A Generalized Logical Framework

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Overview

1. Two-level type theories (2LTT):
   - metaprogramming over a **single model** of a **single type theory**.
   - the chosen model is defined **outside the system**.
   - **only a second-order ("internal")** view on the model.

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In this talk:

1. A syntax of GLF + examples + increasing amount of syntactic sugar.
2. A short overview of semantics.

GLF: basic rules

$\mathbf{U}$	$: \mathbf{U}$	A universe of that supports ETT.
$\mathbf{Base}$	$: \mathbf{U}$	Type of "base categories".
$\mathbf{1}$	$: \mathbf{Base}$	The terminal category as a base category.
$\mathbf{PSh}$	$: \mathbf{Base} \to \mathbf{U}$	Universes of presheaves. Cumulativity: $\mathsf{PSh}_i \subseteq \mathsf{U}$. Supports ETT.
		We can only eliminate from PSh_i to PSh_i.
$\mathbf{Cat}_i$	$: \mathbf{PSh}_i$	$:=$ *type of categories in* PSh_i
$\mathbf{In}$	$: \mathbf{Cat}_i \to \mathbf{U}$	"Permission token" for working in presheaves over some $\mathbb{C} : \mathsf{Cat}_i$.
$\mathbf{base}$	$: \mathbf{In}\,\mathbb{C} \to \mathbf{Base}$	"Using the permission".

We use type-in-type everywhere for simplicity, i.e. $\mathsf{U} : \mathsf{U}$ and $\mathsf{PSh}_i : \mathsf{PSh}_i$.

Basic things we can do

$$\mathsf{U} : \mathsf{U} \qquad \mathsf{Base} : \mathsf{U} \qquad 1 : \mathsf{Base} \qquad \mathsf{PSh} : \mathsf{Base} \to \mathsf{U}$$

$$\mathsf{Cat}_i : \mathsf{PSh}_i := \textit{type of cats in } \mathsf{PSh}_i \qquad \mathsf{In} : \mathsf{Cat}_i \to \mathsf{U} \qquad \mathsf{base} : \mathsf{In}\,\mathbb{C} \to \mathsf{Base}$$

PSh_1 is a universe supporting ETT. Semantically, PSh_1 is a universe of sets.

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At this point, we have no interesting interaction between PSh_1 and PSh_i.

Syntactic sugar: we'll omit "base" in the following.

Example: embedding pure lambda calculus

A **second-order model of pure LC** in PSh_i consists of:

$$
\begin{aligned}
\mathsf{Tm} &: \mathsf{PSh}_i \\
\mathsf{lam} &: (\mathsf{Tm} \to \mathsf{Tm}) \to \mathsf{Tm} \\
\text{–\$–} &: \mathsf{Tm} \to \mathsf{Tm} \to \mathsf{Tm} \\
\beta \quad &: \mathsf{lam}\, f \,\$\, t = f\ t \\
\eta \quad &: \mathsf{lam}\, (\lambda x.\, t \,\$\, x) = t
\end{aligned}
$$

We define $\mathsf{SMod}_i : \mathsf{PSh}_i$ as the above Σ-type.

Example: embedding pure lambda calculus

A **first-order model of pure LC** consists of:

- A category of contexts and substitutions with $\mathsf{Con} : \mathsf{PSh}_i$, $\mathsf{Sub} : \mathsf{Con} \to \mathsf{Con} \to \mathsf{PSh}_i$ and terminal object $\bullet$.
- $\mathsf{Tm} : \mathsf{Con} \to \mathsf{PSh}_i$, plus a term substitution operation.
- A context extension operation $-\triangleright : \mathsf{Con} \to \mathsf{Con}$ such that $\mathsf{Sub}\,\Gamma\,(\Delta\triangleright) \simeq \mathsf{Sub}\,\Gamma\,\Delta \times \mathsf{Tm}\,\Gamma$.
- A natural isomorphism $\mathsf{Tm}\,(\Gamma\triangleright) \simeq \mathsf{Tm}\,\Gamma$ whose components are λ and application.

