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A reintroduction to proofs

Texas State University Undergraduate Colloquium

Plan

1. Logic, constructively
2. $\forall : \Pi :: \exists : \Sigma$
3. Peano's axioms, revisited

∞. $=$

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Logic, constructively

Conjunction and disjunction

Forget truth tables! Instead, define the logical operators "and" $\wedge$ and "or" $\vee$ by:

Conjunction $\wedge$ is the logical operator defined by the rules:

- ${}^{\wedge}$intro: If p is true and q is true, then $p \wedge q$ is true.
- ${}^{\wedge}$elim$_1$: If $p \wedge q$ is true, then p is true.
- ${}^{\wedge}$elim$_2$: If $p \wedge q$ is true, then q is true.

Disjunction $\vee$ is the logical operator defined by the rules:

- ${}^{\vee}$intro$_1$: If p is true, then $p \vee q$ is true.
- ${}^{\vee}$intro$_2$: If q is true, then $p \vee q$ is true.
- ${}^{\vee}$elim: If $p \vee q$ is true, and if r can be derived from p and from q, then r is true.

Introduction rules explain how to prove a proposition involving a particular connective, while elimination rules explain how to use a hypothesis involving a particular connective.

Implication

Implication $\Rightarrow$ is the logical operator defined by the rules:

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Proof:

givens: p, q, r

goal: $((p \Rightarrow q) \wedge (q \Rightarrow r)) \Rightarrow (p \Rightarrow r)$

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Proof: By $^{\Rightarrow}$intro, assume that $(p \Rightarrow q) \wedge (q \Rightarrow r)$ is true; our goal is to prove $p \Rightarrow r$.

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Proof: By ${}^{\Rightarrow}$intro, assume that $(p \Rightarrow q) \wedge (q \Rightarrow r)$ is true; our goal is to prove $p \Rightarrow r$. By ${}^{\wedge}\text{elim}_1$ and ${}^{\wedge}\text{elim}_2$ it follows that $p \Rightarrow q$ and $q \Rightarrow r$ are true.

givens:

p, q, r

$(p \Rightarrow q) \wedge (q \Rightarrow r)$

$p \Rightarrow q$

$q \Rightarrow r$

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givens: p, q, r

$(p \Rightarrow q) \wedge (q \Rightarrow r)$

$p \Rightarrow q$

$q \Rightarrow r$

p

goal: r

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givens:	p, q, r
	$(p \Rightarrow q) \wedge (q \Rightarrow r)$
	$p \Rightarrow q$
	$q \Rightarrow r$
	p
	q
goal:	r

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givens:	p, q, r
	$(p \Rightarrow q) \wedge (q \Rightarrow r)$
	$p \Rightarrow q$
	$q \Rightarrow r$
	p
	q
	r
goal:	r

Type theory

Type theory is a formal system for mathematical statements and proofs that has the following primitive notions:

- types, e.g., $\mathbb{N}$, $\mathbb{Q}$, Group

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Given any types A and B, one may form the

product type $A \times B$, function type $A \to B$, coproduct type $A + B$

whose terms are governed by introduction and elimination (and computation) rules.

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Mathematics in type theory:

- To state a conjecture, one forms a type that encodes its statement.
- To prove the theorem, one constructs a term in that type.

Conjunction and Products

Conjunction $\wedge$ is the logical operator defined by the rules:

- $^{\wedge}$intro: If p is true and q is true, then $p \wedge q$ is true.
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- $^{\wedge}$elim$_2$: If $p \wedge q$ is true, then q is true.

Given types A and B, the product type $A \times B$ is governed by the rules:

- $^{\times}$intro: given terms $a : A$ and $b : B$ there is a term $(a, b) : A \times B$
- $^{\times}$elim$_1$: given a term $p : A \times B$ there is a term $\pi_1 p : A$
- $^{\times}$elim$_2$: given a term $p : A \times B$ there is a term $\pi_2 p : B$

plus computation rules that relate pairings and projections.

