Composing Meaning via Dependent Type Semantics
Day 5: Verification of linguistic theories by implementation

Daisuke Bekki

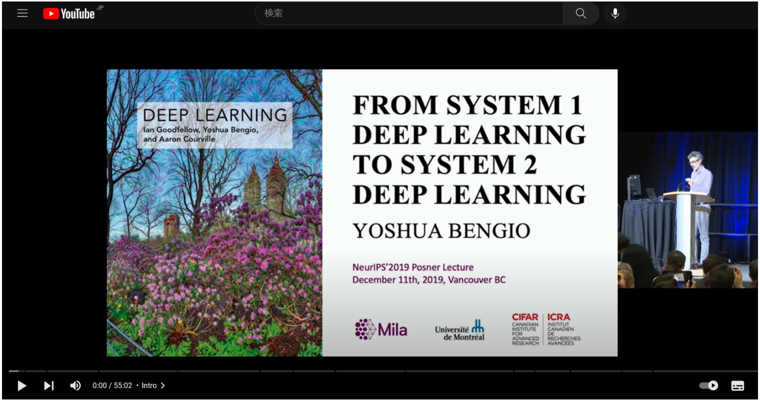
Ochanomizu University
Faculty of Core Research
https://daisukebekki.github.io/

ESSLLI2025, Bochum
1 August (Fri)

Dual Process Theories

Dual Process Theories

"From system 1 deep learning to system 2 deep learning"
by Yoshua Bengio at NeurIPS'2019



Yoshua Bengio: From System 1 Deep Learning to System 2 Deep Learning (NeurIPS 2019)

https://youtu.be/T3sxeTgT4qc

Dual Process Theories

> *"Past progress in deep learning has concentrated mostly on learning from a static dataset, mostly for perception tasks and other System 1 tasks which are done intuitively and unconsciously by humans. However, in recent years, a shift in research direction and new tools such as soft-attention and progress in deep reinforcement learning are opening the door to the development of novel deep architectures and training frameworks for addressing System 2 tasks (which are done consciously), such as reasoning, planning, capturing causality and obtaining systematic generalization in natural language processing and other applications.*

`https://youtu.be/T3sxeTgT4qc`

Dual Process Theories

System 1: An evolutionarily ancient intuitive system underlying unconscious, automatic, fast, parallel and associative processing

System 2: An evolutionarily recent reflective system characterized by conscious, controlled, slow, "rule-governed" serial processes

The descriptions due to Mandelbaum (2022), which ascribe it to Evans and Stanovich (2013).

- Originates in psychology of reasoning: (Sloman, 1996; Smith and DeCoster, 2000; Wilson et al., 2000; Evans and Stanovich, 2013)
- In philosophy: Gendler (2008); Evans and Frankish (2009)
- Recent criticisms on dual process theories: Kruglanski (2013); Osman (2013); Mandelbaum (2016); De Houwer (2019)

Dual Process Theories

Improving mathematical reasoning with process supervision

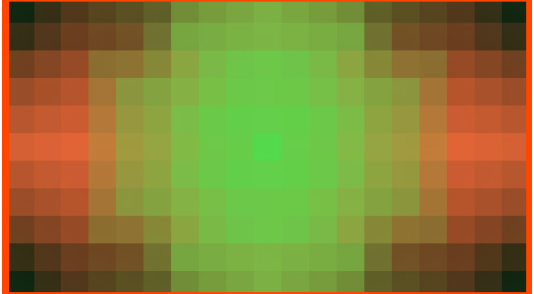


Illustration: Ruby Chen

We've trained a model to achieve a new state-of-the-art in mathematical problem solving by rewarding each correct step of reasoning ("process supervision") instead of simply rewarding the correct final answer ("outcome supervision"). In addition to boosting performance relative to outcome supervision, process supervision also has an important alignment benefit: it directly trains the model to produce a chain-of-thought that is endorsed by humans.

May 31, 2023 `https://openai.com/research/improving-mathematical-reasoning-with-process-supervision`

Linguistic Puzzles as System 1.5 tasks

Karttunen (1976) on Anaphora Accessibility

(1) a. Bill has a car. It is black.

b. Bill doesn't have a car. *It is black.

