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Contractibility as Uniqueness

UCLA Distinguished Lecture Series

An analogy

contractibility :: uniqueness

1. Contractibility as Uniqueness

2. Categorifying Uniqueness

3. ∞-Categorifying Uniqueness

1

## Contractibility as Uniqueness

The algebra of paths

The standard technique used to distinguish your favorite space A from other spaces is to compute an algebraic invariant of the space.

The "algebra of paths" of a space is described in increasing precision by:

- the fundamental group $\pi_1(A, x)$ of loops in A based at x up to homotopy
- the fundamental groupoid $\pi_1 A$ of paths in A up to homotopy
- the fundamental ∞-groupoid $\pi_\infty A$ of paths in A
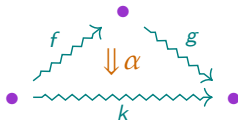
$\pi_\infty A$ has:

- points of A as objects
- paths of A as 1-arrows
- paths between paths in A as 2-arrows
- paths between paths between paths in A as 3-arrows, and so on ...

Witnesses to composition
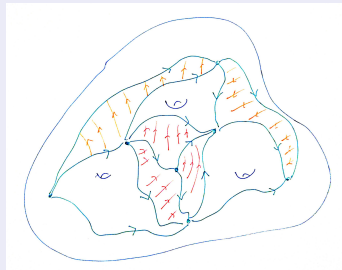
Q: How do we define the composite of two paths?   A: We don't!

Instead of a composition operation, composites of paths are witnessed by higher paths.

Q: How unique is path composition?   Partial A: Unique enough for associativity.

Given composable paths f, g, h and specified higher paths α, β, γ witnessing composition relations, these higher paths compose. More precisely, a 3-arrow expresses a coherence between compositions witnessed by 2-arrows.
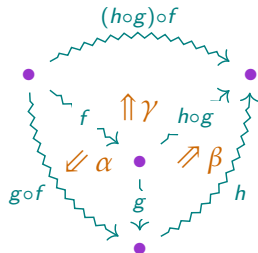
Theorem. The space of composites of two paths f and g in A is contractible.

Proof: The space of composites of paths f and g in A is defined by the pullback:

$$
\begin{array}{ccccc}
S^{n-1} & \longrightarrow & \mathrm{Comp}(f,g) & \hookrightarrow & A^{\Delta} \\
\downarrow & & \downarrow & \lrcorner & \downarrow {\scriptstyle \text{restrict}} \\
D^n & \longrightarrow & * & \xrightarrow{\ f \wedge g\ } & A^{\Lambda}
\end{array}
\qquad \leftrightsquigarrow \qquad
\begin{array}{ccc}
S^{n-1} \times \Delta \cup_{S^{n-1} \times \Lambda} D^n \times \Lambda & \longrightarrow & A \\
\downarrow & & \\
D^n \times \Delta & &
\end{array}
$$

A space is contractible just when any sphere S^{n-1} can be filled to a disk D^n for $n \geq 1$. This filling problem transposes to an extension problem, and the extension exists since the inclusion admits a continuous deformation retract. $\square$

Summary

- In a group(oid), composable arrows have a unique composite.
- In a ∞-group(oid), composable arrows have a contractible space of composites.

The analogy

| ordinary mathematics | :: | higher mathematics |
| uniqueness | :: | contractibility |

can be made even tighter.

Aim: Express the classical notion of uniqueness more categorically.

2

Categorifying Uniqueness

Uniqueness

To say C has a unique element means

$$\exists x \in C, \forall y \in C, x = y$$

Here "$x = y$" is a predicate — a mathematical statement that is either true or false, depending on two free variables $x, y : C$.

In proof-relevant mathematics, we interpret "$x = y$" as the set of all proofs that x equals y (which is empty if x and y are not equal).

Then we can form the set $\sum_{x \in C} \prod_{y \in C} x = y$

inspired by a notational analogy with the sentence $\exists x \in C, \forall y \in C, x = y$.

The set $\sum_{x \in C} \prod_{y \in C} x = y$ is also a set of proofs — but proofs of what?

Proofs of uniqueness

The set $\sum_{x \in C} \prod_{y \in C} x = y$ is also a set of proofs — but proofs of what?

An element of $\sum_{x \in C} \prod_{y \in C} x = y$ is
- the choice of some element $c \in C$
- together with a proof, for all $z \in C$, that c equals z.