Implication and functions

Implication $\Rightarrow$ is the logical operator defined by the rules:

- $^{\Rightarrow}$intro: If q can be derived from the assumption that p is true, then $p \Rightarrow q$ is true.
- $^{\Rightarrow}$elim: If $p \Rightarrow q$ is true and p is true, then q is true.

Given types A and B, the function type $A \to B$ is governed by the rules:

- $^{\to}$intro: if given any term $x : A$ there is a term $b_x : B$,

  then there is a term $\lambda x.b_x : A \to B$
- $^{\to}$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.

A proof in type theory

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Theorem. For any types P, Q, and R, $((P \to Q) \times (Q \to R)) \to (P \to R)$.

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Construction:

givens: P, Q, R

goal: $(P \to Q) \times (Q \to R) \to (P \to R)$

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Theorem. For any types P, Q, and R, $((P \to Q) \times (Q \to R)) \to (P \to R)$.

Construction: By $^{\to}$intro, suppose given $h : (P \to Q) \times (Q \to R)$; our goal is a term of type $P \to R$.

givens: P, Q, R

$h : (P \to Q) \times (Q \to R)$

goal: $P \to R$

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Theorem. For any propositions p, q, and r, $((p \Rightarrow q) \wedge (q \Rightarrow r)) \Rightarrow (p \Rightarrow r)$.

Theorem. For any types P, Q, and R, $((P \to Q) \times (Q \to R)) \to (P \to R)$.

Construction: By ${}^{\to}\mathrm{intro}$, suppose given $h : (P \to Q) \times (Q \to R)$; our goal is a term of type $P \to R$. By ${}^{\times}\mathrm{elim}_1$ and ${}^{\times}\mathrm{elim}_2$, we have $\pi_1 h : P \to Q$ and $\pi_2 h : Q \to R$.

givens:	P, Q, R
	$h : (P \to Q) \times (Q \to R)$
	$\pi_1 h : P \to Q$
	$\pi_2 h : Q \to R$
goal:	$P \to R$

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Construction: By ${}^{\to}$intro, suppose given $h : (P \to Q) \times (Q \to R)$; our goal is a term of type $P \to R$. By ${}^{\times}\mathrm{elim}_1$ and ${}^{\times}\mathrm{elim}_2$, we have $\pi_1 h : P \to Q$ and $\pi_2 h : Q \to R$. By ${}^{\to}$intro again, suppose given $p : P$; now our goal is a term of type R.

givens:	P, Q, R
	$h : (P \to Q) \times (Q \to R)$
	$\pi_1 h : P \to Q$
	$\pi_2 h : Q \to R$
	$p : P$
goal:	R

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Construction: By ${}^{\to}$intro, suppose given $h : (P \to Q) \times (Q \to R)$; our goal is a term of type $P \to R$. By ${}^{\times}\mathrm{elim}_1$ and ${}^{\times}\mathrm{elim}_2$, we have $\pi_1 h : P \to Q$ and $\pi_2 h : Q \to R$. By ${}^{\to}$intro again, suppose given $p : P$; now our goal is a term of type R. By ${}^{\to}$elim, from $p : P$ and $\pi_1 h : P \to Q$, we obtain $\pi_1 h(p) : Q$.

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	$h : (P \to Q) \times (Q \to R)$
	$\pi_1 h : P \to Q$
	$\pi_2 h : Q \to R$
	$p : P$
	$\pi_1 h(p) : Q$
goal:	R

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Construction: By $^{\to}$intro, suppose given $h : (P \to Q) \times (Q \to R)$; our goal is a term of type $P \to R$. By $^{\times}$elim$_1$ and $^{\times}$elim$_2$, we have $\pi_1 h : P \to Q$ and $\pi_2 h : Q \to R$. By $^{\to}$intro again, suppose given $p : P$; now our goal is a term of type R. By $^{\to}$elim, from $p : P$ and $\pi_1 h : P \to Q$, we obtain $\pi_1 h(p) : Q$. By $^{\to}$elim again, from $\pi_1 h(p) : Q$ and $\pi_2 h : Q \to R$, we obtain $\pi_2 h(\pi_1 h(p)) : R$ as desired. $\square$

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	$\pi_1 h : P \to Q$
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	$h : (P \to Q) \times (Q \to R)$
	$\pi_1 h : P \to Q$
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	$p : P$
	$\pi_1 h(p) : Q$
	$\pi_2 h(\pi_1 h(p)) : R$
goal:	R

This constructs a term $\lambda h.\lambda p.\pi_2 h(\pi_1 h(p)) : ((P \to Q) \times (Q \to R)) \to (P \to R)$.