(2) a. Bill saw a unicorn. It had a gold mane.

b. Bill didn't see a unicorn. *It had a gold mane.

(3) a. John wants to catch a fish and eat it for supper. *Do you see it over there?

Presupposition

That *Mary takes care of John's dog* presupposes *John has a dog* can be expressed in the form of family of sentences tests (Kadmon, 2001)

P	Mary takes care of John's dog.
H	John has a dog.
answer:	YES

P	Mary does not take care of John's dog.
H	John has a dog.
answer:	YES

P	If Mary takes care of John's dog, John is happy.
H	John has a dog.
answer:	YES

Presupposition

Filter

P	If John has a dog, Mary takes care of John's dog.
H	John has a dog.
answer:	UNKNOWN

Plug

P	Susan saids that Mary takes care of John's dog.
H	John has a dog.
answer:	UNKNOWN

Math vs. Semantics

- We can provide step-by-step instructions for math problems because
  - We know math rules
  - We know how to use them to solve (elementary, intermediate, and advanced) math problems step-by-step
- Can we provide step-by-step instructions for natural language semantics where
  - We know semantic rules only partially
  - Thus we cannot provide a step-by-step instruction for semantics
  - Is human processing of semantic information step-by-step?

System 1.5 tasks?

Semantic understanding are System 1.5 task that is ought to be done:

- Unconsciously
- Fast
- Yet systemic (governed by a certain law but most of us cannot describe it explicitly)

"Verification by Implementation" Paradigm

FraCaS and MultiFraCaS

FraCaS test suite (Cooper et al. 1996):

`http://www-nlp.stanford.edu/~wcmac/downloads/fracas.xml`

An inference data set that

- covers core semantic phenomena
  - Generalized Quantifiers, Plurals, Nominal anaphora, Ellipsis, Adjectives, Comparatives, Temporal reference, Verbs, Attitudes
- requires minimal world knowledge
- is machine readable (?)
- has been used to evaluate NLP systems

MacCartney and Manning 2007, 2008	Lewis and Steedman 2013	Tian et al. 2014	Abzianidze 2014	Mineshima et al. 2015
Natural Logic	CCG & FOL	DCS	NL Tableau	CCG & HOL

MultiFraCaS: `http://www.ling.gu.se/~cooper/multifracas/`

- Translation of FraCaS test suite into Farsi, German, Greek, and Mandarin

Large NLI datasets: SNLI (**?**), MultiNLI **?**, XNLI, DNC, etc

FraCaS

1 GENERALIZED QUANTIFIERS

1.1 Conservativity

```
Q As are Bs == Q As are As who are Bs
```

fracas-001 answer: yes

P1	An Italian became the world's greatest tenor.
Q	Was there an Italian who became the world's greatest tenor?
H	There was an Italian who became the world's greatest tenor.

fracas-002 answer: yes

P1	Every Italian man wants to be a great tenor.
P2	Some Italian men are great tenors.
Q	Are there Italian men who want to be a great tenor?
H	There are Italian men who want to be a great tenor.
Note	*Note that second premise is unnecessary and irrelevant.*

JSeM test suite

JSeM (Kawazoe et al., 2015b,a): consisting of 8539 problems

`https://github.com/DaisukeBekki/JSeM/`

Multilingual subset
- Japanese counterparts of FraCaS problems (cf. MultiFraCaS project)

Japanese subset
- Universal phenomena not covered by FraCaS e.g. modality, conditionals, adverbs, focus
- Japanese-specific phenomena

JSeM test suite

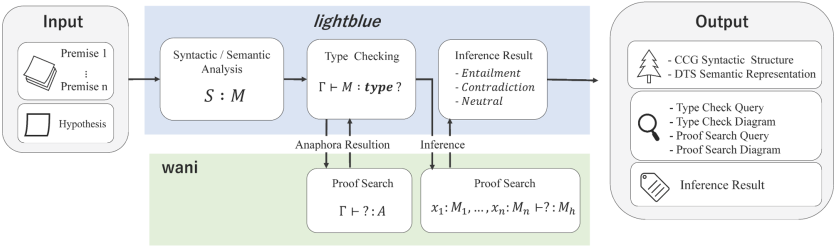
jsem-id:1 answer: yes inference type: entailment phenomena: generalized quantifier, conservativity
linked to: fracas-001 literal translation?: yes same phenomena?: unknown

P1
script あるイタリア人が世界最高のテノール歌手になった。
English An Italian became the world's greatest tenor.
H
script 世界最高のテノール歌手になったイタリア人がいた。
English There was an Italian who became the world's greatest tenor.

