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Path induction and the indiscernibility of identicals

UCLA Distinguished Lecture Series

Plan

1. Induction over the natural numbers
2. Dependent type theory
3. Identity types
4. Path induction
5. Epilogue: what justifies path induction?

Main takeaway:

- natural numbers induction: the natural numbers are freely generated by zero and the successor function
- path induction (substitution for equality): the identity type family is freely generated by the reflexivity proof

Next time:

- arrow induction (Yoneda lemma): the hom type family is freely generated by the identity arrow

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 $\mathrm{succ}_{\mathbb{N}}(n) \in \mathbb{N}$.
- 0 is not the successor of any natural number.
- No two natural numbers have the same successor.
- The principle of mathematical induction:

$$\forall P, P(0) \to (\forall k \in \mathbb{N}, P(k) \to P(\mathrm{succ}_{\mathbb{N}}(k))) \to (\forall n \in \mathbb{N}, P(n))$$

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

Natural numbers induction

In the statement of the principle of mathematical induction:

$$\forall P, P(0) \to (\forall k \in \mathbb{N}, P(k) \to P(\mathrm{succ}_{\mathbb{N}}(k))) \to (\forall n \in \mathbb{N}, P(n))$$

the variable P is a predicate over the natural numbers.

A predicate over the natural numbers is a function

$$P : \mathbb{N} \to \{\top, \bot\}$$

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

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 $P(\mathrm{succ}_{\mathbb{N}}(k))$.

A proof by induction

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

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

- In the base case, when $n = 0$, $0^2 + 0 = 2 \times 0$, which is even.
- For the inductive step, assume for $k \in \mathbb{N}$ that $k^2 + k = 2 \times m$ is even. Then

$$\begin{aligned}(k+1)^2 + (k+1) &= (k^2 + k) + ((2 \times k) + 2) \\ &= (2 \times m) + (2 \times (k+1)) \\ &= 2 \times (m + k + 1)\end{aligned}$$

  is even.

By the principle of mathematical induction, this proves that $n^2 + n$ is even for all $n \in \mathbb{N}$. $\square$

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 $m : \mathbb{N} \to \mathbb{N}$ so that $n^2 + n = 2 \times m(n)$.

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

- In the base case, $0^2 + 0 = 2 \times 0$, so we define $m(0) := 0$.
- For the inductive step, assume for $k \in \mathbb{N}$ that $k^2 + k = 2 \times m(k)$. Then

$$\begin{aligned}(k+1)^2 + (k+1) &= (k^2 + k) + ((2 \times k) + 2) \\ &= (2 \times m(k)) + (2 \times (k+1)) \\ &= 2 \times (m(k) + k + 1)\end{aligned}$$

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

By the principle of mathematical recursion, this defines a function $m : \mathbb{N} \to \mathbb{N}$ 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

$$\forall P, P(0) \to (\forall k \in \mathbb{N}, P(k) \to P(\mathrm{succ}_{\mathbb{N}}(k))) \to (\forall n \in \mathbb{N}, P(n))$$

in which the predicate

$$P \colon \mathbb{N} \to \{\top, \bot\}$$

is replaced by an arbitrary family of sets

$$P \colon \mathbb{N} \to \mathrm{Set}.$$

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 $n \in \mathbb{N}$.

$$\forall P, (p_0 \in P(0)) \to (p_s \in \prod_{k \in \mathbb{N}} P(k) \to P(\mathrm{succ}_{\mathbb{N}}(k))) \to (p \in \prod_{n \in \mathbb{N}} P(n))$$

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

$$p(0) := p_0 \qquad p(\mathrm{succ}_{\mathbb{N}}(n)) := p_s(n, p(n)).$$

The natural numbers in dependent type theory

While Peano's postulates characterize the natural numbers in set theory, the following rules characterize the natural numbers in dependent type theory:

- There is a type $\mathbb{N}$.
- There is a term $0 : \mathbb{N}$ and a function $\mathsf{succ}_{\mathbb{N}} : \mathbb{N} \to \mathbb{N}$.
- For any family of types $P : P \to \mathsf{Type}$ there is a term

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

- Computation rules $p(0) := p_0$ and $p(\mathsf{succ}_{\mathbb{N}}(n)) := p_s(n, p(n))$.