Disjunction and coproducts

Disjunction $\vee$ is the logical operator defined by the rules:

- $^{\vee}$intro$_1$: If p is true, then $p \vee q$ is true.
- $^{\vee}$intro$_2$: If q is true, then $p \vee q$ is true.
- $^{\vee}$elim: If $p \vee q$ is true, and if r can be derived from p and from q, then r is true.

Given types A and B, the coproduct type $A + B$ is governed by the rules:

- $^{+}$intro$_1$: given a term $a : A$, there is a term $\iota_1 a : A + B$
- $^{+}$intro$_2$: given a term $b : B$, there is a term $\iota_2 b : A + B$
- $^{+}$elim: given a types C and terms $c_a, d_b : C$ for each $a : A$ and $b : B$ respectively, there is a term $^{+}\mathrm{ind}(c, d)(x) : C$ for each $x : A + B$

plus computation rules that relate the inclusions and the elimination.

Another proof in type theory

Theorem. For any types A, B, and C, $((A + B) \to C) \to ((A \to C) \times (B \to C))$.

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Construction: By $^{\to}$intro, suppose given $h : (A+B) \to C$; our goal is a term of type $(A \to C) \times (B \to C)$.

- $^{\to}$intro: if given any term $x : A$ there is a term $b_x : B$, there is a term $\lambda x.b_x : A \to B$

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Theorem. For any types A, B, and C, $((A + B) \to C) \to ((A \to C) \times (B \to C))$.

Construction: By ${}^{\to}$intro, suppose given $h : (A + B) \to C$; our goal is a term of type $(A \to C) \times (B \to C)$. By ${}^{\times}$intro, it suffices to define terms of type $A \to C$ and type $B \to C$.

- ${}^{\to}$intro: if given any term $x : A$ there is a term $b_x : B$, there is a term $\lambda x.b_x : A \to B$
- ${}^{\times}$intro: given terms $a : A$ and $b : B$ there is a term $(a, b) : A \times B$

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Theorem. For any types A, B, and C, $((A+B) \to C) \to ((A \to C) \times (B \to C))$.

Construction: By ${}^{\to}$intro, suppose given $h : (A+B) \to C$; our goal is a term of type $(A \to C) \times (B \to C)$. By ${}^{\times}$intro, it suffices to define terms of type $A \to C$ and type $B \to C$. By ${}^{\to}$intro, to define a term of type $A \to C$ it suffices to assume a term $a : A$ and define a term of type C.

- ${}^{\to}$intro: if given any term $x : A$ there is a term $b_x : B$, there is a term $\lambda x.b_x : A \to B$
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- ${}^{\to}$intro: if given any term $x : A$ there is a term $b_x : B$, there is a term $\lambda x.b_x : A \to B$
- ${}^{\times}$intro: given terms $a : A$ and $b : B$ there is a term $(a, b) : A \times B$
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- $^{\to}$intro: if given any term $x : A$ there is a term $b_x : B$, there is a term $\lambda x.b_x : A \to B$
- $^{\times}$intro: given terms $a : A$ and $b : B$ there is a term $(a, b) : A \times B$
- $^{+}$intro$_1$: given a term $a : A$, there is a term $\iota_1 a : A + B$
- $^{\to}$elim: given terms $f : A \to B$ and $a : A$, there is a term $f(a) : B$

