Emily Riehl

Johns Hopkins University

Formalizing ∞-category theory in the Rzk proof assistant

joint with Nikolai Kudasov and Jonathan Weinberger

Interactions of Proof Assistants and Mathematics

Plan

1. Computer formalization of mathematics
2. In search of foundations for higher structures
3. Simplicial type theory and the Rzk proof assistant
4. Synthetic ∞-category theory
5. A formalized proof of the ∞-categorical Yoneda lemma

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Computer formalization of mathematics

Motivation

CAHIERS DE TOPOLOGIE
ET GÉOMÉTRIE DIFFÉRENTIELLE
CATÉGORIQUES

VOL. XXXII-1 (1991)

∞-GROUPOIDS AND HOMOTOPY TYPES

by M.M. KAPRANOV and V.A. VOEVODSKY

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It is well-known [GZ] that CW-complexes X such that $\pi_i(X,x) = 0$ for all $i \geq 2$, $x \in X$, are described, at the homotopy level, by groupoids. A. Grothendieck suggested, in his unpublished memoir [Gr], that this connection should have a higher-dimensional generalisation involving polycategories. viz. polycategorical analogues of groupoids. It is the purpose of this paper to establish such a generalisation.

- 15 statements =
  4 theorems
  + 9 propositions
  + 1 lemma
  + 1 corollary
- 5 short "obvious" proofs + 3 proofs

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- But no explicit mistake was found. Voevodsky: "I was sure that we were right until the fall of 2013 (!!)"

A sociological problem

MATHEMATICS

The Origins and Motivations of Univalent Foundations

A Personal Mission to Develop Computer Proof Verification to Avoid Mathematical Mistakes

By Vladimir Voevodsky • Published 2014

“A technical argument by a trusted author, which is hard to check and looks similar to arguments known to be correct, is hardly ever checked in detail.”

Computer formalized mathematics

> *Formalized mathematics, in tandem with other forms of computerized mathematics[1], provides better management of mathematical knowledge, an opportunity to carry out ever more complex and larger projects, and hitherto unseen levels of precision.*
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Recent successes include:

- the Kepler conjecture, resolving a 1611 conjecture, 2003–2014, HOL Light
- the Feit-Thompson Odd Order Theorem, a foundational result in the classification of finite simple groups, 2006–2012, Coq
- the liquid tensor experiment, formalizing condensed mathematics, 2020–2022, Lean
- the Brunerie number, computing $\pi_4 S^3 \cong \mathbb{Z}/2\mathbb{Z}$, 2015–2022, Cubical agda

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2

In search of foundations for higher structures

Rebuilding the pragmatic foundations for higher structures

I am pretty strongly convinced that there is an ongoing reversal in the collective consciousness of mathematicians: the homotopical picture of the world becomes the basic intuition, and if you want to get a discrete set, then you pass to the set of connected components of a space defined only up to homotopy … Cantor's problems of the infinite recede to the background: from the very start, our images are so infinite that if you want to make something finite out of them, you must divide them by another infinity.

— *Yuri Manin "We do not choose mathematics as our profession, it chooses us: Interview with Yuri Manin" by Mikhail Gelfand*

∞-categories in set theory

Essentially, ∞-categories are 1-categories in which all the sets have been replaced by ∞-groupoids aka homotopy types:

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- categories have sets of objects, ∞-categories have ∞-groupoids of objects, and
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This is why ∞-categories are so difficult to model within set theory.