Note the final two postulates — that 0 is not a successor and $\mathsf{succ}_{\mathbb{N}}$ is injective — are missing because they are provable.

Summary

We summarize the rules

- There is a type $\mathbb{N}$.
- There is a term $0 : \mathbb{N}$ and a function $\mathrm{succ}_{\mathbb{N}} : \mathbb{N} \to \mathbb{N}$.
- For any family of types $P : P \to \mathrm{Type}$ there is a term

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

- Computation rules $p(0) := p_0$ and $p(\mathrm{succ}_{\mathbb{N}}(n)) := p_s(n, p(n))$.

with the slogan:

The natural numbers type $\mathbb{N}$ is freely generated by the terms $0 : \mathbb{N}$ and $\mathrm{succ}_{\mathbb{N}} : \mathbb{N} \to \mathbb{N}$.

2

Dependent type theory

Types, terms, and contexts

Dependent type theory has:

- types $\Gamma \vdash A$, $\Gamma \vdash B$
- terms $\Gamma \vdash x : A$, $\Gamma \vdash y : B$
- dependent types $\Gamma, n : \mathbb{N} \vdash \mathbb{R}^n$, $\Gamma, m, n : \mathbb{N} \vdash M_{m,n}(\mathbb{R})$
- dependent terms $\Gamma, n : \mathbb{N} \vdash \vec{0}^n : \mathbb{R}^n$, $\Gamma, n : \mathbb{N} \vdash I_n : M_{n,n}(\mathbb{R})$

Types and terms can be defined in an arbitrary context of variables from previously-defined types, all of which are listed before the symbol "$\vdash$". Here Γ is shorthand for a generic context, which has the form

$$x_1 : A_1, x_2 : A_2(x_1), x_3 : A_3(x_1, x_2), \ldots, x_n : A_n(x_1, \ldots, x_{n-1})$$

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 and terms from given ones:

- products $A \times B$, coproducts $A + B$, function types $A \to B$,
- dependent pairs $\sum_{x:A} B(x)$, dependent functions $\prod_{x:A} B(x)$.

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

The rules suggest a logical naming for certain types:

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

Product types and function types

Product types are governed by the rules

$^{\times}$-form: given types A and B there is a type $A \times B$

$^{\times}$-intro: given terms $a : A$ and $b : B$ there is a term $(a, b) : A \times B$

$^{\times}$-elim: given $p : A \times B$ there are terms $\mathrm{pr}_1 p : A$ and $\mathrm{pr}_2 p : B$

plus computation rules that relate pairings and projections.

Function types are governed by the rules

$^{\rightarrow}$-form: given types A and B there is a type $A \to B$

$^{\rightarrow}$-intro: if in the context of a variable $x : A$ there is a term $b : B$ there is a term $\lambda x.b : A \to B$

$^{\rightarrow}$-elim: given terms $f : A \to B$ and $a : A$ there is a term $f(a) : B$

plus computation rules that relate λ-abstractions and evaluations.

Mathematics in dependent type theory

$^{\times}$-form: $A,\ B \rightsquigarrow A \times B$	$^{\rightarrow}$-form: A and $B \rightsquigarrow A \to B$
$^{\times}$-intro: $a : A,\ b : B \rightsquigarrow (a, b) : A \times B$	$^{\rightarrow}$-intro: $x : A \vdash b : B \rightsquigarrow \lambda x.b : A \to B$
$^{\times}$-elim: $p : A \times B \rightsquigarrow \mathrm{pr}_1 p : A,\ \mathrm{pr}_2 p : B$	$^{\rightarrow}$-elim: $f : A \to B,\ a : A \rightsquigarrow f(a) : B$

To prove a mathematical proposition in dependent type theory, one constructs a term in the type that encodes its statement.

Proposition. For any types A and B, $(A \times (A \to B)) \to B$.