Thus $\sum_{x \in C} \prod_{y \in C} x = y$ is the set of proofs of the sentence $\exists x \in C, \forall y \in C, x = y$
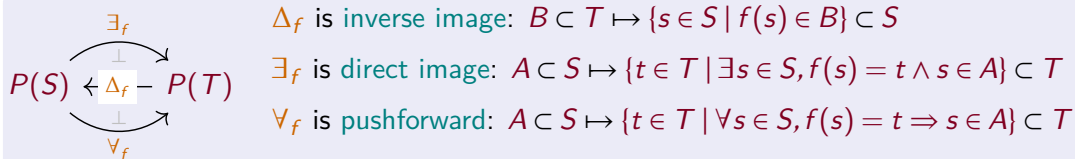
asserting that C has a unique element.

It remains to explain the analogy:

logic	$\exists$	$\forall$
sets	$\sum$	$\prod$

Digression: quantifiers as adjoints

A set function $f : S \to T$ induces order-preserving functions between their powersets:

$$P(S) \xleftarrow{\quad \Delta_f \quad} P(T)$$

with arrows $\exists_f$ (top, $\perp$) and $\forall_f$ (bottom, $\perp$)

Δ_f is inverse image: $B \subset T \mapsto \{s \in S \mid f(s) \in B\} \subset S$

$\exists_f$ is direct image: $A \subset S \mapsto \{t \in T \mid \exists s \in S, f(s) = t \wedge s \in A\} \subset T$

$\forall_f$ is pushforward: $A \subset S \mapsto \{t \in T \mid \forall s \in S, f(s) = t \Rightarrow s \in A\} \subset T$

For the unique function $! : S \to *$ these reduce to $\quad P(S) \xleftarrow{\quad \Delta \quad} P(*) = \{*, \emptyset\}$

with arrows $\exists$ (top, $\perp$) and $\forall$ (bottom, $\perp$)

The set $P(S) = \{A \subset S\}$ can be identified with the set of predicates $p(s)$ with one free variable $s \in S$ — the corresponding subset is $\{s \in S \mid p(s) \text{ is true}\}$. If we interpret the two elements of $P(*)$ by $* =:$ "true" and $\emptyset =:$ "false" then

- $\exists$ is the function that sends the predicate $p(s)$ to the sentence $\exists s \in S, p(s)$
- $\forall$ is the function that sends the predicate $p(s)$ to the sentence $\forall s \in S, p(s)$

Digression: locally cartesian closed categories
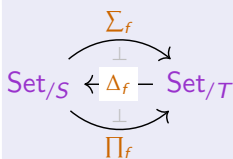
For any function $f: S \to T$ there are functors:

$$P(S) \xleftarrow[\forall_f]{\exists_f} P(T)$$
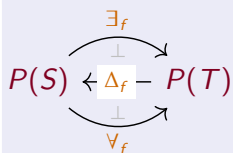
Δ_f is inverse image: $B \subset T \mapsto \{s \in S \mid f(s) \in B\} \subset S$

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In proof-relevant mathematics, it is natural to replace the poset $P(S)$ by the category $\mathsf{Set}_{/S}$ of S-indexed sets. An object $\{P(s)\}_{s \in S}$ is a family of sets where $P(s)$ can be thought of as the set of proofs of some predicate $p(s)$ on $s \in S$.

$$\mathsf{Set}_{/S} \xleftarrow[\prod_f]{\sum_f} \mathsf{Set}_{/T}$$

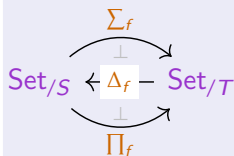Δ_f is substitution: $\{Q(t)\}_{t \in T} \mapsto \{Q(f(s))\}_{s \in S}$

$\sum_f$ is sum: $\{P(s)\}_{s \in S} \mapsto \{\sum_{s \in f^{-1}(t)} P(s)\}_{t \in T}$

$\prod_f$ is product: $\{P(s)\}_{s \in S} \mapsto \{\prod_{s \in f^{-1}(t)} P(s)\}_{t \in T}$

Summary

The triple of adjoint functors

$$
\begin{array}{c}
\Sigma_f \\
\mathsf{Set}_{/S} \xleftarrow{\ \bot\ } \Delta_f \longrightarrow \mathsf{Set}_{/T} \\
\bot \\
\Pi_f
\end{array}
$$

