
\begin{array}{c|c}
A & B \\
\hline
D & E \\
\hline
I \\
\end{array}
\]

\[\downarrow, \ldots\]

\[
\begin{array}{c|c}
A & B \\
\hline
D & E \\
\hline
J \\
\end{array}
\]
Initial Experiment

- Prolog implementation suitable for testing analyses
- Small test suite of 40 examples of average length 6.7 words, roughly comparable in size to Baldridge’s (2002) OpenCCG test suite
- Parse time of 60ms per item in same ballpark
- **Without** normal form constraints, parse time jumps to 4.6s per item, **two orders of magnitude slower**
Discussion and Conclusions
• What is the complexity of parsing with Dynamic Continuized CCG?

• Recent work on parsing with neural networks has moved away from dynamic programming; Lee et al. (2016) have achieved state-of-the-art accuracy with impressive speed using global neural models and A* search.

• By respecting Steedman’s Principle of Adjacency, such techniques become applicable to DyC3 as well.
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• By respecting Steedman’s Principle of Adjacency, such techniques become applicable to DyC$^3$G as well
• Here we’ve shown how scope islands can be **lexicalized**, thereby allowing the freedom to make conditionals and relative clauses scope islands but not *that*-complement clauses, for example
Are Scope Islands Real?

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- In principle, could instead learn where to prefer reset operations in derivations, rather than making them hard constraints.
Here we’ve shown how scope islands can be *lexicalized*, thereby allowing the freedom to make conditionals and relative clauses scope islands but not *that*-complement clauses, for example.

In principle, could instead *learn* where to prefer reset operations in derivations, rather than making them hard constraints.

Making indefinites indifferent to these operations would still greatly simplify the learning task.
Conclusions

• First implemented method to derive the **exceptional scope of indefinites** in a **principled way**
• Charlow’s (2014) dynamic continuized grammars can be combined with Steedman’s CCG “on the bottom,” retaining many of the latter’s computationally attractive properties
• Initial experience with reference implementation suggests that **lifting and lowering on demand** together with **normal form constraints** just might work computationally
Future Work

- Haskell implementation
- Dynamic semantics of anaphora and other order-sensitive phenomena, including negative polarity items
- Selective exceptional scope and focus alternatives
- Split-scope analyses of definites and plurals
- Empirical testing with machine learned–models
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- Mark Steedman, Carl Pollard & OSU Clippers Group
- OSU Targeted Investment in Excellence Award
- NSF IIS-1319318
- ...you!
Extras
Type-Driven Lowering

Lower Right

\[
\begin{array}{c}
\vdots \\
A \\
\vdots \\
B \\
\begin{array}{c}
a : M\alpha \rightarrow \beta \\
b : \gamma \\
\end{array} \\
\downarrow R \\
\vdots \\
C \\
\vdots \\
\begin{array}{c}
a : M\alpha \rightarrow \beta \\
b' : M\alpha \\
\end{array} \\
c : \beta \\
\end{array}
\]

if

\[
\begin{array}{c}
\vdots \\
B \\
\vdots \\
\begin{array}{c}
b : \gamma \\
\end{array} \\
\downarrow B' \\
\vdots \\
C \\
\vdots \\
\begin{array}{c}
b : \gamma \\
\end{array} \\
\downarrow B' \\
\vdots \\
\begin{array}{c}
a : M\alpha \rightarrow \beta \\
b' : M\alpha \\
\end{array} \\
c : \beta \\
\end{array}
\]

and

\[
\begin{array}{c}
\vdots \\
B' \\
\vdots \\
\begin{array}{c}
b' : M\alpha \\
\end{array} \\
\downarrow B' \\
\vdots \\
C \\
\vdots \\
\begin{array}{c}
B' \\
\end{array} \\
\downarrow B' \\
\vdots \\
\begin{array}{c}
a : M\alpha \rightarrow \beta \\
b' : M\alpha \\
\end{array} \\
c : \beta \\
\end{array}
\]
Via type-driven lowering

\[
\begin{array}{ccc}
if & someone \text{ complains} & \ldots \\
S/\langle S \rangle/\langle S \rangle & S/S & S \\
\langle x, x \rangle \rightarrow [ ] & \langle x, x \rangle \rightarrow [ ] & \ldots \\
\lambda xy \cdot (x \rightarrow y)^\eta & \text{complain}(u) & t \\
Mt \rightarrow Mt \rightarrow Mt & (t \rightarrow Mt) \rightarrow Mt & t \\
\end{array}
\]
Recursive Lowering

