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Faculty of Mathematics and Computer Science

Bachelor Thesis

Introduction to Formal Mathematics in Lean with an example in Topology

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Declaration

I hereby declare that this thesis is my own work, and that no other sources have been used except those indicated in the bibliography. I confirm that generative AI tools were not used in developing any part of this thesis, though they may have been used for preliminary research purposes only, and flow refinement. Place, Date Signature

Abstract

This thesis serves as an introduction to formal mathematics using the Lean proof assistant. After a brief overview of the Curry–Howard correspondence, we explore how mathematical structures and properties are defined in Lean. Finally, we present a formalization of the topologist's sine curve, which has been merged into the Mathlib library as a modest contribution to the broader Lean community.

During the work on this thesis, I have explored new concepts in both mathematics and computer science, starting from logic and type theory within the Curry-Howard correspondence. The practice of formal and constructive mathematics has influenced my approach to mathematical reasoning. In building the rational numbers, I explored their algebraic construction using quotients, which is reflected in Lean through quotient types. I further examined how algebraic structures such as groups and rings are defined using structures and type classes. For more technical depth, I studied filters to generalize the notion of convergence in topology. The formalization of the topologist's sine curve has deepened my understanding of connectedness, closures, and continuity.

The full code accompany this project is available [here].

Acknowledgments

I would like to express my sincere gratitude to Prof. David Loeffler for the consistent support. His mentorship has been particualary beneficial in enlightening my path through formal mathematics, shaping the thesis and giving me a chance to actually contribute to Lean community.

Moreover, I deeply thank FernUni for the opportunity to pursue my studies. I feel honored to have been able to study mathematics at this stage of my life, through a flexible and high-quality program.

I hope to continue my studies in the future.

Contents

Chapter 1

Introduction

This serves as a brief starting point for understanding how mathematical proofs can be formalized in Lean, as well as being an introduction to the language itself. Lean is both a **functional programming language** and a **theorem prover**. We'll focus primarily on its role as a theorem prover. But what does this mean, and how can that be achieved?

A programming language defines a **set of rules, semantics, and syntax** for writing programs. To achieve a goal, a programmer must write a program that meets given specifications. There are two primary approaches: **program derivation** and **program verification** ([NPS90] Section 1.1). In **program verification**, the programmer first writes a program and then proves it meets the specifications. This approach checks for errors at **run-time**, when the code executes. In **program derivation**, the programmer writes a proof that a program with certain properties exists, then extracts a program from that proof. This approach enables specification checking at **compilation-time**, catching errors while typing, thus, before execution. This distinction corresponds to **dynamic** versus **static type systems**. Most programming languages combine both approaches; providing basic types for annotation and compile-time checking, while leaving the remaining checks to be performed at runtime.

Example 1.0.1 *In a dynamically typed language, like JavaScript, variables can change type after they are created. For example, a variable defined as a number can later be reassigned to a string:*

```
let price = 100; // Javascript recognizes this variable as a number
price = "100";   // "100" transform the number 100 to a string
```

TypeScript is a statically typed superset of JavaScript. Unlike JavaScript, it performs type checking at compile time. This means we can prevent the previous behavior, while writing our code, simply by adding a type annotation:

```
let price: number = 100;
price = "100";  // Error: Type ’string’ is not assignable to type
’number’
```

Now converting a variable with type annotation number to a string results into a compile time error.

Nonetheless, TypeScript, even though it has a sophisticated type system, cannot fully capture complex mathematical properties. As well as for the most programming languages, program specifications can only be enforced at runtime. Lean, by contrast, uses a much more powerful type system that enables it to express and verify mathematical statements with complete rigor, fully during compilation time. This makes it particularly suitable as a **theorem prover** for formalizing mathematics.

Lean's type system is based on **dependent type theory**, specifically the **Calculus of Inductive Constructions** (CIC) with various extensions. It's important to note that **type theory** is not a single, unified theory, but rather a family of related theories with various extensions, ongoing developments, and rich historical ramifications. Type theory emerged as an alternative foundation for mathematics, addressing paradoxes that arose in naive set theory. Consider Russell's famous paradox: let $S = \{x \mid x \notin x\}$ be the set of all sets that do not contain themselves. This construction is paradoxical, leading to the contradiction $S \in S \iff S \notin S$. Type theory resolves such issues by working with **types** as primary objects rather than sets, and by restricting which constructions are well-formed.

Dependent type theory, the framework underlying Lean, extends basic type systems by allowing types to depend on values. For instance, one can define the type of vectors of length n, where n is a value (a natural number). This capability makes dependent type theory particularly expressive for formalizing mathematics.

Various proof assistants have been developed based on different variants of type theory, including Agda, Coq, Idris, and Lean. Each system makes different design choices regarding which rules and features to include. Lean adopts the **Calculus of Inductive Constructions**, which extends the Calculus of Constructions, introduced in Coq, with **inductive types**. Inductive types allow for the definition of compound types from primitives ones such as **structures**, natural numbers, lists, and trees. Another important addition in Lean are **quotient types**, which facilitate working with equivalence relations.

A fundamental design feature of Lean is its type structure, where **Prop** (the proposition type) plays a special role and exhibits **proof irrelevance**. Proof irrelevance means that all proofs of a given proposition are treated as definitionally equivalent in type theory. What matters is simply whether a proposition is provable, not which specific proof is provided. This separation between propositions (**Prop**) and (**Type**) was first introduced in **N.G. de Bruijn's AUTOMATH system** (1967) ([Tho99], Section 9.1.4, page 334). For our purposes, we do not need to delve deeply into the theoretical foundations; instead, we will introduce the relevant concepts as needed while working with Lean.

1.1 First Steps in Lean

In the language of type theory, and by extension in Lean, we write `x : X` to mean that x is a **term** of type X. For example, `2 : ℕ` annotates 2 as a natural number, or more precisely, as a term of the natural number type. Lean has internally defined types such as `Nat` or `ℕ` (you can type `\Nat` to get the Unicode symbol). The command `#check` allows us to inspect the type of any espression, term or variable.

Example 1.1.1

```
#check 2 -- 2 : Nat
#check 2 + 2 -- 2 + 2 : Nat
```

*[Try this example in Lean Web Editor] By following the link, you can try out the code in your browser. Lean provides a dedicated **infoview** panel on the right side. Position your cursor after `#check 2`, and the infoview will display the output `2 : Nat`. This dynamic interaction, where the infoview responds to your cursor position, is what makes Lean an **interactive theorem prover**. As you move through your code, the infoview continuously updates, showing computations, type information, and proof states at each location.*

At first glance, one might be tempted to view the colon notation as analogous to the membership symbol ∈ from set theory, treating types as if they were sets. While this intuition can be helpful initially, type theory offers a fundamentally richer perspective. The crucial insight is the **Curry-Howard isomorphism**, also known as the **propositions-as-types** principle. This correspondence establishes a deep connection between mathematical proofs and programs. **Propositions correspond to types**, and **proofs correspond to terms** inhabiting those types. Under this interpretation, a term $x : X$ can be, as well be understood as a **computational object**: x is a program or data structure of type X. Lean is a concrete realization of the propositions-as-types principle, proving a theorem, within the language, amounts to constructing a term of the appropriate type. When we write `theorem_name : Proposition`, we are declaring that `theorem_name` is a proof (term) of `Proposition` (type). For example, consider proving that $2 + 2 = 4$.

Example 1.1.2

```
theorem two_plus_two_eq_four : 2 + 2 = 4 := rfl
```

Lean's syntax is designed to resemble the language of mathematics. Here, we use the `theorem` *keyword to encapsulate our proof, giving it the name* `two_plus_two_eq_four`*. This allows us to reference and reuse this result later in our code. After the semicolon,* `:`*, we introduce the statement;* `2 + 2 = 4`*. The* `:=` *operator expects the proof term that establishes the theorem's validity. The proof itself consists of a single term:* `rfl` *(short for* ***reflexivity****). This is a proof term that works by* ***definitional equality****, Lean's kernel automatically reduces both sides of the equation to their normal (definitional) form and verifies they are identical. Since* $2+2$ *computes to* 4*, the proof succeeds immediately. We can now use this theorem in subsequent proofs. For instance:*

```
example : 1 + 1 + 1 + 1 = 4 := two_plus_two_eq_four
```

Well, this example is simple enough for Lean to evaluate by itself: `1 + 1 + 1 + 1 = 2 + 2 = 4` *and conclude with* `two_plus_two_eq_four`*. Actually,* `rfl` *would solve the equation similarly, so this is just applying* `rfl` *again (it's a bit of cheating). Here, I used* `example`*, which is handy for defining anonymous expressions for demonstration purposes. Before diving into the discussion, here is another keyword* `def`*, used to introduce definitions and functions.*

```
def addOne (n : Nat) : Nat := n + 1
```

This definition expects a natural number as its parameter, written `(n : Nat)` *and returns a natural number.*

Let's now turn to how logic is handled in Lean and how the Curry-Howard isomorphism is reflected concretely.

Chapter 2

Logic and Proposition as Types

2.1 First Order Logic

Logic is the study of reasoning, branching into various systems. We refer to **classical logic** as the one that underpins much of traditional mathematics. It's the logic of truthtables. We first introduce **propositional logic**, which is the simplest form of classical logic. Later we will extend this to **predicate (or first-order) logic**, which includes **predicates** and **quantifiers**. In this setting, a **proposition** is a statement that is either true or false, and a **proof** is a logical argument that establishes the truth of a proposition. Propositions can be combined with logical **connectives** such as "and" ($\wedge$), "or" ($\vee$), "not" ($\neg$),"false" ($\bot$), ,"true" ($\top$) "implies" ($\Rightarrow$), and "if and only if" ($\Leftrightarrow$). These connectives allow the creation of complex or compound propositions. Here how connectives are defined in Lean:

Example 2.1.1 (LogicaL connectives in Lean)

```
#check And (a b : Prop) : Prop
#check Or (a b : Prop) : Prop
```

Prop is the proposition type mentioned before.

Logic is often formalized through a framework known as the **natural deduction system**, developed by Gentzen in the 1930s ([Wad15]). This approach brings logic closer to a computable, algorithmic system. It specifies rules for deriving **conclusions** from **premises** (assumptions from other propositions), called **inference rules**.

Example 2.1.2 (Deductive style rule) *Here is an hypothetical example of inference rule ([NPS90], page 35).*

$$\frac{P_1 \qquad P_2 \qquad \cdots \qquad P_n}{C}$$

Where the $P_1, P_2, \ldots, P_n$, above the line, are hypothetical premises and, the hypothetical *conclusion C is below the line.*

The inference rules needed are, **introduction rules** wich specify how to form compound propositions from simpler ones, and **elimination rules** needed to derive information about them. Let's look at how we can define some connectives, first using natural deduction (from [Tho99], Section 1.1).

Conjunction ($\wedge$)

Introduction Rule

$$\frac{A \qquad B}{A \wedge B}\ \wedge\text{-Intro}$$

Elimination Rule

$$\frac{A \wedge B}{A}\ \wedge\text{-Elim}_1 \qquad\qquad \frac{A \wedge B}{B}\ \wedge\text{-Elim}_2$$

Disjunction ($\vee$)

Introduction Rule

$$\frac{A}{A \vee B}\ \vee\text{-Intro}_1 \qquad\qquad \frac{B}{A \vee B}\ \vee\text{-Intro}_2$$

Elimination (Proof by cases)

$$\frac{A \vee B \qquad [A] \vdash C \qquad [B] \vdash C}{C}\ \vee\text{-Elim}$$

Implication ($\rightarrow$)

Introduction Rule

$$\frac{[A] \vdash B}{A \rightarrow B}\ \rightarrow\text{-Intro}$$

Elimination (Modus Ponens)

$$\frac{A \rightarrow B \qquad A}{B}\ \rightarrow\text{-Elim}$$

Notation 2.1.3 *We use $A \vdash B$ (called turnstile) to designate a deduction of B from A. It is used in judgments and type theory with the meaning of "entails that". The square brackets around a premise $[A]$ mean that the premise A is meant to be **discharged** at the conclusion. The classical example is the introduction rule for the* *implication connective. To prove an implication $A \to B$, we assume A (shown as $[A]$), derive B under this assumption, and then discharge the assumption A to conclude that $A \to B$ holds without the assumption.*

2.2 Primitive Types

Type theory employs this porocedure too, by referring to deduction rules as **judments**. A type judgment has the form $\Gamma \vdash t : T$, meaning: under **context** Γ (a list of typed variables), the term t has type T. Using formal inference rules in the type judgment system, such as **introduction** and **elimination** rules, we can construct new compound types from existing ones.

Example 2.2.1 (Judgment style rule)

$$\frac{\Gamma \vdash \quad p_1 : P_1 \quad p_2 : P_2 \quad \cdots \quad P_n}{C}$$

Technically, there are two more inference rules that we will not consider in this setting: **formation rules**, used to declare that a type is well-defined, and **computation rules**, which specify how a term will be evaluated. Moreover, without going too deep into the jargon, one specific judgment is $\Gamma \vdash A \equiv B$ type, which means "types A and B are **judgmentally (or definitionally) equal** in context Γ." Similarly for terms, $\Gamma \vdash t_1 \equiv t_2 : A$ means "terms t_1 and t_2 are judgmentally equal of type A in context Γ."

Brief explanation of equality in type theory In Lean, the operator `:=` stands for definitional equality and is used by the kernel to verify proof equality. A mathematician proving a theorem applies a series of **reduction rules** to simplify the proof. Similarly, one can think of this computational reduction process in formal verification. However, a computer cannot simply employ the same informal approach to equality that a mathematician might use intuitively. A rigorous explanation of definitional equality goes beyond the scope of this thesis. To state it simply: **two terms are definitionally equal when they reduce to the same normal for**. A **normal for** represents the most reduced state of a term, obtained by systematically applying a sequence of reduction rules until no further reductions are possible. In contrast, **propositional equality** requires additional logical bridges and propositions to establish equivalence. Because it is grounded in logical propositions rather than pure computation, propositional equality is not directly computable by the type checker and must be explicitly proved.

Let's now construct new types from given types A and B.

Product Type As a fundamental example, $A \times B$ denotes the type of pairs (a, b) where $a : A$ and $b : B$, called the **product type**.