Construction: By $^{\rightarrow}$-intro, it suffices to assume given a term $p : (A \times (A \to B))$ and define a term of type B. By $^{\times}$-elim, this provides terms $\mathrm{pr}_1 p : A$ and $\mathrm{pr}_2 p : A \to B$. By $^{\rightarrow}$-elim, these combine to give a term $\mathrm{pr}_2 p(\mathrm{pr}_1 p) : B$. Thus we have

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

The natural numbers type, revisited

The natural numbers type is governed by the rules:

$\mathbb{N}$-form: $\mathbb{N}$ exists in the empty context

$\mathbb{N}$-intro: there is a term $0 : \mathbb{N}$ and for any term $n : \mathbb{N}$ there is a term $\mathrm{succ}_{\mathbb{N}}(n) : \mathbb{N}$

The elimination rule strengthens the principle of mathematical induction by replacing the predicate on $\mathbb{N}$ by an arbitrary family of types depending on $\mathbb{N}$.

$\mathbb{N}$-elim: for any type family $n : \mathbb{N} \vdash P(n)$, and for any terms $p_0 : P(0)$ and $p_s : \prod_{n:\mathbb{N}} P(n) \to P(\mathrm{succ}_{\mathbb{N}}(n))$ there is a term $p : \prod_{n:\mathbb{N}} P(n)$

Computation rules establish that p is defined recursively from p_0 and p_s.

Summary: the natural numbers type $\mathbb{N}$ is freely generated by $0 : \mathbb{N}$ and $\mathrm{succ}_{\mathbb{N}} : \mathbb{N} \to \mathbb{N}$.

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, $P(x) \leftrightarrow P(y)$

As a consequence of these rules:

Principle of substitution. To prove that every x, y with $x = y$ has property $P(x, y)$:

- it suffices to prove that every pair x, x (for which $x = x$) has property $P(x, x)$.

Proof: We argue that $\forall x, y, (x = y) \to P(x, y)$ follows from $\forall x, (x = x) \to P(x, x)$. Assuming $x = y$, $P(x, x) \leftrightarrow P(x, y)$ by indiscernibility of identicals. Since $x = x$ by reflexivity, $P(x, x)$ holds and thus so does $P(x, y)$. $\square$

Identity types

The following rules for identity types were developed by Per 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 $\mathrm{refl}_x : x =_A x$

The elimination rule for the identity type is an enhanced version of the principle of substitution: to prove that every x, y with $x = y$ have property P, it suffices to prove that every pair x, x (for which $x = x$) has property P.

$^{=}$-elim: If $P(x, y, p)$ is a type family dependent on $x, y : A$ and $p : x =_A y$, then to prove $P(x, y, p)$ it suffices to assume y is x and p is refl_x.

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

Summary: the identity type family is freely generated by the reflexivity terms.

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?

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.

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.

$$\begin{tikzcd} & \sum_{x,y:A} x =_A y \arrow[d, two heads] \\ A \arrow[ur, dashed, "\lambda x.\mathrm{refl}_x"] \arrow[r, "\lambda x.(x,x)"'] & A \times A \end{tikzcd}$$

4

Path induction

Path induction

Slogan: the identity type family freely generated by the reflexivity terms.

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

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

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

Reversal and concatenation of paths

Path induction: For any family $P(x,y,p)$ over $x,y:A, p:x=_A y$

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

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

Construction: It suffices to assume $p : x =_A y$ and then define a term in the type $P(x,y,p) :\equiv y =_A x$. By path induction, we may reduce to the case $P(x,x,\mathrm{refl}_x) :\equiv x =_A x$, for which we have the term $\mathrm{refl}_x : x =_A x$. □

Proposition. Paths can be darkpurple: $* : x =_A y \to (y =_A z \to x =_A z)$.

Construction: It suffices to assume $p : x =_A y$ and then define a term in the type $Q(x,y,p) :\equiv y =_A z \to x =_A z$. By path induction, we may reduce to the case $Q(x,x,\mathrm{refl}_x) :\equiv x =_A z \to x =_A z$, for which we have the term $\mathrm{id} :\equiv \lambda q.q : x =_A z \to x =_A z$. □

The ∞-groupoid of paths

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

Theorem (Lumsdaine,Garner–van den Berg). The terms belonging to the iterated identity types of any type A form an ∞-groupoid.

