



Emily Riehl

Johns Hopkins University

Path induction and the indiscernibility of identicals

Plan



1. Induction over the natural numbers
2. Dependent type theory
3. Identity types
4. Path induction
5. Epilogue: univalent foundations



1

Induction over the natural numbers

Peano's postulates



In Dedekind's 1888 book "Was sind und was sollen die Zahlen" and Peano's 1889 paper "Arithmetices principia, nova methodo exposita," the natural numbers \mathbb{N} are characterized by:

- There is a natural number $0 \in \mathbb{N}$.
- Every natural number $n \in \mathbb{N}$ has a successor $\text{succ } n \in \mathbb{N}$.
- 0 is not the successor of any natural number.
- No two natural numbers have the same successor.
- The principle of mathematical induction:

$$\forall P, P(0) \rightarrow (\forall k \in \mathbb{N}, P(k) \rightarrow P(\text{succ } k)) \rightarrow (\forall n \in \mathbb{N}, P(n))$$

By Dedekind's categoricity theorem, all triples given by a set \mathbb{N} , an element $0 \in \mathbb{N}$, and a function $\text{succ} : \mathbb{N} \rightarrow \mathbb{N}$ satisfying the Peano postulates are isomorphic.

Natural numbers induction



In the statement of the **principle of mathematical induction**:

$$\forall P, P(0) \rightarrow (\forall k \in \mathbb{N}, P(k) \rightarrow P(\text{suck})) \rightarrow (\forall n \in \mathbb{N}, P(n))$$

the variable P is a **predicate** over the natural numbers.

A **predicate** over the natural numbers is a function

$$P: \mathbb{N} \rightarrow \{\top, \perp\}$$

that associates a truth value \top or \perp to each $n \in \mathbb{N}$.

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Thus, to prove a sentence of the form $\forall n \in \mathbb{N}, P(n)$ it suffices to:

- prove the **base case**, showing that $P(0)$ is true, and
- prove the **inductive step**, showing for each $k \in \mathbb{N}$ that $P(k)$ implies $P(\text{suck})$.

A proof by induction



Theorem. For any $n \in \mathbb{N}$, $n^2 + n$ is even.

Proof: By induction on $n \in \mathbb{N}$:

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- For the inductive step, assume for $k \in \mathbb{N}$ that $k^2 + k = 2 \times m$ is even. Then

$$\begin{aligned}(k+1)^2 + (k+1) &= (k^2 + k) + ((2 \times k) + 2) \\ &= (2 \times m) + (2 \times (k+1)) \\ &= 2 \times (m + k + 1) \quad \text{is even.}\end{aligned}$$

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By the principle of mathematical induction

$$\forall P, P(0) \rightarrow (\forall k \in \mathbb{N}, P(k) \rightarrow P(k+1)) \rightarrow (\forall n \in \mathbb{N}, P(n))$$

this proves that $n^2 + n$ is even for all $n \in \mathbb{N}$.



A construction by induction



The induction proof not only demonstrates for all $n \in \mathbb{N}$ that $n^2 + n$ is even but also defines a function $m : \mathbb{N} \rightarrow \mathbb{N}$ so that $n^2 + n = 2 \times m(n)$.

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Construction: By induction on $n \in \mathbb{N}$:

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so we define $m(k+1) := m(k) + k + 1$.

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so we define $m(k+1) := m(k) + k + 1$.

By the **principle of mathematical recursion**, this defines a function $m : \mathbb{N} \rightarrow \mathbb{N}$ so that $n^2 + n = m(n)$ for all $n \in \mathbb{N}$.

Induction and recursion



Recursion can be thought of as the constructive form of induction

$$\forall P, P(0) \rightarrow (\forall k \in \mathbb{N}, P(k) \rightarrow P(\text{suck})) \rightarrow (\forall n \in \mathbb{N}, P(n))$$

in which the **predicate**

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is replaced by an arbitrary **family of sets**

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The output of a recursive construction is a **dependent function** $p \in \prod_{n \in \mathbb{N}} P(n)$ which specifies a value $p(n) \in P(n)$ for each $n \in \mathbb{N}$.

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The recursive function $p \in \prod_{n \in \mathbb{N}} P(n)$ satisfies **computation rules**:

$$p(0) := p_0 \quad p(\text{suc } n) := p_s(n, p(n)).$$

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- For any family of types $P : \mathbb{N} \rightarrow \text{Type}$ there is a term

$$\mathbb{N}\text{-ind} : (p_0 : P(0)) \rightarrow (p_s : \prod_{k \in \mathbb{N}} P(k) \rightarrow P(\text{succ } k)) \rightarrow (p : \prod_{n \in \mathbb{N}} P(n))$$

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Note the final two postulates — that 0 is not a successor and suc is injective — are missing because they are **provable**.



