Type theory in Lean - 4

Riccardo Brasca

Université Paris Cité

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- Formation rule: there is a well formed type $\mathbb{N}$.

$$(\mathbb{N} : \mathrm{Type})$$

  Its terms are called *natural numbers*.

Constructors

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Moreover, if $(n : \mathbb{N})$ is a natural number, we have another natural number called *the successor of n* and denoted $\mathrm{succ}\ n$:

$$(\mathrm{succ}\ n : \mathbb{N})$$

In particular, we have a function

$$\mathrm{succ} : \mathbb{N} \to \mathbb{N}$$

The fact that succ takes a natural number and gives another natural number is what makes $\mathbb{N}$ an *inductive* type.

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We want to define a term

$$\left(f : \prod_{(n:\mathbb{N})} M\ n\right)$$

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Note that there is no need to tell to rec what M is, Lean will guess it from the type of s (we say that M is an *implicit variable*).

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In particular, if $(n : \mathbb{N})$, then

$$(\mathrm{rec}\ z\ s\ n : M\ n)$$

Universal construction

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Even if one does not write M explicitly as an argument, the variable is still there, so the type of rec is

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To be precise, this is the type of $\mathrm{rec}.\{u\}$, the eliminator for the universe u. Since universes are not terms, we cannot take a further product over universes, and there is no universe big enough to contain all the $\mathrm{Sort}\ u$'s, so this is unavoidable.

Computation rules

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and, if $(n : \mathbb{N})$,

$$\mathrm{rec}\ z\ s\ (\mathrm{succ}\ n) \equiv s\ n\ (\mathrm{rec}\ z\ s\ n)$$

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such that

$$\mathrm{rec}\ z\ s\ 0 \equiv z \text{ and } \mathrm{rec}\ z\ s\ (\mathrm{succ}\ n) \equiv s\ n\ (\mathrm{rec}\ z\ s\ n)$$

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Slogan

Using rec, one can define functions

$$(f : \mathbb{N} \to A)$$

by recursion in the usual way.

Let's go back to the dependent version of the eliminator, but in the special case where the motive ($M : \mathbb{N} \to \mathrm{Prop}$) takes values in $\mathrm{Sort}\ 0 = \mathrm{Prop}$.

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Let's construct such a p.

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We have that $(M\ 0 : \mathrm{Prop})$, so z is now a proof that $M\ 0$ holds. On the other hand, we also have

$$\left(\prod_{(n:\mathbb{N})} M\ n \to M\ (\mathrm{succ}\ n) : \mathrm{Prop}\right)$$

So s corresponds to a proof of the proposition

$$\forall (n : \mathbb{N}), M\ n \to M\ (\mathrm{succ}\ n)$$

that is, $M\ n$ implies $M\ (\mathrm{succ}\ n)$ for all $(n : \mathbb{N})$.

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Slogan

Using rec*, one can prove propositions on* $\mathbb{N}$ *by induction in the usual way.*

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We will see the precise syntax in the examples.

An example: the double function

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so the function $(s : \mathbb{N} \to \mathbb{N} \to \mathbb{N})$ is given by

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First of all we need the image of 0, that is $\mathrm{add}\ 0 : \mathbb{N} \to \mathbb{N}$. This will of course be the identity function, so

$$\mathrm{add}\ 0\ n \equiv n$$

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One can of course use rec directly, but using pattern matching will be much simpler, since one has not to write explicitly the function

$$(s : \mathbb{N} \to (\mathbb{N} \to \mathbb{N}) \to (\mathbb{N} \to \mathbb{N}))$$

that says how to specify $\mathrm{add}\ (\mathrm{succ}\ n)$ given $\mathrm{add}\ n$.

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We will explain in the following lectures why definitional equality implies equality, a notion that at the moment we have not defined.

Using lambda abstraction, we have terms

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for all $(a\ b : \mathbb{N})$ are true, but not definitionally. One can prove such results seeing them as dependent functions and using the eliminator explicitly, but Lean has a much nicer syntax, using the `induction` tactic. Under the hood, one has to use the eliminator.

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  This is proved using that two definitionally equal terms are equal.

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where $(a : \mathbb{N})$. In other words we need to prove that $a + 0 = a$ implies that $\mathrm{succ}\ a + 0 = \mathrm{succ}\ a$ as expected. Since we need to construct a function, we can use lambda abstraction again. In Lean this is easily done using the `intro` and `rw` tactics, but we will see that $a + 0 = a$ is an inductive proposition, so to construct such a function one can use the constructor for $=$.

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In particular one can prove that succ is injective.

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The idea is the following: suppose we have two terms A and B, of any type T, such that we know that $A \neq B$. We consider the function $f \colon \mathbb{N} \to T$ defined, via the eliminator, by

$$f\ 0 = A \text{ and } f\ (\mathrm{succ}\ n) = B$$

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In particular

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This is clear since $A = f\ 0 = f\ 1 = B$

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Remark

We didn't reason by contradiction.

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We have $\mathrm{False} = f\ 0 = f\ (\mathrm{succ}\ n) = \mathrm{True}$, so we are done as before.