Δ_f is substitution: $\{Q(t)\}_{t \in T} \mapsto \{Q(f(s))\}_{s \in S}$

Σ_f is sum: $\{P(s)\}_{s \in S} \mapsto \{\sum_{s \in f^{-1}(t)} P(s)\}_{t \in T}$

Π_f is product: $\{P(s)\}_{s \in S} \mapsto \{\prod_{s \in f^{-1}(t)} P(s)\}_{t \in T}$

gives a more formal way to understand the set

$$
\sum_{x \in C} \prod_{y \in C} x = y
$$

⤳ The set of proofs "$x = y$" defines an indexed set $\{x = y\}_{x,y \in C} \in \mathsf{Set}_{/C \times C}$

⤳ Product along the projection $\pi_1 : C \times C \to C$ gives $\{\prod_{y \in C} x = y\}_{x \in C} \in \mathsf{Set}_{/C}$

⤳ Sum along $! : C \to *$ gives the set $\sum_{x \in C} \prod_{y \in C} x = y \in \mathsf{Set}_{/*} = \mathsf{Set}$
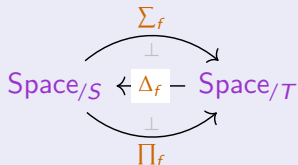
3

∞-Categorifying Uniqueness

A convenient category of spaces

Now replace Set by a convenient category Space of spaces and continuous maps.

A family of spaces $\{E_b\}_{b \in B} \in \text{Space}_{/B}$ is a continuous map $\pi \colon E \to B$, where the space E_b is the fiber over a point $b \in B$ in the base space while the total space $E \simeq \sum_{b \in B} E_b$.

Any continuous $f \colon S \to T$ gives rise to an adjoint triple:

$$\text{Space}_{/S} \xleftarrow[\substack{\Sigma_f \\ \bot \\ \Delta_f \\ \bot \\ \Pi_f}]{} \text{Space}_{/T}$$

Δ_f is pullback

$\sum_f$ is composition

$\prod_f$ is pushforward

Q: For a space C, how to interpret the family of spaces $\{x = y\}_{x,y \in C} \in \mathsf{Space}_{/C \times C}$?

First guess: $\begin{matrix} C \\ \Delta \downarrow \\ C \times C \end{matrix} \in \mathsf{Space}_{/C \times C}$ — but a better choice is the path space $\begin{matrix} C^I \\ \downarrow \\ C \times C \end{matrix} \in \mathsf{Space}_{/C \times C}$.

New idea:

A point $p \in x = y$ is a path from x to y in C, providing a proof that x equals y.

A space of proofs

What is a point in the space $\sum_{x \in C} \prod_{y \in C} x = y$?

The functor $\sum_B : \mathsf{Space}_{/B} \to \mathsf{Space}$ takes $\{E_b\}_{b \in B}$ to the total space $\sum_{b \in B} E_b$.

⤳ a point in $\sum_{b \in B} E_b$ is a pair (a, e_a) of a point $a \in B$ and a point $e_a \in E_a$

The functor $\prod_B : \mathsf{Space}_{/B} \to \mathsf{Space}$ takes $\{E_b\}_{b \in B}$ to the space of sections $\prod_{b \in B} E_b$.

⤳ a point in $\prod_{b \in B} E_b$ is section $s : B \to \sum_{b \in B} E_b$ of the projection to B

- So a point in $\sum_{x \in C} \prod_{y \in C} x = y$ is a pair (c, h) where $c \in C$ and $h \in \prod_{y \in C} c = y$.
- The point $h \in \prod_{y \in C} c = y$ is a section $h : C \to \sum_{y \in C} c = y$ to the projection.

Together $(c, h) \in \sum_{x \in C} \prod_{y \in C} x = y$ defines:

- a center of contraction c and
- a contracting homotopy h,

proving that the space C is contractible!

Contractibility as uniqueness

In summary, a point in the set

$$\sum_{x \in C} \prod_{y \in C} x = y$$

is a proof that C is unique, while a point in the space

$$\sum_{x \in C} \prod_{y \in C} x = y$$

is a proof that C is contractible.

Next time: If identifications $p \in x = y$ are paths, which may carry data, what strategies exist to prove a theorem involving a hypothesis of the form $x = y$? We'll introduce one powerful proof technique: the principle of path induction in homotopy type theory.

Thank you!