Introduction Rule (pairing)

$$\frac{a : A \qquad b : B}{(a, b) : A \times B}$$

In Lean:

```
Prod.mk a b : Prod A B    -- or A × B
(a, b) : A × B
⟨a, b⟩ : A × B
```

Elimination Rules (projections)

$$\frac{p : A \times B}{\mathsf{fst}(p) : A} \qquad\qquad \frac{p : A \times B}{\mathsf{snd}(p) : B}$$

In Lean:

```
  p.1 : A        -- or Prod.fst p
  p.2 : B        -- or Prod.snd p
```

Sum Type The **sum type** $A + B$ (also called a coproduct or disjoint union) consists of values that are either of type A (tagged with inl) or of type B (tagged with inr).

Introduction Rules (injections)

$$\frac{a : A}{\mathsf{inl}(a) : A + B} \qquad\qquad \frac{b : B}{\mathsf{inr}(b) : A + B}$$

In Lean:

```
Sum.inl a : Sum A B    -- or A ⊕ B
Sum.inr b : Sum A B
```

Elimination Rule (case analysis)

$$\frac{p : A + B \qquad f : (A \implies C) \qquad g : (B \implies C)}{\mathsf{cases}(p, f, g) : C}$$

In Lean:

```
example (p : Sum A B) (f : A → C) (g : B → C) : C := by
  cases p with
  | inl x => f x
  | inr y => g y
```

Function Types The type of the form $A \to B$, used in the sum elimination rule represents functions from A to B.

Introduction Rule (function application or lambda abstraction)

$$\frac{x : A \vdash \Phi : B}{f : A \to B}$$

Where f is a function that maps any element $x : A$ to an element $\Phi : B$. In Lean, lambda abstraction is written using `fun` or λ:

```
def identityFun (A : Type) : A → A := fun x => x
```

Elimination Rule (application)

$$\frac{f : A \to B \qquad a : A}{f(a) : B}$$

In Lean, function application is written using juxtaposition:

```
example (f : A → B) (a : A) : B := f a
```

Functions are a primitive concept in type theory. We can **apply** a function $f : A \to B$ to an element $a : A$ to obtain an element of B, denoted $f(a)$. In type theory, it is common to omit the parentheses and write the application simply as $f\,a$.

2.3 The Curry Howard Isomorphism

We have been preparing for this argument, and the reader will have surely noticed a strong similarity when defining logical connectives using deduction rules; they are remarkably similar to types constructed using type judgments. For instance, function types can be seen as implications. This is not a coincidence, but rather a fundamental theorem first proven by Haskell Curry and William Howard. It forms the core of type theory and establishes a deep connection between logic, computation, and mathematics. **Implication** $(P \Rightarrow Q)$ corresponds to the **function type** $(P \to Q)$. A proof of an implication is a function that transforms any proof of the premise into a proof of the conclusion. **Conjunction** $(P \land Q)$ corresponds to the **product type** $(P \times Q)$. A proof of a conjunction consists of a pair containing proofs of both conjuncts. **Disjunction** ($P \lor Q$) corresponds to the **sum type** ($P + Q$). A proof of a disjunction is either a proof of the first disjunct or a proof of the second disjunct. Same goes for the rest of the connectives. Lean uses inference rules and type judgments as well as computing connectives using each related type. For instance, $A \land B$ can be represented as `And(A, B)` or `A ∧ B`. Its introduction rule is constructed by `And.intro _ _` or simply `⟨_, _⟩` (underscores are placeholders). The pair $A \land B$ can then be consumed using elimination rules `And.left` and `And.right`.

Example 2.3.1 *Let's look at a simple Lean example:*

```
example {a b : Prop} (ha : a) (hb : b) : (a ∧ b) := And.intro ha hb
```

Using brackets `{ }`*, we let Lean infer that* `a` *and* `b` *are propositions (*`Prop`*). The example means that given a proof of* `a` *(*`ha`*) and a proof of* `b` *(*`hb`*) , we can form a proof of* $(a \land b)$*.* `And.intro` *is implemented as:*

```
And.intro : p -> q -> (p ∧ q)
```

It says: if you give me a proof of p *and a proof of* q*, then I return a proof of* $p \land q$*. We therefore conclude the proof by directly giving* `And.intro ha hb`*. Here is another way of writing the same statement:*

```
example (ha : a) (hb : b) : And(a, b) := ⟨ha, hb⟩
```

For a more concrete example, let's look at how proof normalization using a system of inference rules corresponds to computation in Lean. To reduce complexity of a **proof tree** in natural deduction, one, tipically, follows a **top-down** approach, unfolding each component to be proved step by step.

Example 2.3.2 (Associativity of Conjunction) *We prove that* $(A \land B) \land C$ *implies* $A \land (B \land C)$*. First, from the assumption* $(A \land B) \land C$*, we can derive* A*:*

$$\dfrac{\dfrac{(A \land B) \land C}{A \land B}\land E_1}{A}\land E_1$$

Second, we can derive $B \land C$*:*

$$\dfrac{\dfrac{\dfrac{(A \land B) \land C}{A \land B}\land E_1}{B}\land E_2 \qquad \dfrac{(A \land B) \land C}{C}\land E_2}{B \land C}\land I$$

Finally, combining these derivations we obtain $A \land (B \land C)$*:*

$$\dfrac{(A \land B) \land C \vdash A \qquad (A \land B) \land C \vdash B \land C}{A \land (B \land C)}\land I$$

Example 2.3.3 (Lean Implementation) *Let us now implement the same proof in Lean.*

```
theorem and_associative {a b c : Prop} : (a ∧ b) ∧ c → a ∧ (b ∧ c) :=
  fun h : (a ∧ b) ∧ c →
  -- First, from the assumption (a ∧ b) ∧ c, we can derive a:
  have hab : a ∧ b := h.left
  have ha : a := hab.left
  -- Second, we can derive b ∧ c (here we only extract b and c and combine
    them in the next step)
  have hc : c := h.right
  have hb : b := hab.right
  -- Finally, combining these derivations we obtain a ∧ (b ∧ c)
  show a ∧ (b ∧ c) from ⟨ha, ⟨hb, hc⟩⟩
```

We introduce the `theorem` *with the name* `and_associative`*. The type signature* `(a ∧ b) ∧ c → a ∧ (b ∧ c)` *represents our logical implication. Here, we construct the implication proof using a function (following the Curry Howard isomorphism) with the* `fun` *keyword. The* `have` *keyword introduces local lemmas within our proof scope, allowing us to break down complex reasoning into manageable intermediate steps, mirroring our natural deduction proof from before. Just before the keyword* `show`*, the info view displays the following context and goal:*

```
a b c : Prop
h : (a ∧ b) ∧ c
hab : a ∧ b
ha : a
hc : c
hb : b
⊢ a ∧ b ∧ c
```

Resembling type judgments, the goal is juxtaposed after the turnstile (⊢). What comes before it is the current context. Finally, `show a ∧ (b ∧ c) from ⟨ha, ⟨hb, hc⟩⟩` *asserts that we are constructing a proof of* `a ∧ (b ∧ c)` *using the term* `⟨ha, ⟨hb, hc⟩⟩`*. The* `show` *keyword makes the proof more readable and ensures that the provided proof term matches the stated goal up to definitional equality. As mentioned already, two types (or terms) are definitionally equal in Lean when they are identical after computation and unfolding of definitions; in other words, when Lean's type checker can mechanically verify they are the same without requiring additional proof steps. Here, the goal* `⊢ a ∧ b ∧ c` *is definitionally equal to* `a ∧ (b ∧ c)` *due to how conjunction associates, so* `show` *accepts this statement. If we had tried to use* `show` *with a type that was only propositionally equal but not definitionally equal, Lean would reject it.*

2.4 Predicate Logic and Dependency

To capture more complex mathematical ideas, we extend our system from propositional logic to **predicate logic**. A **predicate** is a statement or proposition that depends on a variable. In propositional logic we represent a proposition simply by P. In predicate logic, this is generalized. A predicate is written as $P(a)$, where a is a variable. Notice that a predicate is just a function. This extension allows us to introduce **quantifiers**: ∀ ("for all") and ∃ ("there exists"). These quantifiers express that a given formula holds either for every object or for at least one object, respectively. In Lean if α is any type, we can represent a predicate `P` on α as an object of type $\alpha \to$ `Prop`. Thus given an `x :` α (an element with type α) `P(x) : Prop` would be representative of a proposition holding for `x`. We can give an informal reading of the quantifiers as infinite logical operations:

$$\begin{aligned}\forall x.\, P(x) &\equiv P(a) \land P(b) \land P(c) \land \ldots \\ \exists x.\, P(x) &\equiv P(a) \lor P(b) \lor P(c) \lor \ldots\end{aligned}$$

The dot symbol following the quantifier, as in $\forall x.$,, binds every occurrence of the variable x in the expression $P(x)$. The expression $\forall x.\, P(x)$ can be understood as a generalized form of conjunction. It expresses that P holds for all possible values of x. Similarly, $\exists x.\, P(x)$ is a generalized disjunction, expressing that P holds for at least one value of x. Under the Curry-Howard isomorphism, universal quantifiers correspond to **dependent function types** (also called Pi types, written Π), while existential quantifiers correspond to **dependent pair types** (also called Sigma types, written Σ). These are constructs from dependent type theory, which provides a way to interpret predicates or, more generally, types depending on some data or variable. Technically the correspondence is not that immediate and actually Lean implements, `Exists` and `Forall` using as inductive types (this follows also for the previously defined connectives). This time we are not going to involve deduction rules or type judgments. Instead, we will extend the isomorphism to quantifiers directly by presenting the Lean syntax.

Example 2.4.1 (Quantifiers in Lean) *Lean expresses quantifiers as follows:*

```
variable (X : Type) (P : X → Prop)
 (∀ (x : X), P x) -- ∀ corresponds to Pi type Π
 (∃ (x : X), P x) -- ∃ corresponds to Sigma type Σ
```

Example 2.4.2 (Universal introduction in Lean) *The* ***universal introduction rule*** *allows us to prove* $\forall x, P(x)$ *by proving* $P(x)$ *for an* ***arbitrary*** x*. In Lean, this corresponds to constructing a function:*

```
example : ∀ n : Nat, n ≥ 0 :=
  fun n => Nat.zero_le n
```

From the `Nat` *module in Lean, we use* `zero_le`*, a built-in theorem that already proves the statement.*

Example 2.4.3 (Universal elimination in Lean) *The* ***universal elimination rule*** *allows us to instantiate a universally quantified statement with a specific value. In Lean, this is simply function application:*

```
example (h : ∀ n : Nat, n ≥ 0) : 5 ≥ 0 :=
  h 5
```

Example 2.4.4 (Existential introduction in Lean) *When introducing an* ***existential*** *proof, we need a* ***pair*** *consisting of a witness and a proof that this witness satisfies the statement.*

```
example (x : Nat) (h : x > 0) : ∃ y, y < x :=
  ⟨0, h⟩
```

Notice that `⟨0, h⟩` *is a product type holding data (the witness) and a proof that it satisfies the property.*

Example 2.4.5 (Existential elimination in Lean) *The* ***existential elimination rule*** *(*`Exists.elim`*) allows us to prove a proposition* Q *from* $\exists x, P(x)$ *by showing that* Q *follows from* $P(w)$ *for an* ***arbitrary*** *value* w*. The existential quantifier can be interpreted as an infinite disjunction, so existential elimination naturally corresponds to a* ***proof by cases*** *(with a single case). In Lean, this is done using* ***pattern matching*** *with* `cases`*:*

```
example (h : ∃ n : Nat, n > 0) : ∃ n : Nat, n > 0 := by
  cases h with
  | intro witness proof => ⟨witness, proof⟩
```

2.5 Constructive Mathematics

Mathematicians have traditionally worked within **classical logic**, using **sets** as the primary means of structuring mathematical objects. In contrast, **type theory** does not take sets as its primitive notion, nor is it built by first applying logic and then adding structure. Instead, logic is internal to type theory and is based on **constructive** (or **intuitionistic**) logic, introduced by Brouwer and formalized by Heyting (see, e.g., [GTL89], Ch 1, page 6). A major point of departure from classical logic is that, in constructive logic, statements cannot simply be classified as true or false; their truth depends on whether a proof exists. There are many conjectures, such as the Riemann Hypothesis, for which we do not yet know whether a proof or disproof exists, so we cannot say whether they are true or false. Consequently, constructive logic does not universally accept principles such as the **axiom of choice** or the **law of excluded middle** (every proposition is either true or false) as axioms. As a consequence, proof by contradiction does not work in this setting without additional justification. Constructive logic emphasizes that a statement is only considered true if we can explicitly provide a **witness** for it. This is what makes constructive mathematics inherently **computable**. We also emphasized that, constructively, a proof of existence consists of a pair: a witness together with a proof that the stated property holds for that witness.

Example 2.5.1 (Constructive existence proof) *We give a **constructive proof** in Lean that there exist natural numbers a and b such that $a + b = 7$:*

```
example : ∃ a b : Nat, a + b = 7 := ⟨3, 4, rfl⟩
```

*To prove an existential statement, we provide **witnesses** (concrete values $a = 3$ and $b = 4$) and a **proof** that the predicate holds ($3 + 4 = 7$).*

In classical mathematics, one might attempt a proof by contradiction. However, this approach is not directly accepted in constructive mathematics, as it doesn't provide explicit witnesses for the claimed objects. Nonetheless, while constructive at its core, Lean allows users to invoke classical principles, such as contraposition or proof by contradiction, through **tactics** ((to be explained later)) like `exfalso`.

Example 2.5.2 (Reasoning from false) *Here is an example of deriving any proposition from a contradiction:*

```
example (p : Prop) (h : False) : p := by
  exfalso
  exact h
```

This example takes a proposition p to prove and a false hypothesis h. The `exfalso` tactic transforms the goal into $\vdash$ False, meaning we now need to derive a contradiction. Since we already have a false hypothesis h, we can provide it using the `exact` tactic.