Composing paths

In the total singular complex aka the fundamental ∞-groupoid aka the anima or "soul" of a space X, composites of paths are witnessed by higher paths:

$$\begin{tikzcd} & y \arrow[dr, squiggly, "g"] & \\ x \arrow[ur, squiggly, "f"] & & z \end{tikzcd}$$

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$$\begin{tikzcd} \mathrm{Comp}(f,g) \arrow[r, hook] \arrow[d] \arrow[dr, phantom, "\lrcorner", very near start] & \mathrm{Map}(\Delta, X) \arrow[d, two heads, "\text{restrict}"] \\ * \arrow[r, "f \wedge g"'] & \mathrm{Map}(\Lambda, X) \end{tikzcd}$$

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D^n \arrow[r] \arrow[ur, dashed] \arrow[urr, dashed, bend left] & * \arrow[r, "f \wedge g"'] & \mathrm{Map}(\Lambda, X)
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\quad \leftrightsquigarrow \quad
\begin{tikzcd}
S^{n-1} \times \Delta \cup_{S^{n-1} \times \Lambda} D^n \times \Lambda \arrow[r] \arrow[d, hook] & X \\
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A space is contractible just when any sphere S^{n-1} can be filled to a disk D^n for $n \geq 0$. The extension exists since the inclusion admits a continuous deformation retract. $\square$

Could ∞-category theory be taught to undergraduates?

As far as we know, there are no existing formalizations of ∞-category theory in any proof assistant library such as Lean-mathlib, Agda-UniMath, Coq-HoTT,...

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Could ∞-Category Theory Be Taught to Undergraduates?

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1. The Algebra of Paths

It is natural to probe a suitably nice topological space X by means of its *paths*, the continuous functions from the standard unit interval $I \coloneqq [0,1] \subset \mathbb{R}$ to X. But what structure do the paths in X form?

To start, the paths form the edges of a directed graph whose vertices are the points of X: a path $p : I \to X$ defines an arrow from the point $p(0)$ to the point $p(1)$. Moreover, this graph is *reflexive*, with the constant path refl_x at each point $x \in X$ defining a distinguished endoarrow.

Can this reflexive directed graph be given the structure of a category? To do so, it is natural to define the composite of a path p from x to y and a path q from y to z by gluing together these continuous maps—i.e., by concatenating the paths—and then by reparametrizing via the homeomorphism $I \cong I \cup_{1=0} I$ that traverses each path at double speed:

$$\begin{tikzcd} I \arrow[r, "\cong"] \arrow[rr, bend right, "p*q"'] & I \cup_{1=0} I \arrow[r, "p \cup q"] & X \end{tikzcd} \tag{1.1}$$

But the composition operation $*$ fails to be associative or unital. In general, given a path r from z to w, the

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Communicated by Notices *Associate Editor Steven Sam.*

DOI: https://doi.org/10.1090/noti2692

The traditional foundations of mathematics are not really suitable for "higher mathematics" such as ∞-category theory, where the basic objects are built out of higher-dimensional types instead of mere sets. However, there are proposals for new foundations for mathematics that are closer to mathematician's core intuitions, based on Martin-Löf's dependent type theory such as

- homotopy type theory,
- higher observational type theory, and the
- simplicial type theory, that we use here.

∞-categories in homotopy type theory

The identity type family gives each type the structure of an ∞-groupoid: each type A has a family of identity types over $x, y : A$ whose terms $p : x =_A y$ are called paths.

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Emily Riehl and Michael Shulman, A type theory for synthetic ∞-categories, Higher Structures 1(1):116–193, 2017

each type A also has a family of hom types $\mathrm{Hom}_A(x, y)$ over $x, y : A$ whose terms $f : \mathrm{Hom}_A(x, y)$ are called arrows.

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With more of the work being done by the foundation system, perhaps someday ∞-category theory will be easy enough to teach to undergraduates?

3

Simplicial type theory and the RZK proof assistant

Shapes in the theory of the directed interval

Our types may depend on other types and also on shapes $\Phi \subset 2^n$, which are polytopes embedded in a directed cube defined in a language

$$\top, \bot, \wedge, \vee, \equiv \qquad \text{and} \qquad 0, 1, \leq$$

satisfying intuitionistic logic and strict interval axioms.

$$\text{e.g.,} \qquad \Delta^n := \{(t_1, \ldots, t_n) : 2^n \mid t_n \leq \cdots \leq t_1\}$$