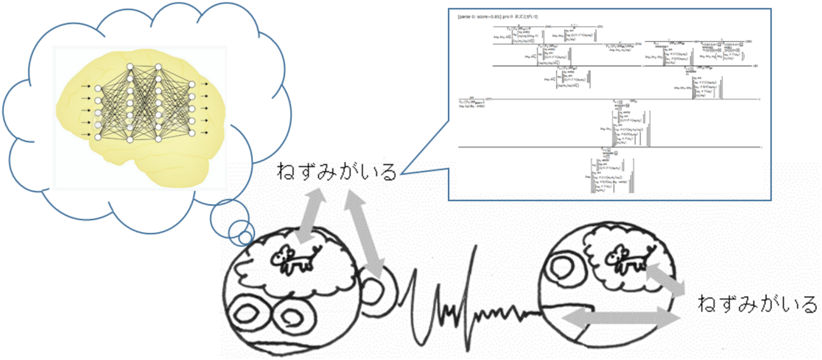
jsem-id:2 answer: yes inference type: entailment phenomena: generalized quantifier, conservativity, Q-no NC
linked to: fracas-001 literal translation?: yes same phenomena?: unknown

P1
script 一人のイタリア人が世界最高のテノール歌手になった。
English An Italian became the world's greatest tenor.
H
script 世界最高のテノール歌手になったイタリア人がいた。
English There was an Italian who became the world's greatest tenor.
Note

lightblue: A linguistic pipeline of CCG and DTS



Two paths toward “natural language understanding” understanding



DTS literature

Dependent Type Semantics (DTS) (Bekki 2014; Bekki and Mineshima 2017; Bekki 2021)

- A framework of natural language semantics
- Unified approach to general inferences and anaphora/presupposition resolution in terms of *tpe checking* and *proof search*

Main features:

1. **Proof-theoretic semantics**:
   From truth-conditions (denotations, models) to verification conditions (proofs, contexts)
2. **Anaphora/Presuppositions**: A proof-theoretic alternative to Dynamic Semantics (DRT, DPL, etc.)
3. **Compositionality**: Syntax-semantics interface via categorial grammars (e.g. CCG, TLG, ACG, etc)
4. **Computation**: Implementation, Applications to Natural Language Processing

Natural language semantics via dependent types: Classics

- Donkey anaphora: Sundholm (1986)
- Translation from DRS to dependent type representations: Ahn and Kolb (1990)
- Summation: Fox (1994a,b)
- Ranta's TTG (Relative and Implicational Donkey Sentences, Branching Quantifiers, Intensionality, Tense): Ranta (1994)
- Translation from Montague Grammar to dependent type representations: Dávila-Pérez (1995)
- Presupposition Binding and Accommodation, Bridging: Krahmer and Piwek (1999), Piwek and Krahmer (2000)

Natural language semantics via dependent types: Frameworks

- Type Theory with Record (TTR): Cooper (2005)
- Modern Type Theory: Luo (1997, 1999, 2010, 2012), Asher and Luo (2012), Chatzikyriakidis (2014)
- Semantics with Dependent Types: Grudzinska and Zawadowski (2014; 2017)
- **Dependent Type Semantics (DTS): Bekki (2014), Bekki and Mineshima (2017)**
- (Dynamic Categorial Grammar: Martin and Pollard (2014))