Chapter 3

Modeling Mathematical Objects

It is interesting to note that a relation, in type theory, can be expressed as a function: `R : α → α → Prop`. Similarly, when defining a predicate (`P : α → Prop`) we must first declare `α : Type` to be some arbitrary type. This is what is called **polymorphism**, more specifically **parametrical polymorphism**. A canonical example is the identity function, written as $\alpha \to \alpha$, where α is a type variable. It has the same type for both its domain and codomain, this means it can be applied to booleans (returning a boolean), numbers (returning a number), functions (returning a function), and so on. In the same spirit, we can define a transitivity property of a relation, for a given type α, as follows:

```
def Transitive (α : Type) (R : α → α → Prop) : Prop :=
  ∀ x y z, R x y → R y z → R x z
```

To use `Transitive`, we must provide both the type α and the relation itself. For example, here is a proof of transitivity for the less-than relation on $\mathbb{N}$ (in Lean `Nat` or $\mathbb{N}$):

```
theorem le_trans_nat : Transitive Nat (· ≤ · : Nat → Nat → Prop) :=
  fun x y z h1 h2 => Nat.le_trans h1 h2 -- another lemma provided by Lean
```

Notice that we used a function to discharge the universal quantifiers required by transitivity. Looking at this code, we immediately notice that explicitly passing the type argument `Nat` is somewhat repetitive. Lean allows us to omit it by letting the type inference mechanism fill it in automatically. This is achieved by using **implicit arguments** with curly brackets:

```
def Transitive {α : Type} (R : α → α → Prop) : Prop :=
  ∀ x y z, R x y → R y z → R x z
theorem le_trans_nat' : Transitive (· ≤ · : Nat → Nat → Prop) :=
  fun x y z h1 h2 => Nat.le_trans h1 h2
```

Let us now revisit the transitivity proof, but this time for the less-than-equal relation on the rational numbers (`Rat` or $\mathbb{Q}$) instead.

```
import Mathlib

theorem rat_le_trans : Transitive (· ≤ · :  Rat → Rat → Prop) :=
  fun _ _ _ h1 h2 => Rat.le_trans h1 h2
```

Here, `Rat.le_trans` is the transitivity lemma for ≤ on rational numbers, provided by Mathlib. We import Mathlib to access `Rat` and `le_trans`. Mathlib is the community-driven mathematical library for Lean, containing a large body of formalized mathematics and ongoing development. It is the defacto standard library for proving in Lean ([Lea20]). We will dig into it as we go along. The underscores indicate unnamed variables that we do not use later. If we had named them, say `x y z`, then: `h1` would be a proof of `x ≤ y`, `h2` would be a proof of `y ≤ z`, and `Rat.le_trans h1 h2` produces a proof of `x ≤ z`. The `Transitive` definition is imported from Mathlib and similarly defined as before.

Example 3.0.1 *The code can be made more readable using* ***tactic mode****. In this mode, you use tactics, commands provided by Lean or defined by users, to carry out proof steps succinctly, avoid code repetition, and automate common patterns. This often yields shorter, clearer proofs than writing the full term by hand.*

```
import Mathlib

theorem rat_le_trans : Transitive (· ≤ · : Rat → Rat → Prop) := by
  intro x y z hxy hyz
  exact Rat.le_trans hxy hyz
```

This proof performs the same steps, but is much easier to read. Using `by` *we enter Lean's tactic mode. Move your cursor just after* `by`*. The goal is initially displayed as* `⊢ Transitive fun x1 x2 ↦ x1 ≤ x2`*. The tactic* `intro` *is mainly used to introduce variables or hypotheses corresponding to universal quantifiers into the context (essentially deconstructing universal quantifiers and implications). Now position your cursor just before* `exact` *and observe the info view again. The goal is now* `⊢ x ≤ z`*, with the context showing the variables and hypotheses introduced by the previous tactic. The* `exact` *tactic closes the goal, by supplying the term* `Rat.le_trans hxy hyz` *that exactly matches the goal (the specification of* `Transitive`*). You can hover over each tactic to see its definition and documentation.*

3.1 Exploring Mathlib (The `Rat` structure)

In these examples we cheated and have used predefined lemmas such as `Nat.le_trans` and `Rat.le_trans`, just to simplify the presentation. We can now dig into the implementation of these lemmas. Let's look at the source code of `Rat.le_trans`. The Mathlib 4 documentation website is at `https://leanprover-community.github.io/`

mathlib4_docs, and the documentation for Rat.le_trans is at https://leanprover-community.github.io/mathlib4_docs/Mathlib/Algebra/Order/Ring/Unbundled/Rat.html#Rat.le_trans. Click the "source" link there to jump to the implementation in the Mathlib repository. In editors like VS Code, you can also jump directly to the definition (Ctrl+click; Cmd+click on macOS). Another way to check source code is by using #print Rat.le_trans.

```
variable (a b c : Rat)
lemma le_trans (hab : a ≤ b) (hbc : b ≤ c) : a ≤ c := by
  rw [Rat.le_iff_sub_nonneg] at hab hbc
  have := Rat.add_nonneg hab hbc
  simp_rw [sub_eq_add_neg, add_left_comm (b + -a) c (-b), add_comm (b +
    -a) (-b), add_left_comm (-b) b (-a), add_comm (-b) (-a),
    add_neg_cancel_comm_assoc, ← sub_eq_add_neg] at this
  rwa [Rat.le_iff_sub_nonneg]
```

The proof uses several tactics and lemmas from Mathlib. The rw or rewrite tactic is very common and sintactically similar to the mathematical practice of rewriting using equalities that hold by definitional equality. In this case, with at, we use it to rewrite the hypotheses hab and hbc by another Mathlib's lemma Rat.le_iff_sub_nonneg. This states that for any two rational numbers x and y, x ≤ y is equivalent to 0 ≤ y - x. Thus we now have the hypotheses tranformerd to :

```
  hab : 0 ≤ b - a
  hbc : 0 ≤ c - b
```

The have tactic introduces an intermediate result. If you omit a name, Lean assigns it the default name this. In our situation, from hab : a ≤ b and hbc : b ≤ c we can derive that b - a and c - b are nonnegative, hence their sum is nonnegative:

```
  this : 0 ≤ b - a + (c - b)
```

The most involved step uses simp_rw to simplify the expression via a sequence of existing Mathlib lemmas. The tactic simp_rw is a variant of rw but performs another tactic called simp to get inside each binder. For instance, in the case of universal quantifiers $\forall x, P(x)$, the variable x is a binder, and simp_rw will penetrate inside it to simplify $P(x)$ for all x. Unlike rw, which works by definitional equality, simp is a more powerful tactic that tries to simplify a goal by applying a set of rules tagged as **simp lemmas**. After these simplifications we obtain:

```
  this : 0 ≤ c - a
```

Clearly, the proof relies mostly on Rat.add_nonneg. Mathlib defines Rat as an instance of a linear ordered field, implemented via a normalized fraction representation: a pair of integers (numerator and denominator) with positive denominator and coprime numerator and denominator ([Lea25]). To achieve this, it uses a **structure**.

In Lean, a structure is a dependent record (or product type) type used to group together related fields or properties as a single data type. Unlike ordinary records, the type of later fields may depend on the values of earlier ones. Defining a structure automatically introduces a constructor (usually mk) and projection functions that retrieve (deconstruct) the values of its fields. Structures may also include proofs expressing properties that the fields must satisfy.

```
structure Rat where
  mk' ::
  num : Int
  den : Nat := 1
  den_nz : den ≠ 0 := by decide
  reduced : num.natAbs.Coprime den := by decide
```

In order to work with rational numbers in Mathlib, we use the `Rat.mk'` constructor to create a rational number from its numerator and denominator, if omitted, by default would be `Rat.mk`. The fields `den_nz` and `reduced` are proofs that the denominator is nonzero and that the numerator and denominator are coprime, respectively. These proofs are automatically generated by Lean's `decide` tactic, which can We will not delve into the type-theoretic formalization of decidability, as it lies somewhat outside the scope of standard mathematical practice. Roughly speaking, however, a proposition is decidable if Lean can run a computation that reduces the statement to `true` or `false`. We refer the interested reader to [NPS90, Section 21.4] for a deeper understanding.

Example 3.1.1 *Here is how we can define rational numbers in Lean.*

```
def half : Rat := Rat.mk' 1 2 -- or (1 / 2 : Rat)
def third : Rat := Rat.mk' 1 3 -- or (1 / 3 : Rat)
```

When working with rational numbers, or more generally with structures, we must provide the required proofs as arguments to the constructor (or Lean must be able to ensure them). For instance `Rat.mk' 1 0` or `Rat.mk' 2 6` would be rejected. In the case of rationals, Mathlib unfolds the definition through `Rat.numDenCasesOn`. This principle states that, to prove a property of an arbitrary rational number, it suffices to consider numbers of the form `n \ d`, with `d > 0` and `gcd n d = 1`. This reduction allows mathlib to transform proofs about $\mathbb{Q}$ into proofs about $\mathbb{Z}$ and $\mathbb{N}$, and then lift the result back to rationals.

Let's return to `Rat.add_nonneg`, which was the important lemma used in the proof of `Rat.le_trans`. We are going to construct our own simplified implementation of rational numbers from Mathlib's approach, and use it to prove the theorem. However, we will keep the same convention used in Mathlib. Projecting to natural and integers first to return a proof for rationals. Let's start by creating the structure:

```
import Mathlib

structure myPreRat where
  num : Int
  den : Nat
  den_pos : 0 < den
```

Notice the similarity with Mathlib's definition. You might have observed that we are not including the coprimality condition, and the name myPreRat will become clear later. Our initial focus is to prove myPreRat.add_nonneg. We structure our code as follows:

```
import Mathlib

structure myPreRat where
  num : Int
  den : Nat
  den_pos : 0 < den

namespace myPreRat

lemma add_nonneg (a b : myPreRat) : 0 ≤ a → 0 ≤ b → 0 ≤ a + b := by
  sorry

end myPreRat
```

The namespace keyword is used to define self-contained modules. For instance, outside of its scope, one can refer to add_nonneg as myPreRat.add_nonneg. At this stage, Lean will complain because we haven't yet defined the operations ≤ or + for our type myPreRat. Let's address this next.

Operations such as addition or less-than-or-equal need to be defined for each type (addition for natural numbers, less-or-equal for integers, and so on). This is achieved through **type classes**. Type classes provide a powerful and flexible way to specify properties and operations that can be shared across different types called **ad hoc polymorphism**. A standard example for ad hoc polymorphism ([WB89]) is overloaded multiplication: the same symbol * denotes multiplication of integers (e.g., 3 * 3) and of floating-point numbers (e.g., 3.14 * 3.14). Lean exposes type classes for common operations like:

```
class Add (α : Type u) where
  add : α → α → α

class LE (α : Type u) where
```

```
  le : α → α → Prop -- less or equal operartion (≤)
```

Type classes are, under the hood, just structures where you similarly describe fields for each operation. The important features of type classes are type inference and **instances**. When we extend a type with an instance of a type class, Lean will automatically apply the new properties defined by the class to it. For example we can register addition for naturals or integers:

```
instance : Add Nat where
  add := Nat.add -- addition implementation for natural numbers

instance : Add Int where
  add := Int.add -- addition implementation for integers
```

In our case, we define instances for `myPreRat`:

```
instance : LE myPreRat where
  le r₁ r₂ := r₁.num * ↑r₂.den ≤ r₂.num * ↑r₁.den -- ↑ is a coercion from Nat to Int (to be explained later)

instance : Add myPreRat where
  add r₁ r₂ := {
    num := r₁.num * ↑r₂.den + r₂.num * ↑r₁.den,
    den := r₁.den * r₂.den,
    den_pos := Nat.mul_pos r₁.den_pos r₂.den_pos
  }
```

Once these instances are defined, Lean can automatically infer which operation to use when we write `a + b` or `a ≤ b` for values of type `myPreRat`. We also want to define zero within our definition of rational numbers:

```
def zero : myPreRat := { num := 0, den := 1, den_pos := by decide }
instance : OfNat myPreRat 0 where
  ofNat := zero
```

With `OfNat` typeclass we are telling Lean that, in a context expecting `myPreRat`, the number `0` must be transfomed into our `zero` definition. Let's finally address the proof:

```
lemma add_nonneg (a b : myPreRat) : 0 ≤ a → 0 ≤ b → 0 ≤ a + b := by
  simp only [nonneg_iff]
  intro ha hb
  apply Int.add_nonneg
  · exact Int.mul_nonneg ha (Int.natCast_nonneg b.den)
  · exact Int.mul_nonneg hb (Int.natCast_nonneg a.den)
```

We first simplify using `nonneg_iff` (to be defined), which states that a rational number is non-negative if and only if its numerator is non-negative. This transforms the goal to ⊢ `0 ≤ a.num → 0 ≤ b.num → 0 ≤ (a + b).num`. We then introduce the two hypotheses `ha : 0 ≤ a.num` and `hb : 0 ≤ b.num` using `intro`. Now we only need to prove that the numerator of their sum is non-negative. By our definition of addition for `myPreRat`, the numerator of `a + b` is `a.num * ↑b.den + b.num * ↑ a.den`. Since the numerator is an integer, we can use lemmas for integers defined in Mathlib. We use `apply` to match our goal with the lemma `Int.add_nonneg` (the relative lemma on integers), which states that the sum of two non-negative integers is non-negative. The `apply` tactic works backwards: given a goal ⊢ `G` and a lemma `lemma : P → Q → G`, it replaces the goal with two new subgoals ⊢ `P` and ⊢ `Q`. In our case, `Int.add_nonneg` requires proving that both summands are non-negative. We close the first goals with `Int.mul_nonneg ha (Int.natCast_nonneg b.den)`, where `ha` provides the non-negativity of the numerator `a.num`, and `Int.natCast_nonneg b.den` provides the non-negativity of the denominator `b.den`. The `Int.natCast_nonneg` is needed to **casts** `b.den` from `Nat` to `Int` (i am going to discuss casting and coercion in later section). The second goal follows symmetrically.

