Models for Axiomatic Type Theory

Daniël Otten and Matteo Spadetto

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We explain and motivate Axiomatic Type Theory (ATT).
(type theory without reductions)

We compare two semantics for a minimal version of ATT:

- comprehension categories: more traditional and well-studied; closely follow the syntax and intricacies of type theory.
- path categories (Van den Berg, Moerdijk 2017): more concise; take inspiration from homotopy theory.

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Our Contributions

Path categories are equivalent to certain comprehension categories. This allows us to turn path categories into actual models as well.

We introduce a more fine-grained notion: display path categories, and show a similar equivalence.

We obtain the following diagram of 2-categories:

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\begin{tikzcd}
\mathrm{PathCat} \arrow[r, "\sim"] \arrow[d, shift left, "C"] & \mathrm{ComprehensionCat}_{\mathrm{Contextual},=,\Sigma_{\beta\eta}} \arrow[d, shift left, "U"] \\
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Equality

Intensional Type Theory (ITT) has two notions of equality:

definitional ($\equiv$)	judgement	reductions	decidable,
propositional ($=$)	type	proofs	undecidable.

Definitional eq is a fragment of propositional eq.

Other fragments:

- larger $\rightsquigarrow$ work in the system,
- smaller $\rightsquigarrow$ find models.

Two extremes:

- Extensional Type Theory (ETT): everything is definitional,
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Other Fragments

Larger:

- If we define
$$\begin{aligned} 0 + n &\equiv n, \\ (\mathsf{S}\, m) + n &\equiv \mathsf{S}\,(m + n), \end{aligned}$$
then we can prove
$$\begin{aligned} m + 0 &= m, \\ m + (\mathsf{S}\, n) &= \mathsf{S}\,(m + n). \end{aligned}$$
But these proven eq are not definitional.
`Agda` allows you to make them definitional.

Smaller:

- Cubical Type Theory: only propositional β-rule for $=$-types.
- Coinductive Types: only propositional β-rule as otherwise definitional eq becomes undecidable.

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Complexity and Conservativity

The complexity of type checking:

- ETT: undecidable,
- ITT: nonelementary,
- ATT: quadratic.

Does ETT prove more than ATT? Yes, namely:

- binder extensionality (bindext),
- uniqueness of identity proofs (uip).

However, these are the only additional things we can prove.

(Winterhalter 2019)

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Without Π-types, we have to strengthen the rules:

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Minimal ATT

In ATT, we change the reduction to an axiom:

$$\frac{\Gamma \vdash A \text{ type}}{\Gamma, x, x' : A \vdash x =_A x' \text{ type}}(=\mathcal{F}),$$

$$\frac{\Gamma \vdash A \text{ type}}{\Gamma, x : A \vdash \mathsf{refl}_x : x =_A x}(=\mathcal{I}),$$

$$\frac{\begin{array}{l}\Gamma, x, x' : A, p : x =_A x', \Delta \vdash C \text{ type} \\ \Gamma, x : A, \Delta[x/x', \mathsf{refl}_x/p] \vdash d : C[x/x', \mathsf{refl}_x/p]\end{array}}{\Gamma, x, x' : A, p : x =_A x', \Delta \vdash \mathsf{ind}^{=}_{C,d,p} : C}(=\mathcal{E}),$$

$$\frac{\begin{array}{l}\Gamma, x, x' : A, p : x =_A x', \Delta \vdash C \text{ type} \\ \Gamma, x : A, \Delta[x/x', \mathsf{refl}_x/p] \vdash d : C[x/x', \mathsf{refl}_x/p]\end{array}}{\Gamma, x : A, \Delta[x/x', \mathsf{refl}_x/p] \vdash \beta^{=}_{C,d,x} : \mathsf{ind}^{=}_{C,d,\mathsf{refl}_x} =_{C[x/x', \mathsf{refl}_x/p]} d}(=\beta_{\mathrm{ax}}).$$

Models

How do we model this minimal ATT?

Two options:

- Follow the syntax and rules. (comprehension category)
  - We require: $=_A$, refl_A, $\mathsf{ind}^{=}_{C,c,p}$, and $\beta^{=}_{C,c,x}$.
- Use intuition from homotopy theory. (path category)
  - We require: $=_A$, refl_A, and that refl_A is an equivalence.

