

CONCEPTS OF MATHEMATICS, SUMMER 1 2014

LECTURE NOTES

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1. ABOUT

These are notes for an introduction to proof-based mathematics given at Carnegie Mellon University in the summer of 2014. Once the course is over, I aim to keep these notes (together with the source files) available on my website: <http://math.cmu.edu/~svasey/>.

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21-127 Students: please let me know if you find any mathematical mistake or typo (even if it just something very easy to fix, like a missing comma or a misspelling). Extra credit will be given to students who report such mistakes.

Date: June 4, 2014.

2. INTRODUCTION: WHAT IS MATHEMATICS, WHAT IS A PROOF?

The material in the entire section will be covered in Lecture 1 (tentative).

2.1. What is mathematics? The course is not meant to be about the philosophy of mathematics, but it is important to realize that this question is still far from being understood. There are people whose only job is to investigate and discuss this topic. One should also understand that there cannot be one absolute all-encompassing answer: Mathematics means different things to different people (even to different mathematicians). Here is a (non-exhaustive) sample of possible answers:

- Mathematics is the language of Science.
- Mathematics is the study of patterns.
- Mathematics is the study of topics such as quantity (numbers), structure, space, and change [Wikb].
- Mathematics is the study of what can precisely be argued to be true or false.
- Mathematics is what mathematicians do.
- Mathematics is the subject in which we never know what we are talking about, nor whether what we are saying is true [Rus03, p. 5].
- Etc. See for example [Wika] for more.

Whatever mathematics is, most mathematicians would agree that it involves *explaining* rather than just *describing*. The most highly-valued form of explanation in mathematics is called a *proof*.

2.2. What is a proof? In mathematics, a proof is a very precise *argument* explaining *why* a given statement is true. The argument must be so convincing that its audience (anybody who reads/hears it, including the writer of the proof) has no doubt about the truth of the statement. Concretely, this means that:

- (1) The statement that is being proven, as well as every step of the proof, must be *unambiguous*: if there is ambiguity on what the statement even says, how can one agree about its truth? In particular, the proof should be understandable to its audience.
- (2) The proof must be *logically sound*: not only must every step be correct, but steps should also be *justified* so that no doubt is left about their validity.
- (3) A proof must rely on *common ground* shared by the entire audience: if the audience disagrees on the truth of every single fact,

including whether $1 + 1 = 2$ or $1 = 1$, then there is no hope of convincing it using pure reason. This common ground includes some (hopefully simple) statement whose truth is taken as granted (the *axioms*), as well as the valid rules of logic that can be used in a proof. This common knowledge should (explicitly or implicitly) be made clear in the proof itself.

Remark 2.1. Thus a proof also depends on its audience. For example, a five year-old child needs to be explained why $2 + 3 = 5$, while most adults take this fact for granted. Similarly in mathematics, it is permissible to omit explanations for facts that the reader thinks the audience will have no difficulty believing. However, this often leads to laziness on the part of the writer (“the proof is left as an exercise”, “obviously, so and so is true”) which in turn leads to mistakes. Words such as “obviously”, “clearly”, etc. are especially dangerous: if a statement is *really* obvious, then one can omit the qualifier entirely (in the “real world”, nobody ever says “clearly, $2 + 3 = 5$ ”).

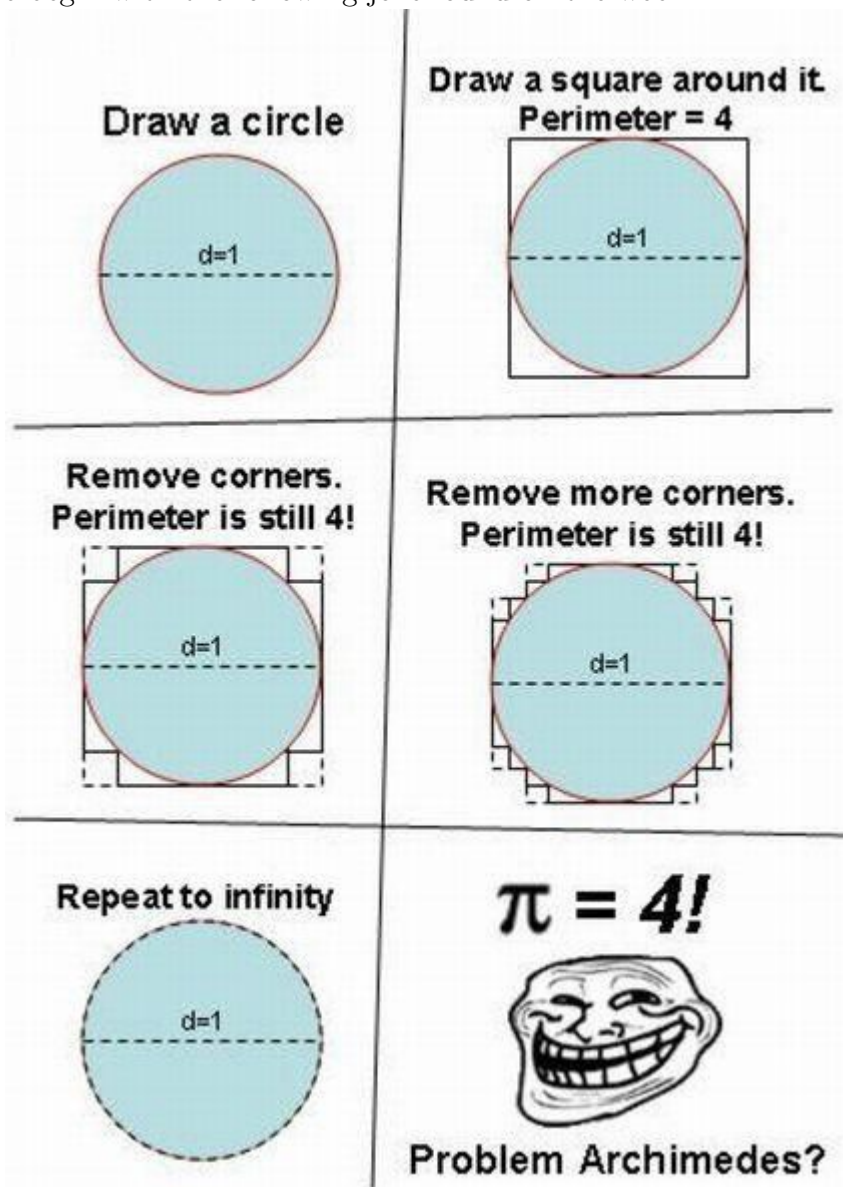
Remark 2.2. On the other hand, there is a danger of writing too much details: this can hurt understanding by burying the most important points of a proof inside pages of easy arguments. A famous extreme case¹ is “Principia Mathematica” [RW25] which takes more than 300 pages to prove that $1 + 1 = 2$ (the statement is accompanied by the comment “The above proposition is occasionally useful”). While leaving no stone unturned, a proof must *emphasize the hard steps*.

We will *not* specify *exactly* what form a proof must take: doing this would force us to impose too many unnatural restrictions, ending up with a programming language-like syntax impossible for humans to work with.

Mathematical proofs can usually be written in plain English, but one must often make use of mathematical symbols to describe something precise that would be too long or too hard to describe in English. Since human languages can be ambiguous, one must often make sure that the argument remains completely clear (additional informal explanations can be marked as such using words such as “intuitively”, or “loosely speaking”). On the other hands, writing in plain English improves readability and understandability, so it is advisable to make use of it whenever appropriate. Remember: a mathematician writes for humans, not computers.

¹Of course, the aim of the authors in writing the book was never to prove to the skeptics that $1 + 1 = 2$, but rather to show that it could in principle be done.

2.3. **Good proofs, bad proofs.** We now consider examples of proofs. We begin with the following joke found on the web²:



Needless to say, this argument has several issues. For a start, the conclusion is wrong. However sometimes even “proofs” for wrong facts

²<http://s254.photobucket.com/user/balthamossa2b/media/1290457745312.jpg.html>

turn out to make instructive mathematical insight³. What will interest us is that many of the points discussed above are not respected:

- (1) Many steps are ambiguous and unclear: What exactly is done when “removing corners”? There are several ways to do it (e.g. one should specify the size of a corner): how should it be done? What exactly is meant by “remove more corners”? Most importantly (and this is where the argument goes wrong), what does it mean to “repeat to infinity”?
- (2) Steps are only briefly justified by a picture. Pictures are very useful in mathematics as an additional explanatory device but can often be misleading (for example⁴, it is possible to cut a ball into a few pieces, move these pieces around, and reassemble those pieces into two balls of the same volume as the earlier one). In general, a picture can never by itself justify a step. Here of course all we have to justify that the “square with removed corners” becomes a circle as we “repeat to infinity” is a picture of a circle.
- (3) The hard step of the proof (the “repeat to infinity”) is not emphasized at all and is written off as just some ordinary easy inference.

After making all those observations, it is no surprise that the proof turns out to be dead wrong. On the other hand, this proof also has some positive aspects: it is fun and very easy to read (since written in plain English, with additional pictures to illustrate) and has educational value!

We now look at a very different style of argument. We say a number x is *non-negative* if $x \geq 0$.

Theorem 2.3. For all non-negative real numbers a and b :

$$a^2 + b^2 \leq (a + b)^2$$

“Proof” 1.

$$a^2 + b^2 \leq (a + b)^2$$

$$a^2 + b^2 \leq a^2 + 2ab + b^2$$

$$0 \leq 2ab$$

³Although this is beyond the scope of this course, this is also the case here: it turns out what makes the argument fail is that one cannot always inverse the order of taking a limit and integrating.

⁴This is called the Banach-Tarski paradox, but is unfortunately beyond the scope of this course.

True because the product of two non-negative numbers is non-negative. \square

First observe that in this case the result and its proof are clearly separated. The result is stated first (we will always call a true statement that we intend to prove a *theorem*⁵), followed by its proof. This is a good idea, as it helps the reader to see immediately what is being proven (as is traditional in mathematical writings, the end of the proof is marked by a box). In addition the argument consists of formal manipulations of equations, so one could hope it will make for a clear, unambiguous proof. There are however several issues: for one thing, one would have liked to see a plain English explanation of what exactly the argument is: as it turns out, each manipulation is correct, but how are they justified? Importantly, the first step is not at all justified, but is exactly what we want to prove! Thus a high level view of the “proof” is that we first assume what we want to prove, obtain a true conclusion, and therefore conclude the original assumption is correct. We will see that this is not logically valid, as it constitutes *circular reasoning* (for example, assume $0 = 1$ is true, multiply both sides by 0, get $0 = 0$, which is true. This does not justify $0 = 1$).

However, *in this particular case* one can revert all our steps and obtain the correct conclusion. Thus a better proof is:

Proof 2. Since the product of non-negative numbers is non-negative,

$$0 \leq 2ab$$

Adding $a^2 + b^2$ to both sides, one gets:

$$a^2 + b^2 \leq a^2 + 2ab + b^2$$

So factoring the right hand side:

$$a^2 + b^2 \leq (a + b)^2$$

which is the desired inequality. \square

It is of course more likely one would come up with an argument like “Proof” 1 first (keeping in mind that the steps can be reversed), but presented as such “Proof” 1 is incorrect and one must make sure to either mention that (and justify why) the argument is reversible, or write up a proof going in the right direction in the first place.

⁵Mathematicians usually make a distinction between theorems, lemmas and propositions depending on the importance of the result, but we will not adopt this approach

There are two different processes at work here: One is the process of *solving* the problem: coming up with all the ideas in the proof. The other is the process of *writing up* the proof itself. It is important that these two be separated: you are allowed to think about a problem in any way you like, but a proof has to satisfy stringent requirements and so must be written up with care.

Notice also that our proof takes several facts as a given. For one thing, the reader is expected to know what real numbers are, what sums and products are, and how they interact with the ordering (e.g. the fact that a product of non-negative numbers is non-negative). We state these facts precisely in the next section and prove a few useful results about the real numbers. This will provide us with examples for a more careful study of the basic logical reasoning involved in proofs (Section 4).

3. NUMBERS AND INEQUALITIES

Tentative lecturing plan: The axiom of the real numbers, the definition of subtraction and division, the basic facts that follow, and the definition of the square should be covered in lecture 2. The definition of the square root, absolute value, the triangle and AGM inequalities should be covered in lecture 3.

3.1. The real numbers. You are probably already familiar with the real numbers. They are a basic object of study in calculus. Examples of real numbers include $0, 1, -1, \frac{1}{2}, \pi, e, \sqrt{2}$; Operations on real numbers include addition, multiplication, subtraction, division, square root, exponentiation, limits, etc.

It is unfortunately very tricky to correctly *define* what a real number is. You may be used to thinking of a real number as an integer followed by a dot and a (possibly infinite) sequence of digits. For example, $\pi = 3.14159265\dots$. This “definition” turns out to have several issues. For one thing, such a sequence of digit is *not* unique (for example there is the infamous fact that $1 = 0.99999999\dots$). More importantly, this definition does not tell us much about what a real number “really is”: it just gives us a way to represent one, but there are many other choices (for example, one could use base 5 instead of base 10, or one could write $1/3$ instead of $0.333333\dots$) and it seems that an infinite sequence of digits is not particularly convenient to work with.

In this course, we will not discuss what real numbers really are, but will instead adopt an *axiomatic approach*: as discussed above, no matter what they are, we all know they must satisfy some properties (for example, $x < x + 1$ for any real number x). We will give a list of

such properties, and start from them (and only from them) to derive other nontrivial facts.

Axiom 3.1 (Axioms of real numbers). ⁶ The real numbers are objects satisfying the following properties:

- (R_0) Among the reals, there are two distinguished elements, 0 and 1, with $0 \neq 1$. 0 and 1 have some special properties discussed below.
- (R_1) Binary operations $+$ and \cdot are defined on the reals (they take two reals as input and produce one real as output).
- (R_2) Between any two reals x and y , one can ask whether $x < y$.
- Addition $(+)$ satisfies the following properties: For all real numbers x, y, z :
 - (A_0) Associativity: $(x + y) + z = x + (y + z)$.
 - (A_1) Commutativity: $x + y = y + x$.
 - (A_2) Zero is the additive identity: $x + 0 = x$.
 - (A_3) Existence of inverse: There is always a unique⁷ real number w such that $x + w = 0$.
- Multiplication (\cdot) satisfies the following properties: For all real numbers x, y, z :
 - (M_0) Associativity: $(x \cdot y) \cdot z = x \cdot (y \cdot z)$.
 - (M_1) Commutativity: $x \cdot y = y \cdot x$.
 - (M_2) One is the multiplicative identity: $x \cdot 1 = x$.
 - (M_3) Existence of inverse: If $x \neq 0$, there is a unique real number w such that $x \cdot w = 1$.
- Multiplication and addition interact as follows: For all real numbers x, y, z :
 - (D_0) Distributive law: $x \cdot (y + z) = (x \cdot y) + (x \cdot z)$.
- The ordering $(<)$ satisfies the following properties: For all real numbers x, y, z :
 - (O_0) Trichotomy: exactly one of the following is true: $0 < x$, $x = 0$, or $x < 0$.
 - (O_1) Closure under addition: If $0 < x$ and $0 < y$, then $0 < x + y$.
 - (O_2) Closure under multiplication: If $0 < x$ and $0 < y$, then $0 < x \cdot y$.
 - (O_3) If $x < y$, then $x + z < y + z$.