We only need to examine `nonneg_iff`:

```
lemma nonneg_iff (r : myPreRat) : 0 ≤ r ↔ 0 ≤ r.num := by
  constructor <;> intro h
  · change 0 * r.den ≤ r.num * 1 at h; simp at h; exact h
  · change 0 * r.den ≤ r.num * 1; simp; exact h
```

Since this is a biconditional statement, we use `constructor` to split the proof into two directions. The combinator `<;>` applies the following tactic to all goals generated by the previous tactic, so `<;> intro h` introduces the hypothesis `h` in both directions. For the forward direction, we have `h : 0 ≤ r` and need to prove `0 ≤ r.num`. The `change` tactic unfolds our definition of ≤ for `myPreRat`. Recall that we defined $\texttt{r}_1 \le \texttt{r}_2$ as $\texttt{r}_1\texttt{.num} * \uparrow\texttt{r}_2\texttt{.den} \le \texttt{r}_2\texttt{.num} * \uparrow\texttt{r}_1\texttt{.den}$. When applied to `0 ≤ r`, this becomes `0 * r.den ≤ r.num * 1`. The command `change 0 * r.den ≤ r.num * 1 at h` applies this transformation to the hypothesis `h`. Then `simp at h` simplifies the arithmetic, reducing `0 * r.den` to `0` and `r.num * 1` to `r.num`, giving us `h : 0 ≤ r.num`. Finally, `exact h` completes the proof. The backward direction follows symmetrically. Here the full proof: [link to Lean live]

3.2 Coercions and Type Casting

We extensively used type casting and coercions in this proof, which requires some explanation ([LM20]). In order to translate between types, like ℕ, ℤ, and ℚ, we need to use explicit type casts or rely on automatic coercions. For example, natural numbers (ℕ) can be coerced to integers (ℤ), and integers can be coerced to rational numbers (ℚ). Casting and coercion are related but distinct concepts:

- **Casting** refers to the explicit conversion of a value from one type to another, typically using functions like `Int.cast` or `Nat.cast`. These functions have accompanying lemmas that preserve properties across type conversions, such as `Int.cast_lt` and `Nat.cast_pos`.
- **Coercion**, on the other hand, is a more general mechanism that allows Lean to automatically convert between types when needed. More generally, in expressions like `x + y` where `x` and `y` are of different types, Lean will automatically coerce them to a common type. For example, if `x : ℕ` and `y : ℤ`, then `x` will be coerced to ℤ.

The notation ↑ denotes an explicit coercion (in between cast and coercion). To illustrate the expected behavior of coercion simplification, consider the expression `↑m + ↑n < (10 : ℤ)`, where `m, n : ℕ` are cast to ℤ. The expected normal form is `m + n < (10 : ℕ)`, since `+`, $<$, and the numeral `10` are polymorphic (i.e., they can work with any numerical type such as ℤ or ℕ). The simplification should proceed as follows:

1. Replace the numeral on the right with the cast of a natural number: `↑m + ↑n < ↑(10 : ℕ)`
2. Factor ↑ to the outside on the left: `↑(m + n) < ↑(10 : ℕ)`
3. Eliminate both casts to obtain an inequality over ℕ: `m + n < (10 : ℕ)`

One needs to apply different rewriting rules to achieve waht explained. Anyway, Lean provides tactics like `norm_cast` to simplify expressions involving such coercions. The `norm_cast` tactic normalizes casts by pushing them outward and eliminating redundant coercions, often simplifying proofs significantly by reducing goals to their “native” types.

3.3 Quotients

Back to our rational numbers definition. We have actually made a very bad construction for rational numbers. Let’s look at what gopes wrong:

```
example : myPreRat.mk 2 4 (by decide) ≠ myPreRat.mk 1 2 (by decide) := by
  simp
```

This example proves that `myPreRat.mk 2 4` and `myPreRat.mk 1 2` are not equal, even though mathematically $\frac{2}{4} = \frac{1}{2}$! Indeed, the name `myPreRat` was already alluding to the need for further work. In mathematics, we treat different representations of the same rational number as equivalent through an **equivalence relation** ([Alg19]). We consider fractions like $\frac{1}{2}$, $\frac{2}{4}$, and $\frac{3}{6}$ as belonging to the same equivalence class.

To be more precise, mathematics uses **quotients** to group elements of a set by an equivalence relation. For instance, the equivalence class $[\frac{1}{2}] = \{\dots, -\frac{1}{2}, \frac{1}{2}, \frac{2}{4}, \frac{3}{6}, \dots\}$ represents all fractions equivalent to $\frac{1}{2}$, up to sign. Thus the set of rational numbers is the set of **representatives** $\mathbb{Q} = \{\dots, [\frac{0}{1}], [\frac{1}{1}], [\frac{1}{2}], [\frac{1}{3}], \dots\}$. Algebraically, each rational number can be represented as a pair of integers (a, b) where the second component is non-zero. Moreover, this construction must be "justified" by an equivalence relation $\sim_{\mathbb{Q}}$:

$$\mathbb{Q} = (\mathbb{Z} \times \mathbb{Z}^*)/\sim_{\mathbb{Q}}$$

The equivalence relation for rational numbers (seen as pairs of integers) is defined as:

$$(a, b) \sim_{\mathbb{Q}} (c, d) \iff ad = bc \quad \text{for all } (a, b), (c, d) \in \mathbb{Z} \times \mathbb{Z}^*$$

The relation $\sim_{\mathbb{Q}}$ must satisfy reflexivity, symmetry, and transitivity. Moreover, each operation defined on the quotient set must be **well-defined**; that is, the result must not depend on our choice of representatives. If we naively define addition as

$$(a, b) + (c, d) = (a + c, b + d) \quad \text{for all } (a, b), (c, d) \in \mathbb{Z} \times \mathbb{Z}^*,$$

we encounter a problem. Consider:

$$(1, 2) + (1, 3) = (1 + 1, 2 + 3) = (2, 5) \quad \text{and} \quad (1, 2) + (2, 6) = (1 + 2, 2 + 6) = (3, 8).$$

But $(1, 3) \sim_{\mathbb{Q}} (2, 6)$ since $1 \cdot 6 = 2 \cdot 3$, yet $(2, 5) \not\sim_{\mathbb{Q}} (3, 8)$ since $2 \cdot 8 = 16 \neq 15 = 5 \cdot 3$. A well-defined definition for addition is instead:

$$(a, b) + (c, d) = (ad + bc, bd) \quad \text{for all } (a, b), (c, d) \in \mathbb{Z} \times \mathbb{Z}^*.$$

We will verify this.

Similarly, in type theory and Lean we have **quotient types**, which allow us to think mathematically and construct new types by mean of equivalence relations. We are going to define proper rational numbers using quotient types in Lean. As mentioned earlier, this differs from Mathlib's approach, which achieves the same goal by mechanically reducing each rational number to a canonical form using coprimality (ensuring the numerator and denominator have no common factors). We need to start from the notion of equivalence relations. We have already seen how to define relations in Lean. The structure `Equivalence` is precisely a relation with fields `refl`, `symm`, and `trans` for defining an equivalence relation. You can inspect its definition using `#print Equivalence`. Another important component in defining a quotient is the `Setoid` typeclass, which encapsulates an equivalence relation on a given type. In particular, it requires that the relation given is indeed an equivalence relation, which is verified through the `iseqv` field. Here is how we begin defining the rational numbers using the `Setoid` typeclass and `Quotient` type:

```
instance myRel : Setoid myPreRat where
  r p q := p.num * q.den = q.num * p.den
  iseqv := by
    constructor
    · intro p; rfl
    · rintro ⟨p, p', hp'⟩ ⟨q, q', hq'⟩
      simp [Eq.comm]
    · rintro ⟨p, p', hp'⟩ ⟨q, q', hq'⟩ ⟨r, r', hr'⟩ hpq hqr
      simp_all
      apply mul_left_cancel₀ (mod_cast hq'.ne' : q' ≠ (0 : ℤ))
      grind

abbrev myRat : Type := Quotient myRel
```

In the iseqv field, we prove reflexivity, symmetry, and transitivity of our relation. The reflexivity case (intro p; rfl) is immediate. The symmetry case uses Eq.comm to swap the sides of the equation. For transitivity, the key step involves multiplying both sides of our equations by q.den and then canceling this common factor using mul_left_cancel₀ (left multiplication cancellation for integers), which states that if $a \cdot b = a \cdot c$ and $a \neq 0$, then $b = c$. The expression mod_cast hq'.ne' : q' ≠ (0 : ℤ) takes hq' (which states 0 < q.den as a natural number) and casts it to a proof that q.den ≠ 0 as an integer. Finally, abbrev is a Lean keyword that creates a type abbreviation. Unlike def, which creates a new definition that must be unfolded explicitly, with abbrev Lean can automatically treats myRat as Quotient myRel without requiring manual unfolding.

We can now propoerly define myRat and adding properties and operations.

```
instance : LE myRat where
  le r₁ r₂ := Quotient.lift₂ (fun a b ↦ a ≤ b) myRel_respects_le r₁ r₂

instance : Add myRat where
  add r₁ r₂ := Quotient.lift₂ (fun a b ↦ ⟦a + b⟧)
    (fun a₁ b₁ a₂ b₂ ha hb ↦ Quotient.sound (myRel_respects_add a₁ b₁ a₂
   b₂ ha hb))
    r₁ r₂

instance : OfNat myRat 0 where
  ofNat := ⟦myPreRat.zero⟧

lemma add_nonneg (a b : myRat) : 0 ≤ a → 0 ≤ b → 0 ≤ a + b := by
  induction a using Quotient.ind with | _ a =>
  induction b using Quotient.ind with | _ b =>
  intro ha hb
  exact myPreRat.add_nonneg a b ha hb
```

Notice how we reuse the previous `add_nonneg` lemma for the quotient type using `Quotient.ind`. The syntax `induction a using Quotient.ind with  _ a =>` unwraps the quotient value `a : myRat` to its underlying representative `a : myPreRat`.

As before, we used the instance mechanism to add operations such as ≤ and + for `myPreRat`. However, when lifting these operations to `myRat` (the quotient type), we need to ensure they are **well-defined**. This is achieved using `Quotient.lift₂`. To define a function from a quotient type, such as $f : \text{Quotient } S \to \beta$ where S is the setoid, it is necessary to provide an underlying function $f' : \alpha \to \beta$ and prove that for all $x, y : \alpha$, if $x \approx y$ (under the equivalence relation), then $f'(x) = f'(y)$. Morover it helps to split the code.

First we prove the underlying property on `myPreRat`, then lift it to the quotient type.

```
theorem myRel_respects_le (a₁ b₁ a₂ b₂ : myPreRat) :
    a₁ ≈ a₂ → b₁ ≈ b₂ → (a₁ ≤ b₁) = (a₂ ≤ b₂) := by
  intro ha hb
  simp only [eq_iff_iff]
  constructor
  · exact le_respects_equiv_forward a₁ b₁ a₂ b₂ ha hb
  · exact fun h => le_respects_equiv_forward a₂ b₂ a₁ b₁ ha.symm hb.symm h
```

In `myRel_respects_le`, we transform the equality of propositions into a biconditional using `eq_iff_iff`, then prove both directions with `constructor`. Since both goals are symmetrical, we reuse `le_respects_equiv_forward`.

```
private theorem le_respects_equiv_forward
    (a₁ b₁ a₂ b₂ : myPreRat)
    (ha : a₁ ≈ a₂) (hb : b₁ ≈ b₂)
    (h : a₁ ≤ b₁) : a₂ ≤ b₂ := by
  have pos_prod : (0: Int) < (a₁.den * b₁.den) :=
    myPreRat.den_prod_pos a₁ b₁
  have pos_prod2 : 0 < (a₂.den * b₂.den : Int) :=
    myPreRat.den_prod_pos a₂ b₂
  apply Int.le_of_mul_le_mul_right _ pos_prod
  calc (a₂.num * b₂.den) * (a₁.den * b₁.den)
      = a₂.num * a₁.den * b₂.den * b₁.den := by ring
    _ = a₁.num * a₂.den * b₂.den * b₁.den := by rw [← ha]
    _ = a₁.num * b₁.den * (a₂.den * b₂.den) := by ring
    _ ≤ b₁.num * a₁.den * (a₂.den * b₂.den) :=
        Int.mul_le_mul_of_nonneg_right h (Int.le_of_lt pos_prod2)
    _ = b₁.num * b₂.den * a₁.den * a₂.den := by ring
    _ = b₂.num * b₁.den * a₁.den * a₂.den := by rw [← hb]
    _ = (b₂.num * a₂.den) * (a₁.den * b₁.den) := by ring
```

The heart of the proof is in `le_respects_equiv_forward`. The `private` keyword ensures that `le_respects_equiv_forward` is only accessible within the current namespace, keeping our interface clean.

Given $h : a_1 \leq b_1$ (meaning $a_1.\text{num} \cdot b_1.\text{den} \leq b_1.\text{num} \cdot a_1.\text{den}$) and equivalences $ha : a_1 \approx a_2$ and $hb : b_1 \approx b_2$ (meaning $a_1.\text{num} \cdot a_2.\text{den} = a_2.\text{num} \cdot a_1.\text{den}$ and $b_1.\text{num} \cdot b_2.\text{den} = b_2.\text{num} \cdot b_1.\text{den}$), we need to prove $a_2 \leq b_2$ (i.e., $a_2.\text{num} \cdot b_2.\text{den} \leq b_2.\text{num} \cdot a_2.\text{den}$). The strategy is to introduce a common positive factor and use the given information. We apply `Int.le_of_mul_le_mul_right`, which states that to prove $X \leq Y$, it suffices to prove $X \cdot Z \leq Y \cdot Z$ for positive Z, then cancel Z. We choose $Z = a_1.\text{den} \cdot b_1.\text{den}$ (shown positive by `pos_prod`). The `calc` block proves $(a_2.\text{num} \cdot b_2.\text{den}) \cdot (a_1.\text{den} \cdot b_1.\text{den}) \leq (b_2.\text{num} \cdot a_2.\text{den}) \cdot (a_1.\text{den} \cdot b_1.\text{den})$: First, we rearrange the left side and substitute using ha:

$$\begin{aligned}(a_2.\text{num} \cdot b_2.\text{den}) \cdot (a_1.\text{den} \cdot b_1.\text{den}) &= a_2.\text{num} \cdot a_1.\text{den} \cdot b_2.\text{den} \cdot b_1.\text{den} \\ &= a_1.\text{num} \cdot a_2.\text{den} \cdot b_2.\text{den} \cdot b_1.\text{den} \quad (\text{by } ha) \\ &= a_1.\text{num} \cdot b_1.\text{den} \cdot (a_2.\text{den} \cdot b_2.\text{den})\end{aligned}$$

Then we apply $h : a_1 \leq b_1$ (i.e., $a_1.\text{num} \cdot b_1.\text{den} \leq b_1.\text{num} \cdot a_1.\text{den}$), multiplying both sides by the positive factor $(a_2.\text{den} \cdot b_2.\text{den})$:

$$a_1.\text{num} \cdot b_1.\text{den} \cdot (a_2.\text{den} \cdot b_2.\text{den}) \leq b_1.\text{num} \cdot a_1.\text{den} \cdot (a_2.\text{den} \cdot b_2.\text{den})$$

Finally, we rearrange the right side and substitute using hb:

$$\begin{aligned} b_1.\text{num} \cdot a_1.\text{den} \cdot (a_2.\text{den} \cdot b_2.\text{den}) &= b_1.\text{num} \cdot b_2.\text{den} \cdot a_1.\text{den} \cdot a_2.\text{den} \\ &= b_2.\text{num} \cdot b_1.\text{den} \cdot a_1.\text{den} \cdot a_2.\text{den} \quad (\text{by } hb) \\ &= (b_2.\text{num} \cdot a_2.\text{den}) \cdot (a_1.\text{den} \cdot b_1.\text{den}) \end{aligned}$$

After canceling the common positive factor $(a_1.\text{den} \cdot b_1.\text{den})$, we obtain $a_2.\text{num} \cdot b_2.\text{den} \le b_2.\text{num} \cdot a_2.\text{den}$, which is precisely $a_2 \le b_2$.