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$$\Delta^1 := \mathbb{2}$$

$$\Delta^2 := \{(t_1, t_2) : \mathbb{2}^2 \mid t_2 \leq t_1\} := \left\{ \begin{tikzcd} & (1,1) \\ (0,0) \arrow[ur, dash, "(t,t)"] \arrow[r, dash, "(t,0)"'] & (1,0) \arrow[u, dash, "(1,t)"'] \end{tikzcd} \right.$$

$$\partial\Delta^2 := \{(t_1, t_2) : \mathbb{2}^2 \mid (t_2 \leq t_1) \wedge ((0 = t_2) \vee (t_2 = t_1) \vee (t_1 = 1))\}$$
$$\Lambda^2_1 := \{(t_1, t_2) : \mathbb{2}^2 \mid (t_2 \leq t_1) \wedge ((0 = t_2) \vee (t_1 = 1))\}$$

Because $\phi \wedge \psi$ implies ϕ, there are shape inclusions such as $\Lambda^2_1 \subset \partial\Delta^2 \subset \Delta^2$.

Extension types

Formation rule for extension types

$$\dfrac{\Phi \subset \Psi \text{ shape} \qquad A \text{ type} \qquad a : \Phi \to A}{\left\langle \begin{array}{ccc} \Phi & \xrightarrow{a} & A \\ \downarrow & \nearrow & \\ \Psi & & \end{array} \right\rangle \text{ type}}$$

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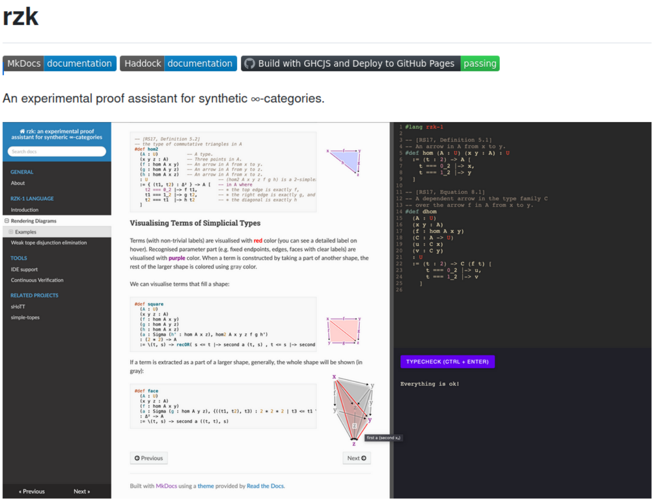
The simplicial type theory allows us to *prove* equivalences between extension types along composites or products of shape inclusions.

An experimental proof assistant Rzk for ∞-category theory



The proof assistant Rzk was written by Nikolai Kudasov:

About this project

This project has started with the idea of bringing Riehl and Shulman's 2017 paper [1] to "life" by implementing a proof assistant based on their type theory with shapes. Currently an early prototype with an online playground is available. The current implementation is capable of checking various formalisations. Perhaps, the largest formalisations are available in two related projects: https://github.com/fizruk/sHoTT and https://github.com/emilyriehl/yoneda. `sHoTT` project (originally a fork of the yoneda project) aims to cover more formalisations in simplicial HoTT and ∞-categories, while `yoneda` project aims to compare different formalisations of the Yoneda lemma.

Internally, `rzk` uses a version of second-order abstract syntax allowing relatively straightforward handling of binders (such as lambda abstraction). In the future, `rzk` aims to support dependent type inference relying on E-unification for second-order abstract syntax [2]. Using such representation is motivated by automatic handling of binders and easily automated boilerplate code. The idea is that this should keep the implementation of `rzk` relatively small and less error-prone than some of the existing approaches to implementation of dependent type checkers.