2

Dependent type theory

Types, terms, and contexts



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- type families, e.g., $\mathbb{R}^- : \mathbb{N} \rightarrow \text{Type}$, $\text{Mat}_{\times -} : \mathbb{N} \rightarrow \mathbb{N} \rightarrow \text{Type}$

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all of which can occur in an arbitrary context of variables from previously-defined types.

In a mathematical statement of the form “Let ...be ...then ...” The stuff following the “let” likely declares the names of the variables in the context described after the “be”, while the stuff after the “then” most likely describes a type or term in that context.

Type constructors



Type constructors build new types from given ones:

- given $A, B \rightsquigarrow$ products $A \times B$, coproducts $A + B$, function types $A \rightarrow B$,
- given $P : A \rightarrow \text{Type} \rightsquigarrow$ dependent pairs $\sum_{x:A} P(x)$, dependent functions $\prod_{x:A} P(x)$
- given $A \rightsquigarrow$ identity types $\bullet =_A - : A \rightarrow A \rightarrow \text{Type}$

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Each type constructor comes with rules:

- (i) **formation**: a way to construct new types
- (ii) **introduction**: ways to construct terms of these types
- (iii) **elimination**: ways to use them to construct other terms
- (iv) **computation**: the way (ii) and (iii) relate

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The rules suggest a logical naming for certain types:

$A \times B$	"A and B"	$\sum_{x:A} P(x)$	" $\exists x. P(x)$ "
$A + B$	"A or B"	$\prod_{x:A} P(x)$	" $\forall x. P(x)$ "
$A \rightarrow B$	"A implies B"	$x =_A y$	"x equals y"

Product types and function types



Product types are governed by the rules

- ×-form: given types A and B there is a type $A \times B$
- ×-intro: given terms $a : A$ and $b : B$ there is a term $(a, b) : A \times B$
- ×-elim: given $p : A \times B$ there are terms $\text{pr}_1 p : A$ and $\text{pr}_2 p : B$

plus computation rules that relate pairings and projections.

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→-form: given types A and B there is a type $A \rightarrow B$

→-intro: if in the context of a variable $x : A$ there is a term $b_x : B$

there is a term $\lambda x. b_x : A \rightarrow B$

→-elim: given terms $f : A \rightarrow B$ and $a : A$ there is a term $f(a) : B$

plus computation rules that relate λ -abstractions and evaluations.

Mathematics in dependent type theory



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\times -elim: $p : A \times B \rightsquigarrow \text{pr}_1 p : A, \text{pr}_2 p : B$

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Proposition. For any types A and B , $\text{modus-ponens} : (A \times (A \rightarrow B)) \rightarrow B$.

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$$\lambda p. \text{pr}_2 p(\text{pr}_1 p) : (A \times (A \rightarrow B)) \rightarrow B. \quad \square$$



3

Identity types

The traditional view of equality



In first order logic, the binary relation “=” is governed by the following rules:

- Reflexivity: $\forall x, x = x$.

- Indiscernibility of Identicals:

$\forall x, y, x = y$ implies that for all predicates P , $P(x) \leftrightarrow P(y)$

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Symmetry and transitivity of equality can be proven from these rules.

Identity types



The following rules for **identity types** were developed by Martin-Löf:

=-form: given a type A and terms $x, y : A$, there is a type $x =_A y$

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The elimination rule for the identity type defines an induction principle analogous to recursion over the natural numbers: it provides sufficient conditions for which to define a dependent function out of the identity type family.

=-elim: for any type family $P(x, y, p)$ over $x, y : A, p : x =_A y$, to prove $P(x, y, p)$ for all x, y, p it suffices to assume y is x and p is refl_x . That is

$$\text{=-ind} : \left(\prod_{x:A} P(x, x, \text{refl}_x) \right) \rightarrow \left(\prod_{x,y:A} \prod_{p:x=_A y} P(x, y, p) \right)$$

Identity types



The following rules for **identity types** were developed by Martin-Löf:

=-form: given a type A and terms $x, y : A$, there is a type $x =_A y$

=-intro: given a type A and term $x : A$ there is a term $\text{refl}_x : x =_A x$

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A computation rule establishes that the proof of $P(x, x, \text{refl}_x)$ is the given one.

