Introduction to Typed Lambda Calculus

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Typed Lambda Calculi: Background

- Developed starting with Church and Curry in 1930's
- Can be viewed model-theoretically (Henkin-Montague perspective) or proof-theoretically (Curry-Howard perspective). For now we focus on the former.
- Underlies higher-order logic (HOL) and functional programming. Widely used in semantics for formalizing theories of meaning, and in linear grammar (LG) for formalizing phenogrammar.

What's in a TLC

- A TLC is specified by giving its *types*, its *terms*, and an *equivalence relation* on the terms.
- There are different kinds of TLCs, depending on what kind of propositional logic its type system is based on.
- The TLC that underlies HOL, called *positive* TLC, is based on *positive intuitionistic propositional logic* (PIPL), which lacks false, negation and disjunction.

Types of Positive TLC

1. There are some *basic* types. For concreteness, here we assume two basic types motivated by NL semantics:

   p (for *propositions*, the kind of meanings expressed by utterances of declarative sentences)
   e (for *entities*, the kind of things that can be meanings of names (just for now assuming a direct reference theory of names))

2. T is a type.
3. If A and B are types, so is $A \wedge B$.
4. If A and B are types, so is $A \rightarrow B$.

Terms of Positive TLC (1/2)

Note: we write '$\vdash a : A$' to mean term a is of type A.

a. There are some *nonlogical constants*. In the typical appplication to NL semantics, these are interpreted as word meanings, e.g.:

$$\vdash \mathsf{fido} : \mathrm{e}$$
$$\vdash \mathsf{bark} : \mathrm{e} \to \mathrm{p}$$
$$\vdash \mathsf{bite} : \mathrm{e} \to \mathrm{e} \to \mathrm{p}$$
$$\vdash \mathsf{give} : \mathrm{e} \to \mathrm{e} \to \mathrm{e} \to \mathrm{p}$$
$$\vdash \mathsf{believe} : \mathrm{e} \to \mathrm{p} \to \mathrm{p}$$

b. There is a *logical constant* $\vdash * : \mathrm{T}$. In the application to NL semantics, this is interpreted as the vacuous meaning.

c. For each type A there are variables $\vdash x_i^A : A$ $(i \in \omega)$.

Terms of Positive TLC (2/2)

d. If $\vdash a : A$ and $\vdash b : B$, then $\vdash (a, b) : A \wedge B$.
e. If $\vdash a : A \wedge B$, then $\vdash \pi(a) : A$.
f. If $\vdash a : A \wedge B$, then $\vdash \pi'(a) : B$.
g. If $\vdash f : A \rightarrow B$ and $\vdash a : A$, then $\vdash \mathsf{app}(f, a) : B$.
h. If $\vdash x : A$ is a variable and $\vdash b : B$, then $\vdash \lambda_x.b : A \rightarrow B$.

Note: $\mathsf{app}(f, a)$ is usually abbreviated to $(f\ a)$.

Positive TLC Term Equivalences (1/3)

Here t, a, b, p, and f are metavariables ranging over terms.

a. Equivalences for the term constructors:

1. $t \equiv *$ (for t a term of type T)
2. $\pi(a, b) \equiv a$
3. $\pi'(a, b) \equiv b$
4. $(\pi(p), \pi'(p)) \equiv p$

Positive TLC Term Equivalences (2/3)

b. Equivalences for the variable binder ('lambda conversion')

  (α) $\lambda_x.b \equiv \lambda_y.[x/y]b$

  (β) $(\lambda_x.b)\ a \equiv [x/a]b$

  (η) $\lambda_x.(f\ x) \equiv f$, provided x is not free in f

Note 1: The notation '$[x/a]b$' means the term resulting from substitution in b of all free occurrences of $x : A$ by $a : A$. This presupposes a is free for x in b.

Note 2: 'Free' and 'bound' are defined just as in FOL, except that λ is the variable binder rather than $\forall$ and $\exists$.

Positive TLC Term Equivalences (2/2)

c. Equivalences of Equational Reasoning

(ρ) $a \equiv a$

(σ) If $a \equiv a'$, then $a' \equiv a$.

(τ) If $a \equiv a'$ and $a' \equiv a''$, then $a \equiv a''$.

(ξ) If $b \equiv b'$, then $\lambda_x.b \equiv \lambda_x.b'$.

(μ) If $f \equiv f'$ and $a \equiv a'$, then $(f\ a) \equiv (f'\ a')$.

The Henkin-Montague Perspective

A **(set-theoretic) interpretation** I of a positive TLC assigns to each type A a set $I(A)$ and to each constant $\vdash a : A$ a member $I(a)$ of $I(A)$, subject to the following constraints:

1. $I(\mathrm{T})$ is a singleton
2. $I(A \wedge B) = I(A) \times I(B)$
3. $I(A \rightarrow B) \subseteq I(A) \rightarrow I(B)$

Note: As in Henkin 1950, the set inclusion in the last clause (3) can be proper, as long as there are enough functions to interpret all functional terms.

Assignments

Just as in FOL, an **assignment** relative to an interpretation is a function that maps each member of a set of variables to a member of the set that interprets the variable's type.