Throughout the proof, we use the `ring` tactic from Mathlib. This tactic automates proofs like associativity and commutativity in commutative rings (such as $\mathbb{Z}$).

We also need to prove that the addition operation is well-defined on the quotient:

```
theorem myRel_respects_add (a₁ b₁ a₂ b₂ : myPreRat) :
    a₁ ≈ a₂ → b₁ ≈ b₂ → (a₁ + b₁) ≈ (a₂ + b₂) := by
  intro ha hb
  calc (a₁.num * b₁.den + b₁.num * a₁.den) * (a₂.den * b₂.den)
      = a₁.num * b₁.den * a₂.den * b₂.den + b₁.num * a₁.den * a₂.den *
    b₂.den
        := by ring
    _ = a₂.num * a₁.den * b₁.den * b₂.den + b₂.num * b₁.den * a₁.den *
    a₂.den
        := by rw [← ha, ← hb]; ring
    _ = (a₂.num * b₂.den + b₂.num * a₂.den) * (a₁.den * b₁.den)
        := by ring
```

We need to show that if $a_1 \approx a_2$ and $b_1 \approx b_2$, then $(a_1 + b_1) \approx (a_2 + b_2)$. By unfolding the addition definition and the relation we end up proving:

$$\begin{aligned} &(a_1.\text{num} \cdot b_1.\text{den} + b_1.\text{num} \cdot a_1.\text{den}) \cdot (a_2.\text{den} \cdot b_2.\text{den}) \\ &= \\ &(a_2.\text{num} \cdot b_2.\text{den} + b_2.\text{num} \cdot a_2.\text{den}) \cdot (a_1.\text{den} \cdot b_1.\text{den}) \end{aligned}$$

The `calc` proof proceeds in three steps. First, we distribute the product over the sum on the left side using `ring`. Next, we apply the equivalences ha and hb using `rw [← ha, ← hb]`, which substitutes $a_1.\text{num} \cdot a_2.\text{den}$ with $a_2.\text{num} \cdot a_1.\text{den}$ and $b_1.\text{num} \cdot b_2.\text{den}$ with $b_2.\text{num} \cdot b_1.\text{den}$. Finally, we factor the expression back into sum-times-product form using `ring`, obtaining the right side of the desired equality.

We finally have a minimal and well-defined solution for showing `myRat.add_nonneg`. However, our original discussion was about proving transitivity of the less-or-equal operator. In our earlier work with natural numbers, we used `Nat.le_trans`, a theorem specifically for natural numbers that is part of Lean's core library. However, the transitivity property holds not only for naturals but also for integers, reals, and any partially ordered set. Rather than duplicating this theorem for each type, Mathlib provides a general lemma le_trans that works for any type α endowed with a partial ordering.

Mathlib achieves this through type classes and a carefully constructed algebraic hierarchy. We have already touched on this concept when we used type classes such as Add and LE to define operations on myRat. Aware that rational numbers form a totally ordered set, we now enhance myRat with the LinearOrder type class:

```
noncomputable instance : LinearOrder myRat where
  le_refl p := by
    induction p using Quotient.ind with | _ a =>
    exact myPreRat.le_refl a

  le_trans p q r := by
    induction p using Quotient.ind with | _ a =>
    induction q using Quotient.ind with | _ b =>
    induction r using Quotient.ind with | _ c =>
    intro hab hbc
    exact myPreRat.le_trans a b c hab hbc

  le_antisymm p q := by
    induction p using Quotient.ind with | _ a =>
    induction q using Quotient.ind with | _ b =>
    intro hab hba
    exact Quotient.sound (myPreRat.le_antisymm a b hab hba)

  le_total p q := by
    induction p using Quotient.ind with | _ a =>
    induction q using Quotient.ind with | _ b =>
    cases Int.le_total (a.num * b.den) (b.num * a.den) with
    | inl h => exact Or.inl h
    | inr h => exact Or.inr h

  toDecidableLE  := Classical.decRel _
end myRat
```

The structure follows the same pattern we saw earlier: use Quotient.ind to unwrap quotient values to their representatives, then apply the corresponding proof for myPreRat. The antisymmetry case uses Quotient.sound, which states that if two representatives are equivalent (i.e., $a \approx b$), then their quotient equivalence classes are equal (i.e., $\llbracket a \rrbracket = \llbracket b \rrbracket$).

The underlying proofs for myPreRat are:

```
theorem le_refl (a : myPreRat) : a ≤ a := by
  exact Int.le_refl _

theorem le_trans (a b c : myPreRat) : a ≤ b → b ≤ c → a ≤ c := by
  intro hab hbc
  apply Int.le_of_mul_le_mul_right _ b.den_pos_int
  calc (a.num * c.den) * b.den
      = (a.num * b.den) * c.den := by ring
    _ ≤ (b.num * a.den) * c.den :=
      Int.mul_le_mul_of_nonneg_right hab (Int.le_of_lt c.den_pos_int)
    _ = (b.num * c.den) * a.den := by ring
    _ ≤ (c.num * b.den) * a.den :=
      Int.mul_le_mul_of_nonneg_right hbc (Int.le_of_lt a.den_pos_int)
    _ = (c.num * a.den) * b.den := by ring

theorem le_antisymm (a b : myPreRat) : a ≤ b → b ≤ a → a ≈ b := by
  intro hab hba
  exact Int.le_antisymm hab hba
```

Reflexivity and antisymmetry are straightforward applications of the corresponding integer properties. For transitivity, given $hab : a \leq b$ (meaning $a.\text{num} \cdot b.\text{den} \leq b.\text{num} \cdot a.\text{den}$) and $hbc : b \leq c$ (meaning $b.\text{num} \cdot c.\text{den} \leq c.\text{num} \cdot b.\text{den}$), we need to prove $a \leq c$ (i.e., $a.\text{num} \cdot c.\text{den} \leq c.\text{num} \cdot a.\text{den}$). The strategy is to introduce a common positive factor $b.\text{den}$, prove $(a.\text{num} \cdot c.\text{den}) \cdot b.\text{den} \leq (c.\text{num} \cdot a.\text{den}) \cdot b.\text{den}$, then cancel it using `Int.le_of_mul_le_mul_right`. The `calc` chain proceeds as follows: we rearrange to introduce $a.\text{num} \cdot b.\text{den}$, apply hab (multiplying by the positive factor $c.\text{den}$ to preserve the inequality), rearrange to introduce $b.\text{num} \cdot c.\text{den}$, apply hbc (multiplying by $a.\text{den}$), and finally rearrange to match the required form. After canceling $b.\text{den}$, we obtain $a \leq c$.

Finally, we must address the `le_total` field and the computational aspects of the instance. The property `le_total` asserts that the order is total: for any a, b, either $a \leq b$ or $b \leq a$. By unwrapping the quotient, this reduces to an inequality of integers. Since integers are already linearly ordered, we apply `Int.le_total` to the cross-products of the numerators and denominators.

The field `decidableLE := Classical.decRel _` requires special attention. In Mathlib, a `LinearOrder` is not merely a set of axioms; it is a structure that automatically defines `min` and `max` functions. By default, `min a b` is defined as `if a ≤ b then a else b`. To evaluate this conditional, Lean requires the relation ≤ to be *decidable* (i.e., there must be an algorithm to determine if it is true or false). While we could write an explicit comparison algorithm for our rationals, we opted for a concise mathematical approach using `Classical.decRel`. This invokes classical logic, where every proposition is intrinsically true or false. However, because this relies on the axiom of choice rather than an executable algorithm, the resulting functions cannot be computed by the kernel. This necessitates marking the entire instance as `noncomputable`.

Here the full construction of myRat: [link to Lean live]

With the use of type classes such as `LinearOrder`, we thus enhanced `myRat`. This allows us to use general theorems about linear orders, such as transitivity of less-or-equal, without redefining them specifically for `myRat`.

3.4 Type Classes and Algebraic Hierarchy

Structures and type classes are heavily used in Mathlib for providing properties such as ordered rings, fields, metric spaces, and topological spaces, which we refer to as **algebraic structures**. An algebraic structure is defined by a carrier type and a set of operations and properties. We write $C\,\alpha$ where α is the **carrier type** (the underlying set of elements) and C is the **structure** (the operations and properties defined on that type). For example, in a group structure $\mathrm{Group}\,\alpha$, α is the carrier type (such as $\mathbb{Z}$ or $\mathbb{Q}$), and Group defines the multiplication, identity element, and inverse operation on α. Under the hood, a type class is a structure. The main difference between the two is that type classes use **instance resolution**; a mechanism that allows Lean to automatically infer properties about a type when the latter is declared as an instance of a type class. Using structures alone would require explicitly passing the structure as an argument to functions that need it, which is cumbersome.

Let's examine a simple example to see the main difference. Using a structure:

```
structure Semigroup' (α : Type*) where
  mul : α → α → α
  mul_assoc : ∀ a b c : α, mul (mul a b) c = mul a (mul b c)

def double {α : Type*} (s : Semigroup' α) (x : α) : α :=
  s.mul x x

def Semigroup'_Int : Semigroup' ℤ where
  mul := (· + ·)
  mul_assoc := Int.add_assoc

def Semigroup'_Rat : Semigroup' ℚ where
  mul := (· + ·)
  mul_assoc := Rat.add_assoc

#eval double Semigroup'_Int (-2)    -- -4
#eval double Semigroup'_Rat (1/2)   -- 1
```

The `double` function takes an explicit `Semigroup' α` argument to perform the doubling operation. When calling `double`, we must explicitly provide the semigroup instance, such as `Semigroup'_Int` or `Semigroup'_Rat`.

In contrast, using a type class:

```
class Semigroup'' (α : Type*) where
  mul : α → α → α
  mul_assoc : ∀ a b c : α, mul (mul a b) c = mul a (mul b c)

instance : Semigroup'' ℤ where
  mul := (· + ·)
  mul_assoc := Int.add_assoc

instance : Semigroup'' ℚ where
  mul := (· + ·)
  mul_assoc := Rat.add_assoc

def double' {α : Type*} [Semigroup'' α] (x : α) : α :=
  Semigroup''.mul x x

#eval double' (-2 : ℤ)    -- -4
#eval double' (1/2 : ℚ)   -- 1
```

Notice the square brackets `[Semigroup'' α]` in the definition of `double'`. This syntax indicates that `Semigroup'' α` is a type class constraint. When we call `double'`, we do not need to explicitly provide the semigroup instance. Instead, Lean automatically infers the appropriate instance based on the type of the argument. This is the power of instance resolution.

We chose the semigroup example because it is simple yet demonstrates how algebraic structures can be extended. A semigroup can be extended to a monoid or a group by adding more properties. Using structures and type classes, we can implement this inheritance pattern:

```
class Group'' (α : Type*) extends Semigroup'' α where
  one : α
  left_id : ∀ a : α, mul one a = a
  right_id : ∀ a : α, mul a one = a
  inv : α → α
  left_inv : ∀ a : α, mul (inv a) a = one
  right_inv : ∀ a : α, mul a (inv a) = one

instance : Group'' ℤ where
  --omitted

instance : Group'' ℚ where
  --omitted

theorem mul_cancel₀ {α : Type*} [Group'' α]  (a b c : α)
    (h : Semigroup''.mul a b = Semigroup''.mul a c) : b = c := by sorry
```

Now we can embed the algebraic structure of a group and use general theorems such as the cancellation law without redefining it for each type. We have already demonstrated this principle when discussing transitivity of the less-or-equal relation and when enhancing `myRat` with the partial order algebraic structure.

Mathlib builds an extensive algebraic hierarchy using type classes. This hierarchy is far from being a simple tree; there are different nuances and technical approaches that are beyond the scope of this thesis. For a detailed discussion on the design and implementation of Mathlib's algebraic hierarchy, we refer the reader to [Lea20].

Analysis and the `TopologicalSpace` Class

We have briefly seen how one can build rational numbers from natural numbers and integers using quotient types. In our implementation of `myRat`, we invoked `Classical` axioms merely for brevity, to avoid writing an explicit decision procedure for the inequality. However, when moving to real numbers, reliance on non-constructive tools becomes much more unavoidable. In Mathlib, real numbers are defined as equivalence classes of Cauchy sequences of rational numbers [Lea25]. Although experimental libraries for computable reals in Lean exist, such as the exact real arithmetic implementation by Christiansen and Licata [CL22], the standard `Real` type used for topology relies on classical axioms. Consequently, most operations on it are marked as `noncomputable`, indicating they cannot be executed algorithmically. For example, the sine function requires this marker:

```
noncomputable def realSin (x : ℝ) : ℝ := Real.sin x
```

Real numbers are instances of various algebraic and topological structures like: linear ordered field, normed space, metric space, and topological space ([Lea20]). In the next section, I will present an example of formalization that requires working with real numbers their topological space. The latter provides foundational tools for analysis concepts like continuity and convergence. Given that $\mathbb{R}$ is a metric space, these notions in can, of course, be defined using the familiar ε formulation:

```
def ConvergesTo (s : ℕ → ℝ) (a : ℝ) :=
  ∀ ε > 0, ∃ N, ∀ n ≥ N, |s n - a| < ε
```

where `s` is a sequence and `a` is the limit point. More generally, these concepts are formalized in topology. In standard textbooks, a topological space is defined as a set equipped with a collection of open sets satisfying certain axioms. This is reflected in Mathlib's `TopologicalSpace` type class:

```
class TopologicalSpace (α : Type*) where
  IsOpen : Set α → Prop
  isOpen_univ : IsOpen univ
  isOpen_inter : ∀ s t, IsOpen s → IsOpen t → IsOpen (s ∩ t)
  isOpen_sUnion : ∀ s, (∀ t ∈ s, IsOpen t) → IsOpen (sUnion s)
```

Recall that Lean treats sets as predicates (`Set α := α → Prop`), where set membership is function application. Here, `IsOpen` is a predicate on sets indicating whether they are open. The three axioms correspond to the standard topological axioms:

- The whole space is open (`isOpen_univ`)
- The intersection of two open sets is open (`isOpen_inter`)
- The union of any collection of open sets is open (`isOpen_sUnion`)

Note 3.4.1 *The empty set is open, as it is the union of an empty collection of open sets.*

Using this structure, global continuity can be defined in terms of open sets, and, indeed, this is how it is defined in Mathlib:

```
structure Continuous (f : X → Y) : Prop where
  isOpen_preimage : ∀ s, IsOpen s → IsOpen (f ⁻¹' s)
```

However, when proving results about limits, convergence, and continuity, Mathlib uses an alternative way based on **filters**. This approach may seem more abstract initially, but it provides a more general and powerful framework that works uniformly across all topological spaces and, by extension, metric spaces.