The homotopical interpretation of dependent type theory



Note that identity types can be iterated:

given $x, y : A$ and $p, q : x =_A y$ there is a type $p =_{x=_A y} q$.

Does this type always have a term? In other words, are identity proofs unique?

The homotopical interpretation of dependent type theory



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No! From the existence of homotopical models of dependent type theory — in which **types** are interpreted as “**spaces**” and **terms** are interpreted as **points** — we know that iterated identity types can have interesting higher structure.

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The total space of the identity type family $\sum_{x,y:A} x =_A y$ is interpreted as the **path space** of A and a term $p : x =_A y$ may be thought of as a **path** from x to y in A .

$$\begin{array}{ccc} & \sum_{x,y:A} x =_A y & \\ \nearrow \lambda x. \text{refl}_x & & \downarrow \text{pr}_1 \\ A & \xrightarrow{\lambda x. (x,x)} & A \times A \end{array}$$



4

Path induction

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The homotopical interpretation of dependent type theory reflects the fundamental structure of Martin-Löf's identity types — even though it was discovered decades later!

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Now that terms $p : x =_A y$ are called **paths**, we re-brand **=-elim** as:

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Path induction: For any type family $P(x, y, p)$ over $x, y : A, p : x =_A y$, to prove $P(x, y, p)$ for all x, y, p it suffices to assume y is x and p is refl_x . That is

$$\text{path-ind} : \left(\prod_{x:A} P(x, x, \text{refl}_x) \right) \rightarrow \left(\prod_{x,y:A} \prod_{p:x=_A y} P(x, y, p) \right).$$

Reversal and concatenation of paths



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Proposition. Paths can be reversed: $(-)^{-1} : \prod_{x,y:A} x =_A y \rightarrow y =_A x$.

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Proposition. Paths can be concatenated: $*$: $\prod_{x,y,z:A} x =_A y \rightarrow (y =_A z \rightarrow x =_A z)$.

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The ∞ -groupoid of paths

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The ∞ -groupoid structure of A has

- terms $x : A$ as objects
- paths $p : x =_A y$ as 1-morphisms
- paths of paths $h : p =_{x=_A y} q$ as 2-morphisms, ...

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- **constant paths** (reflexivity) $\text{refl}_x : x = x$
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and furthermore concatenation is associative and unital, the associators are coherent ...

The higher coherences in path algebra



Path induction proves the (higher) coherences in the ∞ -groupoid of paths:

Proposition. For any type A and terms $w, x, y, z : A$

$$\text{assoc} : \prod_{p:w=Ax} \prod_{q:x=Ay} \prod_{r:y=Az} (p * q) * r =_{w=Az} p * (q * r).$$

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$$\prod_{q:w=Ay} \prod_{r:y=Az} q * r =_{w=Az} q * r,$$

for which we have the proof $\text{refl}_{q*r} : q * r =_{w=Az} q * r$.



Indiscernibility of Identicals as path lifting



Indiscernibility of Identicals: $x = y$ implies that for all predicates P , $P(x) \leftrightarrow P(y)$

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Indiscernibility of Identicals: $x = y$ implies that for all predicates P , $P(x) \leftrightarrow P(y)$

Let $P : A \rightarrow \text{Type}$ be any family of types over A .

Proposition. For any $x, y : A$ if $p : x =_A y$ then $\text{tr}_{P,p} : P(x) \rightarrow P(y)$.

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Corollary. For any $x, y : A$ if $p : x =_A y$ then $P(x) \simeq P(y)$.

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Corollary. For any $x, y : A$ if $p : x =_A y$ then $P(x) \simeq P(y)$.

Construction: By path induction, it suffices to assume y is x and p is refl_x , in which case we have the identity equivalence. □



5

Epilogue: univalent foundations

The homotopy type theoretic Rosetta stone



type theory	logic	set theory	homotopy theory
A	proposition	set	space
$x : A$	proof	element	point
$\emptyset, 1$	\perp, \top	$\emptyset, \{\emptyset\}$	$\emptyset, *$
$A \times B$	A and B	set of pairs	product space
$A + B$	A or B	disjoint union	coproduct
$A \rightarrow B$	A implies B	set of functions	function space
$P : A \rightarrow \mathbf{Type}$	predicate	family of sets	fibration
$f : \prod_{x:A} P(x)$	conditional proof	family of elements	section
$\prod_{x:A} P(x)$	$\forall x. P(x)$	product	space of sections
$\sum_{x:A} P(x)$	$\exists x. P(x)$	disjoint union	total space
$p : x =_A y$	proof of equality	$x = y$	path from x to y
$\sum_{x,y:A} x =_A y$	equality relation	diagonal	path space for A