⁶In this course, an “Axiom” is a basic principle that we assume as a given. A “Fact” is a result which follows from the axioms but will not be proved: you can take it as a given.

⁷In fact, uniqueness follows from the other properties (exercise).

- (C_0) The completeness axiom (*will not be discussed in this course*): If F is a non-empty collection of real numbers and there is a real number x such that for all y in F , $y < x$, then one can choose x with the additional property that for any $x' < x$ there is y in F with $x' < y$.

This is a very long list and you are not expected to learn all the properties by heart, nor remember their names. The completeness axiom is especially tricky and you will not be required to know anything about it. It turns out that those axioms *characterize* the reals: in a very precise sense only the real numbers satisfy those axioms. In fact, all true results about the reals can be proven using only these properties.

Before discussing the properties further, we introduce some notation:

Notation 3.2. When brackets are not present, multiplication should be done first, i.e. for x, y real numbers, $x \cdot y + x$ means $(x \cdot y) + x$, and *not* $x \cdot (y + x)$. We often write xy instead of $x \cdot y$. By associativity, the order of summation does not matter, so we write $x + y + z$ for $(x + y) + z$ (which is the same thing as $x + (y + z)$). Similarly for multiplication⁸.

We write $y > x$ to mean $x < y$. We write $x \leq y$ to mean that $x < y$ or $x = y$. $x \geq y$ means $y \leq x$. We say x is *positive* if $0 < x$, *negative* if $x < 0$, *non-negative* if $0 \leq x$. When we want to emphasize that x is not zero, we may say “strictly positive” or “strictly negative”.

Notice that it is necessary to explicitly define relations such as $>$ since all our axioms talk about is $<$. We can similarly define subtraction and division:

Definition 3.3. For x a real number, we define the *negative* of x to be the *unique* real number w such that $x + w = 0$ (this is guaranteed to exist by the axiom of existence of additive inverse). We write $-x$ for the negative of x . Similarly, define the *reciprocal* of a nonzero x to be the *unique* w such that $xw = 1$. We write x^{-1} for the reciprocal of x .

For real numbers x, y , we define $x - y$ to mean $x + (-y)$. Similarly, for y nonzero, we define x/y (also written $\frac{x}{y}$) to mean $x \cdot y^{-1}$.

Definition 3.4. The number 2 is defined to be $1 + 1$. Similarly, $3 = 1 + 1 + 1$, $4 = 1 + 1 + 1 + 1$, etc. The *natural numbers* are $0, 1, 2, 3, \dots$ (a more precise definition will be given later in the course).

The *integers* consist of the natural numbers and their negative. The *rational numbers* consist of all numbers of the form n/m where n, m are integers and m is not zero.

⁸Associativity is used so often that we will never mention we are using it. Note that not all operations are associative. For example, subtraction is not: $(0 - 1) - 1 = -2$ is different from $0 - (1 - 1) = 0$

Remark 3.5. Even though it has been thousands of years since the number 0 was introduced, some people are still debating whether the “right” definition of the natural numbers should contain zero. Depending on the kind of mathematics one is doing, it may or may not be convenient to have it included, and your experience with other courses may vary. From a foundational point of view, there are several good arguments for zero to be a natural number. The computer scientist Edsger Dijkstra has also given several other simple reasons [Dij]. Thus in this course, we will assume that 0 is a natural number.

You may take the following facts for granted. We will prove them once we have the tools to state a more formal definition of the natural numbers.

Fact 3.6.

- (1) For all integers m and n , $m + n$ and $m \cdot n$ are integers.
- (2) For all natural numbers m and n , $m + n$ and $m \cdot n$ are natural numbers.

From the axioms and the definitions of subtraction and division, we can go on to prove many more elementary properties. The arguments are usually quite boring (you will be asked to do a few of them in your homework). We list here all the elementary facts we will need (you can use them freely).

Fact 3.7 (Properties of addition and multiplication). For all real numbers x, y, z, w :

- (F_0) : $x \cdot 0 = 0$.
- (F_1) : $-(xy) = (-x)y$.
- (F_2) : $-x = (-1)x$.
- (F_3) : $(-x)(-y) = xy$.
- (F_4) : If $xy = 0$, then $x = 0$ or $y = 0$ (or both).
- (F_5) : $(x + y)(z + w) = xz + xw + yz + yw$.

Fact 3.8 (Properties of the ordering). For all real numbers x, y, z, w :

- (F_6) : Totality: Exactly one of $x < y$, $x = y$, $y < x$ always holds. Exactly one of $x \leq y$ or $y < x$ always holds.
- (F_7) : Reflexivity: $x \leq x$.
- (F_8) : Antisymmetry: If $x \leq y$ and $y \leq x$, then $x = y$.
- (F_9) : Transitivity: If $x \leq y$ and $y \leq z$, then $x \leq z$. Similarly if \leq is replaced by $<$.
- Interaction with addition and multiplication:
 - (F_{10}) : $0 < 1$.

- (F_{11}) : If $x \leq y$ and $z \leq w$, then $x + z \leq y + w$. Similarly if \leq is replaced by $<$.
- (F_{12}) : If $x \leq y$, then $-y \leq -x$. Similarly if \leq is replaced by $<$.
- (F_{13}) : If $x \leq y$ and $0 \leq z$, then $xz \leq yz$.
- (F_{14}) : If $0 \leq x$ and $0 \leq y$, then $0 \leq xy$. Similarly if \leq is replaced by $<$.
- (F_{15}) : $0 \leq x \cdot x$, and if $0 < x$ then $0 < x \cdot x$.
- (F_{16}) : If $0 < x$, then $0 < x^{-1}$.
- (F_{17}) : If $0 < x < y$, then $0 < y^{-1} < x^{-1}$.

Remark 3.9. Given real numbers x, y, z , if $x \leq y$ and z is arbitrary, then we *cannot conclude* that $xz \leq yz$: the hypothesis that $0 \leq z$ is needed. To see this, we give a *counterexample*: Take $x = 1$, $y = 2$, and $z = -1$. Then $x < y$ (exercise) but $zy < zx$ (by (F_{12}) and (F_2)).

We will use Fact 3.1 and Fact 3.7 without explicitly mentioning them each time.

3.2. Squares, roots, and absolute value.

Notation 3.10. For x a real number, we write x^2 for $x \cdot x$.

Theorem 3.11. For all real numbers x and y :

- $(x + y)^2 = x^2 + 2xy + y^2$.
- $(x - y)^2 = x^2 - 2xy + y^2$.
- $(x + y)(x - y) = x^2 - y^2$.

Proof. We use property (F_5) of Fact 3.7 and do the algebraic manipulations you should all be familiar with. For example:

$$\begin{aligned}
 (x + y)^2 &= (x + y) \cdot (x + y) \\
 &= x^2 + xy + yx + y^2 \\
 &= x^2 + xy + xy + y^2 \\
 &= x^2 + 1 \cdot xy + 1 \cdot xy + y^2 \\
 &= x^2 + (1 + 1)xy + y^2 \\
 &= x^2 + 2xy + y^2
 \end{aligned}$$

The other proofs are similar. □

Remark 3.12. We will often call the process of going from a sum (as in $x^2 + 2xy + y^2$) to a product (as in $(x + y)^2$) *factoring*. We refer to the inverse operation (going from the product to the sum) as *expanding*.

Definition 3.13. A real number x is said to be a *square root* of a real number y if x is non-negative and $x^2 = y$.

By property (F_{15}) from Fact 3.7, x^2 is always non-negative, so *only non-negative real numbers have a real square root*. Moreover, the square root is unique:

Theorem 3.14 (Uniqueness of the square root). Given x, y non-negative real numbers, assume $x^2 = y^2$. Then $x = y$.

Proof. Subtracting y^2 from both sides, we have that $x^2 - y^2 = 0$. Factoring, $(x - y)(x + y) = 0$. Thus (by (F_4)) either $x - y = 0$ (and so $x = y$) or $x + y = 0$ (and so $x = -y$). In the first case, we are done. In the second case, since $0 \leq x$, we must have $0 \leq -y$, so taking the negation on both sides and reversing the inequality (see (F_{12})), $y \leq 0$, and so by antisymmetry (F_8) , $y = 0$. Therefore $x = -y = (-1)y = 0 = y$, as desired. \square

Remark 3.15. This is an example of what is called a *proof by cases*: We show that one of two cases must happen, and show that from each one we can prove the result, so the result must be true.

We will not discuss the proof here (it uses the completeness axiom), but square roots exist:

Fact 3.16. Every non-negative real number has a square root.

Notation 3.17. For x a non-negative real number, we write \sqrt{x} for the unique square root of x .

Example 3.18. We have that $\sqrt{4} = 2$, $\sqrt{1} = 1$, $\sqrt{0} = 0$. We will see later that $\sqrt{2}$ is a real number that is *not* rational.

Warning. Assume that x, y are real numbers and $x^2 = y$. Do we have $x = \sqrt{y}$? *No*, because we do *not* know that x is non-negative. Indeed, it turns out that $-\sqrt{y}$ is also a possible solution, which will be different from \sqrt{y} if $y > 0$. Using uniqueness of the square root, it is not hard to see that these are the only possible solutions.

How do square roots play with the ordering? It turns out taking a square root preserves the ordering.

Theorem 3.19. For x, y real numbers, if $0 \leq x \leq y$, then $x^2 \leq xy \leq y^2$ and $\sqrt{x} \leq \sqrt{y}$.

Proof. Multiplying the first inequality by x (remembering that x is non-negative), we obtain $x^2 \leq xy$. Similarly, multiplying the first inequality by y , we obtain $xy \leq y^2$. Thus we obtain $x^2 \leq xy \leq y^2$.

To see $\sqrt{x} \leq \sqrt{y}$, we assume it is not true. Then we must have $x \neq y$ and $\sqrt{y} < \sqrt{x}$. By definition of the square root, \sqrt{y} , \sqrt{x} are both non-negative, thus we can apply the fact we just proved (x standing for \sqrt{y} , y standing for \sqrt{x}) to get that $(\sqrt{y})^2 \leq (\sqrt{x})^2$, so $y \leq x$. Because $y \neq x$, $y < x$, a contradiction to the assumption. \square

Remark 3.20. This is an example of a *proof by contradiction*: The result we want can be either true or false. We assume it is false and derive something ridiculously wrong, so the result must have been true in the first place.

Finally, we observe that taking square root and squares preserve products:

Theorem 3.21. For all real numbers x and y :

- $(xy)^2 = x^2y^2$.
- If x and y are non-negative, $\sqrt{xy} = \sqrt{x}\sqrt{y}$.

Proof. Exercise. \square

Definition 3.22. The *absolute value* $|x|$ of a real number x is defined by:

$$|x| = \begin{cases} x & \text{if } x \geq 0 \\ -x & \text{if } x < 0 \end{cases}$$

Theorem 3.23 (Elementary properties of the absolute value). For all real numbers x and y :

- (1) $x^2 = |x|^2$.
- (2) $|x| = \sqrt{x^2}$.
- (3) $x \leq |x|$.
- (4) $|xy| = |x||y|$.

Proof. Exercise. \square

3.3. Inequalities. Sometimes, it is very hard to know what a given quantity is *exactly* equal to, but it is possible to *estimate it*, namely give a lower (or upper) bound for it. This is what we will now investigate. We start with perhaps the most important inequality involving the real numbers, which allows us to estimate the absolute value of a sum in terms of the sum of the absolute values.

Theorem 3.24 (The triangle inequality). For all real numbers x, y , $|x + y| \leq |x| + |y|$.

Proof. First observe that $2xy \leq 2|x||y|$ (to see this, first use Theorem 3.23.(3) to obtain $2xy \leq |2xy|$, and then use Theorem 3.23.(4) to see $|2xy| = 2|x||y|$). Adding $x^2 + y^2$ to both sides and using that $x^2 = |x|^2$ and $y^2 = |y|^2$, one obtains $x^2 + 2xy + y^2 \leq |x|^2 + 2|x||y| + |y|^2$. Factoring, $(x + y)^2 \leq (|x| + |y|)^2$. Since $(x + y)^2 = |x + y|^2$, we can take the square roots on both sides of the inequality and obtain the result from Theorem 3.19. \square

Remark 3.25. It is often valuable to try to understand when an inequality is strict (meaning that \leq can be replaced by $<$) and when it is not. In case of the triangle inequality, we can give examples for both cases: If $x = y = 1$, equality holds, while if $x = 1$ and $y = -1$, the inequality is strict. Can you come up with a condition on x and y characterizing when the inequality is strict?

For more practice, we prove the following important inequality:

Theorem 3.26 (The arithmetic mean, geometric mean (AGM) inequality). For all non-negative real numbers x, y , $\sqrt{xy} \leq \frac{x+y}{2}$.

Proof. Note first that since x and y are non-negative, xy is non-negative (by (F_{14})), so it makes sense to talk about \sqrt{xy} .

We start the proof by observing that $0 \leq (x-y)^2$ (because squares are always non-negative (F_{15})). Expanding and adding $2xy$ on both sides, we obtain $2xy \leq x^2 + y^2$. Adding $2xy$ again and factoring the right hand side, we get $4xy \leq (x + y)^2$. By Theorem 3.19, $\sqrt{4xy} \leq \sqrt{(x + y)^2}$. Using Theorem 3.21, we can expand the left hand side to $2\sqrt{xy}$. Using Theorem 3.23, $\sqrt{(x + y)^2} = |x + y| = x + y$ (since both x and y are non-negative and a sum of non-negative numbers is non-negative by (F_{11})). Thus we obtain $2\sqrt{xy} \leq x + y$, so (using (F_{16}) to see that $\frac{1}{2}$ is positive and (F_{13}) to multiply both sides by $\frac{1}{2}$) $\sqrt{xy} \leq \frac{x+y}{2}$, as desired. \square

Remark 3.27. In the AGM inequality, equality holds precisely when $x = y$: First, it is not difficult to check that equality holds if $x = y$. Now if $x \neq y$, then $0 < (x - y)^2$, and one can repeat the proof with \leq replaced by $<$, so the inequality ends up being strict.

4. BASIC LOGIC

Lecture 4 will cover the basic logical operators, Lecture 5 will cover quantifiers (tentative)

We now start our study of the *elementary logic* inherent in all mathematical reasonings (including the reasonings done in the past section).

Believe it or not, we have already been doing quite a bit of logic in the past section: For example, we used words such as “for all”, “for any”, “exists”, “assume”, “if”, “then”, “and”, “or”, “therefore”, “thus”, etc (some are synonyms). In mathematics, those words have a very precise meaning, sometimes different from their colloquial use in English. Since proofs must be unambiguous, it is important that everybody agrees on what those words *exactly* mean. This will allow us to discuss questions that are very foreign to everyday English. For example, we will see what exactly should be proven to show that the statement “For any non-negative real number x , if $x \neq 2$, then either $0 = 1$ or $x \neq 3$ ” is false.

We start with the basic concept of a *proposition*. A proposition is an unambiguous mathematical statement that is either true or false⁹. Examples include:

- Every real number has a real square root.
- For all real numbers x and y , $|x + y| \leq |x| + |y|$.
- Every even natural number strictly larger than 2 is the sum of two primes.
- $2 + 3 = 5$.
- $2 + 2 = 7$.