We define $\mathsf{FMod}_i : \mathsf{PSh}_i$ as the above Σ-type.

FMod is mechanically derivable from SMod.[1]

[1] Ambrus Kaposi & Szumi Xie: *Second-Order Generalised Algebraic Theories*.

Example: embedding pure lambda calculus

GLF rule

Assuming M : FMod_i and j : $\mathsf{In}\, M$, we have S_j : SMod_j.

(In "In M" we implicitly convert M to its underlying category.)

Now we have a 2LTT inside PSh_j:

- ETT type formers in PSh_j comprise the outer level.
- S_j comprises the inner level.

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Y-combinator as example:

$$\mathsf{YC} : \mathsf{Tm}_{\mathsf{S}_j}$$

$$\mathsf{YC} := \mathsf{lam}_{\mathsf{S}_j}(\lambda\, f.\, (\mathsf{lam}_{\mathsf{S}_j}(\lambda x.\, x \,\$_{\mathsf{S}_j}\, x))\, \$_{\mathsf{S}_j}\, (\mathsf{lam}_{\mathsf{S}_j}(\lambda f.\, \mathsf{lam}_{\mathsf{S}_j}(\lambda x.\, f \,\$_{\mathsf{S}_j}\, (x \,\$_{\mathsf{S}_j}\, x)))))$$

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\end{aligned}$$

With a reasonable amount of sugar:

$$\begin{aligned}
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&\mathsf{YC} := \mathsf{lam}\, f.\,(\mathsf{lam}\, x.\, x\, x)\,(\mathsf{lam}\, f.\,\mathsf{lam}\, x.\, f\,(x\, x))
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- Hence: all 2LTTs are syntactic fragments of GLF.
- (For each 2LTT, the semantics of GLF restricts to the standard presheaf semantics of the 2LTT.)

Yoneda: conversion between internal & external views

GLF rule: Yoneda embedding for pure LC

Assuming $M : \mathsf{FMod}_i$ and writing $\simeq$ for definitional isomorphism, we have

$$\begin{aligned} \mathsf{Y} : \mathsf{Con}_M & \to ((j : \mathsf{In}_M) \to \mathsf{PSh}_j) \\ \mathsf{Y} : \mathsf{Sub}_M\,\Gamma\,\Delta & \simeq ((j : \mathsf{In}_M) \to \mathsf{Y}\,\Gamma\,j \to \mathsf{Y}\,\Delta\,j) \\ \mathsf{Y} : \mathsf{Tm}_M\,\Gamma & \simeq ((j : \mathsf{In}_M) \to \mathsf{Y}\,\Gamma\,j \to \mathsf{Tm}_{\mathsf{S}_j}) \end{aligned}$$

such that Y preserves empty context and context extension:

$$\begin{aligned} \mathsf{Y} \bullet j & \simeq \top \\ \mathsf{Y}\,(\Gamma \triangleright)\,j & \simeq \mathsf{Y}\,\Gamma\,j \times \mathsf{Tm}_{\mathsf{S}_j} \end{aligned}$$

and Y preserves all other structure strictly.

Notation: we write Λ for inverses of Y.

LC examples, sugar

Y and Λ allow ad-hoc switching between first-order and second-order notation. Let's redefine some operations using second-order notation:

$$
\begin{array}{ll}
\mathsf{id} : \mathsf{Sub}_M\,\Gamma\,\Gamma & \mathsf{comp} : \mathsf{Sub}_M\,\Delta\,\Theta \to \mathsf{Sub}_M\,\Gamma\,\Delta \to \mathsf{Sub}_M\,\Gamma\,\Theta \\
\mathsf{id} := \Lambda\,(\lambda\,j\,\gamma.\,\gamma) & \mathsf{comp}\,\sigma\,\delta := \Lambda\,(\lambda\,j\,\gamma.\,\mathsf{Y}\,\sigma\,(\mathsf{Y}\,\delta\,\gamma\,j)\,j)
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Or even:

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Example for "pattern matching" notation:

$$\begin{array}{ll} \mathsf{p} : \mathsf{Sub}_M\,(\Gamma\triangleright)\,\Gamma & \\ \mathsf{p} := \Lambda\,(\gamma,\,\alpha).\,\gamma & \textit{Note: } \mathsf{Y}\,(\Gamma\triangleright) \simeq \mathsf{Y}\,\Gamma \times \mathsf{Tms}_{S_j} \end{array}$$

Second-order notation

- When working with CwF-s, De Bruijn indices and substitutions can be hard to read.
- Handwaved "named" binders in CwFs have been used in literature (e.g. by me).
- GLF provides a rigorous implementation of such notation.
- For many use cases, we can use second-order notation and just forget about the first-order combinators.

Embedding dependent type theories

In a first order model, we have:

$$\begin{aligned}
\mathsf{Con} &: \mathsf{PSh}_i \\
\mathsf{Sub} &: \mathsf{Con} \to \mathsf{Con} \to \mathsf{PSh}_i \\
\mathsf{Ty} &: \mathsf{Con} \to \mathsf{PSh}_i \\
\mathsf{Tm} &: (\Gamma : \mathsf{Con}) \to \mathsf{Ty}\,\Gamma \to \mathsf{PSh}_i \\
\ldots
\end{aligned}$$

In a second order model, we have

$$\begin{aligned}
\mathsf{Ty} &: \mathsf{PSh}_i \\
\mathsf{Tm} &: \mathsf{Ty} \to \mathsf{PSh}_i \\
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\end{aligned}$$

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Yoneda embedding:

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\mathsf{Y} : \mathsf{Ty}_M\,\Gamma &\simeq ((j : \mathsf{In}\,M) \to \mathsf{Y}\,\Gamma\,j \to \mathsf{Ty}_{\mathsf{S}_j}) \\
\mathsf{Y} : \mathsf{Tm}_M\,\Gamma\,A &\simeq ((j : \mathsf{In}\,M) \to (\gamma : \mathsf{Y}\,\Gamma\,j) \to \mathsf{Tm}_{\mathsf{S}_j}\,(\mathsf{Y}\,A\,j\,\gamma))
\end{aligned}$$

Embedding dependent type theories

Sugar for contexts:

$$(\Gamma \triangleright A \triangleright B) : \mathsf{Con}_M \quad \text{is equal to} \quad \Gamma \triangleright (\Lambda\, \gamma. \mathsf{Y} A\, \gamma) \triangleright (\Lambda\, (\gamma, \alpha). \mathsf{Y} B\, (\gamma, \alpha))$$

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This suggests the notation:

$$(\gamma : \Gamma,\, \alpha : \mathsf{Y} A\, \gamma,\, \beta : \mathsf{Y} B\, (\gamma,\, \alpha)) : \mathsf{Con}_M$$

With implicit Y:

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Sugar for $\mathbf{Tm}_M$. We have

$$\mathsf{Tm}_M\,(\Gamma \triangleright A \triangleright B)\,C \;=\; \mathsf{Tm}_M\,(\Gamma \triangleright A \triangleright B)\,(\Lambda\,(\gamma,\,\alpha,\,\beta).\,B\,(\gamma,\,\alpha,\,\beta))$$

which suggests the notation

$$\mathsf{Tm}_M\,(\gamma : \Gamma,\, \alpha : A\,\gamma,\, \beta : B\,(\gamma,\,\alpha))\,(B\,(\gamma,\,\alpha,\,\beta))$$

Embedding dependent type theories

Example: a construction which looks awful in explicit CwF notation[2]

$$
\begin{aligned}
&\mathsf{Con}^\circ\,\Gamma && :\equiv \mathsf{Ty}\,(F\,\Gamma) \\
&\mathsf{Ty}^\circ\,\Gamma^\circ\,A && :\equiv \mathsf{Ty}\,(F\,\Gamma \triangleright \Gamma^\circ \triangleright F\,A[\mathsf{p}]) \\
&\mathsf{Tm}^\circ\,\Gamma^\circ\,A^\circ\,t && :\equiv \mathsf{Tm}\,(F\,\Gamma \triangleright \Gamma^\circ)\,(A^\circ[\mathsf{id},\,F\,t[\mathsf{p}]]) \\
&\Gamma^\circ \triangleright^\circ A^\circ && :\equiv \Sigma(\Gamma^\circ[\mathsf{p} \circ F_{\triangleright.1}])(A^\circ[\mathsf{p} \circ F_{\triangleright.1} \circ \mathsf{p},\,\mathsf{q},\,\mathsf{q}[F_{\triangleright.1} \circ \mathsf{p}]]) \\
&\ldots
\end{aligned}
$$