An important part of `rzk` is a tope layer solver, which is essentially a theorem prover for a part of the type theory. A related project, dedicated just to that part is available at https://github.com/fizruk/simple-topes. `simple-topes` supports used-defined cubes, topes, and tope layer axioms. Once stable, `simple-topes` will be merged into `rzk`, expanding the proof assistant to the type theory with shapes, allowing formalisations for (variants of) cubical, globular, and other geometric versions of HoTT.

rzk-lang.github.io/rzk

A formalized proof of the ∞-categorical Yoneda lemma

Our initial aim was to write a formalized proof of the ∞-categorical Yoneda lemma.

github.com/emilyriehl/yoneda or emilyriehl.github.io/yoneda/

- proof from Emily Riehl & Mike Shulman, A type theory for synthetic ∞-categories, Higher Structures 2017.
- formalizations written by Nikolai Kudasov, Emily Riehl, Jonathan Weinberger.
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Our ultimate aim is to compare ∞-category theory in simplicial type theory with ordinary category theory in traditional foundations. Thus,

- We've included a formalization of the 1-categorical Yoneda lemma in `Lean` by Sina Hazratpour as part of an Introduction to Proofs course at Johns Hopkins.
- We wrote a first version of `yoneda-lemma-precategories.lagda.md`.

More recently, we've professionalized our library, implementing a style guide suggested by Fredrik Bakke, who also contributed some formalizations.

Future work: formalize synthetic ∞-category theory

Help us formalize other results from synthetic ∞-category in Rzk!

We have suggested some formalization goals at

github.com/rzk-lang/sHoTT or rzk-lang.github.io/sHoTT

that should be achievable if you have prior familiarity with homotopy type theory.

It is also possible to formalize standard (book) homotopy type theory in Rzk, and these background results are used as prerequisites for our main project.

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Synthetic ∞-category theory

Hom types

In the simplicial type theory, any type A has a family of hom types depending on two terms in $x, y : A$:

$$\mathrm{Hom}_A(x,y) := \left\langle \begin{tikzcd} \partial\Delta^1 \arrow[r, "{[x,y]}"] \arrow[d, hook] & A \\ \Delta^1 \arrow[ur, dashed] & \end{tikzcd} \right\rangle \text{ type}$$

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A type A also has a family of identity types or path spaces $x = y$ depending on two terms in $x, y : A$, which we will connect to the hom-types momentarily.

Pre-∞-categories

defn (Riehl–Shulman after Joyal). A type A is a pre-∞-category if every pair of arrows $f : \mathrm{Hom}_A(x, y)$ and $g : \mathrm{Hom}_A(y, z)$ has a unique composite, i.e.,

$$\left\langle \begin{tikzcd} \Lambda^2_1 \arrow[r, "{[f,g]}"] \arrow[d, tail] & A \\ \Delta^2 \arrow[ur, dashed] & \end{tikzcd} \right\rangle \quad \text{is contractible.}^a$$

[a] A type C is contractible just when $\sum_{c:C} \prod_{x:C} c = x$.

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By contractibility, $\left\langle \begin{tikzcd} \Lambda^2_1 \arrow[r, "{[f,g]}"] \arrow[d, tail] & A \\ \Delta^2 \arrow[ur, dashed] & \end{tikzcd} \right\rangle$ has a unique inhabitant $\mathrm{comp}_{f,g} : \Delta^2 \to A$.

Write $g \circ f : \mathrm{Hom}_A(x,z)$ for its inner face, *the* composite of f and g.

Identity arrows

For any $x : A$, the constant function defines a term

$$\mathsf{id}_x := \lambda t.x : \mathsf{Hom}_A(x,x) := \left\langle \begin{tikzcd} \partial\Delta^1 \arrow[r, "{[x,x]}"] \arrow[d, hook] & A \\ \Delta^1 \arrow[ur, dashed] & \end{tikzcd} \right\rangle,$$

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which we denote by id_x and call the identity arrow.

For any $f : \mathrm{Hom}_A(x,y)$ in a pre-∞-category A, the term in the contractible type

$$\lambda(s,t).f(t) : \left\langle \begin{tikzcd} \Lambda^2_1 \arrow[r, "{[\mathrm{id}_x, f]}"] \arrow[d, hook] & A \\ \Delta^2 \arrow[ur, dashed] & \end{tikzcd} \right\rangle$$

witnesses the unit axiom $f = f \circ \mathrm{id}_x$.