The first and last propositions are false (why?), but nevertheless they have a clear mathematical meaning. The third example¹⁰ (do not worry if you do not remember what an even number or a prime is) is also a proposition, but interestingly, mathematicians do not know (as of May 2014) whether it is true or false. Most *believe* it is true, but nobody knows a proof. Such propositions are called *conjectures*. We will see that we can reason with propositions, even if we do not know whether they are true or false.

On the other hand, the following are not propositions:

- Mathematics is boring.
- 42.

The first one has no precise mathematical meaning, while the second one has no truth value (it is not saying something which is either true or false).

⁹You may object (and you would be right) that this is not a good definition, since we have left undefined what words like “mathematical statement”, “true”, and “false” mean. Making all of this completely precise would force us to introduce programming language-like formalisms that, while essential to a deeper understanding of mathematical reasoning, are dry and not too relevant in everyday mathematical practice. We will not go down that road here.

¹⁰Which goes by the name of Goldbach’s conjecture.

4.1. Logical operators. We can combine propositions using *logical operators* such as *and* or *or*. For example, “ $2 + 3 = 5$ or $2 + 2 = 7$ ” is a proposition. Is it true or false? It is true: in mathematics, the “or” (also called the *disjunction*) of two propositions is true when *at least* one of them is true (so “or” is inclusive: “ $2 + 3 = 5$ or $3 + 2 = 5$ ” is true). Notice that this does not always match English usage. For example when in a restaurant you are told that your side can be either French fries or cole slaw, this means you cannot choose both (unless you pay extra). On the other hand, if while on a beach you are told that you should protect yourself from the sun using a cap or a T-shirt, this means it is also fine if you use both.

Closer to English usage, the “and” (also called the *conjunction*) of two propositions is true when *both* propositions are true. Thus “ $2 + 3 = 5$ and $2 + 2 = 7$ ” is false, but “ $2 + 3 = 5$ and $3 + 2 = 5$ ” is true.

When considering compound propositions with many ands and ors, using English becomes annoying, so we introduce a formal “algebra” of propositions. We specify that the simplest propositions will be T (which simply abbreviates true and is always true) and F (which is always false).

For p and q propositions, we introduce symbols to stand for “or” and “and”: we will write $p \vee q$ for p or q , and $p \wedge q$ for p and q . We *define* these operators using a *truth table*. A truth table specifies exactly how an operator behaves by simply listing all possible truth values for p and q . Here is the truth table of \vee and \wedge :

p	q	$p \vee q$	$p \wedge q$
F	F	F	F
F	T	T	F
T	F	T	F
T	T	T	T

For example, the first line tells us that if both p and q are false, then $p \vee q$ and $p \wedge q$ are also false. Using truth tables, we can reason about propositions without worrying about the ambiguities of the English language. Let’s now introduce more operators!

A seemingly simple operator is the *negation*: The *negation* of a proposition p , written $\neg p$ and read “not p ”, is false if the proposition is true, and true if it is false. Using a truth table, this translates to:

p	$\neg p$
F	T
T	F

Since the “and” of two propositions is also a proposition, we are allowed to take its negation. To avoid ambiguities, we use brackets to say which operation is to be done first. $\neg(p \wedge q)$ takes the negation of $p \wedge q$, while $(\neg p) \wedge q$ first takes the negation of p , and then “and”s this with q . By convention, negations are taken first, so $\neg p \wedge q$ will say the same thing as $(\neg p) \wedge q$.

Is there a simple way of expressing the negation of $p \wedge q$? Let’s see what this would say in plain English: if I know that it is false that both p and q hold, what do I know about p and q ? Well, *at least* one of them must be false. Said symbolically, $\neg p \vee \neg q$. Since it is tricky to conduct those reasonings in plain English, you should *not* consider the previous sentences as a proof, only as an indication of what you are looking for. To make our argument precise, let’s use a truth table:

p	q	$\neg p$	$\neg q$	$p \wedge q$	$\neg(p \wedge q)$	$\neg p \vee \neg q$
F	F	T	T	F	T	T
F	T	T	F	F	T	T
T	F	F	T	F	T	T
T	T	F	F	T	F	F

We see that indeed $\neg(p \wedge q)$ and $\neg p \vee \neg q$ behave in exactly the same way. We say that they are *logically equivalent* (or just equivalent) and write $\neg(p \wedge q) \equiv \neg p \vee \neg q$. This result has a name:

Theorem 4.1 (De Morgan’s laws for logical operators). For all propositions p and q :

- $\neg(p \wedge q) \equiv \neg p \vee \neg q$.
- $\neg(p \vee q) \equiv \neg p \wedge \neg q$.

Proof. The first result has just been proven, and the proof of the second is similarly done using a truth table (exercise). \square

We now introduce an important and often misunderstood operator: implication.

Definition 4.2. For propositions p and q , the operator $p \rightarrow q$ (read “ p implies q ”, or “if p , then q ”) is *defined* by the following truth table:

p	q	$p \rightarrow q$
F	F	T
F	T	T
T	F	F
T	T	T

Notice that if p is false, then $p \rightarrow q$ is true *regardless of* q (using our notation, $F \rightarrow q \equiv T$). For example, both $(0 = 1) \rightarrow (1 = 1)$ and

$(0 = 1) \rightarrow (1 \neq 1)$ are true propositions. This may be best understood by an example: Consider the statement “If it is raining, then the road is wet”. The only way this statement could be *false*, is if there had been a day when it was raining, yet the road wasn’t wet. The statement does not tell us anything about days when it is not raining: in that case, the road may or may not be wet (maybe the road is near the sea and waves can reach it, or maybe it’s just some road in the desert where it never rains).

Concretely, this means that to *prove* that a statement of the form $p \rightarrow q$ is true, it suffices to *assume* p is true (since if p is false, the statement holds regardless of q), and show that q must also be true.

We can express $p \rightarrow q$ using the operators previously defined:

Theorem 4.3. For all propositions p and q , $p \rightarrow q \equiv \neg p \vee q$.

Proof. Exercise. □

Note that even if $p \rightarrow q$ is true, this does *not* necessarily mean that $q \rightarrow p$ holds. Using the previous example, even if we know that the road gets wet whenever it is raining, we cannot conclude that it is raining from the fact the road is wet (maybe somebody just poured some water on it). This is a *very* common source of errors. Another operator expresses this case:

Definition 4.4. For propositions p and q , the operator $p \leftrightarrow q$ (read “ p if and only if q ”, or “ p and q are logically equivalent”) is *defined* by the following truth table:

p	q	$p \leftrightarrow q$
F	F	T
F	T	F
T	F	F
T	T	T

Theorem 4.5. $p \leftrightarrow q \equiv (p \rightarrow q) \wedge (q \rightarrow p)$.

Proof. Exercise. □

4.2. Quantifiers. A proposition such as “For any real number x , $0 \leq x^2$ ” can be seen as a simple “propositional function”, $0 \leq x^2$, together with a *universal quantifier* “For any real number” telling us that this holds regardless of the exact value of x . Notice that this is more complicated than simply saying something like “ $0 \leq 1^2$ and $0 \leq 2^2$ ”. We now enlarge our “algebra of propositions” with such quantifiers.

First, we introduce the notion of a *propositional function*. A *propositional function* is a statement with variables that become a proposition

once the variables are assigned values. For example, $0 \leq x^2$ is not a proposition since it has no meaning if we do not specify x , but it becomes a proposition once x is specified. We could of course have more than one variable, as in $x = \sqrt{y}$. The truth value of the propositional function could depend on the value of the variables. For example, $x = \sqrt{y}$ is true if $x = y = 0$, but false if $x = -1$ and $y = 0$. Note that it is *implicit* that the variables always take their values in a particular *domain of discourse* (here the real numbers). It is always a good idea to state this domain of discourse explicitly.

Given a propositional function $p(x)$ with variable x , we would like to turn it into a proposition. We have already seen one way to do it: plug in a particular value for x . Another way is to qualify it with a *quantifier*. We will consider two of them here: “for all” and “there exists”.

Definition 4.6. Assume $p(x)$ is a propositional function with variable x .

We define the proposition $\forall x p(x)$ (said “For all x , $p(x)$ ”, or “For any x , $p(x)$ ”) to be true precisely if $p(x)$ is true for *any* value of the variable x in the domain of discourse.

We define the proposition $\exists x p(x)$ (said “There exists x such that $p(x)$ ”, or “There is x such that $p(x)$ ”) to be true precisely if $p(x)$ is true for *at least one* value of x in the domain of discourse.

Example 4.7.

- Formalizing the example above, we get $\forall x 0 \leq x^2$, where the domain of discourse is the real numbers.
- We can formalize the statement “For any non-negative real number x , if $x \neq 2$, then either $0 = 1$ or $x \neq 3$ ” by $\forall x (x \neq 2 \rightarrow (0 = 1 \vee x \neq 3))$, where the domain of discourse is the non-negative real numbers. Alternatively, we could set the domain of discourse to be all the real numbers, and formalize the statement by:

$$\forall x (x \geq 0 \rightarrow (x \neq 2 \rightarrow (0 = 1 \vee x \neq 3)))$$

- We can formalize the statement “Every real number has a real square root” by $\forall x \exists y (y^2 = x \wedge y \geq 0)$. The domain of discourse is again the real numbers.
- The statement of the triangle inequality can be written as $\forall x \forall y |x + y| \leq |x| + |y|$.
- The statement p that every even natural number strictly larger than 2 is the sum of two primes can be said in many different ways. Let $\text{Prime}(x)$ stand for the statement “ x is a prime

number, and $\text{Even}(x)$ stand for the statement “ x is an even number”. Then p can be written:

$$\forall x ((\text{Even}(x) \wedge x > 2) \rightarrow (\exists y \exists z \text{Prime}(y) \wedge \text{Prime}(z) \wedge x = y + z))$$

Where the domain of discourse is the natural numbers.

Several remarks are in order. First, formalizing statements in this way can make them hard to read, so it is best to use this kind of notation sparingly and prefer plain English when there is no ambiguity. On the other hand, once formalized, we will see it is easy to reason about the statement itself (e.g. to take its negation, or to see what exactly one will have to do to prove the statement). Translating from English could be a bit tricky, since there are many synonyms to express the same thing. For example, “Assume x is a real number, then $0 \leq x^2$ ”, “Let x be a real number, then $0 \leq x^2$ ”, “For any real number x , $0 \leq x^2$ ” are all saying the same thing.

Notice also that the truth of a proposition could depend on the domain of discourse. For example,

$\forall x \exists y y^2 = x$ is false if the domain of discourse is the real numbers (why?) but it is true if the domain of discourse is the *non-negative* real numbers.

We now turn to the interplay between quantifiers and negations: Assume $p(x)$ is a propositional function with variable x . Is there a simple way to write $\neg \forall x p(x)$? Unfortunately, we cannot use truth tables to figure it out anymore, but we can still think about what the question means in plain English: what does it mean for example to say that not all sheep are black. Well, there must exist a *counter-example*: a sheep that is not black. Thus $\neg \forall x p(x)$ is *logically equivalent* (i.e. $(\neg \forall x p(x)) \leftrightarrow (\exists x \neg p(x))$ is always true) to $\exists x \neg p(x)$. Similarly, if it is false that there exists a black sheep, this means no sheep is black, or in other words, all sheep are non-black. In symbols, $\neg \exists x p(x) \equiv \forall x \neg p(x)$. We will unfortunately not be able to *prove* these laws, since to avoid spending too much time on boring formalisms, we have avoided defining words such as “propositions” too precisely. We will see them as basic laws of reasoning that should be taken as granted. We state them again for reference:

Axiom 4.8 (De Morgan’s laws for quantifiers). For any propositional function $p(x)$:

- $\neg \forall x p(x) \equiv \exists x \neg p(x)$.
- $\neg \exists x p(x) \equiv \forall x \neg p(x)$.

To see the analogy with De Morgan's laws for logical operators, you should think of $\forall x$ as a possibly infinite “and” over all the elements of the domain of discourse, and $\exists x$ as a similar possibly infinite “or”.

Concretely, this shows us that to *disprove* a statement of the form “For all x , $p(x)$ ”, it is enough to find one x such that $\neg p(x)$ (a *counterexample*). Recall that we had already used this reasoning unconsciously before.

Example 4.9. The negation of the proposition “Every real number has a square root” is:

$$\begin{aligned}\neg \forall x \exists y \ y^2 = x &\equiv \exists x \neg \exists y \ (y^2 = x \wedge y \geq 0) \\ &\equiv \exists x \forall y \ \neg (y^2 = x \wedge y \geq 0)\end{aligned}$$

This tells us that to prove that “Every real number has a square root” is false, it is enough to prove that there exists a real number x such that for every real number y , y is not the square root of x , or in other words, there exists a real number that is not the square of any other (non-negative) real number (This is true, since one can take $x = -1$).

We close with an important warning: *the order of quantifiers matters*: For $p(x, y)$ a propositional function, the statements $\forall x \exists y \ p(x, y)$ and $\exists y \forall x \ p(x, y)$ are *not* logically equivalent. Let's think about an everyday example: assume $p(h, k)$ is the statement “ k is a key that unlocks the door of house h ”. The statement “ $\forall h \exists k \ p(h, k)$ ” says that for any fixed house, there is a key that opens its door. This sounds reasonable. On the other hand, the statement “ $\exists k \forall h \ p(h, k)$ ” says that there is a key that opens *every* house. In the first statement, each door might be opened by a different key, but the second statement tells us that *the same* key opens every door.

Example 4.10. Here is a more mathematical example: The statement “For every real number x , there is a real number y such that $x < y$ ” is true (why? If x is a real, then $y = x + 1$ does the job), but the statement “There exists a real number y such that for every real number x , $x < y$ is false (why? Given any real number y , $x = y + 1$ is such that $\neg(x < y)$).

We will see that it *is* always true that $(\exists y \forall x \ p(x, y)) \rightarrow (\forall x \exists y \ p(x, y))$. You may want to convince yourself of this fact before moving on.

5. ELEMENTARY PROOF TECHNIQUES

Lecture 6 started here

Now that we have some understanding of mathematical statements, let's look at some of the most useful techniques to prove them.

Assume you are given a proposition p which you would like to prove is true (note that if instead you want to prove that it is *false*, then it is the same as proving that $\neg p$ is true, and we have seen some tools in the previous section to make $\neg p$ into a simpler equivalent proposition ("pushing the negation inside")). You should realize that there is no algorithm or clear method that always works. However, there are some logical steps that are useful to know about and show up over and over again when proving certain types of statements. This is what this section focusses on.

5.1. Direct proof. This is the simplest method and the one that you should try first. You are given p a proposition you would like to prove. Let's look at what form your proposition could have. First it could be that p is so simple you can determine its truth value right away, e.g. maybe it is T (or maybe you can see by truth table that it is logically equivalent to T), or maybe it is $0 \neq 1$ (which is true simply because it is an axiom), etc.

Most often however, your proposition is too complicated to just be an axiom, but instead will be a *compound* proposition, i.e. it will contain simpler propositions that are put together using and, or, implies, quantifiers, etc. We would like to reduce the problem of proving p to the problem of proving these simpler propositions. It turns out that for each logical operator, there is a clear direct method of doing so. Below, q and r are propositions.