Including case for missing arguments

\[
\begin{array}{c|c|c}
   & \text{base} & \text{recursive} \\
\hline
A | S & S | S & S | S \\
S & A & A & A \\
g[] & g[] & g[] & g[] \\
a & p & \lambda x.g[(px)\eta] & a \\
A & A & C & C \\
g[a^\eta] & A & g[c] & \\
\hline
\end{array}
\]

where \( A \) is \( S/Y \) or \( S\backslash Y \)

if \( A : a \) then \( C : c \)
Relative Clause Scope Island

Enforced by relative pronoun

<table>
<thead>
<tr>
<th>senator</th>
<th>who</th>
<th>everyone likes</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>N\N/(S/NP)</td>
<td>S</td>
</tr>
<tr>
<td>senator</td>
<td>\lambda qx px \land qx</td>
<td>\lambda x. like(y, x)</td>
</tr>
</tbody>
</table>

\[
\frac{S \mid S}{S/NP} \\
\frac{N\N/N}{S/NP} \\
\frac{[\ ]}{\lambda px px \land \forall y \text{like}(y, x)^\eta} \\
\frac{S \mid S}{N} \\
\frac{[\ ]}{\lambda x. \text{senator}(x) \land \forall y \text{like}(y, x)^\eta}
\]
Inverse linking derivation in paper

Example

- [a voter in [every state]] protests  \((\forall > \exists)\)
- [few voters; in [every state] who; supported Trump] participated in the protests  \((\forall > \text{few})\)
Universals sometimes invert from the subjects of sentential complements even in episodic sentences (Farkas & Giannakidou 1996, contra Fox & Sauerland 1996 and Steedman 2012)

Example

- Yesterday, a guide made sure that \(<[\text{every tour to the Louvre} \text{ was fun}]\) ( ∀ > ∃ )
Linear Order and Negative Polarity Items

With Steedman’s CCG, it appears to be impossible to get one without the other below

**Example**

- Kim gave [no\textsubscript{i} bone] [to any\textsubscript{j} dog] \((i < j)\)
- * Kim gave [to any\textsubscript{j} dog] [no\textsubscript{i} bone] \((* j < i)\)
Linear Order and Negative Polarity Items

With Steedman’s CCG, it appears to be impossible to get one without the other below

Example

- Kim gave [no; bone] [to any; dog] \((i < j)\)
- * Kim gave [to any; dog] [no; bone] \((* j < i)\)

Cf.

\[
\begin{align*}
\text{Kim gave} & \quad \text{to a dog} & \quad \text{a very heavy bone} \\
\text{s/pp/np} & \quad \text{s\,(s/pp)} & \quad \text{np} \\
\text{s/np} & \quad \text{s/np} & \quad \text{s} \\
\end{align*}
\]
Linear Order and Negative Polarity Items

With Steedman’s CCG, it appears to be impossible to get one without the other below.

**Example**

- Kim gave [no\textsubscript{i} bone] [to any\textsubscript{j} dog] \ (i < j)
- * Kim gave [to any\textsubscript{j} dog] [no\textsubscript{i} bone] \ (* j < i)

Cf.

\[
\begin{array}{c}
\text{Kim gave} \\
\text{to a dog} \\
\text{a very heavy bone}
\end{array}
\]

\[
\begin{array}{c}
s/\text{pp}/\text{np} \\
s\backslash (s/\text{pp}) < Bx \\
s/\text{np} \\
s/\text{np}
\end{array}
\]

\(\Rightarrow\) Not a problem for Barker & Shan’s Continuized CCG though.