Theorembeweiserpraktikum

Inductive Types

Jakob von Raumer, Sebastian Ullrich | SS 2021

LEAN THEOREM PROVER

Outline

- Type families
- Dependent function types
- Recursive definitions on inductive types
- Structures

Type Families

- We have seen last time: *Predicates* take the form of functions `p : α → Prop` for some type `α`.
- What about functions `β : α → Type`? We call these *type families* on `α`.
- Mathematically, they can be used to model set-valued functions.
- Some common examples for type families:
  - The family `Fin : Nat → Type` of *finite ordinal types*.
  - The family `Vec : Type → Nat → Type` of *vectors* (lists of a given length).
  - The family `Bij : Type → Type → Type` of *bijections* between types.

Dependent Functions

- What happens if we take the universal quantifier `∀ x, β x` of such type families?
- We can see them as functions that assign to each `x : α` an element of the type `β x`.
- Example: The function which returns the vector repeating an element `x : α` a given number of times: `repeat : α → ∀ n : Nat, Vec α n`.
- Lean offers an alternative notation to the above: `repeat : α → (n : Nat) → Vec α n`.
- In definitions:

```
def repeat (α : Type) (x : α) (n : Nat) : Vec α n := ...
```

Implicit Arguments

- Suppose we have a function `append` which appends two vectors. Its type would be

```
def append (m n : Nat) (v : Vec α n) (w : Vec α m) : Vec α (m + n) := ...
```

- The value of the first and second argument is *uniquely determined* by the third and fourth!
- We can use `{...}` to mark such arguments as *implicit*:

```
def append {m n : Nat} (v : Vec α n) (w : Vec α m) : Vec α (m + n) := ...
```

  to use the function as `append v w` instead of `append m n v w`.
- Single-letter undeclared variables are automatically turned into implicit arguments, so we could just leave out `{m n : Nat}` above.
- We can use `@append` to make all arguments explicit, and `append (n := ...)` to do so for `n` only.

Inductive Types: Natural Numbers

- So far, all inductive types we have defined were *non-recursive*.
- More interesting and especially infinite types can be constructed using *recursive* constructors.
- Example: The type of natural numbers `Nat` :

```
inductive Nat : Type where
  | zero : Nat
  | succ : Nat → Nat
```

- Intuitively, the type is supposed to contain all terms which can be composed using the two constructors:

```
zero
succ zero
succ (succ zero)
succ (succ (succ zero))
...
```

Inductive Types: Constructors and Recursors

- The presence of the constructors ensures that `Nat` contains *at least* those terms.
- How to state that `Nat` does not contain more? $\rightsquigarrow$ *Recursors*!
- The definition of `Nat` postulates, besides `Nat.zero` and `Nat.succ` , the following function:

```
#check @Nat.rec
/- output:
  Nat.rec : {motive : Nat → Sort u_1} →
    motive Nat.zero → ((n : Nat) → motive n → motive (Nat.succ n)) → (t : Nat) → motive t
-/
```

- Special cases:
  - `motive := fun _ => α` : Recursively defined functions on `Nat` .
  - `motive := fun n => p n` for a predicate `p` : Proof by induction.

Recursive `match` blocks

Recursors are best not used directly, Lean's `match` syntax is a convenience feature to do this for us:

```
def add (m n : Nat) : Nat :=
  match n with
  | Nat.zero   => m
  | Nat.succ n => Nat.succ (add m n)
```

produces the same result as

```
def add' (m : Nat) : Nat → Nat := @Nat.rec (fun _ => Nat) m (fun _ r => Nat.succ r)
```

Note: This means that `m + (n + 1)` is definitionally equal to `(m + n) + 1`, but not `(m + 1) + n` to `m + (1 + n)`!

Indexed Inductive Types

- Like with predicates, we can define inductive type families with *indices*.
- Example: A definition of the type of vectors could look like this:

```
inductive Vec (α : Type) : Nat → Type where
  | nil  : Vec α 0
  | cons : {n : Nat} → α → Vec α n → Vec α (n + 1)
```

- We now can define the `append` function as follows:

```
def append (v : Vec α m) (w : Vec α n) : Vec α (n + m) :=
  match v with
  | Vec.nil      => w
  | Vec.cons a v => Vec.cons a (append v w)
```

Here the last line works because `(n + m) + 1` is definitionally equal to the expected index `n + (m + 1)`.

Structures

- You have already seen examples of inductive types with exactly one constructor (`And` , `Iff`).
- Those have some special properties and syntax in Lean. The code

```
structure Point (α : Type) where
  x : α
  y : α
```

means roughly the same as

```
inductive Point (α : Type) : Type where
  | intro : (x : α) → (y : α) → Point α
```

Structures

- Structures offer notation access to the constructor arguments (*fields*), as you have seen in `And.left`:

```
def fivethree : Point Nat := { x := 5, y := 3 }

#eval fivethree.x  -- prints 5
```

- Structures can be extended by structures with more fields:

```
structure Triplet (α : Type) extends Point α where
  z : α
```

contains the fields `x`, `y`, and `z`.

Namespaces

- *Namespaces* are a way to organize names of definitions hierarchically.
- Constructors and recursors of inductive types are automatically put into a namespace of the same name, see `Vec.nil` .
- We can `open` namespaces, to remove the prefix:

```
namespace Topic  -- starts a namespace

def exampleDef := ...

end Topic  -- ends a namespace
#check Topic.exampleDef

open Topic -- removes the necessity for the prefix "Topic."
#check exampleDef
```

- Definitions marked with `protected` keep their prefix when the namespace is opened.