Limits and Convergence with Filters

The concept of a limit is quiet extended, there are many types of limits to consider. For intance the limit of a sequence or a function at a point, limits at infinity (from above or below), one-sided limits (from the left or right) and so on. Defining each of these separately would require a huge amount of work to include in Mathlib, with significant duplication of theorems and proofs. Moreover, many fundamental theorems (like the characterization of continuity via limits) would need to be reproved for each type of limit. Fortunately, Bourbaki solved this issue by introducing the notion of **filters** to unify all concepts of limits, convergence, neighborhoods and terms like eventually or frequently often into a single framework. Intuitively, a filter represents a notion of "sufficiently large" subsets. More fomrally, a filter F on a type X is a collection of subsets of X satisfying three axioms:

```
structure Filter (α : Type*) where
  sets : Set (Set α)
  univ_sets : Set.univ ∈ sets
  sets_of_superset {x y} : x ∈ sets → x ⊆ y → y ∈ sets
  inter_sets {x y} : x ∈ sets → y ∈ sets → x ∩ y ∈ sets
```

The field sets suggests to think of a filter as a collection sets. The three axioms correspond to:

- $X \in F$ (the whole space is in the filter)
- If $U \in F$ and $U \subseteq V$, then $V \in F$ (supersets of "large" sets are "large")
- If $U, V \in F$, then $U \cap V \in F$ (finite intersections of "large" sets are "large")

Note that if F is a filter that contains the empty set, then it contains all subsets of X. Filters are quiet categorical objects, and we are going to intuivetly make use of them instead of descibing it fomrally. In particular, we are going to use some of the following concetps:

- **Neighborhood filter** $\mathcal{N}$ x: In a topological space, this filter contains all neighborhoods of the point x. This recall the standard defintion of neighborhoods in topology. A set is in $\mathcal{N}$ x if it contains an open set containing x. This captures the idea of "near x."

- **At top filter** `atTop : Filter ℕ`: Contains sets that include all sufficiently large natural numbers. Formally, $U \in$ `atTop` if and only if there exists N such that $\{n \mid n \geq N\} \subseteq U$. This captures the idea of "$n \to \infty$."

- `∀ᶠ x in f, p x` (`f.Eventually p`): "Eventually in filter f, property p holds." This means there exists some set $U \in f$ such that p holds for all $x \in U$.

- `∃ᶠ x in f, p x` (`f.Frequently p`): "Frequently in filter f, property p holds." This means for every set $U \in f$, there exists some $x \in U$ where p holds. This captures the idea that p holds "infinitely often" or "arbitrarily close."

- `Tendsto f l₁ l₂`: "Function f tends from filter l_1 to filter l_2." This is used for convergence.

Example 3.4.2 *We can express convergence of a sequence s_n to its limit a using filters.* `Tendsto s atTop (𝓝 a)`*; meaning $s_n \to a$ as $n \to \infty$*

Example 3.4.3 *Another more insigthfull example is the definition of local continuity; at a point x or restricted to a subset. As seen before, the structure* `Continuous`*, for global continuity, is defined in terms of open sets. However, Mathlib also provides alternative definitions for local continuity:* `ContinuousAt` *defines continuity at a single point,* `ContinuousWithinAt` *defines continuity within a set at a point, and* `ContinuousOn` *defines continuity on an entire set. All these local characterizations are defined in terms of filters. The connection between the global continuity definition and the filter-based local definitions is established by the following fundamental theorem:*

```
theorem Continuous.tendsto (hf : Continuous f) (x) :
    Tendsto f (𝓝 x) (𝓝 (f x)) :=
  ((nhds_basis_opens x).tendsto_iff <| nhds_basis_opens <| f x).2 fun t ⟨
   hxt, ht⟩ =>
    ⟨f ⁻¹' t, ⟨hxt, ht.preimage hf⟩, Subset.rfl⟩
```

The key concept here is `FilterBasis`*. Similar to how a topological space can be defined via a basis of open sets, a filter can be defined via a basis of sets. A basis B for a filter F is a nonemprty collection of sets wich preserve intersections; for any two sets $U, V \in B$, there exists a set $W \in B$ such that $W \subseteq U \cap V$.*

```
structure FilterBasis (α : Type*) where
  sets : Set (Set α)
  nonempty : sets.Nonempty
  inter_sets {x y} : x ∈ sets → y ∈ sets → ∃ z ∈ sets, z ⊆ x ∩ y
```

Given a basis, we can not only generate a filter, but also help proving properties about it, restricitng to one basis only.

To better understand the proof, we can expand it slightly:

```
theorem Continuous'.tendsto (hf : Continuous f) (x) :
    Tendsto f (𝓝 x) (𝓝 (f x)) := by
  rw [(nhds_basis_opens x).tendsto_iff (nhds_basis_opens (f x))]
  intro t ⟨hft_in, ht_open⟩
  use f ⁻¹' t
  constructor
  · exact ⟨hft_in, ht_open.preimage hf⟩
  · exact Subset.rfl
```

The statemnt `Tendsto f (𝓝 x) (𝓝 (f x))` is reformulation of continuity in terms of neighborhood filters `𝓝 x`. Meaning that for every neighborhood of $f(x)$, there exists a neighborhood of x that maps into it under f. In particular the neighborhood filter `𝓝 x` has a basis consisting of all open sets containing the point x, wich is stated by `nhds_basis_opens x`. Thus the line `rw [(nhds_basis_opens x).tendsto_iff (nhds_basis_opens (f x))]` restricts the goal in terms of these basis open sets. This converts our goal to: for every open neighborhood (set) t of $f(x)$, there exists an open neighborhood s of x with $f^{-1}s \subseteq t$. Next, we introduce an arbitrary open neighborhood t of $f(x)$ using `intro t ⟨hft_in, ht_open⟩`. The natural choice for the witness neighborhood s is given by `use f ⁻¹' t`. Now, the first part of the goal is to show that $x \in f^{-1}(t)$ and that $f^{-1}(t)$ is open. This is done using `constructor`; `exact ⟨hft_in, ht_open.preimage hf⟩`. With `ht_open.preimage hf` we are leveraging the global continuity of f. Since t is open and f is continuous, the preimage $f^{-1}(t)$ is also open. The second part of the goal is to show that $\forall x \in f^{-1}(t), f(x) \in t$, which always holds by the definition of preimage; `exact Subset.rfl`. Here the full example: [link to Lean live]

Using this bridge from global to local continuity, we can understand the following connection:

```
def ContinuousAt (f : X → Y) (x : X) :=
  Tendsto f (𝓝 x) (𝓝 (f x))
theorem Continuous.continuousAt (h : Continuous f) : ContinuousAt f x :=
  h.tendsto x
```

The remaining local continuity concepts are defined similarly:

```
def ContinuousWithinAt (f : X → Y) (s : Set X) (x : X) : Prop :=
  Tendsto f (𝓝[s] x) (𝓝 (f x))
def ContinuousOn (f : X → Y) (s : Set X) : Prop :=
  ∀ x ∈ s, ContinuousWithinAt f s x
```

Note that `𝓝[s] x` denotes the neighborhood filter of x restricted to the set s, allowing us to study the behavior of functions on arbitrary subsets. Next we will use `ContinuousOn` in our formalization.

Chapter 4

Formalizing the topologist's sine curve

As part of my thesis work, with the help and revision from Prof David Loeffler, I have formalized a well-known counterexample in topology: the **topologist's sine curve**. This classic example illustrates a space that is **connected** but not **path-connected**. My original proof follows Conrad's paper ([Con]), with a few modifications and some differences from the final formalization **Counterexamples – Topologist's Sine Curve**. The topologist's sine curve is defined as the graph of $y = \sin(1/x)$ for $x \in (0, \infty)$, together with the origin $(0, 0)$.

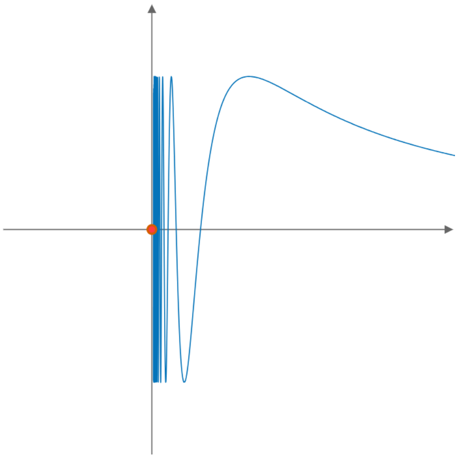

Figure 4.0.0.1: Topologist's sine curve.

We define three sets in $\mathbb{R}^2$:

- S: the oscillating curve $\{(x, \sin(1/x)) : x > 0\}$
- Z: the singleton set $\{(0, 0)\}$
- T: their union $S \cup Z$

In Lean, this is expressed as follows:

```
open Real Set
def pos_real := Ioi (0 : ℝ)
noncomputable def sine_curve := fun x ↦ (x, sin (x⁻¹))
def S : Set (ℝ × ℝ) := sine_curve '' pos_real
def Z : Set (ℝ × ℝ) := { (0, 0) }
def T : Set (ℝ × ℝ) := S ∪ Z
```

We open the `Real` and `Set` namespaces to avoid prefixing real number and set operations with `Real.` and `Set.`, respectively. We define the interval $(0, \infty)$ as `pos_real`, using the predefined notation `Ioi 0`, from `Set`. The function `sine_curve` maps a positive real number to a point on the topologist's sine curve in $\mathbb{R}^2$. Here, `''` denotes the image of a set under a function. It's noncomputable because it involves the sine function, which is not computable in Lean's core logic. The sets `S`, `Z`, and `T` are defined using set operations, and `{ (0, 0) }` denotes the singleton set containing the point $(0, 0)$. The sets are subsets of the product space $\mathbb{R}^2$, represented as ℝ × ℝ. The sin function `sin` is defined in the `Real`.

The goal is to prove that T is connected but not path-connected. Let's start with connectedness.

4.1 T is connected

First of all one can directlly see that S is connected, since it is the image of the set $((0, \infty))$ under the continuous map $x \mapsto (x, \sin(1/x))$ and a interval in $\mathbb{R}$ is connected. Moreover, the closure of S is connected, and every set in between a connected set and its closure are connected. Since T is contained in the closure of S, T is connected. This is how a mathematician would argue informally, using known facts. However, in a formal proof, one must justify each step. For instance, justifying that S is connected requires proving that the map $x \mapsto (x, \sin(1/x))$ is continuous on $(0, \infty)$ and that $(0, \infty)$ is connected. As we have seen, even showing that a rational number is non-negative requires several steps and the use of various lemmas from Mathlib. Similarly, proving that a set is connected can involve multiple steps for the newer programmer. We can use the structure `IsConnected`, to set up the statement and see if we can argue similarly in Lean.

```
lemma S_is_conn : IsConnected S := by sorry
```

In the file where `IsConnected` is defined, `Topology/Connected/Basic.lean`, we see that it requires S to be nonempty and preconnected. One can verify this by unfolding `IsConnected` in the goal.

```
lemma S_is_conn : IsConnected S := by
  unfold IsConnected
  ⊢ S.Nonempty ∧ IsPreconnected S
  sorry
```

Following the definition of `IsPreconnected`, we see that it captures the usual definition; S cannot be partitioned into two nonempty disjoint open sets. This trivially requires nonemptiness to make sense. The `unfold` tactic helps to expand definitions; one can use it to expand the definition of S or `pos_real` defined before, as well as other Mathlib expressions. Reflecting our argument, we can check if Mathlib includes the fact that every interval is connected and that connectedness is preserved under continuous maps. Indeed, in `Topology/Connected/Interval.lean`, we find the theorem `isConnected_Ioi.image`, stating that the image of an interval of the form (a, ∞) under a continuous map is connected.

```
lemma S_is_conn : IsConnected S := by
  apply isConnected_Ioi.image
  -- ⊢ ContinuousOn sine_curve (Ioi 0)
  sorry
```

The theorem `isConnected_Ioi.image` requires proving the continuity of the map on the interval $(0, \infty)$, which is expressed as `ContinuousOn sine_curve (Ioi 0)`. The predicate `ContinuousOn f S` expresses that a function f is continuous on a set S, which is what we need to prove now. The function $x \mapsto (x, \sin(1/x))$ is continuous on $(0, \infty)$ as the product of two functions continuous on the given domain; the identity map $x \mapsto x$ and the map $x \mapsto \sin(1/x)$. Here is the full proof in Lean:

```
lemma inv_is_continuous_on_pos_real : ContinuousOn (fun x : ℝ => x⁻¹)
    (pos_real) := by
  apply ContinuousOn.inv₀
  · exact continuous_id.continuousOn
  · intro x hx; exact ne_of_gt hx

lemma sin_comp_inv_is_continuous_on_pos_real : ContinuousOn
 (sine_curve) (pos_real) := by
  apply ContinuousOn.prodMk continuous_id.continuousOn
  apply continuous_sin.comp_continuousOn
  exact inv_is_continuous_on_pos_real
```