Contractible types



The homotopical perspective on type theory suggests new definitions:

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A type A is **contractible** if it comes with a term of type

$$\text{is-contr}(A) := \sum_{a:A} \prod_{x:A} a =_A x$$

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The homotopical perspective on type theory suggests new definitions:

A type A is **contractible** if it comes with a term of type

$$\text{is-contr}(A) := \sum_{a:A} \prod_{x:A} a =_A x$$

By Σ -elim a proof of contractibility provides:

- a term $c : A$ called the **center of contraction** and
- a dependent function $h : \prod_{x:A} c =_A x$ called the **contracting homotopy**, which can be thought of as a continuous choice of paths $h(x) : c =_A x$ for each $x : A$.

The hierarchy of types



Contractible types, those types A for which the type

$$\text{is-contr}(A) := \sum_{a:A} \prod_{x:A} a =_A x$$

has a term, form the bottom level of Voevodsky's hierarchy of types.

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- a proposition if

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- a **set** or **0-type** if

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- a **succ(n)-type** for $n : \mathbb{N}$ if

$$\text{is-succ}(n)\text{-type}(A) := \prod_{x,y:A} \text{is-}n\text{-type}(x =_A y)$$

Equivalences



Similarly, homotopy theory suggests definitions of when two types A and B are **equivalent** or when a function $f : A \rightarrow B$ is an **equivalence**:

An **equivalence** between types A and B is a term of type:

$$A \simeq B := \sum_{f:A \rightarrow B} \left(\sum_{g:B \rightarrow A} \prod_{a:A} g(f(a)) =_A a \right) \times \left(\sum_{h:B \rightarrow A} \prod_{b:B} f(h(b)) =_B b \right)$$

A term of type $A \simeq B$ provides:

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The univalence axiom

Another notion of sameness between types is provided by the **universe** \mathcal{U} of types, which has (small) types A, B as its terms $\rightsquigarrow A, B : \mathcal{U}$.

Q: How do the types $A =_{\mathcal{U}} B$ and $A \simeq B$ compare?

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“Identity is equivalent to equivalence.”

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- The **structure-identity principle**, which specializes to the statement that for set-based structures (monoids, groups, rings) **isomorphic** structures are **identical**.
- **Function extensionality**: for any $f, g : A \rightarrow B$, the canonical function defines an equivalence between the identity type and the type of homotopies:

$$\text{id-to-htpy} : (f =_{A \rightarrow B} g) \rightarrow \left(\prod_{a:A} f(a) =_B g(a) \right)$$

- By **indiscernibility of identicals**, if $x, y : A$ and $x =_A y$ then $P(x) \simeq P(y)$ for any $a : A \vdash P(a)$. By univalence, whenever $A \simeq B$ then $A =_u B$ and thus any type constructed from A is equivalent to the corresponding type constructed from B .

Via **path induction**, Voevodsky's univalence axiom — which is justified by the homotopical model of type theory — captures the common mathematical practice of applying results proven about one object to any other object that is equivalent to it!

What justifies the path induction principle?

Path induction: For any type family $P(x, y, p)$ over $x, y : A, p : x =_A y$, to prove $P(x, y, p)$ for all x, y, p it suffices to assume y is x and p is refl_x .

$$\text{path-ind} : \left(\prod_{x:A} P(x, x, \text{refl}_x) \right) \rightarrow \left(\prod_{x,y:A} \prod_{p:x=_A y} P(x, y, p) \right).$$

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Path induction asserts that to map out of a **path space** $\sum_{x,y:A} x =_A y$ it suffices to define the images of the reflexivity paths.

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By univalence, the equivalence $A \simeq \left(\sum_{x,y:A} x =_A y \right)$ gives rise to an equivalence

$$\left(\prod_{x:A} P(x, x, \text{refl}_x) \right) \simeq \left(\prod_{(x,y,p):\sum_{x,y:A} x=_A y} P(x, y, p) \right) \simeq \left(\prod_{x,y:A} \prod_{p:x=_A y} P(x, y, p) \right).$$

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HoTTEST Summer School, July–August 2022

discord.gg/tkhJ9zCGs9

Thank you!