but is reasonable in sugary GLF notation:

$$
\begin{aligned}
&\mathsf{Con}^\circ\,\Gamma && :\equiv \mathsf{Ty}\,(\gamma : F\,\Gamma) \\
&\mathsf{Ty}^\circ\,\Gamma^\circ\,A && :\equiv \mathsf{Ty}\,(\gamma : F\,\Gamma,\,\gamma^\circ : \Gamma^\circ\,\gamma,\,\alpha : F\,A\,\gamma) \\
&\mathsf{Tm}^\circ\,\Gamma^\circ\,A^\circ\,t && :\equiv \mathsf{Tm}\,(\gamma : F\,\Gamma,\,\gamma^\circ : \Gamma^\circ\,\gamma)\,(A^\circ\,(\gamma,\,\gamma^\circ,\,F\,t\,\gamma)) \\
&\Gamma^\circ \triangleright^\circ A^\circ && :\equiv \Lambda\,(F_{\triangleright.1}(\gamma,\,\alpha)).\,\Sigma(\gamma^\circ : \Gamma^\circ\,\gamma) \times A^\circ\,(\gamma,\,\gamma^\circ,\,\alpha)
\end{aligned}
$$

It's a fair amount of sugar, but we can always rigorously desugar when it doubt!

[2] Kaposi, Huber, Sattler: *Gluing for Type Theory*, Section 5

General GLF rules

For every second-order generalized algebraic signature $\mathbb{T}$:

- We compute (externally to GLF) $\mathsf{FMod}_{(\mathbb{T},\, i)}$ and $\mathsf{SMod}_{(\mathbb{T},\, i)}$.
- We specify that GLF has $\mathsf{S}_{(\mathbb{T},\, i)}$.
- We specify that GLF has Yoneda embedding.

It's not simple compute the specification of Yoneda embedding from $\mathbb{T}$! Doing this is part of future work.

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It's not simple compute the specification of Yoneda embedding from $\mathbb{T}$! Doing this is part of future work.

Also, these are not all rules that we might want to have!

- *For example:* conversion between internal and external natural numbers, i.e. $\mathbb{N}_i \simeq ((j : \mathsf{In}_M) \to \mathbb{N}_j)$ where $M : \mathsf{Cat}_i$.
- This can be broadly generalized to an isomorphism of "external" and "internal" 2LTT models.
- But we're not sure yet which rules are the best to enshrine in GLF syntax.

Semantics

Each PSh_i should be an universe of internal presheaves over an internal category.

We should work with **Cat** somehow, but there are issues with that:

- There's no general Π.
- Π-types of presheaves and universes of presheaves are not stable under reindexing by arbitrary functors.

In GLF, the categorical part (Base, In) is purely for bookkeeping, we can't do synthetic category theory. We can only do interesting things with presheaves.

Semantic contexts are certain *trees of categories*, containing a mix of discrete and non-discrete fibrations, and tree morphisms only have nontrivial action on discrete parts of trees.

Semantics

Notation:

- For a category C and a split fibration A over it, we write $C \triangleright A$ for the total category.
- For a presheaf A, we write $\mathrm{Disc}\, A$ for the derived discrete fibration.

Definition. A *category telescope* is either the terminal category, or it is (inductively) of the form $C \triangleright \mathrm{Disc}\, A \triangleright B$ where C is a category telescope. We write $C : \mathrm{CatTel}$ for a category telescope.