Associativity of composition

Prop. In a pre-∞-category A, composition is associative: for any arrows $f : \mathrm{Hom}_A(x,y)$, $g : \mathrm{Hom}_A(y,z)$, and $h : \mathrm{Hom}_A(z,w)$, we have $h \circ (g \circ f) = (h \circ g) \circ f$.

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Proof: Consider the composable arrows in the pre-∞-category $\Delta^1 \to A$:

$$\begin{tikzcd}
 & y \arrow[dr, "g"] \arrow[dd, "g"'] \arrow[dddr, "h\circ g"] & \\
x \arrow[ur, "f"] \arrow[dr, "g\circ f"] \arrow[dd, "f"'] & & z \arrow[dd, "h"] \\
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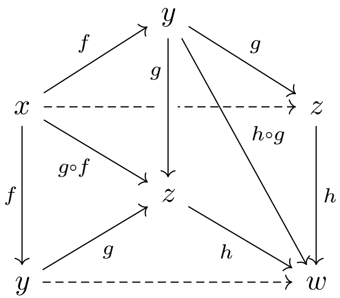

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x \arrow[ur, "f"] \arrow[rr, dashed] \arrow[dr, "g\circ f"'] \arrow[ddrr, dashed, bend left=15, "\ell"] \arrow[dd, "f"'] & & z \arrow[dd, "h"] \\
 & z \arrow[dr, "h"] & \\
y \arrow[ur, "g"] \arrow[rr, dashed] & & w
\end{tikzcd}$$

Composing defines a term in the type $\Delta^2 \to (\Delta^1 \to A)$ which defines an arrow $\ell : \mathrm{Hom}_A(x, w)$ so that $\ell = h \circ (g \circ f)$ and $\ell = (h \circ g) \circ f$.

Isomorphisms

An arrow $f \colon \mathrm{Hom}_A(x, y)$ in a pre-∞-category is an isomorphism if it has a two-sided inverse $g \colon \mathrm{Hom}_A(y, x)$. However, the type

$$\sum_{g \colon \mathrm{Hom}_A(y,x)} (g \circ f = \mathrm{id}_x) \times (f \circ g = \mathrm{id}_y)$$

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$$\mathsf{is\text{-}iso}(f) := \left(\sum_{g\colon \mathsf{Hom}_A(y,x)} g \circ f = \mathsf{id}_x \right) \times \left(\sum_{h\colon \mathsf{Hom}_A(y,x)} f \circ h = \mathsf{id}_y \right).$$

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For $x, y : A$, the type of isomorphisms from x to y is:

$$x \cong_A y :\equiv \sum_{f:\mathsf{Hom}_A(x,y)} \text{is-iso}(f).$$

∞-categories

By path induction, to define a map

$$\mathsf{iso\text{-}eq} \colon (x =_A y) \to (x \cong_A y)$$

for all $x, y : A$ it suffices to define

$$\mathsf{iso\text{-}eq}(\mathsf{refl}_x) := \mathsf{id}_x.$$

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$$\text{iso-eq} \colon \prod_{x,y:A} (x =_A y) \to (x \cong_A y)$$

is an equivalence.

∞-groupoids

Similarly by path induction define

$$\mathsf{arr\text{-}eq} : (x =_A y) \to \mathsf{Hom}_A(x, y)$$

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A type A is an ∞-groupoid iff every arrow is an identity, i.e., iff arr-eq is an equivalence.

Prop. A type is an ∞-groupoid if and only if it is an ∞-category and all of its arrows are isomorphisms.

Proof:

$$\begin{tikzcd} x =_A y \arrow[rr, "\text{arr-eq}"] \arrow[dr, "\text{iso-eq}"'] & & \text{Hom}_A(x, y) \\ & x \cong_A y \arrow[ur, hook] & \end{tikzcd}$$

defn. An ∞-groupoid is a type in which arrows are equivalent to identities:

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- and in which isomorphisms are equivalent to identities:

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5

A formalized proof of the ∞-categorical Yoneda lemma

Covariant type families

defn (Riehl–Shulman after Joyal). A type family $B(x)$ over $x : A$ is covariant if for every $f : \mathrm{Hom}_A(x, y)$ and $u : B(x)$ there is a unique lift of f with domain u.