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Comprehension Categories

In a comprehension category we have:

- a category of contexts with terminal object ϵ,
- a category of types,
- for every type A a context map $p_A : \Gamma.A \to \Gamma$. (display map)
- for every type A in context Γ and context map $\sigma : \Delta \to \Gamma$, a type $A[\sigma]$ in context Δ. (substitution)
- satisfying some universal properties.

The terms of A are the maps $a : \Gamma \to \Gamma.A$ such that $p_A \circ a = \mathrm{id}_\Gamma$.

Each type former gives additional requirements. For equality:

- $=$-types: for A a type $=_A$ and terms refl_A, $\mathsf{ind}^{=}_{A,C,d}$, $\beta^{=}_{A,C,d}$,
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Strict Models

To model ATT, we need choices that are split:

$$A[\mathrm{id}_\Gamma] = A,$$
$$A[\tau \circ \sigma] = A[\sigma][\tau].$$

And strongly stable:

$$=_A[\sigma] = \;=_{A[\sigma]},$$
$$\mathsf{refl}_A[\sigma] = \mathsf{refl}_{A[\sigma]},$$
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We can turn a comprehension category into one that satisfies this:

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Path Categories

A path category is a category $\mathcal{C}$ with two classes of maps:

- fibrations: closed under pullbacks and compositions,
- (weak) equivalences: satisfying 2-out-of-6, so, if we have

$$A \xrightarrow{f} B \xrightarrow{g} C \xrightarrow{h} D$$

where $g \circ f$ and $h \circ g$ are equivalences,
then f, g, h, and $h \circ g \circ h$ are equivalences.

If a map is both then we call it a trivial fibration. We require that:

- isomorphisms are trivial fibration,
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$\mathcal{C}$ has a terminal object 1 and every map $A \to 1$ is a fibration.

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$\mathcal{C}$ has a terminal object 1 and every map $A \to 1$ is a fibration.

Path Objects

Lastly, a path category has a path object for every object A:

- a factorisation of the diagonal $\delta_A = (\mathrm{id}_A, \mathrm{id}_A)$:

$$\begin{tikzcd} A \arrow[rr, "\delta_A"] \arrow[dr, "r_A"', "\sim"] & & A \times A \\ & PA \arrow[ur, two heads, "(s_A, t_A)"'] & \end{tikzcd}$$

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Homotopy Theory

We call two maps $f, g : A \to B$ homotopic, written $f \simeq g$, if there exists a map $h : A \to PB$ such that $s_B \circ h = f$ and $t_B \circ h = g$.

We call $f : A \to B$ an homotopy equivalence, if there exists a map $g : B \to A$ such that $g \circ f \simeq \mathrm{id}_A$ and $f \circ g \simeq \mathrm{id}_B$.

The homotopy equivalences are precisely the weak equivalences.

In addition, we have a lifting theorem: for a commutative square

$$\begin{tikzcd} A \arrow[r] \arrow[d, "w"', "\wr"] & C \arrow[d, two heads, "p"] \\ B \arrow[r] \arrow[ur, dashed] & D \end{tikzcd}$$

where w is an equivalence and p is a fibration, there is a map $d : B \to C$ unique up to homotopy such that the lower triangle commutes and the upper triangle commutes up to homotopy.

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Path Category $\rightsquigarrow$ Comprehension Category

We can view a path category $\mathcal{C}$ as a comprehension category:

- the contexts are given by $\mathcal{C}$,
- the types are given by the full subcategory $\mathcal{C}^{\text{fib}} \subseteq \mathcal{C}^{\rightarrow}$,
- the display map for $p \in \mathcal{C}^{\text{fib}}$ is p itself,
- the substitution $p[\sigma]$ is the pullback $\sigma^* p$.

We will show that it has additional structure:

- weakly stable $=$-types,
- weakly stable Σ-types with β and η reductions,
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Weakly Stable =-Types

For a type A we define:

$$=_A := (s_A, t_A) : P_A \twoheadrightarrow A \times A, \qquad \text{(formation)}$$
$$\mathrm{refl}_A := r_A : A \xrightarrow{\sim} PA. \qquad \text{(introduction)}$$

The elimination and β-axiom follow from our lifting theorem and the fact that r_A is an equivalence.