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Construction: By ${}^{\to}$intro, suppose given $h : (A + B) \to C$; our goal is a term of type $(A \to C) \times (B \to C)$. By ${}^{\times}$intro, it suffices to define terms of type $A \to C$ and type $B \to C$. By ${}^{\to}$intro, to define a term of type $A \to C$ it suffices to assume a term $a : A$ and define a term of type C. By ${}^{+}$intro$_1$, we then have a term $\iota_1 a : A + B$. Then by ${}^{\to}$elim we obtain a term $h(\iota_1 a) : C$. Similarly, by ${}^{\to}$intro, ${}^{+}$intro$_2$, and ${}^{\to}$elim we have $\lambda b.h(\iota_2 b) : B \to C$. □

- ${}^{\to}$intro: if given any term $x : A$ there is a term $b_x : B$, there is a term $\lambda x.b_x : A \to B$
- ${}^{\times}$intro: given terms $a : A$ and $b : B$ there is a term $(a, b) : A \times B$
- ${}^{+}$intro$_1$: given a term $a : A$, there is a term $\iota_1 a : A + B$
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- ${}^{\to}$intro: if given any term $x : A$ there is a term $b_x : B$, there is a term $\lambda x.b_x : A \to B$
- ${}^{\times}$intro: given terms $a : A$ and $b : B$ there is a term $(a, b) : A \times B$
- ${}^{+}$intro$_1$: given a term $a : A$, there is a term $\iota_1 a : A + B$
- ${}^{\to}$elim: given terms $f : A \to B$ and $a : A$, there is a term $f(a) : B$

This constructs $\lambda h.(\lambda a.h(\iota_1 a), \lambda b.h(\iota_2 b)) : ((A+B) \to C) \to ((A \to C) \times (B \to C))$.

2

$$\forall : \Pi :: \exists : \Sigma$$

Universal and existential quantification

Let $p : X \to \{\bot, \top\}$ be an X-indexed family of propositions, a predicate $p(x)$ on $x \in X$.
For example:

- "$2^{2^n} - 1$ is prime" is a predicate on $n \in \mathbb{N}$
- "$z^2 = -1$" is a predicate on $z \in \mathbb{C}$

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- "$z^2 = -1$" is a predicate on $z \in \mathbb{C}$

Universal quantification $\forall x \in X, p(x)$ is the logical formula defined by the rules:

- $^\forall$intro: If $p(x)$ can be derived from the assumption that x is an arbitrary element of X, then $\forall x \in X, p(x)$ is true.
- $^\forall$elim: If $\forall x \in X, p(x)$ is true and $a \in X$, then $p(a)$ is true.

Existential quantification $\exists x \in X, p(x)$ is the logical formula defined by the rules:

- $^\exists$intro: If $a \in X$ and $p(a)$ is true, then $\exists x \in X, p(x)$ is true.
- $^\exists$elim: If $\exists x \in X, p(x)$ is true and q can be derived from the assumption that $p(a)$ is true for some $a \in X$, then q is true.

Exchanging quantifiers

$^\forall$-intro: If $p(x)$ for any $x \in X$, then $\forall x \in X, p(x)$.
$^\forall$elim: If $\forall x \in X, p(x)$ and $a \in X$, then $p(a)$.

$^\exists$-intro: If $a \in X$ and $p(a)$, then $\exists x \in X, p(x)$.
$^\exists$elim: If $\exists x \in X, p(x)$ and q follows from $p(a)$ for some $a \in X$, then q.

Theorem. For any predicate $p(x, y)$ on $x \in X$ and $y \in Y$,

$$\exists y \in Y, \forall x \in X, p(x, y) \Rightarrow \forall x' \in X, \exists y' \in Y, p(x', y').$$

Exchanging quantifiers

$^{\forall}$-intro: If $p(x)$ for any $x \in X$, then $\forall x \in X, p(x)$.
$^{\forall}$elim: If $\forall x \in X, p(x)$ and $a \in X$, then $p(a)$.