- If p is $q \wedge r$, then it is enough to prove both q and r .
- If p is $q \vee r$, then it is enough to prove one of q or r .
- If p is $q \rightarrow r$, then it is enough to prove r *assuming* q , i.e. you can take q for granted in your proof of r . q is often called the *hypothesis*, and r the *conclusion* of the statement p .
- If p is $q \leftrightarrow r$, then it is enough (since they are equivalent by Theorem 4.5) to prove both $q \rightarrow r$ and $r \rightarrow q$. The statement $r \rightarrow q$ is called the *converse* of $q \rightarrow r$.

We can similarly give similar guidelines for quantifiers. Below, $q(x)$ is a propositional function.

- If p is $\exists x q(x)$, then it is enough to exhibit some element a in the domain of discourse such that $q(a)$ can be proven to be true.

- If p is $\forall x q(x)$, then it is enough to fix an arbitrary element a of your domain of discourse, and prove that $q(a)$ is true. This step is often expressed by a sentence such as “Let a be an arbitrary real number” (if the domain of discourse is the real numbers).

At an abstract level, proving a statement boils down to managing a list of known facts and axioms, and *using* them wisely to obtain the result. The facts we know can also be written as propositions, so let’s see how we can use them. Assuming we already *know* that proposition p is true, we can similarly unpack p to make it more transparent. Below, q and r are propositions.

- If p is $q \wedge r$, then we know both q and r .
- If p is $q \vee r$, then we know that at least one of q or r is true.
- If p is $q \rightarrow r$, then whenever we also know that q holds, we know that r holds.
- If p is $q \leftrightarrow r$, then we know both that $q \rightarrow r$ and $r \rightarrow q$.

Let’s finally look at what happens if p has quantifiers. Below, $q(x)$ is a propositional function.

- If p is $\forall x q(x)$, then for an *arbitrary* element a in the domain of discourse, $q(a)$ will be true.
- If p is $\exists x q(x)$, then we know that we can *pick* (or *fix*) an element a in the domain of discourse such that $q(a)$ is true.

You might think the above is just repeating redundant information about the meaning of propositions. Yet it turns out that those steps are used over and over again in almost any proofs, so it is useful to keep them in mind.

Remark 5.1 (From something false, anything follows). The rules for dealing with known facts of the form $q \rightarrow r$ tells us something important about logical reasoning: Assume that q is a false proposition. From the definition of an implication, we know that $q \rightarrow r$, holds, *regardless of r* . Thus if we make a single “tiny” mistake in a mathematical proof and manage to show that q is true, we will be able to derive *any nonsense we like*¹¹. This is why mathematicians put so much emphasis on correct proofs.

Let’s try to use those principles on some example.

Theorem 5.2. For all propositional functions $p(x, y)$, $(\exists y \forall x p(x, y)) \rightarrow (\forall x \exists y p(x, y))$ is always true.

¹¹The mathematician Bertrand Russel was once challenged by one of his student to prove from $0 = 1$ that he was the pope. Here is his proof: adding 1 to both sides of the equation, we get $1 = 1 + 1$. The pope and I, form 2 persons, but since $2 = 1$, we actually are only one person, therefore I am the pope.

Proof. We want to prove a statement of the form $q \rightarrow r$, where q is $\exists y \forall x p(x, y)$, and r is $\forall x \exists y p(x, y)$. Thus we assume q as a given, and want to prove r . r is of the form $\forall x s(x)$, where $s(x)$ is $\exists y p(x, y)$, thus we let a be an arbitrary element of the domain of discourse, and we want to show that $s(a)$ holds. This is an existential statement, so it is enough to exhibit a single b such that $p(a, b)$. For this, we use q : we know there exists a single y such that something depending on y holds. We *fix* such a y and take¹² $b := y$. q tells us that for an *arbitrary* x , $p(x, y)$, and so *in particular* if we take $x = a$, $p(a, b)$ holds. This is exactly what we wanted to show. \square

For more practice, we continue playing with numbers.

Definition 5.3 (Even and odd integers). An integer n is *even* if it can be written as $n = 2m$ for m an integer (or, in other words, if *there exists* an integer m such that $n = 2m$). n is *odd* if it can be written as $n = 2m + 1$ for m an integer.

Example 5.4. 0 is even, since $0 = 2 \cdot 0$. 2 is even, since $2 = 2 \cdot 1$. 1 is odd, since $1 = 2 \cdot 0 + 1$. We will see that a number is even exactly when it is not odd.

Theorem 5.5 (Sum of odds and evens). Assume n and m are integers.

- (1) n is even if and only if $-n$ is even. n is odd if and only if $-n$ is odd.
- (2) If n and m are even, then $n + m$ is even.
- (3) If n and m are odd, then $n + m$ is even.
- (4) If n is odd and m is even, then $n + m$ is odd.
- (5) If n is even, then nm is even.
- (6) If n and m are odd, then nm is odd.

Proof.

- (1) Assume first that n is even. Then $n = 2k$ for k an integer. Thus $-n = -2k = (-1)2k = 2(-1)k = 2(-k)$. Since k is an integer, $-k$ is also an integer (by definition of the integers), so $-n$ is even. For the converse, assume that $-n$ is even. Then by the first part $-(-n) = n$ is even, as desired. The proof of the second statement is similar (exercise).
- (2) Assume that n and m are even. By definition, this means that $n = 2k$ for k an integer, and $m = 2k'$ for k' a possibly different

¹²We use $b := y$ instead of $b = y$ to emphasize that b is *defined* to be y (so $b = y$ is not a consequence of any previous fact). Mathematically, $b := y$ and $b = y$ mean the same thing.

integer. Thus we have that $n + m = 2k + 2k' = 2(k + k')$. Since the sum of two integer is an integer (Fact 3.6), $n + m$ is even.

- (3) Assume that n and m are odd. By definition, this means that $n = 2k + 1$ for k an integer, and $m = 2k' + 1$ for k' an integer. Thus we have that $n + m = 2k + 1 + 2k' + 1 = 2k + 2k' + 2 = 2(k + k' + 1)$. Since the sum of two integer is an integer (Fact 3.6), $n + m$ is even.
- (4) Assume that n is odd and m is even. By definition, this means that $n = 2k + 1$ for k an integer, and $m = 2k'$ for k' an integer. Thus we have $n + m = 2k + 1 + 2k' = 2(k + k') + 1$. Since $k + k'$ is an integer, $n + m$ is odd.
- (5) Exercise.
- (6) Exercise.

□

As a particular case, we obtain that for any even integer n , n^2 , $n + 2$, and $n - 2$ are even, and $n + 1$ and $n - 1$ are odd.

5.2. Proof by contradiction. We sometimes get “stuck” trying to apply the direct methods above. For example, assume we want to prove p which is of the form $\forall x q(x)$. Proving something holds for *every* element in the domain of discourse can be challenging, so sometimes it might be easier to derive a *contradiction* (i.e. a false proposition) from the negation of p . Formally, if we could show that $\neg p \rightarrow F$ is true, then looking at the truth table of the implication operator, this must mean that $\neg p$ is false, and hence that p is true. In symbol:

Theorem 5.6 (The principle of reasoning by contradiction). For any proposition p , $(\neg p \rightarrow F) \rightarrow p$ is always true.

Proof. Exercise: use a truth table. □

The power of the method of proof by contradiction is that *when we want to prove p , we can assume $\neg p$ holds for free*. Let us look at an example:

Theorem 5.7. For any even integer n , n is not odd.

Proof. By definition $n = 2m$ for some integer m . We would like to show that n is not odd, i.e. it is false that there exists an integer k so that $n = 2k + 1$, or equivalently, for any integer k , $n \neq 2k + 1$. It is not so clear how to proceed, so we *assume for a contradiction* that the opposite is true, namely there exists an integer k so that $n = 2k + 1$.

Then $2m = 2k + 1$, so $2(m - k) = 1$, so $m - k = \frac{1}{2}$. Now recall that $0 < \frac{1}{2} < 1$ (why?), so $\frac{1}{2}$ cannot be an integer, but $m - k = m + (-k)$

is an integer by Fact 3.6. Thus we obtain the proposition “ $m - k$ is an integer and $m - k$ is not an integer” which is a contradiction. Therefore it must be that n is not odd. \square

Using a technique called *induction*, we will later prove:

Fact 5.8. Any integer is either even or odd (but not both by the previous theorem).

Here, lecture 6 ended and lecture 7 started.

From this, we can prove:

Theorem 5.9. For any integer n , n is even if and only if n^2 is even.

Proof. If n is even, then by Theorem 5.5 n^2 is even.

For the converse, assume n^2 is even, and suppose for a contradiction that n is not even. By the previous fact, it must be odd. But then n^2 is odd by Theorem 5.5. Since n cannot be both even and odd, this is a contradiction. \square

Recall that a real number is rational if it can be written in the form n/m for n and m integers, m nonzero. A number which is not rational is called *irrational*. For the next example, we will also need (and this will also be proven later using induction):

Fact 5.10. Given a rational number r , there exists integers n and m with $r = n/m$, m nonzero, and at least one of n or m is odd.

Theorem 5.11. $\sqrt{2}$ is irrational.

Proof. We have to prove that there does *not* exist integers n, m with m nonzero and $\sqrt{2} = n/m$. It is unclear how to proceed, so we assume for a contradiction that this is false, i.e. $\sqrt{2}$ is rational. Use the previous fact to pick an integer n and a nonzero integer m such that at least one of them is odd and $\sqrt{2} = \frac{n}{m}$. Taking squares on both sides, $2 = \left(\frac{n}{m}\right)^2 = \frac{n^2}{m^2}$. Multiplying both sides by m^2 , $2m^2 = n^2$. This shows that n^2 must be even, but then by Theorem 5.9, n is even. Thus $n = 2k$ for some integer k , and so $2m^2 = n^2 = 4k^2$. Hence $m^2 = 2k^2$ must be even, and hence m must be even. Since at least one of n or m must be odd, this is a contradiction. \square

5.3. Proof by cases. Assume again that we want to prove the proposition p . We have already seen examples where we are stuck, but we would know what to do assuming some proposition q , and we would also know what to do assuming some proposition r . Assume further that we know that at least one of these always holds, i.e. $q \vee r \equiv T$. Then we are done proving p . In symbols:

Theorem 5.12 (The principle of reasoning by cases). For all propositions p, q, r :

$$((q \vee r) \wedge (q \rightarrow p) \wedge (r \rightarrow p)) \rightarrow p \text{ is always true.}$$

Proof. Exercise: use a truth table. \square

Very often, r will just be $\neg q$, and then $q \vee r$ is always true (why?). Let's look at an example. For this, we need to define the operation x^y for x a positive real number and y an arbitrary real number. This turns out to be very tricky, so we will just take the existence of this operation as a given:

Fact 5.13. There is an operation x^y for x a strictly positive real number and y a real number satisfying the following properties. For any strictly positive x , and real numbers y and z :

- (1) $x^0 = 1$
- (2) $x^1 = x$.
- (3) $x^{y+z} = x^y \cdot x^z$.
- (4) $(x^y)^z = x^{y \cdot z}$.

It turns out there are many such maps, and that to characterize the usual exponentiation, one needs to add the condition that for a fixed x the map $y \mapsto x^y$ is continuous. There is no need for you to worry about this detail here.

Theorem 5.14. There exists irrational numbers x and y such that x^y is rational.

Proof. We split our proof into two cases. Recall that $\sqrt{2}$ is irrational (Theorem 5.11).

Case 1: $\sqrt{2}^{\sqrt{2}}$ is rational. Then we can take $x = y = \sqrt{2}$ which are irrational by the observation above.

Case 2: $\sqrt{2}^{\sqrt{2}}$ is irrational. Then let $x := \sqrt{2}^{\sqrt{2}}$ and $y := \sqrt{2}$. x is irrational by assumption, y is irrational by the above, and

$$x^y = \left(\sqrt{2}^{\sqrt{2}} \right)^{\sqrt{2}} = \sqrt{2}^{\sqrt{2} \cdot \sqrt{2}} = \sqrt{2}^2 = \sqrt{2}^{1+1} = \sqrt{2} \cdot \sqrt{2} = 2$$

which is rational.

Since for any proposition p , $p \vee \neg p$ is always true (exercise), we see that either case 1 or case 2 happens, so we are done. \square

The downside of such a proof is that it is *nonconstructive*: It gives us no information as to *which case* is true. We know one of them must

be, but we do not know which one. It is a hard theorem of Kuzmin (beyond the scope of this course) that $\sqrt{2}^{\sqrt{2}}$ is actually irrational.

6. INTRODUCTION TO SETS

Previously, we “defined” the natural numbers to be 0, 1, 2, 3, ... What do these three dots actually mean? The intended meaning is that we keep adding 1 “forever”, generating more and more natural numbers. This is of course a lousy explanation, but even if we accept it, how can we make this intended meaning precise? An alien ignorant of terrestrial mathematics might believe this means 0, 1, 2, 3, 2, 1, 0, ... How can we precisely tell such an alien what we mean?

At this point, the concept of a *set* becomes useful. The situation is somewhat analogous to the real numbers: you are probably already familiar with sets: examples include the empty set, the set of real numbers, the set of natural numbers, the set $\{0, 1, 4\}$, the set $\{a, b\}$, etc; Operations on sets include union, intersection, complementation, etc.

Similarly to the case of the real numbers, it is very tricky to *define* what a set is. Some textbooks define a set as a collection of objects. This is not very satisfying: isn’t “collection” another word for “set”? Isn’t this “definition” analogous to saying that a real number is a quantity denoting a magnitude?

Another issue is that the intuitive meaning of the term “collection” is not quite what is intended. For example, you will prove in your homework that there cannot be a set containing all sets.

In these notes, we will adopt an *axiomatic* approach: we assume that there are objects we call sets, and give a list of some of their properties.

Axiom 6.1 (First axioms of sets). *Sets* are objects satisfying the following properties:

- (\in): Given an object a and a set A , we can ask whether a is in A (written $a \in A$). If $a \in A$, we say that a is an *element*, or a *member* of the set A .
- (E): Extensionality: A set is determined by its elements: for all sets A and B , if for any $a \in A$ we have $a \in B$, and for any $b \in B$ we have $b \in A$, then $A = B$.
- (S): Specification: Given a set A , and $p(x)$ a propositional function with variable x taking values in A , we can form the set B of elements of A satisfying p (written $B := \{a \in A \mid p(a)\}$. This is sometimes called the *set-builder notation*). An object a will be in B exactly when it is in A and it satisfies $p(a)$.

- (P) : Pairing: For any two (not necessarily distinct) objects a and b , we can form the set $A := \{a, b\}$. An object x will be in A exactly when $x = a$ or $x = b$.