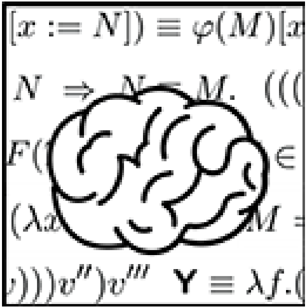
Semantic Analyses by DTS

- Generalized Quantifiers : Tanaka (2014)
- Honorification : Watanabe et al. (2014)
- Conventional Implicature : Bekki and McCready (2015), Matsuoka et al. (2023)
- Factive Presuppositions : Tanaka et al. (2015)(2017)
- Dependent Plural Anaphora : Tanaka+(2017)
- Paycheck sentences : Tanaka+(2018) in NLCS2018
- Coercion and Metaphor : Kinoshita+(2018)
- Questions : Watanabe+(NLCS'19), Funakura (2022) in LENLS19
- Comparision with DRT : Yana+(2019) in JoLLI

Recent Developments of DTS

- Development of an automated theorem prover for the fragment of DTS: Daido and Bekki (2020) in LENLS17
- A Proof-theoretic Analysis of Weak Crossover: Bekki (2021) in LENLS18
- The proviso problem from a proof-theoretic perspective: Yana+(2021) in LACL2021
- Japanese Tense: Matsuoka+(2023) in NALOMA'23
- Integrating Deep Neural Network with Dependent Type Semantics: Bekki+(2021) in LACompLing2021, Bekki+(2022) in NALOMA'22, and Iinuma+(2023) in ProsComps2023.

Thank you!



This work is supported by JSPS KAKENHI Grant Number JP23H03452, Japan, and JST CREST Grant Number JPMJCR20D2, Japan.

Reference I

Ahn, R. and H.-P. Kolb. (1990) Discourse Representation meets Constructive Mathematics. Akademiai Kiado.

Asher, N. and Z. Luo. (2012) "Formalisation of coercions in lexical semantics", In the Proceedings of *Sinn und Bedeutung 17*. pp.63–80.

Bekki, D. (2014) "Representing Anaphora with Dependent Types", In the Proceedings of N. Asher and S. V. Soloviev (eds.): *Logical Aspects of Computational Linguistics (8th international conference, LACL2014, Toulouse, France, June 2014 Proceedings), LNCS 8535*. pp.14–29, Springer, Heiderburg.

Bekki, D. and E. McCready. (2015) CI via DTS, Vol. LNAI 9067. Springer.

Reference II

Bekki, D. and K. Mineshima. (2017) Context-Passing and Underspecification in Dependent Type Semantics, pp.11–41, Studies of Linguistics and Philosophy. Springer.

Chatzikyriakidis, S. (2014) Adverbs in a Modern Type Theory. Springer.

Cooper, R. (2005) "Records and Record Types in Semantic Theory", *Journal of Logic and Computation* **15**(2), pp.99–112.

Dávila-Pérez, R. (1995) "Semantics and Parsing in Intuitionistic Categorial Grammar", Thesis. Ph.D. thesis.

De Houwer, J. (2019) "Moving Beyond System 1 and System 2", *Experiental Psychology* **66**(4), pp.257–265.

Evans, J. S. B. and K. Frankish. (2009) *In Two Minds: Dual Processes and Beyond*. Oxford University Press.

Reference III

Evans, J. S. B. and K. E. Stanovich. (2013) "Dual-Process Theories of Higher Cognition: Advancing the Debate", *Perspectives on Psychological Science* **8**(3), pp.223–241.

Fox, C. (1994a) "Discourse Representation, Type Theory and Property Theory", In the Proceedings of H. Bunt, R. Muskens, and G. Rentier (eds.): *the International Workshop on Computational Semantics*. pp.71–80.

Fox, C. (1994b) "Existence Presuppositions and Category Mistakes", *Acta Linguistica Hungarica* **42**(3/4), pp.325–339. Published 1996.

Gendler, T. (2008) "Alief and Belief", *Journal of Philosophy* **105**(10), pp.634–663.

Kadmon, N. (2001) *Formal Pragmatics*. Blackwell.

Reference IV

Karttunen, L. (1976) Discourse Referents, Vol. 7, pp.363–85. New York, Academic Press.

Kawazoe, A., R. Tanaka, K. Mineshima, and D. Bekki. (2015a) "A Framework for Constructing Multilingual Inference Problem", In the Proceedings of *1st International Workshop on the Use of Multilingual Language Resources in Knowledge Representation Systems (MLKRep2015)*.

