Grammar as logic, processing as deduction, actions as theorems, states as propositions

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In short

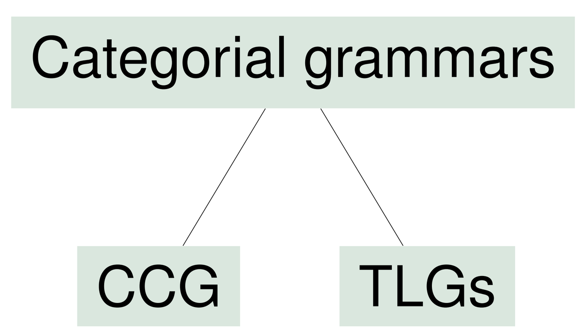
It's time to adopt the **categorial** approach as a **unifying** framework for analyzing competence and performance!

Background

- Formal grammar is still important in the era of LLM [1]
- But Chomsky's approach has serious problems
  - Lack of formality [2]
  - Incompatibility with real-time processing [3]
- Recent success of CCG [4] in psycholinguistic modeling [5,6,7]

⇒ Time for a more general theory of the categorial approach to sentence processing!

Going type-logical



- While CCG is implementation-friendly, **type-logical grammars (TLGs)** [8,9] are more elegant and illuminating
- TLGs view **grammar as logic**
- Extensively studied as a competence theory
- Linguistic expressions are assigned **types**
  - Basic types: S, NP, etc.
  - Derived types: A/B, $B\backslash A$ (cf. fractions), etc.
- Basic rules of inference (Lambek calculus [7])

$$\frac{B \quad B\backslash A}{A}\backslash E \qquad \frac{A/B \quad B}{A}/E \qquad \frac{\begin{array}{c}[B]_i \ldots \\ \vdots \\ A\end{array}}{B\backslash A}\backslash I_i \qquad \frac{\begin{array}{c}\ldots [B]_i \\ \vdots \\ A\end{array}}{A/B}/I_i$$

- A basic example:

$$\dfrac{\dfrac{\text{Pat}}{NP} \quad \dfrac{\dfrac{\text{saw}}{(NP\backslash S)/NP} \quad \dfrac{\text{Kim}}{NP}}{NP\backslash S}/E}{S}\backslash E$$

★ Can account for key characteristics of human sentence processing

Incrementality, predictivity, grammar-guidedness

- Incremental parse just by mechanisms equipped in the grammar (strict competence hypothesis; [4])
- **Parsing as deduction**; hypothetical reasoning as prediction

$$\frac{\text{Pat}}{NP} \Rightarrow \frac{\text{Pat}}{NP}\ \frac{\text{saw}}{(NP\backslash S)/NP} \Rightarrow \dfrac{\dfrac{\dfrac{\text{Pat}}{NP} \quad \dfrac{\dfrac{\text{saw}}{(NP\backslash S)/NP} \quad [NP]_1}{NP\backslash S}/E}{S}\backslash E}{S/NP}/I_1$$

("S if NP follows")

- Incremental processing of long-distance dependencies, which can be a headache for mainstream-based approaches [10], is also possible just within grammar
- While CCG poses a fixed limit on incrementality (by the choice of rules) [11], TLGs offer a scale of complexity

Resource sensitivity

- TLG-based processing is resource-efficient in two ways, overcoming limitations in cognitive resources [12]
  - **Actions as theorems**: Multiple inference steps can be chunked as a theorem, e.g.,

$$\frac{NP \quad (NP\backslash S)/NP}{S/NP}\text{Theorem}$$

⋆ CCG can be seen as a set of theorems

  - **States as propositions (types)**: Types provide an austere summary of the past input; once a type is inferred for the string, no need to maintain what was in between, e.g.,:

$$\frac{\text{Pat saw}}{S/NP}\text{whatever}$$

- [6,7] show (CCG-based) chunking failure predicts slowdown in English and Japanese reading time datasets

$$\frac{\dfrac{\text{the article that}}{NP/(S\mid NP)} \quad \dfrac{\text{the student}}{NP}}{}\ \text{***No rule to apply***}$$

Resilience and vulnerability to structural ambiguity

- A puzzling contrast in the magnitude of garden-path effect:
  - "NP/S" ambiguity: *Pat knows the baby cried.* **not too hard**
  - "NP/Z" ambiguity: *When Pat dressed the baby cried.* **very hard**
- TLGs' conjunction operators, ⊓ 'and' and ⊔ 'or', offer a new approach to ambiguity, accounting for the puzzle
- Lexical type assignments based on semantic considerations:
  - *know* → $(NP\backslash S)/(NP\sqcup S)$
  - *dressed* → $((NP\backslash S)/NP)\sqcap(NP\backslash S)$
- "NP/S" ambiguity requires reanalysis of the NP only

$$\dfrac{\begin{array}{c}\text{Pat knows}\\ \vdots \\ S/(NP\sqcup S)\end{array} \quad \dfrac{\dfrac{\text{the baby}}{NP}}{NP\sqcup S}\sqcup I_1}{S}/E$$

- "NP/Z" ambiguity requires reanalysis of the verb and the NP

$$\dfrac{\dfrac{\begin{array}{c}\text{When Pat}\\ \vdots\end{array} \quad \begin{array}{c}\dfrac{\dfrac{\text{dressed}}{((NP\backslash S)/NP)\sqcap(NP\backslash S)}}{(NP\backslash S)/NP}\sqcap E_1\\ \vdots\end{array}}{(S/S)/NP} \quad \dfrac{\text{the baby}}{NP}}{S/S}/E$$

References

[1] Futrell & Mahowald 2025 *arXiv* [2] Borsley & Müller 2021 In Müller et al. (eds) *HPSG handbook* [3] Sag & Wasow 2011 In Borsley & Börjars (eds) *Non-transformational syntax* [4] Steedman 2000 *The syntactic process* [5] Stanojević et al. 2023 *Cog Sci* [6] Isono 2024 *Cogn* [7] Isono et al. 2025 *PsyArXiv* [8] Lambek 1958 *Am Math Mon* [9] Moortgat 1997 In van Benthem & ter Meulen (eds) *Handbook of Logic and Lang* [10] Hunter 2019 In Berwick & Stabler (eds) *Minimalist Parsing* [11] Demberg 2012 *TAG+11* [12] Christiansen & Chater 2016 *Behav & Brain Sci*

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