We will introduce more axioms later, but some remarks are in order:

- We are effectively cheating, because we are not saying what an “object” is. You can just take it to mean “anything we will use sets with”. For example, numbers are objects, but sets are also objects, so one can define a set containing other sets. We sometimes call such a set a *collection* of sets or a *family* of sets.
- Extensionality tells us in particular that *sets are unordered*: the sets $\{1, 2\}$ and $\{2, 1\}$ are the same. Later, we will define the notion of an *ordered pair*, and the ordered pair $(1, 2)$ will be different from the ordered pair $(2, 1)$.
- The pairing axiom tells us in particular that for any object a , we can form the set $\{a, a\}$ which by the extensionality axiom is the same as the set $\{a\}$ containing the single element a . We will see later how to form sets with more than two elements.
- In the axiom of specification, it is important that we start with a given set A , and then “refine” it to obtain a new set B . It is *not* possible to start with a propositional function $p(x)$ and form the set of all a such that $p(a)$. If it were possible, we could take $p(x)$ to be “ x is a set”, and form the set of all sets. You will see in your homework that it already follows from the axioms above such a set cannot exist.

From the axioms above, we can already form a special set that plays an important role:

Theorem 6.2 (Existence of the empty set). There is a unique set that contains no elements. We write \emptyset for this set.

Proof. By the axiom of pairing, we can form the set $A := \{1, 2\}$. By the axiom of specification, we can form $B := \{a \in A \mid F\}$ (recall that F denotes the proposition that is always false). By definition, B does not contain any element. B is unique with this property, since sets are determined by their elements. \square

Remark 6.3. In mathematics, it often happens that we have to prove existence of a unique object satisfying some properties (like in the previous result). The proof of such a result usually has two parts: we prove the object exists, usually by constructing it, and then we prove it is unique by showing that any two objects with the required property must be the same.

We now define the important notion of being a subset:

Definition 6.4. A set A is a *subset* of a set B (written $A \subseteq B$) if for all $a \in A$, $a \in B$. We say A is a *proper subset* of B (written $A \subset B$) if $A \subseteq B$ but $A \neq B$. We write $A \supseteq B$ to mean $B \subseteq A$, and $A \supset B$ for $B \subset A$.

Remark 6.5. Some people write $A \subset B$ for $A \subseteq B$, while using $A \subsetneq B$ to emphasize that the inclusion is proper.

For example, $\emptyset \subseteq A$ for all sets A , and $\{1\} \subset \{1, 2\}$.

Directly from the axiom of extensionality, we obtain:

Theorem 6.6. Two sets A and B are equal if and only if $A \subseteq B$ and $B \subseteq A$.

Proof. If $A = B$, they have in particular the same elements, and so $A \subseteq B$ and $B \subseteq A$ follow. If $A \subseteq B$ and $B \subseteq A$, then the definition of the axiom of extensionality tells us that $A = B$. \square

This tells us that in virtually all cases, *to prove that two sets are equal, we must show that each is a subset of the other.*

Just like for numbers and propositions, we would like to define some operation on sets. Here is one of the most important:

Definition 6.7. Given two sets A and B , the *intersection* of A and B (written $A \cap B$) is the set $\{a \in B \mid a \in A \text{ and } a \in B\}$.

More generally, let \mathcal{F} be a nonempty family of sets. Pick some set $B \in \mathcal{F}$. The intersection of the family \mathcal{F} (written $\bigcap_{A \in \mathcal{F}} A$) is the set

$$\{a \in B \mid a \in A \text{ for all } A \in \mathcal{F}\}$$

Thus the intersection of two sets is simply the set of all objects contained in both sets, and more generally, the intersection of a (possibly infinite) family of sets is the set of objects contained in all sets of the family. You should convince yourself that the definition of the intersection of a family \mathcal{F} does not depend on the choice of $B \in \mathcal{F}$.

Example 6.8. For any sets A and B :

- $\bigcap_{C \in \{A, B\}} C = A \cap B$.
- $A \cap A = A$.
- $A \cap \emptyset = \emptyset$.
- $\{1, 2\} \cap \{2, 3\} = \{2\}$.
- If for each $n \in \mathbb{N}$, A_n is a set, and \mathcal{F} is a set of the form $\{A_0, A_1, \dots\}$, then $\bigcap_{A \in \mathcal{F}} A$ is sometimes written as $A_0 \cap A_1 \cap \dots$, or $\bigcap_{n=0}^{\infty} A_n$, and is the set of elements that are in A_n for all $n \in \mathbb{N}$.

Here, lecture 7 ended and lecture 8 started.

Another natural construction would be to replace the “for all $A \in \mathcal{F}$ ” above by “there exists $A \in \mathcal{F}$ ”. Such a construction is called the *union* of a family of sets. For example, $A \cup B$ would be the sets of objects that are either in A or in B . However, it never appears in the axioms stated so far that this should be a set. Thus we make it a new axiom:

Axiom 6.9 (Union axiom). (*U*): For any two sets A and B , we can form a set C such that $c \in C$ exactly if $c \in A$ or $c \in B$. C is called the *union* of A and B and we write $C = A \cup B$. More generally, for any family \mathcal{F} of sets, we can form a set C such that $c \in C$ exactly if there exists $A \in \mathcal{F}$ such that $c \in A$. We call C the *union* of the family \mathcal{F} and write $C = \bigcup_{A \in \mathcal{F}} A$.

Example 6.10. If $\mathcal{F} = \{\{0\}, \{0, 1\}, \{0, 1, 2\}, \dots\}$ (it turns out that, assuming more axioms, it is a set), then $\bigcup_{A \in \mathcal{F}} A = \{0\} \cup \{0, 1\} \cup \{0, 1, 2\} \cup \dots = \mathbb{N}$. Even though we will only be able to make this precise and prove it once we have a definition of the natural numbers, you should be able to convince yourself that this is true: given any element in the union, it has to be in some $\{0, 1, 2, \dots, n\}$, for n a natural number, and some must be a natural number $\leq n$. This shows the left hand side is contained in the right hand side. Now given a natural number n , n is in $\{0, 1, 2, \dots, n\}$ which is part of \mathcal{F} , hence it is in the union. This shows the right hand side is contained in the left hand side.

Theorem 6.11. Let \mathcal{F} be a non-empty family of sets. Let $B \in \mathcal{F}$.

- $B \subseteq \bigcup_{A \in \mathcal{F}} A$.
- $\bigcap_{A \in \mathcal{F}} A \subseteq B$.

Proof. For the first statement, take $b \in B$ arbitrary. We show that $b \in \bigcup_{A \in \mathcal{F}} A$. By definition of the union, we have to see there exists $A \in \mathcal{F}$ such that $b \in A$. We take $A = B$, and since we assumed $B \in \mathcal{F}$, we are done.

For the second statement, let $b \in \bigcap_{A \in \mathcal{F}} A$ be arbitrary. By definition of the intersection, b is in all $A \in \mathcal{F}$, so in particular, $b \in B$, as needed. \square

For more practice in showing inclusions, we prove a distributive law for sets:

Theorem 6.12. For any sets A, B, C , $A \cap (B \cup C) = (A \cap B) \cup (A \cap C)$.

Proof. By Theorem 6.6, it is enough to show each of those set is a subset of the other.

We first show the left hand side is contained in the right hand side. Let $x \in A \cap (B \cup C)$ be arbitrary. Then x is in A , and x is in $B \cup C$. We consider two cases: either $x \in B$, or $x \in C$. If x is in B , then x is in A and B , so in $A \cap B$, so in $(A \cap B) \cup (A \cap C)$. If x is in C , then x is in A and C , so in $A \cap C$, so in $(A \cap B) \cup (A \cap C)$.

We now show the right hand side is contained in the left hand side. Let $x \in (A \cap B) \cup (A \cap C)$ be arbitrary. Then x is either in $A \cap B$ or in $A \cap C$. We consider two cases depending on which happens. If x is in $A \cap B$, then x is in A and in B , so x is in A and in $B \cup C$, so $x \in A \cap (B \cup C)$. If x is in $A \cap C$, then x is in A and in C , so in A and in $B \cup C$, so in $A \cap (B \cup C)$.

We have shown that the left hand side and the right hand side are subsets of each other, so they must be equal. \square

Using the union axioms, we can form sets with more than two objects. Suppose a, b, c are objects. By pairing, we can form the sets $\{a, b\}$ and $\{b, c\}$. We can then take the union of the sets to obtain the set $\{a, b, c\}$. We can of course iterate this process to build sets with more elements. Even then, it is not clear how to build sets with infinitely many elements, so we add another *axiom*:

Axiom 6.13. (*R*): The real numbers form a set. We call this set \mathbb{R} .

Finally, we also have to define another operation on sets:

Axiom 6.14 (The power set axiom). (*P*): For any set A , there exists a set B whose elements are exactly the subsets of A : $x \in B$ if and only if $x \subseteq A$. We write $B = \mathcal{P}(A)$ and call B the *power set* of A .

Example 6.15. $\mathcal{P}(\{1, 2\}) = \{\emptyset, \{1\}, \{2\}, \{1, 2\}\}$.

We now have that $\mathcal{P}(\mathbb{R})$, $\mathcal{P}(\mathcal{P}(\mathbb{R}))$, ... are all sets, and we can also take their union or use the axiom of separation to restrict them to what we want. This basically shows that any collection (in the informal sense) of objects we are likely to care about will be a set, so we adopt the following principle:

Fact 6.16. Any collection of real numbers, sets of real numbers, sets of sets of real numbers, etc. is a set. Also, any finite collection of objects is a set.

In short, unless you really exaggerate, any collection you are likely to build will be a set. Thus we will be careless and won't justify every time exactly why an object we build is a set.

We are now ready to precisely define the set of natural numbers. We intend to build a set X whose elements are 0, 1, 2, 3, 4, ... In particular, we would like that:

- (1) $0 \in X$.
- (2) For all $x \in \mathbb{R}$, if $x \in X$, then $x + 1 \in X$.

Call such a set an *inductive set*. There are many such sets that are not the natural numbers (for instance, \mathbb{R} itself is such a set). In a sense however, we want the properties above and no more, i.e. we want the natural numbers to be the *smallest* set satisfying those properties. In set-theoretic language, we will take the *intersection* of all sets satisfying those properties.

Definition 6.17. The set \mathbb{N} of natural numbers is defined to be the intersection of all inductive sets (see above). In symbols¹³

$$\mathbb{N} := \bigcap_{A \in \mathcal{F}} A$$

Where

$$\mathcal{F} := \{A \in \mathcal{P}(\mathbb{R}) \mid A \text{ is an inductive set}\}$$

Note first that \mathcal{F} above is non-empty (\mathbb{R} is an inductive set). Moreover, \mathbb{N} is also an inductive set (i.e. it has the properties above). From the definition of the natural numbers and Theorem 6.11, we have that:

Theorem 6.18. If S is an inductive set, then $\mathbb{N} \subseteq S$.

As an exercise in understanding the definition, let's prove an easy property of \mathbb{N} :

Theorem 6.19. If x is a negative real number, then $x \notin \mathbb{N}$.

Proof. The set $\mathbb{R}_{\geq 0} = \{y \in \mathbb{R} \mid y \geq 0\}$ is an inductive set that does not contain x . As \mathbb{N} is contained in any inductive set, $\mathbb{N} \subseteq \mathbb{R}_{\geq 0}$, and so $x \notin \mathbb{N}$. \square

We can also redefine the integers and rational numbers more precisely:

Definition 6.20.

- The set \mathbb{Z} of *integers* is defined by:

$$\mathbb{Z} := \mathbb{N} \cup \{x \in \mathbb{R} \mid x = -n \text{ for some } n \in \mathbb{N}\}$$

¹³This is yet another example where using symbols make things harder to understand. In your own writeup, it is perfectly fine if you choose to describe a set in words (e.g. if you say that the set of natural numbers is the intersection of all inductive sets), but you should make sure you are aware of the precise meaning of those words.

- The set \mathbb{Q} of *rational*s is defined by:

$$\mathbb{Q} := \{x \in \mathbb{R} \mid x = n/m \text{ for some } n, m \in \mathbb{Z} \text{ with } m \neq 0\}$$

These definitions in our belt, we are now ready to prove statements about the natural numbers.

7. INDUCTION

We previously got stuck trying to prove that any natural number was either even or odd. What went wrong and what should a proof of this look like? For a start, we know that 0 is even, and we know that if n is even, then $n + 1$ is odd, and if n is odd, then $n + 1$ is even. Thus 1 is odd, 2 is even, 3 is odd, and so on. This “and so on” is usually a good indication that one has to use the principle of mathematical induction:

Theorem 7.1 (The principle of mathematical induction). Assume $p(x)$ is a propositional function, where the variable x takes values in the natural numbers. Assume we know that:

- (1) $p(0)$ is true.
- (2) For any natural number n , if $p(n)$ is true, then $p(n + 1)$ is true.

Then $p(n)$ is true for all natural numbers n .

Proof. Let S be the set of natural numbers where p holds. In symbols:

$$S := \{n \in \mathbb{N} \mid p(n)\}$$

From the assumptions on p , we know that S is an inductive set, so by Theorem 6.18, $\mathbb{N} \subseteq S$. By definition, $S \subseteq \mathbb{N}$, and so $S = \mathbb{N}$. Thus for any natural number n , $n \in S$, so $p(n)$ is true. \square

The principle of mathematical induction tells us that to prove a statement holds of all natural numbers it is enough to prove it holds for 0 (sometimes called the base case), and that it holds for $n + 1$ whenever it holds for n (sometimes called the inductive step). When proving $p(n)$ implies $p(n + 1)$, $p(n)$ is called the *inductive hypothesis*. The intuitive justification for this principle is the following: assume we know that $p(0)$ holds and $p(n + 1)$ holds whenever $p(n)$ holds. Then taking $n = 0$, $p(0 + 1) = p(1)$ holds. Taking $n = 1$, $p(2)$ holds. Taking $n = 2$, $p(3)$ holds, and so on. One image to have in mind is that of climbing a ladder: to climb an entire ladder, it is enough to start on the first step ($p(0)$), and from step n , move up to step $n + 1$.

We are finally ready to prove Fact 5.8.

Theorem 7.2. Any natural number is either even or odd.

Proof. We use the principle of mathematical induction on the propositional function $p(x)$ saying “ x is either even or odd”.

Base case. $p(0)$ holds, since $0 = 2 \cdot 0$, so is even.

Inductive step. We want to show that for any natural number n , $p(n)$ implies $p(n + 1)$. Recall from the section on direct proofs that to do this we have to take an arbitrary natural number n , and show assuming $p(n)$ is true that $p(n + 1)$ is true. So take an arbitrary natural number n , and assume $p(n)$ is true, i.e. n is either even or odd. If n is even, then $n + 1$ is odd, so $p(n + 1)$ holds. If n is odd, then $n + 1$ is even, so $p(n + 1)$ holds. Thus in both cases, $p(n + 1)$ holds.

Therefore by the principle of mathematical induction $p(n)$ holds for any natural number n , i.e. any natural number is either even or odd. \square

Since it is easy to make mistakes while using the principle of mathematical induction, I strongly recommend you to format your proof according to the basic template above, namely:

- (1) Say that you are going to use the principle of mathematical induction (or just induction) and explicitly state the propositional function $p(x)$ you are going to use it with.
- (2) Make a subsection for the base case, and give its proof.
- (3) Make a subsection for the inductive step, and give its proof.
- (4) Conclude by quoting the principle of mathematical induction.

Here, lecture 8 ended and lecture 9 started.

Theorem 7.3. Any integer is either even or odd.