The codomain of the unique lift defines a term $f_* u : B(y)$.

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Prop. Fix $a : A$. The type family $\mathrm{Hom}_A(a, x)$ over $x : A$ is covariant if and only if A is a pre-∞-category.

Covariant type families

defn (Riehl–Shulman after Joyal). A type family $B(x)$ over $x : A$ is *covariant* if for every $f : \mathrm{Hom}_A(x, y)$ and $u : B(x)$ there is a unique lift of f with domain u

The codomain of the unique lift defines a term $f_* u : B(y)$.

Prop. Fix $a : A$. The type family $\mathrm{Hom}_A(a, x)$ over $x : A$ is covariant if and only if A is a pre-∞-category.

Prop. When A is a pre-∞-category, for any $u : B(x)$, $f : \mathrm{Hom}_A(x, y)$, and $g : \mathrm{Hom}_A(y, z)$, then $g_*(f_* u) = (g \circ f)_* u$ and $(\mathrm{id}_x)_* u = u$.

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Prop. For any covariant families $B(x)$ and $C(x)$ over $x : A$, a pre-∞-category, any family of maps $\phi : \prod_{x:A} B(x) \to C(x)$ is natural.

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Prop. For any covariant families $B(x)$ and $C(x)$ over $x : A$, a pre-∞-category, any family of maps $\phi : \prod_{x:A} B(x) \to C(x)$ is natural.

Prop. If $B(x)$ is covariant over $x : A$, a pre-∞-category, then each fiber $B(x)$ is an ∞-groupoid.

The Yoneda lemma

Let $B(x)$ be a covariant family over $x : A$, a pre-∞-category, and fix $a : A$.

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Yoneda lemma. The maps

$$\mathsf{evid} := \lambda\phi.\phi(a, \mathsf{id}_a) : \left(\prod_{x:A} \mathsf{Hom}_A(a,x) \to B(x)\right) \to B(a) \quad \text{and}$$

$$\mathsf{yon} := \lambda u.\lambda x.\lambda f.f_* u : B(a) \to \left(\prod_{x:A} \mathsf{Hom}_A(a,x) \to B(x)\right)$$

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Proof: By definition, $\mathsf{evid} \circ \mathsf{yon}(u) := (\mathsf{id}_a)_* u$. By functoriality $(\mathsf{id}_a)_* u = u$, so yon is a section of evid.

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Proof: By definition, $\mathsf{evid} \circ \mathsf{yon}(u) :\equiv (\mathrm{id}_a)_* u$. By functoriality $(\mathrm{id}_a)_* u = u$, so yon is a section of evid. To see that yon is a retraction of evid, start from the definition $\mathsf{yon} \circ \mathsf{evid}(\phi)(x, f) :\equiv f_*\phi(a, \mathrm{id}_a)$. By naturality of ϕ and the identity law for pre-∞-categories $f_*\phi(a, \mathrm{id}_a) = \phi(x, f \circ \mathrm{id}_a) = \phi(x, f)$. $\square$

Conclusions and future work

Observations:

- ∞-category theory is significantly easier to formalize in a foundation system based on homotopy type theory.
- By moving much of the complexity of "higher structures" into the background foundation system, the gap between ∞-category theory and 1-category narrows substantially.
- A computer proof assistant is a fantastic tool for learning to write proofs in new foundations — indeed, through formalization in Rzk we caught an error of circular reasoning in the Riehl–Shulman paper!

Future work:

- We would love help formalizing more results from ∞-category theory in Rzk.
- But the initial version of the simplicial type theory is not sufficiently powerful to prove all results about ∞-categories, so further extensions of this synthetic framework are needed.

References

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Danke!