Starting from the bottom lemma, `ContinuousOn.prodMk` states that the product of two functions continuous on a set is continuous on that set, requiring a proof of the continuity of each component. The first component is the identity map, which is continuous on any set. Mathlib provides `continuous_id.continuousOn` for this purpose. The second component is the composition of the sine function with the inverse function. The sine function is continuous everywhere, and for this we can use `continuous_sin`. The method `comp_continuousOn` is accessible from the fact that `continuous_sin` gives an instance of a continuous map and is generalized in the `ContinuousOn` module. The theorem `Continuous.comp_continuousOn` states that the composition of a continuous function with a function that is continuous on a set is continuous on that set, and requires proof of the continuity on the set of the inner function. We separate the proof that the inverse function is continuous on the positive reals into the auxiliary lemma `inv_is_continuous_on_pos_real`. The theorem `continuousOn_inv₀` states that, if a function is continuous and non-zero on a set, then its inverse is continuous on that set. The continuity of the identity map is proved as before. The second argument requires proving that $x \neq 0$ for all x in $(0, \infty)$.

```
  · intro x hx
    exact ne_of_gt hx
```

The hypothesis `hx` states that x is in $(0, \infty)$, which implies that $x > 0$. The theorem `ne_of_gt` states that if a real number is greater than zero, then it is non-zero, which completes the proof. Thus the final proof goes as follows:

```
lemma S_is_conn : IsConnected S := by
  apply isConnected_Ioi.image
  · exact sin_comp_inv_is_continuous_on_pos_real
```

When writing a proof, one starts by working out the informal argument on paper. Then one tries to translate it into Lean, step by step, looking for theorems in Mathlib. Afterwards, one can try to optimize the proof by removing unnecessary steps or refactoring it. Proving properties like continuity and connectedness is very common, and there are obviously ways to achieve this with less work. Let's showcase a refactoring of the entire proof. First, the auxiliary lemmas can be reduced to one-liners.

```
lemma inv_is_continuous_on_pos_real : ContinuousOn (fun x : ℝ => x⁻¹)
    (pos_real) :=
  ContinuousOn.inv₀ (continuous_id.continuousOn) (fun _ hx =>  ne_of_gt hx)

lemma sin_comp_inv_is_continuous_on_pos_real : ContinuousOn
 (sine_curve) (pos_real) :=
 ContinuousOn.prodMk continuous_id.continuousOn <|
  Real.continuous_sin.comp_continuousOn <| (inv_is_continuous_on_pos_real)
```

We removed the `by` keyword since we can provide a **term** that directly proves the statement. In `inv_is_continuous_on_pos_real`, we directly apply `ContinuousOn.inv₀` with the two required arguments. Notice that we can use a lambda function `fun _ hx =>  ne_of_gt hx` to prove that $x \neq 0$ for all x in $(0, \infty)$ (recall the propositions-as-types correspondence). In the next lemma, we use the <\| reverse application operator, which allows us to avoid parentheses by changing the order of application. This means that f < g <| h| is equivalent to f (g h). We can inline these two lemmas into the main proof to get a final one-liner:

```
lemma S_is_conn : IsConnected S :=
  isConnected_Ioi.image sine_curve <| continuous_id.continuousOn.prodMk <|
    continuous_sin.comp_continuousOn <|
    ContinuousOn.inv₀ continuous_id.continuousOn (fun _ hx => ne_of_gt hx)
```

Notice again the use of the **pipe** operator. Reading from left to right, we are building up the proof by successive applications:

- We start with isConnected_Ioi.image sine_curve, which states that the image of $(0, \infty)$ under sine_curve is connected if we can prove the function is continuous.

- We then apply continuous_id.continuousOn.prodMk, which constructs the product of two continuous functions.

- Next, continuous_sin.comp_continuousOn provides the continuity of the sine composition.

- Finally, ContinuousOn.inv$_0$ continuous_id.continuousOn (fun _ hx => ne_of_gt hx) proves the continuity of the inverse function on positive reals.

The entire chain can be read as building the continuity proof from the innermost function (the inverse) outward to the complete sine curve function, which is then used to prove that S is connected.

Since the intersection of Z and S is empty, we cannot directly conclude that T is connected from the connectedness of its components alone. However, we can use the fact that every subset between a connected set and its closure is connected.

Theorem 4.1.1 *Let C be a connected topological space, and denote $\overline{C}$ as its closure. It follows that every subset $C \subseteq S \subseteq \overline{C}$ is connected.*

In Mathlib, this theorem is available as IsConnected.subset_closure. We can set up the statement and progress from there.

```
theorem T_is_conn : IsConnected T := by
  apply IsConnected.subset_closure
  · exact S_is_conn -- ⊢ IsConnected ?s
  · tauto_set -- ⊢ S ⊆ T
  · sorry -- ⊢ T ⊆ closure S
```

The theorem requires three goals:

- That S is connected, which was already proved in `S_is_conn`.
- That $S \subseteq T$, which is a trivial set operation. The tactic `tauto_set` handles this kind of set tautologies.
- That $T \subseteq \overline{S}$ (the closure of S), which requires proof.

Let's continue with the final point.

```
lemma T_sub_cls_S : T ⊆ closure S := by
  intro x hx
  cases hx with
  | inl hxS => exact subset_closure hxS
  | inr hxZ =>
      sorry
```

Proving that one set is contained in another can be done naively in a pointwise manner. We introduce an element $x \in \mathbb{R}^2$ together with the proof that $x \in T$. Since T is a union, we use `cases` to separate the two cases. When $x \in S$, the goal is trivially solved by `exact subset_closure hxS`. The case where $x \in Z$, requires more work.

Now a trick. Looking for existing theorems using mathlib documentation is quiet challenging, while you are still learning the sintax and adapt to the naming convention. One can use several ways to look for the exact theorems. A useful tool is Loogle (similar to Haskell's Hoogle), which helps you find theorems by their type signature or name patterns. You can access it at `https://loogle.lean-lang.org/` or use it directly in VS Code. Depending on the previous work in the file, Lean can already unify the goal with available theorems and suggest the next step. For some tactics, adding a question mark causes Lean to automatically search for the next step involving the use of that tactic. For instance, one can type `apply?` or `exact?`, which search for applicable lemmas or definitions to close the goal. The tactics `rw?` and `simp?` work similarly but for rewriting and simplification.

At this point, `apply?` suggests several ways to proceed, some involving filters:

```
Try this: refine Frequently.mem_closure ?_
Remaining subgoals:
  ⊢ ∃ᶠ (x : ℝ × ℝ) in 𝓝 x, x ∈ S
```

and others following the more familiar metric space approach:

```
Try this: refine Metric.mem_closure_iff.mpr ?_
Remaining subgoals:
  ⊢ ∀ ε > 0, ∃ b ∈ S, dist x b < ε
```

The best approach, however, is to think first about how you would tackle the problem on paper, as mentioned earlier. Since we are working with a metrizable topology on $\mathbb{R}$, we know that the closure of a set contains all its limit points. To show that the point $(0,0)$ is contained in the closure of S, we need to show that it is a limit point of S. Thus, one can define a sequence in S tending to $(0,0)$, and the result follows. Instead of using properties of a metric space, we use filters, as explained before to work with limits. We can prove that $T \subseteq \overline{S}$, by showing that the origin is a limit point of S. We construct a sequence $f : \mathbb{N} \to \mathbb{R}^2$ in S converging to $(0,0)$ using `Tendsto`:

```
lemma T_sub_cls_S : T ⊆ closure S := by
  intro x hx
  cases hx with
  | inl hxS => exact subset_closure hxS
  | inr hxZ =>
    rw [hxZ]
    -- Define sequence: f(n) = (1/(nπ), 0)
    let f : ℕ → ℝ × ℝ := fun n => ((n * Real.pi)⁻¹, 0)
    -- Show f converges to (0, 0)
    have hf : Tendsto f atTop (𝓝 (0, 0)) := by
      refine Tendsto.prodMk_nhds ?_ tendsto_const_nhds
      exact tendsto_inv_atTop_zero.comp
        (Tendsto.atTop_mul_const' Real.pi_pos
   tendsto_natCast_atTop_atTop)
    -- Show f eventually takes values in S
    have hf' : ∀ᶠ n in atTop, f n ∈ S := by
      filter_upwards [eventually_gt_atTop 0] with n hn
      exact ⟨(n * Real.pi)⁻¹,
        inv_pos.mpr (mul_pos (Nat.cast_pos.mpr hn) Real.pi_pos),
        by simp [f, sine_curve, inv_inv, Real.sin_nat_mul_pi]⟩
    -- Apply sequential characterization of closure
    exact mem_closure_of_tendsto hf hf'
```

The proof is already reduced as much as possible. Let's break down what's happening in without getting into details. Using `let`, we define $f(n) = \left(\frac{1}{n\pi}, 0\right)$, which we will show converges to $(0,0)$ and stays in S.

- **Convergence proof** (`hf`): We show `Tendsto f atTop (𝓝 (0, 0))`. With `Tendsto.prodMk_nhds`, we need to show that both coordinates tend to 0, separately. For the first coordinate, we compose `tendsto_inv_atTop_zero` (which states $\frac{1}{x} \to 0$ as $x \to \infty$) with the fact that $n\pi \to \infty$. The second constant coordinate is handled by `tendsto_const_nhds`

- **Membership proof** (`hf'`): We show `∀ᶠ n in atTop, f n ∈ S`, meaning $f(n) \in S$ for all sufficiently large n. We use `filter_upwards`, which allows us to combine hypotheses about properties that hold eventually to prove another property holds eventually. Here, we combine it with `eventually_gt_atTop 0`, which states that eventually $n > 0$. For such n, we show $f(n) = \left(\frac{1}{n\pi}, 0\right)$ is in S by noting that the second term is:

$$\sin\left(\frac{1}{\left(\frac{1}{n\pi}\right)}\right) = \sin(n\pi) = 0.$$

Finally, `mem_closure_of_tendsto` combines these facts: if a sequence eventually stays in S and converges to x, then x is in the closure of S.

Finalising the first part of the proof

If you are a one-liner enthusiast like me, you don't mind trying to combine bits and pieces to get a clean final result. We can simplify the final theorem as follows initially:

```
theorem T_is_conn : IsConnected T :=
  IsConnected.subset_closure S_is_conn (by tauto_set) T_sub_cls_S
```

The second argument is still in tactic mode with `by tauto_set`, but it looks clean and we can keep it as is. With a bit of courage, we can also inline the proof of `S_is_conn` (while `T_sub_cls_S` is way too long to inline) to get a more self-contained one-liner:

```
theorem T_is_conn : IsConnected T :=
  IsConnected.subset_closure (isConnected_Ioi.image sine_curve <|
    continuous_id.continuousOn.prodMk <|
    Real.continuous_sin.comp_continuousOn <|
    ContinuousOn.inv₀ continuous_id.continuousOn
    (fun _ hx => ne_of_gt hx)) (by tauto_set) T_sub_cls_S
```

Making these amendments is not only for the sake of shortening the proof. Lean will, obviously, compile the proof faster by not entering tactic mode or using multiple tactics. Tactics internally hide many operations they automatically perform to close the goal. Moreover, if we directly provide a term for the proof, Lean will infer and unify everything by definitional equality. By providing explicit proof terms, we give Lean less work to do, making the proof more transparent and efficient. This practice of "golfing" is essential in a huge library such as Mathlib community that needs to balance performance and maintainability. From now on the rest of th code will be presented in it's reduced form. Here is the link to the entire first part of the proof: [link to Lean live]

Note 4.1.2 *The proof merged into the Mathlib library, takes Z as $\{0\} \times [-1, 1]$ instead of the singleton $\{(0, 0)\}$. This, together with the fact that T equals the closure of S, yields a stronger and more general result. This stronger version shows that* *a closed set (specifically, the closure of S) can be connected but not path-connected. Showing that forming closure can destroy the property of path connectedness for subsets of a topological space.*

4.2 T is not path-connected

The main and most substantial part is showing that T is not path-connected. Showing this informally already requires constructing and pointing out various steps in order to convince an ideal reader. One can argue informally by contradiction. Suppose a path exists in the topologist's sine curve T connecting a point in S to a point in Z. As the path approaches the y-axis (where $x \to 0$), the y-coordinate must oscillate infinitely between -1 and 1 due to the behavior of $\sin(1/x)$ as $x \to 0^+$. This infinite oscillation contradicts the continuity of the path, which is a fundamental requirement for path-connectedness. To be more precise, we need to construct a sequence that it eventually oscillates, establishing the contradiction. We start by setting up the theorem:

```
theorem T_is_not_path_conn : ¬ (IsPathConnected T) :=
  by sorry
```

In mathematics, we normally define a path-connected space as follows.

Definition 4.2.1 *A topological space X is said to be path-connected if for every two points $a, b \in X$, there exists a path, i.e., a continuous map $p : [0, 1] \to X$ such that $p(0) = a$ and $p(1) = b$.*

The interval $[0, 1]$ is the standard choice for the domain of paths. `IsPathConnected S` is a predicate used to infer that a subset S of a topological space is path-connected.

```
def IsPathConnected (F : Set X) : Prop :=
  ∃ x ∈ F, ∀ ⦃y⦄, y ∈ F → JoinedIn F x y
```

The auxiliary predicate `JoinedIn` is defined as:

```
def JoinedIn (S : Set X) (x y : X) : Prop :=
  ∃ γ : Path x y, ∀ t, γ t ∈ S
```

where `Path x y` denotes a continuous map $\gamma : [0, 1] \to X$ with $\gamma(0) = x$ and $\gamma(1) = y$. We can use the `unitInterval` **subtype** of $\mathbb{R}$ representing the interval $[0, 1]$.

Now let's start with the first part of the proof:

```
theorem T_is_not_path_conn : ¬ (IsPathConnected T) := by
  -- Assume we have a path from z = (0, 0) to w = (1, sin(1))
  have hz : z ∈ T := Or.inr rfl
  have hw : w ∈ T := Or.inl ⟨1, ⟨zero_lt_one' ℝ, rfl⟩⟩
  intro p_conn
  apply IsPathConnected.joinedIn at p_conn
  specialize p_conn z hz w hw
  let p := JoinedIn.somePath p_conn
```

We introduce two points: $z = (0,0)$ and $w = (1, \sin(1))$, and prove they are both in T, in `hz hw` and `hw` (we use the introduction rule for Or, seen it as a sum type). Using `intro p_conn`, we assume that T is path-connected. Notice that the goal is now `False`, meaning we must find a contradiction. The last three lines extract an explicit path `p` connecting z and w. `apply IsPathConnected.joinedIn at p_conn` transforms the path-connectedness assumption into the statement that any two points in T are joined. `specialize p_conn z hz w hw` specializes this to our specific points z and w. Then we extrat a path and store it using `let p := JoinedIn.somePath p_conn`.

