



# Theorembeweiserpraktikum

## Type Classes

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# Normalisation of Terms

- If we do not assume any global axioms via `axiom`, Lean is able to compute any function:

```
#eval if (5 % 3 = 2) then "This" else "That" -- outputs "This"
```

- Every closed (= not depending on any free variables) expression of a type  $A$  can be reduced to a repeated application of constructors of  $A$ . This is called *normalisation*.
- That's convenient: Let's define a function that returns 1 if the Riemann hypothesis is true and 0 otherwise:

```
def RH : Prop := _ -- add a formalization of the proposition that is the Riemann hypothesis here  
  
def RH_nat : Nat := if RH then 1 else 0
```

- Unfortunately gives the output

```
failed to synthesize instance Decidable RH
```

# Decidability

The type `Decidable` is just an inductive type that looks very much like `Or` :

```
class inductive Decidable (p : Prop) : Type where
| isFalse (h : ¬ p) : Decidable p
| isTrue  (h : p)   : Decidable p
```

The difference to  $p \vee \neg p$  is that this is an inductive *data type* in `Type` .

**Note:** We can always match on objects of inductive data types, but we can only match on objects of inductive propositions when our goal is a proposition! This prevents that our definitions can make a difference on *which* proof of a premise we give.

# The Law of Excluded Middle

- The only thing that stands between us and our fame is an instance of something like  $RH \vee \neg RH$ .
- We need to choose our poison:
  - ① Get better at analytic number theory and either prove or refute the Riemann hypothesis.
  - ② Write 'open Classical', making all propositions decidable. But then, we're not axiom free anymore and lose computability!

```
open Classical
```

```
noncomputable def RH_nat : Nat := if RH then 1 else 0
```

- Wait, but how did Lean compute the first example, then?
- Even without `Classical`, we are able to show decidability for *some* propositions.
- Lean uses *type classes* to automate decidability proofs!

# Decidability of the Equality on Nat

To prove that equality on `Nat` is decidable, we match on both numbers:

```
theorem decideNatEq (m n : Nat) : Decidable (m = n) :=  
  match m, n with  
  | zero, zero   => isTrue rfl  
  | zero, succ n => isFalse (fun h => by injection h)  
  | succ m, zero  => isFalse (fun h => by injection h)  
  | succ m, succ n =>  
    match decideNatEq m n with  
    | isTrue h   => isTrue (h ▸ rfl)  
    | isFalse h  => isFalse (fun h' => by injection h' with h'; exact h h')
```

The tactic `injection` proves that constructors like `succ` are injective and that they are distinct, i. e. that  $\neg(\text{zero} = \text{succ } n)$ .

# Deciding More Complex Terms

- Let's give Lean something tougher to chew on:

```
#eval if (4, 2) = (5 - 1, 1 + 1) ^ ([ "Hello", "World"].length < 3) then 0 else 1 -- outputs 0
```

- This is how `if ... then ... else ...` is defined:

```
def ite (c : Prop) [h : Decidable c] (t e :  $\alpha$ ) :  $\alpha$  :=
  match h with
  | isTrue _ => t
  | isFalse _ => e
```

- This is how decidability of conjunction is proved:

```
instance [dp : Decidable p] [dq : Decidable q] : Decidable (And p q) :=
  match dp with
  | isTrue hp =>
    match dq with
    | isTrue hq => ...
```

# What Do the Square Brackets Stand for?

- Lean's way to automatically track closure properties is by *type classes*.
- Using type classes happens in three steps:
  - ① Mark an inductive type, proposition, or structure as `class` (in place of `structure` in the latter case)
  - ② Generate instances of the type class by marking theorems or definitions by using `instance` instead of `theorem` or `def`.

The declaration name is optional for `instance`, since we usually use them implicitly.

- ③ Mark arguments of theorems or definitions using the type class to use Lean's inference mechanism by marking them with square brackets `[inst : MyTypeClass]` or `[MyTypeClass]` instead of curly brackets.

Lean will then try to recursively fill in those arguments with the available instances.

# Examples of Type Classes

- Decidable  $p$  for a proposition  $p : \text{Prop}$ .
- Nonempty  $\alpha$  for a type  $\alpha : \text{Type}$ .
- Algebraic structures on a given type (or two types, e. g. vector spaces).



# Type Classes and Notation

We can use type class resolution to resolve the “canonical” structure behind a notation:

```
-- 1. Define the type class
class HasMul ( $\alpha$  : Type) : Type where
  mul :  $\alpha \rightarrow \alpha \rightarrow \alpha$ 

-- 2. Define the notation itself
infixl:65 " *" => HasMul.mul

-- 3. Instantiate the type class
instance : HasMul Nat := { mul := Nat.mul }

-- 4. Profit
#eval 5 * 2 -- outputs 10
```

# Be Careful with Type Class Instances

- Type class instance resolution happens silently, so we do not automatically get feedback on which type class Lean found.
- It is good style to make sure only one instance exists for each set of parameters or they are at least equal.
- We can print the name of the instance with the command `#synth HasMul Nat` .