Proof. Let x be an integer. Then x is either a natural number (in which case we use the previous theorem), or $x = -n$ for some natural number n . Pick such an n . By the previous theorem, n is either even or odd. If it is even, then $-n$ will be even, and if it is odd, then $-n$ will be odd (Theorem 5.5). Therefore x is either even or odd. \square

The principle of mathematical induction similarly applies if we start somewhere else than 0. For example, if we prove only that $p(1)$ and $p(n)$ implies $p(n + 1)$ for $n \geq 1$, then we get that $p(n)$ holds for all natural numbers $n \geq 1$. More generally:

Theorem 7.4 (The generalized principle of mathematical induction). Assume m is an integer. Assume $p(x)$ is a propositional function, where the variable x takes values in the integers $\geq m$. Assume we know that:

- (1) $p(m)$ is true.
- (2) For any integer $n \geq m$, if $p(n)$ is true, then $p(n + 1)$ is true.

Then $p(n)$ is true for any integer $n \geq m$.

Proof. Consider the propositional function $q(x)$ (where x is a natural number) which says that $p(x + m)$ is true. Then $q(0)$ is the same as $p(m)$ which is true by assumption, and for any natural number n , if $q(n)$ holds, then $p(n + m)$ holds, so $p(n + m + 1)$ holds, so $q(n + 1)$ holds. By the principle of mathematical induction, $q(n)$ holds for all natural numbers n , and hence $p(n + m)$ holds for all natural numbers n , so in other words, $p(n)$ holds for all natural numbers $n \geq m$. \square

We now turn to *inductive definitions*. We would like to make sense of objects such as the sum $0 + 1 + 2 + \dots + n$, where n is a natural number, or the product $x \cdot x \cdot \dots \cdot x$ (n times). Again, we want to get rid of the ambiguities raised by the three dots. For this, we introduce new notation:

Definition 7.5. For n a natural number and x a real number, we *inductively* define x^n as follows:

- $x^0 = 1$.
- $x^{n+1} = x^n \cdot x$.

Remark 7.6. We have defined $0^0 = 1$. It turns out to be a very useful convention, but there are some issues with giving a definite value to 0^0 . For example, the functions 0^x and x^0 have limits 0 and 1 respectively as x approaches 0 from the right (this is why 0^0 is typically an undeterminate form in calculus textbooks). This shows that one must in general be careful when dealing with exponentiation, limits, and the number zero. In this course, we shall be safe, as we will not deal with limits.

Fully justifying why this style of definition is permissible would take us too far, but you can think of it as a consequence of the principle of mathematical induction: we know that x^n is defined for $n = 0$, and we know that if x^n , then x^{n+1} is defined. Therefore x^n is defined for all natural numbers n . The definition is not circular, since we are only relying on the definition at stage n to define stage $n + 1$ (i.e. we always rely on past stages, never on current or future stages).

Note that $x^2 = x^1 \cdot x = x^0 \cdot x \cdot x = x \cdot x$, so this agrees with our previous definition of the square of a number.

Let's look at how we would do the same thing for sums:

Definition 7.7 (Σ notation). Assume $f(i)$ is some expression¹⁴ depending on i , and n is a natural number. We define $\sum_{i=1}^n f(i)$ as follows:

- $\sum_{i=1}^n f(i) = 0$ if $n = 0$.

¹⁴We will later introduce the concept of a function and make this precise.

- $\sum_{i=1}^{n+1} f(i) = f(n+1) + \sum_{i=0}^n f(i)$.

We can similarly define $\sum_{i=k}^n f(i)$ for k a natural number. If $k > n$, we adopt the convention that this is zero.

Remark 7.8. It is sometimes simply more convenient to write three dots instead of introducing new notation. We may in the future do so, but you should keep in mind that this is only a *convenience*, and that this could be made precise using induction. Sometimes, we may also need to be absolutely clear and avoid using the three dots. In your own writing, you should use your own judgment as to which is best: a more readable notation, or a more precise one?

Example 7.9.

- $\sum_{i=1}^n 1 = 1 + 1 + 1 + \dots + 1 = n$ (the ones repeat n times).
- $\sum_{i=1}^n i = 1 + 2 + 3 + \dots + n$.

Is there a simple formula giving us the value of $\sum_{i=1}^n i$? It turns out there is:

Theorem 7.10. For any natural number n :

$$\sum_{i=1}^n i = \frac{n(n+1)}{2}$$

Proof. We use the principle of mathematical induction on the propositional function $p(x)$ saying “ $\sum_{i=1}^x i = \frac{x(x+1)}{2}$ ”.

Base case. If $p(0)$ just says that $\sum_{i=1}^0 i = 0$. This is true since the left hand side is zero by definition.

Inductive step. Let n be an arbitrary natural number, and assume $p(n)$ holds, i.e. $\sum_{i=1}^n i = \frac{n(n+1)}{2}$. We want to see that the same formula holds with n replaced by $n+1$, namely $\sum_{i=1}^{n+1} i = \frac{(n+1)(n+2)}{2}$. We compute:

$$\sum_{i=1}^{n+1} i = n+1 + \sum_{i=1}^n i = n+1 + \frac{n(n+1)}{2} = \frac{2(n+1) + n(n+1)}{2} = \frac{(n+2)(n+1)}{2}$$

Where the first equality uses the definition of Σ notation, the second uses the *inductive assumption* $p(n)$, and the last two hold by some elementary algebra (that could easily be justified from the facts we know about the real numbers). This completes the proof of the inductive step.

By the principle of mathematical induction, $p(n)$ holds for any natural number n , as desired. \square

7.1. Strong induction. In the inductive step of a proof by induction we have to prove $p(n+1)$ holds assuming $p(n)$. Wouldn't it be nice if we could assume that $p(k)$ for $k \leq n$ also holds? Since we think of proving something by induction as climbing a ladder, and we have already climbed all steps $\leq n$ before reaching step $n+1$, this sounds reasonable. This is what the principle of strong induction tells us:

Theorem 7.11 (The principle of strong induction). Assume $p(x)$ is a propositional function, where the variable x takes values in the natural numbers. Assume we know that:

- (1) $p(0)$ is true.
- (2) For any natural number $n \geq 1$, if $p(m)$ is true for any natural number $m < n$, then $p(n)$ is true.

Then $p(n)$ is true for all natural numbers n .

Proof. We use the principle of mathematical induction on the proposition $q(x)$ which says “ $p(m)$ is true for any natural number $m \leq x$ ”.

Base case. $q(0)$ just says that $p(x)$ is true for any natural number $m \leq 0$, but since the only such natural number is zero, it is enough to see that $p(0)$ is true, and it is by assumption.

Inductive step. Let n be an arbitrary natural number, and assume $q(n)$ holds. We show $q(n+1)$, i.e. $p(m)$ holds for all $m \leq n+1$. The induction hypothesis $q(n)$ already tells us that $p(m)$ holds for every $m \leq n$, so it is enough to see that $p(n+1)$ holds. But this is the case by assumption (2). Therefore $q(n+1)$ is true.

By the principle of mathematical induction, $q(n)$ is true for all natural numbers n . In particular, $p(n)$ is true for all natural numbers n . \square

Remark 7.12. We can combine the two conditions of the principle of strong induction into only one: For any natural number n , if $p(m)$ is true for all $m < n$, then $p(n)$ is true. This is the same as (2) if $n \geq 1$, and if $n = 0$, then the statement “ $p(m)$ is true for any natural number $m < 0$ ” is always *vacuously true*, i.e. it holds simply because there is no natural number below 0.

As an application of the principle of strong induction, we prove that every natural number is a product of primes.

Definition 7.13. An integer m *divides* an integer n (written $m|n$) if there exists an integer k such that $n = mk$.

Here are some easy properties of dividing:

Theorem 7.14. For all integers n, m, k :

- (1) n is even if and only if 2 divides n .
- (2) If $n = m \cdot k$, then both m and k divide n .
- (3) For m nonzero, m divides n if and only if n/m is an integer.
- (4) m divides 0.
- (5) 1 divides n .
- (6) 0 divides n if and only if $n = 0$.
- (7) m divides n if and only if $\pm m$ divides $\pm n$.
- (8) If m divides n and n is nonzero, then $|m| \leq |n|$.
- (9) If k divides m and m divides n , then k divides n .

Proof.

- (1) By definition.
- (2) By definition.
- (3) If m divides n , there exists an integer r such that $n = mr$, so since m is nonzero, $r = n/m$, so n/m is an integer. Conversely, if n/m is an integer r , then $mr = n$, so m divides n .
- (4) $0 = 0 \cdot m$.
- (5) $n = 1 \cdot n$.
- (6) If 0 divides n , then $n = r \cdot 0 = 0$ for some integer r . Conversely, by (4) any integer divides 0, and so in particular 0 divides 0.
- (7) If m divides n , then $n = mr$ for some integer r . Thus $-n = m(-r)$, so m divides $-n$, and also $n = (-m)(-r)$, so $-m$ divides n . This shows one can change the signs of m and n arbitrarily without changing divisibility, and the result follows. This also proves the converse.
- (8) Assume m divides n and n is nonzero. By (7), we can replace n and m by their absolute value, so assume that n and m are already natural numbers. Fix an integer r such that $n = mr$. Since n is nonzero, both r and m are nonzero. Since n and m are natural numbers, r is a natural number, so must be positive. Thus we have $1 \leq r = n/m$, so multiplying by m , $m \leq n$, as needed.
- (9) Assume k divides m and m divides n . Fix integers m' and n' such that $m = km'$ and $n = mn'$. Then $n = k(n'm')$, so k divides n .

□

Here, lecture 9 ended and lecture 10 started

Definition 7.15. A natural number p is *prime* if $p \geq 2$ and if any natural number that divides p is either 1 or p . A natural number ≥ 2 which is not prime is called *composite*.

Example 7.16. You should convince yourself that 2 and 3 are prime, but 4 is not prime, as $4 = 2 \cdot 2$, so 2 divides 4. The next primes are 5, 7, 11, 13, ... We will see that there are infinitely many primes.

Theorem 7.17. A natural number $n \geq 2$ is composite if and only if there exists natural numbers m and k with $1 < k \leq m < n$ and $n = m \cdot k$.

Proof. If there exists m and k with $1 < k \leq m < n$ and $n = mk$, then they witness that n is composite. Conversely, if n is composite, there exists a natural number m that is not 1 or n and divides n . Since n is nonzero and both n and m are natural numbers, Theorem 7.14.(8) tells us that $m \leq n$. By assumption, $m \neq 1$, $m \neq n$, so $1 < m < n$. Since m divides n , $k := n/m$ is a natural number and it is easy to check that $1 < k < n$. Exchanging the role of m and k if necessary, we can assume without loss of generality that $k \leq m$. \square

Theorem 7.18. Let $n \geq 2$ be a natural number. Then n is a product of primes, i.e. there exists a natural number r , and primes p_0, \dots, p_r such that $n = p_0 p_1 \cdots p_r$.

Proof. We use the principle of strong induction on the proposition $p(x)$ which says that x is a product of primes. We start our induction at $x = 2$ and prove $p(x)$ holds for every natural number $x \geq 2$.

Base case. $p(2)$ holds since 2 is prime.

Inductive step. Let n be an arbitrary natural number, $n > 2$. Assume $p(m)$ holds for every $m < n$. If n is prime, we are done. If n is not prime, we use the previous theorem to see that there exists natural numbers k and m with $1 < k \leq m < n$ so that $n = m \cdot k$. By the induction hypothesis, $p(m)$ and $p(k)$ hold, so $m = p_0 \cdots p_l$ and $k = p_{l+1} \cdots p_r$ for primes $p_0, \dots, p_l, \dots, p_r$. Therefore $n = m \cdot k = p_0 \cdots p_r$ is also a product of primes.

By the principle of strong induction, every natural number $n \geq 2$ is a product of prime. \square

Remark 7.19. In this sense, the primes are the building blocks of the natural numbers. We will see later that this decomposition into primes is unique (up to the ordering of the primes).

Example 7.20. $4 = 2 \cdot 2$ (so the same prime may appear several times in the decomposition). $10 = 2 \cdot 5$, $150 = 2 \cdot 3 \cdot 5 \cdot 5$.

To continue, we need the concept of a minimal element

Definition 7.21. Assume $a \in \mathbb{R}$ and $X \subseteq \mathbb{R}$. a is a *minimal element* (or *minimum*) of X if $a \in X$ and for any $b \in X$, $a \leq b$.

Example 7.22.

- The set \mathbb{Z} has no minimal elements: if $a \in \mathbb{Z}$, $b := a - 1$ is strictly smaller.
- The set $\mathbb{R}_{>0}$ of positive real numbers has no minimal elements: If $a \in \mathbb{R}_{>0}$, then $a/2$ is strictly smaller.
- The set $\mathbb{R}_{\geq 0}$ has minimal element 0.

Remark 7.23. If $X \subseteq \mathbb{R}$ has a minimal element a , then it is unique: if $a' \in X$ is a minimal element, then $a \leq a'$ and $a' \leq a$ by definition of a minimal element, and so $a = a'$.

As another application of strong induction, you will prove in your homework:

Theorem 7.24 (The well-ordering principle). Any non-empty subset of \mathbb{N} has a minimal element.

We will use it to prove Fact 5.10. In fact, we will prove more:

Definition 7.25. Two integers n and m are called *coprime* if no prime divides both n and m .

Example 7.26.

- If n and m are even, then they are not coprime, as the prime 2 divides both of them.
- If p and q are distinct primes, then p and q are coprime.
- 8 and 15 are coprime (you can check it by trying all the primes below 8), even though they are not prime (2 divides 8, 3 divides 15).
- 6 and 15 are not coprime, as 3 divides both of them.

Fact 5.10 follows from:

Theorem 7.27. Given a rational number r , there exists coprime integers n and m with m nonzero such that $r = n/m$.

Proof. It is enough to prove it for non-negative rational numbers (if $r < 0$, use the result on $-r$ and use that the dividing relation is insensitive to change of signs). Let r be a non-negative rational number. By the well-ordering principle, find natural numbers m and n with m nonzero such that $r = n/m$ and $n + m$ is minimal (formally, we consider the set of natural numbers x for which there exists natural numbers n and m such that $x = n + m$ and $r = n/m$, use the well ordering principle to pick a minimal element x of this set, and then pick n and m with $x = n + m$). We claim that n and m are coprime. Assume for a contradiction they are not. Then there exists a prime p that divides n

and m . Let $n' := n/p$, $m' := m/p$. Since $p \geq 2$, $n' < n$, $m' < m$, so $n' + m' < n + m$ and $r = n/m = n'/m'$. This contradicts the minimality of $n + m$.

□

8. SET THEORY

Now that we have some basic understanding of proofs, it is worth spending some time studying sets further. One of our first goal is to define the notion of a function: In a calculus course, a function is usually defined as a rule associating each object in its domain to another. This is a somewhat imprecise definition, and we will do much better in this chapter. Once functions have been properly defined, we will be able to use them to put sets in one-to-one correspondence, and make sense of the *size* of a set. This will work even for infinite sets, and will lead us to see that there are different “sizes” of infinity!

8.1. Functions and relations.

8.1.1. *Ordered pairs.* We start by defining the notion of an *ordered* pair. Recall that sets are unordered: for two objects a and b , $\{a, b\} = \{b, a\}$. We now define a notion of pairing such that the order matters:

Definition 8.1. For objects a and b , the *ordered pair* (a, b) is an object such that for any two other objects c and d , $(a, b) = (c, d)$ if and only if $a = c$ and $b = d$.