We have $p(0) \in (0,0)$. Conrad's paper ([Con]) defines a time $t_0 \in (0,1]$ as the first time the path p jumps from $(0,0)$ to the graph of $\sin(1/x)$, where the x-coordinate map $(x : \mathbb{R}^2 \to \mathbb{R})$ of p is positive.

$$t_0 = \inf\{t \in [0,1] : x(p(t)) > 0\}$$

The argument then uses the continuity of the x-coordinate map composed with the path p. By continuity at t_0, we can find a neighborhood around t_0 where the path stays close to $(0,0)$. Specifically, with $\varepsilon = 1/2$, there exists $\delta > 0$ such that for all t with $|t - t_0| < \delta$, we have $\|p(t) - p(t_0)\| < 1/2$. We want to show the oscillating behavior around (0,0) indeed. To simplify some steps, we instead define

$$t_0 = \sup\{t \in [0,1] : x(p(t)) = 0\}$$

to be the last time the path remains at $(0,0)$. The same continuity argument applies with this definition.

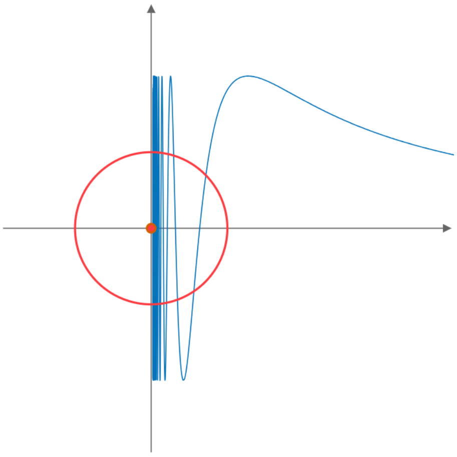

Figure 4.2.1.1: Topologist's sine curve with ball around $(0, 0)$.

```
-- Consider the composition of the x-coordinate map with p, which is
    continuous
have xcoord_pathcont : Continuous fun t ↦ (p t).1 := continuous_fst.comp
    p.continuous
-- Let t₀ be the last time the path is on the y-axis
let t₀ : unitInterval := sSup {t | (p t).1 = 0}
let xcoord_path := fun t => (p t).1
-- The x-coordinate of the path at t₀ is 0
have hpt₀_x : (p t₀).1 = 0 :=
  (isClosed_singleton.preimage xcoord_pathcont).sSup_mem ⟨0, by aesop⟩
-- By continuity of the path, we can find a δ > 0 such that
-- for all t in [t₀ - δ, t₀ + δ], ||p(t) - p(t₀)|| < 1/2
-- Hence the path stays in a ball of radius 1/2 around (0, 0)
obtain ⟨δ, hδ, ht⟩ : ∃ δ > 0, ∀ t, dist t t₀ < δ →
  dist (p t) (p t₀) < 1/2 :=
  Metric.eventually_nhds_iff.mp <| Metric.tendsto_nhds.mp (p.continuousAt
    t₀) _ one_half_pos
```

The final statement uses the `obtain` tactic to extract witnesses from an existential statement. This tactic destructures the existential quantifier $\exists \delta > 0, \ldots$ into δ (the distance), `hδ` (the proof that $\delta > 0$), and `ht` (the proof that the distance condition holds). Since $\mathbb{R}^2$ is a metric space, we can work with the distance function `dist : ℝ × ℝ → ℝ × ℝ → ℝ`, which computes the Euclidean distance between two points. The statement `dist t t₀ < δ` expresses $|t - t_0| < \delta$ in the unit interval, while `dist (p t) (p t₀) < 1/2` expresses $\|p(t) - p(t_0)\| < 1/2$ in $\mathbb{R}^2$. We assert that the path p is continuous at t_0 by `p.continuousAt t₀`. `Metric.tendsto_nhds.mp` converts this to the metric space characterization: for any $\varepsilon > 0$, there exists $\delta > 0$ such that points within δ of t_0 map to points within ε of $p(t_0)$. While, `Metric.eventually_nhds_iff.mp` further unpacks this into the $\forall t, \mathit{dist}\ t\ t_0 < \delta \to \mathit{dist}\ (p\ t)\ (p\ t_0) < \varepsilon$ form, requiring positivity of $\varepsilon = 1/2$ (`one_half_pos`).

We can find a time t_1 greater than t_0 that remains in the neighborhood of t_0, and obtain a point $a = x(p(t_1))) > 0$ which is positive.

```
-- Let t₁ be a time when the path is not on the y-axis
-- t₁ is in (t₀, t₀ + δ], hence t₁ > t₀
obtain ⟨t₁, ht₁⟩ : ∃ t₁, t₁ > t₀ ∧ dist t₀ t₁ < δ := by
  let s₀ := (t₀ : ℝ) -- cast t₀ from unitInterval to ℝ for manipulation
  let s₁ := min (s₀ + δ/2) 1
  have hs₀_delta_pos : 0 ≤ s₀ + δ/2 := add_nonneg t₀.2.1 (by positivity)
  have hs₁ : 0 ≤ s₁ := le_min hs₀_delta_pos zero_le_one
  have hs₁': s₁ ≤ 1 := min_le_right ..
  sorry
-- Let a = xcoord_path t₁ > 0
-- This follows from the definition of t₀ and t₀ < t₁
-- so t₁ must be in S, which has positive x-coordinate
let a := (p t₁).1
have ha : a > 0 := by
  obtain ⟨x, hxI, hx_eq⟩ : p t₁ ∈ S := by
    cases p_conn.somePath_mem t₁ with
    | inl hS => exact hS
    | inr hZ =>
      -- If p t₁ ∈ Z, then (p t₁).1 = 0
      have : (p t₁).1 = 0 := by rw [hZ]
      -- So t₁ ≤ t₀, contradicting t₁ > t₀
      have hle : t₁ ≤ t₀ := le_sSup this
      have hle_real : (t₁ : ℝ) ≤ (t₀ : ℝ) := Subtype.coe_le_coe.mpr hle
      have hgt_real : (t₁ : ℝ) > (t₀ : ℝ) := Subtype.coe_lt_coe.mpr ht₁.1
      linarith
  simpa only [a, ← hx_eq] using hxI
```

The code is quite convoluted, and i will omit a detailed explanation as well as some part of it. However, it's worth mentioning a few key technical points. The type `unitInterval` is a **subtype** of $\mathbb{R}$, defined as $\{x : \mathbb{R} \mid 0 \leq x \leq 1\}$. In Lean, a subtype `{x : α // P x}` bundles a value x of type α together with a proof that x satisfies the predicate P, similar as for `Set`. Anyway, rather than being `Set` (as subsets), they are type itself. In particular, their terms do not share the type of the underlying `Set`. Consequently, they lack of arithmetic properties of the real numbers for instance. We need to cast them to $\mathbb{R}$ (with `let s₀ := (t₀ : ℝ)`) first, then cast back to `unitInterval`, by providing proofs that the bounds $[0, 1]$ are satisfied (`hs₁`, `hs₁'`). In the second case of the inner statment of have `ha : a > 0`, if $p(t_1) \in Z$, then $(p\ t_1).1 = 0$ by definition of $Z = \{(0, 0)\}$. This implies $t_1 \leq t_0$ by the definition of t_0

as the supremum. However, we also have $t_1 > t_0$ from our construction of t_1 (`ht₁.1`). The tactic `linarith`, an automated solver for linear arithmetic, recognizes this contradiction by observing both `hle_real : (t₁ : ℝ) ≤ (t₀ : ℝ)` and `hgt_real : (t₁ : ℝ) > (t₀ : ℝ)`. Since these statements are contradictory, `linarith` proves `False`. Lemmas like `Subtype.coe_lt_coe` allow us to transfer inequalities between the subtype and its underlying type, needed for `linarith`.

Finally, `simpa only [a, ← hx_eq] using hxI` completes the proof. The tactic `simpa` combines simplification (`simp`) with assumption matching. The directive `only [a, ← hx_eq]` unfolds the definition of $a = (p\ t_1).1$ and rewrites using `hx_eq` in the reverse direction, transforming the goal from `(p t₁).1 > 0` to `(sine_curve x).1 > 0`. Since `sine_curve x = (x, sin(1/x))`, this simplifies to `x > 0`, which is exactly the hypothesis `hxI`. The `using hxI` clause, applies this hypothesis to close the goal.

Next, the image $x(p([t_0, t_1]))$ is connected (as the continuous image of a connected set), and it contains $0 = x(p(t_0))$ and $a = x(p(t_1))$. Since every connected subset of $\mathbb{R}$ is an interval, we have

$$[0, a] \subseteq x(p([t_0, t_1]))$$

This will be crucial for the next step, where we show that the path must oscillate.

```
  -- The image x(p([t₀, t₁])) is connected and contains 0 and a
  -- Therefore [0, a] ⊆ x(p([t₀, t₁]))
  have Icc_of_a_b_sub_Icc_t₀_t₁: Set.Icc 0 a ⊆ xcoord_path '' Set.Icc t₀
    t₁ :=
      IsConnected.Icc_subset
       ((isConnected_Icc (le_of_lt ht₁.1)).image _
    xcoord_pathcont.continuousOn)
       (⟨t₀, left_mem_Icc.mpr (le_of_lt ht₁.1), hpt₀_x⟩)
       (⟨t₁, right_mem_Icc.mpr (le_of_lt ht₁.1), rfl⟩)
```

Now we construct a sequence that demonstrates the contradiction. Recall that $\sin(\theta) = 1$ if and only if $\theta = \frac{(4k+1)\pi}{2}$ for some $k \in \mathbb{Z}$. Therefore, $(x, \sin(1/x)) = (x, 1)$ when

$$x = \frac{2}{(4k+1)\pi}$$

for $k \in \mathbb{N}$. As $k \to \infty$, these x-values approach 0, so infinitely many of them lie in any interval $[0, a]$. We define this sequence and establish its key properties:

```
noncomputable def xs_pos_peak := fun (k : ℕ) => 2/((4 * k + 1) * Real.pi)
lemma xs_pos_peak_tendsto_zero : Tendsto xs_pos_peak atTop (𝓝 0) := sorry
lemma xs_pos_peak_nonneg : ∀ k : ℕ, 0 ≤ xs_pos_peak k := sorry
lemma sin_xs_pos_peak_eq_one (k : ℕ) : Real.sin ((xs_pos_peak k)⁻¹) = 1 :=
   sorry
```

The crucial property is that this sequence eventually enters $[0, a]$:

```
-- For any k ∈ ℕ, sin(1/xs_pos_peak(k)) = 1
-- Since xs_pos_peak converges to 0 as k → ∞,
-- there exist indices i ≥ 1 for which xs_pos_peak i ∈ [0, a]
have xpos_has_terms_in_Icc_of_a_b : ∃ i : ℕ, i ≥ 1 ∧ xs_pos_peak i ∈
    Set.Icc 0 a := sorry
```

This gives us points on the topologist's sine curve with y-coordinate equal to 1, lying arbitrarily close to the y-axis.

Now we can establish the final contradiction. Since $[0, a] \subseteq x(p([t_0, t_1]))$ by the previous argument, and $\text{xs\_pos\_peak}(i) \in [0, a]$ for some i, there must exist some $t' \in [t_0, t_1]$ such that $x(p(t')) = \text{xs\_pos\_peak}(i)$. This means $p(t') = (\text{xs\_pos\_peak}(i), \sin(1/\text{xs\_pos\_peak}(i))) = (\text{xs\_pos\_peak}(i), 1)$, so the y-coordinate of $p(t')$ equals 1. However, since $t' \in [t_0, t_1] \subseteq [t_0, t_0 + \delta)$, we have $\text{dist}(t', t_0) < \delta$, which by our earlier continuity argument implies $\|p(t') - p(t_0)\| < 1/2$. But $\|p(t') - (0, 0)\| \geq |(p(t')).2| = |1| = 1 > 1/2$, yielding a contradiction.

```
-- Show there exists time t' in [t₀, t₁] ⊆ [t₀, t₀ + δ) such that p(t') =
    (*, 1)
obtain ⟨t', ht', hpath_t'⟩ : ∃ t' ∈ Set.Icc t₀ t₁, (p t').2 = 1 := sorry
-- Derive the final contradiction using t', ht', hpath_t'
-- First show that p t₀ = (0, 0)
have hpt₀ : p t₀ = (0, 0) := sorry
-- t' is within δ of t₀ (since t' ∈ [t₀, t₁] and dist t₀ t₁ < δ)
have t'_close : dist t' t₀ < δ := by
  calc dist t' t₀
      ≤ dist t₁ t₀ := dist_right_le_of_mem_uIcc (Icc_subset_uIcc' ht')
    _ = dist t₀ t₁ := dist_comm _ _
    _ < δ := ht₁.2
-- By continuity, p(t') should be close to p(t₀)
have close : dist (p t') (p t₀) < 1/2 := ht t' t'_close
-- But p(t') has y-coordinate 1, so it's actually far from p(t₀) = (0, 0)
have far : 1 ≤ dist (p t') (p t₀) := by
  calc 1 = |(p t').2 - (p t₀).2| := by simp [hpath_t', hpt₀]
      _ ≤ ‖p t' - p t₀‖ := norm_ge_abs_snd
      _ = dist (p t') (p t₀) := by rw [dist_eq_norm]
-- This is a contradiction: 1 ≤ dist (p t') (p t₀) < 1/2
linarith
```

4.3 Conclusion

Finally, we combine the two parts in the following concise and pleasant theorem:

```
theorem T_is_conn_not_pathconn : IsConnected T ∧ ¬IsPathConnected T :=
  ⟨T_is_conn, T_is_not_path_conn⟩
```

And now, since this code compiles successfully, these two lines stand as verified witnesses to the correctness of our entire proof. This showcases the power of proof assistants and formal reasoning. Mathematics becomes not only more rigorous but also automatically verifiable. Furthermore, the formalization becomes a learning tool in its own right. Future readers can inspect each part of the code. Here the full proof: [link to Lean live]

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