Definition. A tree of categories is inductively defined as:

$$
\begin{aligned}
&\mathbf{data}\ \mathrm{Tree}\,(B : \mathrm{CatTel}) : \mathrm{Set}\ \mathbf{where} \\
&\quad \mathrm{node} : (\Gamma : \mathrm{PSh}\, B) \\
&\qquad \to (n : \mathbb{N}) \\
&\qquad \to (C : \mathrm{Fin}\, n \to \mathrm{Fib}\,(B \triangleright \mathrm{Disc}\,\Gamma)) \\
&\qquad \to ((i : \mathrm{Fin}\, n) \to \mathrm{Tree}\,(B \triangleright \mathrm{Disc}\,\Gamma \triangleright C\, i)) \\
&\qquad \to \mathrm{Tree}\, B
\end{aligned}
$$

Semantics

$$\mathsf{node} : (\Gamma : \mathsf{PSh}\ B)(n : \mathbb{N})(C : \mathsf{Fin}\ n \to \mathsf{Fib}\,(B \triangleright \mathsf{Disc}\,\Gamma)) \to ((i : \mathsf{Fin}\ n) \to \mathsf{Tree}\,(B \triangleright \mathsf{Disc}\,\Gamma \triangleright C\ i)) \\ \to \mathsf{Tree}\ B$$

A GLF context is an element of Tree 1. Some examples for semantic contexts. We have $\mathbb{N}_i : \mathsf{PSh}_i$. We use $- \triangleright -$ for "context extension" in presheaves as well.

$$\begin{aligned}
\bullet \quad & := \mathsf{node}\,1\,0\,[]\,[] \\
(\bullet \triangleright \mathbb{N}_1) \quad & := \mathsf{node}\,(1 \triangleright \mathbb{N})\,0\,[]\,[] \\
(\bullet \triangleright \mathbb{N}_1 \triangleright \mathsf{In}\ C) \quad & := \mathsf{node}\,(1 \triangleright \mathbb{N})\,1\,[C]\,[\mathsf{node}\,1\,0\,[]\,[]] \\
(\bullet \triangleright \mathbb{N}_1 \triangleright i : \mathsf{In}\ C \triangleright \mathbb{N}_{(\mathsf{base}\ i)}) & := \mathsf{node}\,(1 \triangleright \mathbb{N})\,1\,[C]\,[\mathsf{node}\,(1 \triangleright \mathbb{N})\,0\,[]\,[]]
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Semantics

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\end{aligned}$$

- A Base in context Γ points to a node in Γ.
- An $\mathsf{In}\, C$ in context Γ points to a subtree of a node.
- Extending a context with $A : \mathsf{PSh}_i$ extends the presheaf in node i.
- Extending a context with $j : \mathsf{In}\, C$ for $C : \mathsf{Cat}_j$ adds a new subtree at node j.

Semantics

$$\mathsf{node} : (\Gamma : \mathsf{PSh}\, B)(n : \mathbb{N})(C : \mathsf{Fin}\, n \to \mathsf{Fib}\,(B \triangleright \mathsf{Disc}\, \Gamma)) \to ((i : \mathsf{Fin}\, n) \to \mathsf{Tree}\,(B \triangleright \mathsf{Disc}\, \Gamma \triangleright C\, i))$$
$$\to \mathsf{Tree}\, B$$

Tree morphisms are defined inductively & levelwise, containing

- natural transformations between $\Gamma : \mathsf{PSh}\, B$ components
- functions for reindexing subtrees of type $\mathsf{Fin}\, n \to \mathsf{Fin}\, m$

such that the non-discrete fibrations are preserved.

A semantic $\mathbf{PSh}_i$ in context Γ is a presheaf over the category given by the path from the root of Γ to the node i.

Further work

- Decide on the exact rules of GLF.
- Compute the specification of Yoneda embedding from SOGAT signatures, define semantics in this generality.
- Investigate syntactic metatheory.
    - For computer implementation, we need to wean ourselves off extensional TT!
        - (but informal extensional GLF is already useful)
    - Definitional isos for Y are unusual in syntax.
    - Simpler syntactic fragments of GLF could be useful & easier to implement.

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Thank you!