Kawazoe, A., R. Tanaka, K. Mineshima, and D. Bekki. (2015b) "An Inference Problem Set for Evaluating Semantic Theories and Semantic Processing Systems for Japanese", In the Proceedings of *LENLS12*. pp.67–73.

Reference V

Krahmer, E. and P. Piwek. (1999) Presupposition Projection as Proof Construction, Studies in Linguistics Philosophy Series. Dordrecht, Kluwer Academic Publishers.

Kruglanski, A. W. (2013) "Only One? The Default Interventionist Perspective as a Unimodel—Commentary on Evans & Stanovich (2013)", *Perspectives on Psychological Science* **8**(3), pp.242–247.

Luo, Z. (1997) Coercive subtyping in type theory. Heidelberg, Springer.

Luo, Z. (1999) "Coercive subtyping", *Journal of Logic and Computation* **9**(1), pp.105–130.

Reference VI

Luo, Z. (2010) "Type-theoretical semantics with coercive subtyping", In the Proceedings of *Semantics and Linguistic Theory 20 (SALT 20)*.

Luo, Z. (2012) "Formal Semantics in Modern Type Theories with Coercive Subtyping", *Linguistics and Philosophy* **35**(6).

Mandelbaum, E. (2016) "Attitude, Inference, Association: On the Propositional Structure of Implicit Bias", *Nous* **50**(3), pp.629–658.

Mandelbaum, E. (2022) Associationist Theories of Thought. The Stanford Encyclopedia of Philosophy, Metaphysics Research Lab, Stanford University, Winter 2022 edition.

Reference VII

Martin, S. and C. J. Pollard. (2014) "A dynamic categorial grammar", In the Proceedings of *Formal Grammar 19, LNCS 8612*.

Matsuoka, D., D. Bekki, and H. Yanaka. (2023) "Analyzing Japanese Relative Tense with Dependent Type Theory", In the Proceedings of *Proceedings of Natural Logic Meets Machine Learning IV (NALOMA23), IWCS2023 workshop, extended abstract*. Association of Computational Linguistics.

Osman, M. (2013) "A case study: Dual-process theories of higher cognition—Commentary on Evans & Stanovich (2013)", *Perspectives on Psychological Science* **8**(3), pp.248–252.

Reference VIII

Piwek, P. and E. Krahmer. (2000) Presuppositions in Context: Constructing Bridges, Applied Logic Series. Dordrecht, Kluwer Academic Publishers.

Ranta, A. (1994) *Type-Theoretical Grammar*. Oxford University Press.

Sloman, S. A. (1996) "The Empirical Case for Two Systems of Reasoning", *Psychological Bulletin* **119**(1), pp.3–22.

Smith, E. R. and J. DeCoster. (2000) "Dual-Process Models in Social and Cognitive Psychology: Conceptual Integration and Links to Underlying Memory Systems", *Personality and Social Psychology Review* **4**(2), pp.108–131.

Sundholm, G. (1986) Proof theory and meaning, Vol. **III**, pp.471–506. Reidel, Kluwer.

Reference IX

Tanaka, R. (2014) "A Proof-Theoretic Approach to Generalized Quantifiers in Dependent Type Semantics", In the Proceedings of R. de Haan (ed.): *the ESSLLI 2014 Student Session, 26th European Summer School in Logic, Language and Information*. pp.140–151.

Tanaka, R., K. Mineshima, and D. Bekki. (2015) "Factivity and Presupposition in Dependent Type Semantics", In the Proceedings of *TYpe Theory and LExical Semantics (TYTLES), ESSLLI2015 workshop*.

Watanabe, N., E. McCready, and D. Bekki. (2014) "Japanese Honorification: Compositionality and Expressivity", In the Proceedings of S. Kawahara and M. Igarashi (eds.): *FAJL 7: Formal Approaches to Japanese Linguistics, the MIT Working Papers in Linguistics 73*. pp.265–276.

Reference X

Wilson, T. D., S. Lindsey, and T. Y. Schooler. (2000) “A model of dual attitudes”, *Psychological Review* **107**(1), pp.101–126.