We get weak stability because we can show that path objects are preserved by taking pullbacks.

This uses ideas of (Van den Berg 2018).

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Weakly Stable Σ-Types with β and η

We obtain Σ-types because path categories do not distinguish between a single extension $\Gamma.A$ and $\Gamma.A_0.\ldots.A_{n-1}$.

The requirements on a comprehension category can be simplified:

for $\Gamma.A.B$ we have a type $\Sigma_A B$ and an iso $\Gamma.A.B \xrightarrow{\cong} \Gamma.\Sigma_A B$ making the square commute:

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Holds in path categories: fibrations are closed under composition.

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A comprehension category is contextual if for every Γ we have:

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Comprehension Category $\rightsquigarrow$ Path Category

We can turn a comprehension category $\mathcal{C}$ with weakly stable $=$, $\Sigma_{\beta,\eta}$, and contextuality into a path category by taking:

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Display Path Categories

In a display path category we distinguish $\Gamma.A$ and $\Gamma.A_0.\ldots.A_{n-1}$.

Instead of fibrations we use display maps as a primitive notion.

Fibrations are compositions of display maps and isomorphisms.

In addition, we replace path objects for objects Γ with a seemingly weaker notion: path objects for display maps $A \to \Gamma$.

This is sufficient: we can use a lifting theorem and transport to inductively construct path objects for objects.

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Equivalence

We obtain the following diagram of 2-categories:

$$\begin{array}{ccc}
\mathrm{PathCat} & \xrightarrow{\sim} & \mathrm{ComprehensionCat}_{\mathrm{Contextual},=,\Sigma_{\beta\eta}} \\
U\big\uparrow \dashv \big\downarrow C & & F\big\uparrow \dashv \big\downarrow U \\
\mathrm{DisplayPathCat} & \xrightarrow[\sim]{} & \mathrm{ComprehensionCat}_{\mathrm{Contextual},=}
\end{array}$$

Here the U's are forgetful, F is a free, and C is a cofree.

We end this talk with some open questions:

- Can we simplify other type formers as we did with $=$-types?
- In particular, are propositional Σ-types and Π-types homotopical left and right adjoints of pullback.
- Connect with (Maietti 2005) and (Clairembault, Dybjer 2013).

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$$\begin{tikzcd} \mathrm{PathCat} \arrow[r, "\sim"] \arrow[d, shift left, "C"] & \mathrm{ComprehensionCat}_{\mathrm{Contextual},=,\Sigma_{\beta\eta}} \arrow[d, shift left, "U"] \\ \mathrm{DisplayPathCat} \arrow[r, "\sim"'] \arrow[u, shift left, "U"] \arrow[u, phantom, "\dashv"] & \mathrm{ComprehensionCat}_{\mathrm{Contextual},=} \arrow[u, shift left, "F"] \arrow[u, phantom, "\dashv"] \end{tikzcd}$$

Here the U's are forgetful, F is a free, and C is a cofree.

We end this talk with some open questions:

- Can we simplify other type formers as we did with $=$-types?
- In particular, are propositional Σ-types and Π-types homotopical left and right adjoints of pullback.
- Connect with (Maietti 2005) and (Clairembault, Dybjer 2013).

Equivalence

We obtain the following diagram of 2-categories:

$$\begin{tikzcd} & \mathrm{PathCat} \arrow[r, "\sim"] \arrow[d, shift left=2, "C"] \arrow[d, phantom, "\dashv"] & \mathrm{ComprehensionCat}_{\mathrm{Contextual},=,\Sigma_{\beta\eta}} \arrow[d, shift left=2, "U"] \arrow[d, phantom, "\dashv"] \\ & \mathrm{DisplayPathCat} \arrow[r, "\sim"'] \arrow[u, shift left=2, "U"] & \mathrm{ComprehensionCat}_{\mathrm{Contextual},=} \arrow[u, shift left=2, "F"] \end{tikzcd}$$

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