Remark 8.2. It is rather unfortunate that in calculus and analysis, the notation (a, b) for real numbers a and b also denotes the open interval with endpoints a and b . It is usually clear from context which of the two is meant though.

Surprisingly, it turns out sets can be used to code ordered pairs: you will see in your homework that for objects a and b , the set $\{\{a\}, \{a, b\}\}$ is a good way to code the pair (a, b) . Using this definition and iterating the power set axiom as many times as necessary, it is not too hard to see the following:

Fact 8.3. Assume A and B are sets. Then there exists a set C whose elements are exactly the ordered pairs (a, b) with $a \in A$ and $b \in B$. We call C the *cartesian product* of A and B , and write $C = A \times B$.

Example 8.4.

- $\mathbb{R} \times \mathbb{R}$ (sometimes also written \mathbb{R}^2) is the set of all pairs of real numbers. We can see a pair of real number as giving the

coordinates of a point in the plane, so we sometimes just call \mathbb{R}^2 the plane.

- For any set A , $\emptyset \times A = A \times \emptyset = \emptyset$.
- $\{1, 2\} \times \{3, 4\} = \{(1, 3), (1, 4), (2, 3), (2, 4)\}$.
- As the example above shows, in general, $A \times B \neq B \times A$, as $(1, 3) \in \{1, 2\} \times \{3, 4\}$ but $(1, 3) \notin \{3, 4\} \times \{1, 2\}$. This case shows that we can even have $(A \times B) \cap (B \times A) = \emptyset$.

Here, lecture 10 ended and lecture 11 started.

8.1.2. *Relations.* There are many ways to compare two real numbers x and y : we can ask whether $x \leq y$, whether $x = y^2$, whether $x \neq y$, whether x or y is an integer, etc. More generally, a relation on \mathbb{R} is simply a way to compare x and y . Now that we have the notion of ordered pairs, we can make this precise:

Definition 8.5. Let A and B be sets. A *relation* R on $A \times B$ is a subset of $A \times B$. If $B = A$, we say R is a relation on A .

Notation 8.6. For R a relation on $A \times B$, and $x \in A$, $y \in B$, we think of x and y as being related if $(x, y) \in R$, and write xRy (read “ x is related to y ”) for $(x, y) \in R$.

Example 8.7.

- (1) The set $R := \{(x, y) \in \mathbb{R} \times \mathbb{R} \mid x \leq y\}$ is a relation and xRy if and only if $x \leq y$. We can even see \leq as being R itself.
- (2) The set $G := \{(x, y) \in \mathbb{R} \times \mathbb{R} \mid y = x^2\}$ is a relation. This is a special one, since every $x \in \mathbb{R}$ has exactly one y related to it. We will end up calling such relations *functions*.

8.1.3. *Equivalence relations.* Here are some structural properties relations can have:

Definition 8.8. A relation R on a set A is called:

- (1) *Reflexive* if for any x in A , xRx .
- (2) *Symmetric* if for any x and y in A , xRy implies yRx .
- (3) *Transitive* if for any x , y , and z in A , xRy and yRz imply xRz .

Example 8.9. Take $A = \mathbb{R}$. The relation \leq is reflexive and transitive but is not symmetric (as $0 \leq 1$ but $1 \not\leq 0$). The relation $<$ is transitive but not reflexive and not symmetric. The relation xRy if and only if $y = x^2$ is not reflexive ($2 \neq 2^2$), not transitive ($16 = 4^2$, $4 = 2^2$, but $16 \neq 2^2$), and not symmetric ($4 = 2^2$ but $2 \neq 4^2$). The equality relation is reflexive, symmetric, and transitive.

In a sense, relations that satisfy the three properties above look like the equality relation. We give such relations a name:

Definition 8.10. A relation R on a set A which is both reflexive, symmetric, and transitive is called an *equivalence relation on A* .

Equivalence relations appear in many different parts of mathematics and computer science. They are a witness to the power one gets by generalizing many different cases into one.

Example 8.11.

- (1) As already observed, for any set A , equality on A (i.e. $\{(x, x) \in A \times A \mid x \in A\}$) is an equivalence relation on A .
- (2) If $f : A \rightarrow B$ is a function, then the relation E on A defined by xEy if and only if $f(x) = f(y)$ is an equivalence relation.
- (3) Take A to be the set of integers, and let n be an integer. Say xEy if and only if n divides $x - y$. This is an equivalence relation. When xEy , we write $x \equiv y \pmod n$, and say x is *congruent to y modulo n* . For $n = 0$, we obtain regular equality: $x \equiv y \pmod 0$ if and only if $x = y$, and for $n = 1$ (or $n = -1$), we obtain that everything is equivalent: For any integer x and y , $x \equiv y \pmod 1$. For $n = 2$, we get that $x \equiv 0 \pmod 2$ if and only if x is even, and $x \equiv 1 \pmod 2$ if and only if x is odd.
- (4) For $A = \mathcal{P}(\mathbb{N})$, say xEy if and only if x and y have the same finite number of elements (this will be defined precisely later), or x and y are both infinite. This is an equivalence relation.

8.1.4. Functions.

Definition 8.12. A relation f on a set $A \times B$ (together with A and B) is called a *function* if for every $x \in A$, there is a unique $y \in B$ such that $(x, y) \in f$. In this case, we write $y = f(x)$. We call A the *domain* and B the *codomain* of f , and write $f : A \rightarrow B$ (said “ f is a function from A to B ”) to say that f is a function with domain A and codomain B .

Remark 8.13. In calculus, it is customary to define functions by saying something like “Let $f : A \rightarrow B$ be the function defined by $f(x) = E(x)$ ”, where E is some expression defining the function. This is fine, but there are many other ways to define functions. For example, one can write it as an explicit set, or one can just use words to describe what it does.

Remark 8.14. The domain and codomain are part of the function, so for example the functions $f : \mathbb{R} \rightarrow \mathbb{R}$ defined by $f(x) = x^2$ and $g : \mathbb{R} \rightarrow \{x \in \mathbb{R} \mid x \geq 0\}$ defined by $g(x) = x^2$ are different as they do not have the same codomain.

Example 8.15.

- The relation $\{(x, y) \in \mathbb{R} \times \mathbb{R} \mid y = x^2\}$ defines a function from \mathbb{R} to \mathbb{R} .
- The relation $\{(x, y) \in \mathbb{R} \times \mathbb{R} \mid x \leq y\}$ does not define a function, as for a given x , there are many y such that $x \leq y$ (for example x or $x + 1$)
- The relation $\{(x, y) \in \mathbb{R} \times \mathbb{R} \mid x = y^2\}$ does not define a function, since for a negative x , there is no y such that $x = y^2$, and for positive x , there are two different y such that $y^2 = x$ (namely \sqrt{x} and $-\sqrt{x}$). If one restricts x and y to lie in the set $\mathbb{R}_{\geq 0}$ of non-negative real numbers, one obtains the function $f : \mathbb{R}_{\geq 0} \rightarrow \mathbb{R}_{\geq 0}$ given by $f(x) = \sqrt{x}$.
- Another example of a function is the map¹⁵ $f : \mathbb{R} \rightarrow \mathbb{R}$ given by

$$f(x) = \begin{cases} 1 & \text{if } x \text{ is rational} \\ 0 & \text{if } x \text{ is irrational} \end{cases}$$

- Functions don't have to have sets of numbers as domain or codomain. For example one can define a function f mapping the set S of days of the week to itself, by $f(x) =$ the day after x (so for example $f(\text{Sunday}) = \text{Monday}$). Another example: take $A = \{a, b, c\}, B = \{c, d\}$ and define $f : A \rightarrow B$ by $f(a) = c, f(b) = f(c) = d$.
- A weird consequence of the definition: For any set B , there is a unique function $f : \emptyset \rightarrow B$, the “empty” function, which is just the empty set! Also, if $f : A \rightarrow \emptyset$, then we must have $A = \emptyset$ (if A were non-empty, there would be nowhere to send the elements of A to!).
- Given a set A , the function $f : A \rightarrow A$ defined by $f(x) = x$ is called the *identity function*.
- We can see a propositional function $p(x)$ with domain of discourse A as a function from A to $\{F, T\}$ that to each member of A associates the truth value of the proposition $p(a)$.

8.1.5. Some operations on functions.

Definition 8.16 (Image and inverse image). Let A and B be sets and $f : A \rightarrow B$ be a function.

- (1) For $C \subseteq A$, The *image of C under f* , written $f[C]$ is the set $\{b \in B \mid \text{there exists } c \in C \text{ such that } f(c) = b\}$. The *range* of f is $f[A]$.

¹⁵“map” and “function” are synonymous.

- (2) For $C \subseteq B$, the *inverse image of C under f* , written $f^{-1}[C]$ is the set $\{a \in A \mid f(a) \in C\}$.

Example 8.17. The range of the function $f : \mathbb{R} \rightarrow \mathbb{R}$ given by $f(x) = x^2$ is all the non-negative real numbers. The range of the function $g : \mathbb{R} \rightarrow \mathbb{R}$ which is 1 if the input is rational and 0 otherwise is $\{0, 1\}$. The inverse image of $\{1/2\}$ under this function is the empty set, and the inverse image of $\{0\}$ under this function is the set of irrational numbers. For x a non-negative number, the inverse image of $\{x\}$ under f is $\{-\sqrt{x}, \sqrt{x}\}$.

Here, lecture 11 stopped and lecture 12 started.

Definition 8.18 (Composition of functions). Let A, B, C be sets and $f : A \rightarrow B, g : B \rightarrow C$ be functions. The *composition* of f and g (written $g \circ f$) is the function $h : A \rightarrow C$ defined by $h(a) = g(f(a))$.

Example 8.19.

- (1) The composition of the functions $f : \mathbb{R} \rightarrow \mathbb{R}$ and $g : \mathbb{R} \rightarrow \mathbb{R}$ defined by $f(x) = x^2$ and $g(x) = x + 1$ is $(g \circ f)(x) = g(f(x)) = g(x^2) = x^2 + 1$. In contrast, $(f \circ g)(x) = f(x + 1) = (x + 1)^2$, so even if domains and codomains are all the same, $f \circ g \neq g \circ f$.
- (2) The composition of any function $f : A \rightarrow B$ with the identity g on B (recall that the identity is the function that sends every element to itself) is just $(g \circ f)(x) = f(x)$, so $g \circ f = f$.

8.2. Cardinalities. We have seen that given a function $f : A \rightarrow B$, it was possible that some elements in B were not the image of any element in A , or that distinct elements in A mapped to the same element in B . When this does not happen, the function is easier to understand, and we give these conditions names:

Definition 8.20 (Injection, surjection, bijection). Assume A and B are sets and $f : A \rightarrow B$ is a function.

- f is a *surjection* (we also say f is *surjective*) if for every $b \in B$, there exists $a \in A$ such that $f(a) = b$.
- f is an *injection* (we also say f is *injective*) if for every a and a' in A , $f(a) = f(a')$ implies $a = a'$.
- f is a *bijection* (we also say f is *bijective*) if it is both an injection and a surjection.

An injection is a function that sends distinct elements in its domain to distinct elements in its codomain, while a surjection covers the entire codomain of the function. The definition of a bijection makes precise the notion of “one to one correspondance”.

Example 8.21.

- (1) The map $f : \mathbb{R} \rightarrow \mathbb{R}$ defined by $f(x) = x^2$ is not a bijection: it is neither injective nor surjective. It is not injective because $f(-1) = f(1)$ (so distinct members of the domain can get sent to the same element), and it is not surjective because there is no real number x such that $f(x) = -1$.
- (2) On the other hand, the map $g : \mathbb{R}_{\geq 0} \rightarrow \mathbb{R}_{\geq 0}$ defined by $g(x) = x^2$ is a bijection: it is injective: if $a, a' \in \mathbb{R}_{\geq 0}$ and $f(a) = f(a')$, then $a^2 = (a')^2$, and since they are both non-negative, uniqueness of the square root gives us that $a = a'$. It is surjective: given a non-negative b , one can take $a := \sqrt{b}$, and then $f(a) = b$.
- (3) Let $A := \{1, 2, 3\}$, $B := \{2, 4\}$. The map $f : A \rightarrow B$ given by $f(1) = f(2) = 2$ and $f(3) = 4$ is a surjection that is not an injection. The map $g : B \rightarrow A$ given by $g(2) = 1$, $g(4) = 2$ is an injection that is not a surjection.

Theorem 8.22. $f : A \rightarrow B$ is a bijection if and only if for each $b \in B$ there is a unique $a \in A$ such that $f(a) = b$.

Proof. Assume f is a bijection. Let $b \in B$. Since f is a surjection, there is $a \in A$ such that $f(a) = b$. a is unique: if $a' \in A$ is such that $f(a') = b$, then $f(a) = f(a')$, so since f is injective, $a = a'$.

Conversely, assume that for every $b \in B$ there is a unique $a \in A$ such that $f(a) = b$. Then in particular f is surjective. To see f is injective, assume $a, a' \in A$ and $f(a) = f(a')$. There is a unique a'' such that $f(a'') = f(a)$, so $a'' = a = a'$, as needed. \square

Bijections are a particularly nice class of functions. For a start, one can start from a bijection, and produce an *inverse*:

Definition 8.23. Given a bijection $f : A \rightarrow B$, the *inverse* of f is the function $g : B \rightarrow A$ that to each $b \in B$ associates the unique $a \in A$ so that $f(a) = b$. We write $g = f^{-1}$.

Remark 8.24. For any (not necessarily bijective) function $f : A \rightarrow B$ and any $C \subseteq B$, the *inverse image* $f^{-1}[C]$ is always defined, even though the function f^{-1} itself need not be.

Example 8.25.

- The inverse of the map $f : \mathbb{R}_{\geq 0} \rightarrow \mathbb{R}_{\geq 0}$ given by $f(x) = x^2$ is $f^{-1}(x) = \sqrt{x}$.
- The map $f : \mathbb{R}_{>0} \rightarrow \mathbb{R}_{>0}$ given by $f(x) = \frac{1}{x}$ is a bijection (exercise), and $f^{-1} = f$.

- The inverse of the map $f : \{1, 2, 3\} \rightarrow \{4, 5, 6\}$ given by $f(1) = 1$, $f(2) = 6$, $f(3) = 5$ is given by $f^{-1} : \{4, 5, 6\} \rightarrow \{1, 2, 3\}$ defined as $f^{-1}(6) = 2$, $f^{-1}(5) = 3$, $f^{-1}(1) = 1$.
- Assume A is the set of days of the week. The map f that maps each day to the next one is a bijection (why?), and its inverse maps each day of the week to the preceeding one.

Theorem 8.26. Assume $f : A \rightarrow B$ is a bijection. Then f^{-1} is a bijection.

Proof. Exercise. □

8.2.1. *Cardinalities of sets.* If two sets A and B contain 5 elements, say $A = \{a_1, \dots, a_5\}$, $B = \{b_1, \dots, b_5\}$, we can build a bijection from A to B that sends a_i to b_i for each $1 \leq i \leq 5$. Conversely, if A has 6 elements and B has 5 elements, we expect not to be able to put A and B in one to one correspondence. This motivates the following definition:

Definition 8.27. Two sets A and B are said to *have the same cardinality* or to be *equipotent* if there is a bijection $f : A \rightarrow B$.