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Proof:

givens: p

goal: $\exists y \in Y, \forall x \in X, p(x, y) \Rightarrow \forall x' \in X, \exists y' \in Y, p(x', y')$

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p
$\exists y \in Y, \forall x \in X, p(x, y)$
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p
$\exists y \in Y, \forall x \in X, p(x, y)$
y_0
$\forall x \in X, p(x, y_0)$
x'
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givens:

p

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y_0

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$p(x', y_0)$

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Dependent type theory

Dependent type theory is a formal system for mathematical statements and proofs that has the following primitive notions. In addition to the:

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- dependent terms, e.g., $\vec{0}^{\bullet} : \prod_{n:\mathbb{N}} \mathbb{R}^n$, $I_{\bullet} : \prod_{n:\mathbb{N}} \mathsf{Mat}_{n,n}$, $S_{\bullet} : \prod_{n:\mathbb{N}} \mathsf{Group}$

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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.

Universal quantification and dependent functions

For any predicate $p : X \to \{\bot, \top\}$, the universal quantification $\forall x \in X, p(x)$ is the logical formula defined by the rules:

- $^{\forall}$intro: If $p(x)$ can be derived from the assumption that x is an arbitrary element of X, then $\forall x \in X, p(x)$ is true.
- $^{\forall}$elim: If $\forall x \in X, p(x)$ is true and $a \in X$, then $p(a)$ is true.

For any family of types $B : A \to \mathrm{Type}$, the dependent function type $\prod_{x:A} B(x)$ is governed by the rules:

- $^{\Pi}$intro: if in the context of a variable $x : A$ there is a term $b_x : B(x)$

  there is a term $\lambda x.b_x : \prod_{x:A} B(x)$
- $^{\Pi}$elim: given terms $f : \prod_{x:A} B(x)$ and $a : A$ there is a term $f(a) : B(a)$

plus computation rules that relate λ-abstractions and evaluations.

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For a constant type family $B : A \to \text{Type}$, the dependent function type recovers $A \to B$

Existential quantification and dependent sums

For any predicate $p : X \to \{\bot, \top\}$, the Existential quantification $\exists x \in X, p(x)$ is the logical formula defined by the rules:

- $^{\exists}$intro: If $a \in X$ and $p(a)$ is true, then $\exists x \in X, p(x)$ is true.
- $^{\exists}$elim: If $\exists x \in X, p(x)$ is true and q can be derived from the assumption that $p(a)$ is true for some $a \in X$, then q is true.

For any family of types $B : A \to \mathrm{Type}$, the dependent sum type $\sum_{x:A} B(x)$ is governed by the rules:

- $^{\Sigma}$intro: if there are terms $a : A$ and $b : B(a)$, there is a term $(a, b) : \sum_{x:A} B(x)$
- $^{\Sigma}$elim: given a term $p : \sum_{x:A} B(x)$ there are terms $\pi_1 p : A$ and $\pi_2 p : B(\pi_1 p)$

plus computation rules that relate pairings and projections.

For a constant type family $B : A \to \mathrm{Type}$, the dependent sum type recovers $A \times B$.

Exchanging quantifiers, revisited

Theorem. For any $p(x, y)$, $\exists y \in Y, \forall x \in X, p(x, y) \Rightarrow \forall x' \in X, \exists y' \in Y, p(x', y')$.

Theorem. For any $P : X \to Y \to \mathrm{Type}$, $\Sigma_{y:Y} \Pi_{x:X} P(x, y) \to \Pi_{x':X} \Sigma_{y':Y}, P(x', y')$.

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Proof: By $^{\to}$intro, we may assume $h : \Sigma_{y:Y}\Pi_{x:X}P(x, y)$; our goal is of type $\Pi_{x':X}\Sigma_{y':Y}P(x', y')$.

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Proof: By ${}^{\to}$intro, we may assume $h : \Sigma_{y:Y}\Pi_{x:X}P(x, y)$; our goal is of type $\Pi_{x':X}\Sigma_{y':Y}P(x', y')$. By ${}^{\Sigma}$elim, we have $\pi_1 h : Y$ and $\pi_2 h : \Pi_{x:X}P(x, \pi_1 h)$. By ${}^{\Pi}$intro, we may fix $x' : X$; our goal is of type $\Sigma_{y':Y}P(x', y')$. But by ${}^{\Pi}$elim, we have $\pi_2 h(x') : P(x', \pi_1 h)$.