Extending an Interpretation Relative to an Assignment

Given an assignment α relative to an interpretation I, there is a unique extension of I, denoted by I_α, that assigns interpretations to all terms, such that:

1. for each variable x, $I_\alpha(x) = \alpha(x)$
2. for each constant a, $I_\alpha(a) = I(a)$
3. if $\vdash a : A$ and $\vdash b : B$, then $I_\alpha((a, b))$ is $\langle I_\alpha(a), I_\alpha(b)\rangle$
4. if $\vdash p : A \wedge B$, then $I_\alpha(\pi(p))$ is the first component (= projection onto $I(A)$) of $I_\alpha(p)$; and $I_\alpha(\pi'(p))$ is the second component (= projection onto $I(B)$) of $I_\alpha(p)$
5. if $\vdash f : A \to B$ and $\vdash a : A$, then $I_\alpha((f\ a)) = (I_\alpha(f))(I_\alpha(a))$
6. if $\vdash b : B$, then $I_\alpha(\lambda_{x \in A}.b)$ is the function from $I(A)$ to $I(B)$ that maps each $s \in I(A)$ to $I_\beta(b)$, where β is the assignment that coincides with α except that $\beta(x) = s$.

Observations about Interpretations

- Two terms $\vdash a : A$ and $\vdash b : B$ of positive TLC are term-equivalent iff $A = B$ and, for any intepretation I and any assignment α relative to I, $I_\alpha(a) = I_\alpha(b)$.
- Another way of stating the preceding is to say that term equivalence (viewed as an equational proof system) is sound and complete for the class of set-theoretic interpretations described earlier.
- For any term a, $I_\alpha(a)$ depends only on the restriction of α to the free variables of a.
- In particular, if a is a closed (i.e. has no free variables), then $I_\alpha(a)$ is independent of α so we can simply write $I(a)$.
- Thus, an interpretation for the basic types and constants extends uniquely to all types and all closed terms.

Sequent-Style ND with Proof Terms

- This is a style of ND designed to analyze not just provability, but also proofs.
- We illustrate how this for PIPL, starting from the (term-free) sequent-style ND for PIPL already introduced.
- We'll see that in addition to being thought of as denoting elements of models, TLC terms can also be thought of as notations for proofs.
- This idea was first articulated by Curry (1934, 1958), then elaborated by Howard (1969 [1980]), Tait (1967), etc..
- We'll use this kind of ND for phenos and meanings in linear grammar derivations.

Preliminary Definitions

1. A (TLC) term is called **closed** if it has no free variables.
2. A closed term is called a **combinator** if it contains no nonlogical constants.
3. A type is said to be **inhabited** if there is a closed term of that type.

Curry-Howard Correspondence (1/2)

- Types are (the same thing as) formulas.
- Type constructors are logical connectives.
- (Equivalence classes of) terms are proofs.
- The free variables of a term are the undischarged hypotheses on which the proof depends.
- The nonlogical constants of a term are the nonlogical axioms used in the proof.
- A type is a theorem iff it is inhabited.
- A type is a pure theorem (requires no nonlogical axioms to prove it) iff it is inhabited by a combinator.

Curry-Howard Correspondence (2/2)

- Application corresponds to Modus Ponens.
- Abstraction corresponds to Hypothetical Proof (discharge of hypothesis).
- Pairing corresponds to Conjunction Introduction.
- Projections correspond to Conjunction Eliminations.
- Identification of free variables corresponds to collapsing of duplicate hypotheses (Contraction).
- Vacuous abstraction corresponds to discharge of a nonexistent hypothesis (Weakening).

Notation for Sequent-Style ND with Proof Terms

Judgments are of the form $\Gamma \vdash a : A$, read 'a is a proof of A with hypotheses Γ', where

1. A is a formula (= type)
2. a is a term (= proof)
3. Γ, the **context** of the judgment, is a set of variable/formula pairs of the form $x : A$, with a distinct variable in each pair.

Axiom Schemas

Hypotheses:

$$x : A \vdash x : A$$

(x a variable of type A)

Nonlogical Axioms:

$$\vdash a : A$$

(a a nonlogical constant of type A)

Logical Axiom:

$$\vdash * : \mathrm{T}$$

Rule Schemas for Implication

$\rightarrow$-Elimination or Modus Ponens:

$$\frac{\Gamma \vdash f : A \rightarrow B \qquad \Delta \vdash a : A}{\Gamma, \Delta \vdash (f\ a) : B} \rightarrow\mathrm{E}$$

This presupposes no variable occurs in both Γ and Δ.

$\rightarrow$-Introduction or Hypothetical Proof:

$$\frac{x : A, \Gamma \vdash b : B}{\Gamma \vdash \lambda_x . b : A \rightarrow B} \rightarrow\mathrm{I}$$

Other Rule Schemas

There are also rules schemas (which we will not need) for:

- pairing/conjunction introduction
- projections/conjunction elimination
- identifying variables/contraction
- useless hypotheses/weakening

For details see e.g. John C. Mitchell and Philip J. Scott (1989) "Typed lambda models and cartesian closed categories", **Contemporary Mathematics** 92:301-316.