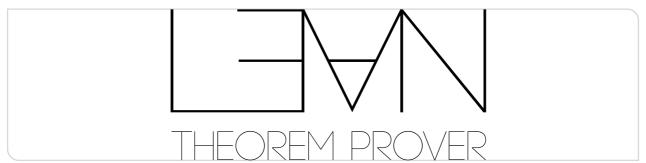




### Theorembeweiserpraktikum

#### **Decidability and 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 ist 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  $p \lor \neg p$  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!<sup>1</sup> This prevents our definitions from depending on *which* proof of a premise we give.

 $<sup>^1</sup>$ Exception: We can always match propositions with only one constructor and no type valued constructor arguments, e.g. And .

### The Law of Excluded Middle



- The only thing that stands between us and our fame is an instance of something like RH V ¬RH.
- We need to choose our poison:
  - Get better at analytic number theory and either prove or refute the Riemann hypothesis.
  - 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 ¬(zero = succ n).





Let's give Lean something tougher to chew on:

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

■ This is how if ... then ... else ... is defined:

```
def ite (c : Prop) [h : Decidable c] (t e : α) : α :=
  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 => ...
```





- Lean's way to automatically track closure properties is by type classes.
- Using type classes happens in three steps:
  - Mark an inductive type, proposition, or structure as class (in place of structure in the latter case)
  - 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.
  - 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.





- Decidable p for a proposition p: Prop.
- Nonempty α for a type α: 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 (α : Type) : Type where
  mul:\alpha\to\alpha\to\alpha
#check @HasMul.mul -- Prints HasMul.mul : \{\alpha : Type\} \rightarrow [self : HasMul \ \alpha] \rightarrow \alpha \rightarrow \alpha \rightarrow \alpha
-- 2. Define the notation itself
infix1:65 " *' " => HasMul.mul
-- 3. Instantiate the type class
instance : HasMul Nat := { mul := Nat.mul }
-- 4. Profit
#eval 5 *' 2 -- outputs 10
```





- Type class instance resolution happens silently, so we do not automatically get feedback on which type class instance 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 .