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Proof: By $^{\to}$intro, we may assume $h : \Sigma_{y:Y}\Pi_{x:X}P(x, y)$; our goal is of type $\Pi_{x':X}\Sigma_{y':Y}P(x', y')$. By $^{\Sigma}$elim, we have $\pi_1 h : Y$ and $\pi_2 h : \Pi_{x:X}P(x, \pi_1 h)$. By $^{\Pi}$intro, we may fix $x' : X$; our goal is of type $\Sigma_{y':Y}P(x', y')$. But by $^{\Pi}$elim, we have $\pi_2 h(x') : P(x', \pi_1 h)$. So by $^{\Sigma}$intro, we then have $(\pi_1 h, \pi_2 h(x')) : \Sigma_{y':Y}P(x', y')$. $\square$

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The constructs $\lambda h.\lambda x'.(\pi_1 h, \pi_2 h(x')) : \Sigma_{y:Y}\Pi_{x:X}P(x,y) \to \Pi_{x':X}\Sigma_{y':Y}, P(x',y')$.

3

Peano's axioms, revisited

The natural numbers

Dedekind's Categoricity Theorem. The natural numbers $\mathbb{N}$ are characterized by Peano's postulates:

- There is a natural number $0 \in \mathbb{N}$.
- Every natural number $n \in \mathbb{N}$ has a successor $\mathsf{suc}\, n \in \mathbb{N}$.
- 0 is not the successor of any natural number.
- No two natural numbers have the same successor.
- The principle of mathematical induction: for all predicates $p : \mathbb{N} \to \{\bot, \top\}$

$$P(0) \Rightarrow (\forall k \in \mathbb{N}, P(k) \Rightarrow P(\mathsf{suc}\, k)) \Rightarrow (\forall n \in \mathbb{N}, P(n))$$

A proof by induction

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

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- In the base case, when $n = 0$, $0^2 + 0 = 2 \times 0$, which is even.

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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

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

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

By the principle of mathematical induction

$$\forall P, P(0) \Rightarrow (\forall k \in \mathbb{N}, P(k) \Rightarrow P(\mathrm{suc}\,k)) \Rightarrow (\forall n \in \mathbb{N}, P(n))$$

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

A construction by induction

The inductive 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 $n^2 + n = 2 \times m(n)$.

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Theorem. There is a function $m\colon \mathbb{N} \to \mathbb{N}$ so that $n^2 + n = 2 \times m(n)$ for all $n \in \mathbb{N}$.

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

A construction by induction

The inductive 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 $n^2 + n = 2 \times m(n)$.

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

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

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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 $n \in \mathbb{N}$. $\square$

Induction and recursion

Recursion can be thought of as the constructive form of induction

$$\forall P, P(0) \Rightarrow (\forall k \in \mathbb{N}, P(k) \Rightarrow P(\mathsf{suc}\,k)) \Rightarrow (\forall n \in \mathbb{N}, P(n))$$

in which the predicate

$$P : \mathbb{N} \to \{\top, \bot\} \quad \text{such as} \quad P(n) \coloneqq \exists m \in \mathbb{N}, n^2 + n = 2 \times m$$

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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 $n \in \mathbb{N}$.

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

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

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

The natural numbers in dependent type theory

The natural numbers type $\mathbb{N}$ is governed by the rules:

- $^{\mathbb{N}}$intro: there is a term $0 : \mathbb{N}$ and for any term $n : \mathbb{N}$ there is a term $\mathsf{suc}\, n : \mathbb{N}$

The elimination rule strengthens the principle of mathematical induction by replacing the predicate $P : \mathbb{N} \to \{\perp, \top\}$ by an arbitrary family of types $P : \mathbb{N} \to \mathsf{Type}$.

- $^{\mathbb{N}}$elim: for any type family $P : \mathbb{N} \to \mathsf{Type}$, to prove $p : \prod_{n:\mathbb{N}} P(n)$ it suffices to prove $p_0 : P(0)$ and $p_s : \prod_{k:\mathbb{N}} P(k) \to P(\mathsf{suc}\, k)$. That is

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Note the other two Peano postulates are missing because they are provable!