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, …

The required structures are proven from the path induction principle:

- constant paths (reflexivity) $\mathsf{refl}_x : x = x$
- reversal (symmetry) $p : x = y$ yields $p^{-1} : y = x$
- concatenation (transitivity) $p : x = y$ and $q : y = z$ yield $p * q : x = z$

and furthermore concatenation is associative and unital, the associators are coherent …

The higher coherences in path algebra

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

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

$$\mathsf{assoc} : \prod_{p : w =_A x} \prod_{q : x =_A y} \prod_{r : y =_A z} (p * q) * r =_{w =_A z} p * (q * r).$$

Construction: By path induction, it suffices to assume x is w and p is refl_w, reducing to the case

$$\prod_{q : w =_A y} \prod_{r : y =_A z} (\mathsf{refl}_w * q) * r =_{w =_A z} \mathsf{refl}_w * (q * r).$$

By the computation rules for path induction $\mathsf{refl}_w * -$ is the identity function. Thus, we must show

$$\prod_{q : w =_A y} \prod_{r : y =_A z} q * r =_{w =_A z} q * r,$$

for which we have the proof $\mathsf{refl}_{q*r} : q * r =_{w =_A z} q * r$. $\square$

Indiscernibility of Identicals

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

Let $x : A \vdash P(x)$ be any family of types over A.

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

Construction: By path induction, it suffices to assume y is x and p is refl_x, in which case we have the identity function $\lambda x.x : P(x) \to P(x)$. $\square$

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. $\square$

5

Epilogue: what justifies path induction?

The Curry-Howard-Voevodsky Correspondence

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

Contractible types

The homotopical perspective on type theory suggests new definitions:

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

$$\sum_{a:A} \prod_{x:A} a =_A x$$

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.

The contracting homotopy 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.

A type A

- is a proposition if
$$\text{is-prop}(A) := \prod_{x,y:A} \text{is-contr}(x =_A y)$$
- is a set or 0-type if
$$\text{is-set}(A) := \prod_{x,y:A} \text{is-prop}(x =_A y)$$
- is an $\text{succ}_{\mathbb{N}}(n)$-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 when two types A and B are equivalent or when a function $f : A \to B$ is an equivalence:

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

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

A term of type $A \simeq B$ provides functions $f : A \to B$, $g, h : B \to A$ and homotopies α and β relating the composite functions $g \circ f$ and $f \circ h$ to the identities. Using this data, one can define a homotopy from g to h.

So why not say $f : A \to B$ is an equivalence just when:

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

This type is not a proposition and may have non-trivial higher structure.

What justifies the path induction principle?

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

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

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.

Proposition. For each $x : A$, the based path space $\sum_{y:A} x =_A y$ is contractible with center of contraction given by the point (x, refl_x).

Thus, path induction is justified by the equivalence

$$\lambda x.\mathsf{refl}_x : A \simeq \left(\sum_{x,y:A} x =_A y\right).$$

The univalence axiom

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

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

By path induction, there is a canonical function

$$\text{id-to-equiv} : (A =_{\mathcal{U}} B) \to (A \simeq B)$$

defined by sending refl_A to the identity equivalence id_A.

The univalence axiom, which is justified by the homotopical model of type theory, asserts that id-to-equiv is an equivalence.

"Identity is equivalent to equivalence."

$$(A =_{\mathcal{U}} B) \simeq (A \simeq B)$$

This axiom justifies the common mathematical practice of applying results proven about one object to any other object that is equivalent to it.

Consequences of univalence

There are myriad consequences of the univalence axiom:

$$(A =_{\mathcal{U}} B) \simeq (A \simeq B)$$

- 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 $f, g : A \to B$, the canonical function defines an equivalence between the identity type and the type of homotopies:

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

- 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 $A =_{\mathcal{U}} B$ and any type constructed from A is equivalent to the corresponding type constructed from B.

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`https://discord.gg/tkhJ9zCGs9`

Thank you!