Theorem 8.28. Let U be a set. The relation E on $\mathcal{P}(U)$ defined by xEy if and only if x and y are equipotent is an equivalence relation.

Proof. Exercise. □

Definition 8.29. For n a natural number, we define the set $[n]$ to be $\{1, 2, \dots, n\}$. More precisely, $[n] := \{m \in \mathbb{N} \mid 1 \leq m \leq n\}$ (so $[0] = \emptyset$). For n a negative integer, we also define $[n] = \emptyset$.

We now prove the seemingly obvious, but crucial:

Theorem 8.30. Assume n and m are natural numbers. Then $[n]$ and $[m]$ are equipotent if and only if $n = m$.

Proof. If $n = m$, then the identity function $f : [n] \rightarrow [n]$ defined by $f(x) = x$ is a bijection from $[n]$ to $[n]$ (exercise).

For the converse, we use induction on the propositional function $p(x)$ which says “If $f : [m] \rightarrow [x]$ is a bijection, then $m = x$ ”.

Base case. If $n = 0$, then since the only function with codomain the empty set is the empty function we must have $f : \emptyset \rightarrow \emptyset$ so $m = 0 = n$.

Inductive step. Assume $p(n)$ holds. Assume $f : [m] \rightarrow [n + 1]$ is a bijection, and we have to show $m = n + 1$. Notice that $m > 0$, as the only bijection with empty domain is the empty bijection, so $m = 0$ would imply $n + 1 = 0$, which is impossible. Let $r := f^{-1}(n + 1)$. Define the function $g : [m - 1] \rightarrow [n]$ by

$$g(k) = \begin{cases} f(k) & \text{if } k < r \\ f(k+1) & \text{if } k \geq r \end{cases}$$

First observe that the codomain of g is indeed $[n]$, since $g(k) \neq f(r) = n+1$ for any k . We claim that g is a bijection. It is injective: if $g(k) = g(k')$, assume without loss of generality that $k \leq k'$. Then either $f(k) = f(k')$ or $f(k+1) = f(k'+1)$ in which case $k = k'$, or $f(k) = f(k'+1)$, so $k = k' + 1$, which is impossible since we assumed $k \leq k'$. g is also surjective: given $b \in [n]$, use surjectivity of f to find $a \in [m]$ such that $f(a) = b$. Now let k be a if $a < r$, or $a - 1$ if $a \geq r$. Then it is easy to check that $g(k) = f(a) = b$, as needed.

Since g is a bijection, by the induction hypothesis, $m - 1 = n$, so $m = n + 1$. \square

Theorem 8.31. Assume A is a set and n, m are natural numbers such that A is equipotent to $[n]$ and $[m]$. Then $n = m$.

Proof. Exercise. \square

Thus we see that a set can be equipotent to *at most one* $[n]$. We can now define precisely what it means for a set to have n elements. Here, lecture 12 stopped and lecture 13 started.

Definition 8.32. For n a natural number, a set A is said to have *cardinality* n or to *have n elements* (written $|A| = n$) if A and $[n]$ are equipotent.

We say A is *finite* if there is a natural number n such that $|A| = n$. We say A is *infinite* if it is not finite.

Remark 8.33. If A is infinite, we will *not* define what $|A|$ means, but given another set B , we can still ask whether A and B have the same cardinality.

Example 8.34.

- (1) $|\emptyset| = 0$, and more generally for a natural number n , $|[n]| = n$.
- (2) \mathbb{N} is infinite. To see this, assume for a contradiction that $f : \mathbb{N} \rightarrow [n]$ is a bijection. Define a new function $g : \mathbb{N} \rightarrow [n+1]$ by

$$g(m) = \begin{cases} f(m-1) & \text{if } m \geq 1 \\ n+1 & \text{if } m = 0 \end{cases}$$

It is easy to check that g is a bijection. This contradicts Theorem 8.31.

8.2.2. *To infinity and beyond.* How does the notion of having the same cardinality match our intuition for infinite sets? We will see some very surprising facts happen. For a start, recall that $\mathbb{N} \subset \mathbb{Z}$ and $\mathbb{Z} \setminus \mathbb{N}$ is infinite. However:

Theorem 8.35. \mathbb{N} and \mathbb{Z} are equipotent: there is a bijection $f : \mathbb{N} \rightarrow \mathbb{Z}$.

Proof. Define

$$f(n) = \begin{cases} -\frac{n}{2} & \text{if } n \text{ is even} \\ \frac{n+1}{2} & \text{if } n \text{ is odd} \end{cases}$$

(So the sequence of values $f(0), f(1), f(2), f(3), \dots$ looks like $0, 1, -1, 2, -2, \dots$).

f is an injection: if $f(n) = f(n')$, then clearly if n and n' are both even (or both odd), $n = n'$, so assume without loss of generality that n is even and n' is odd. Then we have $-\frac{n}{2} = \frac{n'+1}{2}$, so $-n = n' + 1$, so $0 = n' + n + 1$. Now n' and n are both natural numbers, so $n' + n + 1 > 0$, a contradiction.

f is a surjection: given $m \in \mathbb{Z}$, we consider two cases. Either $m > 0$, in which case $2m - 1 \in \mathbb{N}$ and $f(2m - 1) = m$, or $m \leq 0$, in which case $-2m \in \mathbb{N}$ and $f(-2m) = m$.

Therefore f is a bijection, as needed. \square

This tells us that we can “rename” the natural numbers to make them into the integers. In other words, one can give a list of all the integers that looks like a_0, a_1, a_2, \dots . We give this property a name:

Definition 8.36. A set is called *countable* if it is equipotent to \mathbb{N} . An infinite set that is not countable is called *uncountable*. A set is called *at most countable* if it is countable or finite.

So the previous result tells us that \mathbb{Z} is countable. To show a set A is countable, we have to *exhibit* a bijection from \mathbb{N} to A , or intuitively we have to show how to *list* A as a_0, a_1, a_2, \dots in such a way that the list contains no repetitions and that for every $a \in A$ there is $n \in \mathbb{N}$ such that $a_n = a$. There is a more general definition for such lists

Definition 8.37. A *sequence* is a function $s : \mathbb{N} \rightarrow A$, where A is a set. We often describe a sequence by simply listing its elements as s_0, s_1, s_2, \dots instead of $s(0), s(1), s(2), \dots$.

In a sense, the countable sets are the “smallest” possible infinite sets:

Theorem 8.38. Assume A is an infinite subset of \mathbb{N} . Then A is countable.

Proof. We define a bijection $f : \mathbb{N} \rightarrow A$ *inductively* as follows:

- $f(0)$ is the minimal element of A (note that A is infinite, so non-empty).
- $f(n+1)$ is the minimal element of $A \setminus \{f(0), \dots, f(n)\}$. Note that the latter set is non-empty, since we are assuming that A is infinite.

f is an injection: if $f(n) = f(m)$, assume by symmetry $n \leq m$. If $n < m$, then as $f(m)$ is an element of $A \setminus \{f(0), \dots, f(n)\}$, $f(m) \neq f(n)$, so $n = m$.

f is a surjection: if not, let m be the minimal element of A that is not in the range of f (i.e. there is no $n \in \mathbb{N}$ such that $f(n) = m$). Then we must have $f(m) \geq m$, but the definition of f tells us that $f(m) < m$. Let k be minimal such that $f(k) \geq m$. Then by minimality of m we must have $f(k) = m$, a contradiction. \square

By some “renaming” left as an exercise, we can prove:

Theorem 8.39.

- (1) A set A is countable if and only if A is infinite and there is an *injection* $f : A \rightarrow \mathbb{N}$.
- (2) An infinite subset of a countable set is countable.

Proof. Exercise. \square

We then obtain:

Theorem 8.40. If $f : \mathbb{N} \rightarrow A$ is a surjection, then A is at most countable. More generally, if B is countable and $f : B \rightarrow A$ is a surjection, then A is at most countable.

Proof. We prove the first part. The second follows by “renaming” B to \mathbb{N} (exercise).

One can define $g : A \rightarrow \mathbb{N}$ by $g(a) =$ the minimal n such that $f(n) = a$. g is an injection: if $g(a) = g(a') = n$, then $f(n) = a = a'$. If A is finite, there is nothing to prove, and if A is infinite, we apply Theorem 8.39.(1) to see that A is countable. \square

Are there sets that are larger than countable? Now that we have seen that \mathbb{Z} is countable, the next natural candidate would be \mathbb{Q} . It turns out it is also countable. First, we prove the following stronger result:

Theorem 8.41. $\mathbb{N} \times \mathbb{N}$ is countable.

Proof sketch. We list the pairs of natural numbers in the following way

$$(0, 0), (0, 1), (1, 0), (2, 0), (1, 1), (0, 2), (3, 0), (2, 1), (1, 2), (3, 0), \dots$$

Explicitly, there are only finitely many pairs whose components sum to 0, and list them first. Then we list the pairs whose components sum to 1, then those whose components sum to 2, and so on. This is injective, since we never repeat the same pair. This is surjective, since given a pair $(a, b) \in \mathbb{N} \times \mathbb{N}$, there are only finitely many pairs with sum $< n := a + b$, and only finitely many pairs with sum $\leq n$ before (a, b) .

Although it can be done, it is a bit painful and not too insightful to explicitly write the bijection we obtain, so we will leave this as an exercise. \square

Another more formal but less conceptual proof. We use problem 3 of assignment 5 to see that every positive natural number n can be uniquely written as $n = 2^m k$ for k, m natural numbers and k odd. In other words, n can be associated to the pair (m, k) . We do not yet have our bijection, since k is required to be odd, and n positive, but we are very close. Define the function $f : \mathbb{N} \rightarrow \mathbb{N} \times \mathbb{N}$ by $f(n) = (m, \frac{k-1}{2})$, where k and m are such that $n + 1 = 2^m k$ and k is odd. We leave it as an exercise to see that f is a bijection. \square

By some renaming left as an exercise, we obtain the more general:

Theorem 8.42. If A and B are countable, then $A \times B$ is countable.

Theorem 8.43. \mathbb{Q} is countable.

Proof. By Theorem 8.35, \mathbb{Z} is countable. By Theorem 8.42, $\mathbb{Z} \times \mathbb{Z}$ is countable. Now the map $f : \mathbb{Z} \times \mathbb{Z} \rightarrow \mathbb{Q}$ given by $f(m, n) := \frac{m}{|n|+1}$ is a surjection (why?). It is easy to check that \mathbb{Q} is infinite (exercise) and we have just seen that $\mathbb{N} \times \mathbb{N}$ is countable. Therefore by Theorem 8.40, \mathbb{Q} is countable. \square

We can also obtain the following very handy result:

Theorem 8.44. Assume \mathcal{F} is an at most countable family of at most countable sets, i.e. $\mathcal{F} = \{A_0, A_1, \dots\}$, where A_n is at most countable for each $n \in \mathbb{N}$. Then the union $\bigcup_{A \in \mathcal{F}} A = \bigcup_{n=0}^{\infty} A_n$ is at most countable.

Proof. For each $n \in \mathbb{N}$, we may assume by putting more elements inside A_n (e.g. by replacing A_n by $A_n \cup \mathbb{N}$) that A_n is countable. Let $A := \bigcup_{n=0}^{\infty} A_n$. Let $f : \mathbb{N} \times \mathbb{N} \rightarrow A$ be defined by $f(n, m) := f_n(m)$ (i.e. we pick the m th element from the n th set). Note that f need not be injective, as there could be duplicate elements, but we claim that f is surjective: given $a \in A$, $a \in A_n$ for some n , and hence since f_n is surjective there exists m so that $f_n(m) = a$. Thus $f(n, m) = a$. This proves that f is surjective. By Theorem 8.40, A is at most countable. \square

Now that we know \mathbb{Q} is countable, it is natural to ask whether \mathbb{R} is countable. It turns out this is not true: \mathbb{R} is uncountable. We will need the following fact, whose proof uses the completeness axiom:

Fact 8.45. Every real number $0 < x < 1$ has a decimal expansion, i.e. there is an infinite sequence a_0, a_1, a_2, \dots with $a_i \in \{0, \dots, 9\}$ such that $x = 0.a_0a_1a_2\dots$ ¹⁶. In general, this sequence is not unique, i.e. there could be two sequences describing the same number (like $0.1000000\dots = 0.099999\dots$). However, two distinct sequences which do not contain any 9 describe distinct real numbers.

We are now ready to prove uncountability of the reals. The method of proof is called *diagonalization* and is due to Cantor:

Theorem 8.46. \mathbb{R} is uncountable.

Proof. \mathbb{R} is infinite, so it is enough to see it is not countable. Assume for a contradiction that it is. Then any infinite subset of it is also countable. In particular, the set X of real numbers $0 < x < 1$ which have a decimal expansion containing only 0s and 1s is countable. Let $f : \mathbb{N} \rightarrow X$ be a bijection. Write a_i instead of $f(i)$. Then we have a list of all the elements of X containing no repetitions: a_0, a_1, a_2, \dots . Each a_i has a decimal expansion $a_{i,0}, a_{i,1}, a_{i,2}, \dots$ with $a_{i,j} \in \{0, 1\}$ for all i and j . Here is a table of the elements of X and their decimal expansion:

$$\begin{array}{l} 0.a_{0,0}a_{0,1}a_{0,2}a_{0,3}a_{0,4}\dots \\ 0.a_{1,0}a_{1,1}a_{1,2}a_{1,3}a_{1,4}\dots \\ \dots \\ 0.a_{i,0}a_{i,1}a_{i,2}a_{i,3}a_{i,4}\dots a_{i,i} \\ \dots \end{array}$$

From this table, we build a new member of X : For i a natural number, we let b_i be $1 - a_{i,i}$, i.e. it is 0 if $a_{i,i}$ is 1, and 1 if $a_{i,i}$ is 0. Let $x := 0.b_0b_1b_2\dots$. Intuitively, the decimals of x are built by going through the diagonal of the table and taking the opposite of each number there. Then $x \in X$ since its decimal expansion contains only zeroes and ones. Since f is surjective, there is a natural number i such that $a_i = x$, and so by uniqueness of decimal expansions containing no 9, we must have $a_{i,j} = b_j$ for all natural numbers j . In particular, $a_{i,i} = b_i$, but this is impossible since we defined b_i to be $1 - a_{i,i}$. We

¹⁶We have not defined what this means exactly, but you can just think of it as saying that from the sequence one can reconstitute the number.

arrived at a contradiction, and this means X (and therefore \mathbb{R}) is not countable. \square

From this result, we can conclude that in a well-defined sense, \mathbb{R} has *many* more elements than \mathbb{N} : there are infinitely many reals and infinitely many natural numbers, but the infinity of reals is strictly bigger than the infinity of natural numbers! This has many consequences, some of which you will explore in your homework. For example, we can deduce that there are uncountably many irrational numbers, or that there are problems no computer program will ever be able to solve. Using a similar method, one can also show that there is no largest size of infinity: for every set A , there is a set B that is “strictly bigger” than A , in the sense that there is no surjection from A to B .
End of lecture 13 (tentative).

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