∞

$=$

Identity types

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

Given a type A and terms $x, y : A$, the identity type $x =_A y$ is governed by the rules:

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

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 $x, y : A$ and $p : x =_A y$, 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

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

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

Symmetry and transitivity of identifications

${}^{=}$elim: For any type family $P(x, y, p)$ over $x, y : A$ and $p : x =_A y$,

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Functions preserve identifications

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In set theory, a function $f : X \to Y$ is well-defined: if $x = x'$ then $f(x) = f(x')$.

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Theorem. For any $f : A \to B$, $a, a' : A$, and $p : a =_A a'$, there is a term

$$\mathrm{ap}_f\, p : f(a) =_B f(a').$$

Construction: Let $f : A \to B$. By $^{=}$elim applied to the family $P(x, y, p) :\equiv f(x) =_B f(y)$, to define $\mathrm{ap}_f : \prod_{a,a':A}(a =_A a') \to (f(a) =_B f(a'))$ we may reduce to the case $\prod_{a:A} f(a) =_B f(a)$, for which we have $\lambda a.\mathrm{refl}_{f(a)} : \prod_{a:A} f(a) =_B f(a)$. □

Inductive constructions over the natural numbers

$^{\mathbb{N}}$elim: For any type family $P(n)$ over $n : \mathbb{N}$,

$$^{\mathbb{N}}\text{ind} : P(0) \to \left(\prod_{k \in \mathbb{N}} P(k) \to P(\text{suc}k)\right) \to \left(\prod_{n \in \mathbb{N}} P(n)\right)$$

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- $\mathsf{dist}_{2\times} : \prod_{m:\mathbb{N}} \prod_{n:\mathbb{N}} 2 \times m + 2 \times n =_{\mathbb{N}} 2 \times (m + n)$ is defined by

$$ \begin{cases} \mathsf{dist}_{2\times}(m, 0) :\equiv \mathsf{refl}_{2\times m} \\ \mathsf{dist}_{2\times}(m, \mathsf{suc}k) :\equiv \mathsf{ap}_{\mathsf{suc}\circ\mathsf{suc}}(\mathsf{dist}_{2\times}(m, n)) \end{cases} $$

A constructive proof revisited

We proved for any $n \in \mathbb{N}$, that $n^2 + n$ is even by induction and by recursively defining $m : \mathbb{N} \to \mathbb{N}$ so that $n^2 + n = 2 \times m(n)$.

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- For $\mathsf{suc}\,k : \mathbb{N}$, from $m(k) : \mathbb{N}$ and $p(k) : \mathsf{square{+}self}(k) =_{\mathbb{N}} 2 \times m(k)$ we have:

$$\mathsf{ap}_{+2\times\mathsf{suc}\,k}\, p(k) : \mathsf{square{+}self}(k) + 2 \times \mathsf{suc}\,k =_{\mathbb{N}} 2 \times m(k) + 2 \times \mathsf{suc}\,k$$
$$\mathsf{dist}_{2\times}(m(k), 2 \times \mathsf{suc}\,k) : 2 \times m(k) + 2 \times \mathsf{suc}\,k =_{\mathbb{N}} 2 \times (m(k) + \mathsf{suc}\,k)$$

Composing these identifications yields the desired term:

$$(m(k) + \mathsf{suc}\,k, \mathsf{ap}_{+2\times\mathsf{suc}\,k}\, p(k) \cdot \mathsf{dist}_{2\times}(m(k), 2 \times \mathsf{suc}\,k)) : \sum_{m:\mathbb{N}} \mathsf{square{+}self}(\mathsf{suc}\,k) =_{\mathbb{N}} 2 \times m \quad \square$$

References

A reintroduction to proofs using introduction and elimination rules:

- Clive Newstead, An Infinite Descent into Pure Mathematics
  `https://infinitedescent.xyz/`

On dependent type theory and identity types (plus much more):

- Egbert Rijke, Introduction to Homotopy Type Theory,
  `arXiv:2212.11082` and forthcoming from *Cambridge University Press*

Thank you!