





































Operational notes

Document updated on **July 30, 2022**.

















































The following colors are **not** part of the final product, but serve as highlights in the editing/review process:

















- text that needs attention from the Subject Matter Experts: Mirco, Anna,& Jan
- terms that have not yet been defined in the book
- things that need to be checked only at the very final typesetting stage (and it doesn't make sense to do them before)
- text that needs advice from the communications/marketing team: Aaron & Shane
- text that needs to be completed or otherwise edited (by Sylvia)

11 **Todo list**

12	 Sylvia: This subsection should be in the introduction of the book as it applies to the	
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14	 zero-knowledge proofs	12
15	 add references	12
16	 Sylvia: This subsection should be in the introduction of the book as it applies to the	
17	entire math part	13
18	 Sylvia: We should put this table into the same introduction as 3.1.1	14
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28	 Check change of wording	62
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30	 Check if following Alg is floated too far	89
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43	 disambiguate	115
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MoonMath manual

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TechnoBob and the Least Scruples crew

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Chapter 1

Introduction

This is dump from other papers as inspiration for the intro:

Zero knowledge proofs are a class of cryptographic protocols in which one can prove honest computation without revealing the inputs to that computation. A simple high-level example of a zero-knowledge proof is the ability to prove one is of legal voting age without revealing the respective age. In a typical zero knowledge proof system, there are two participants: a prover and a verifier. A prover will present a mathematical proof of computation to a verifier to prove honest computation. The verifier will then confirm whether the prover has performed honest computation based on predefined methods. Zero knowledge proofs are of particular interest to public blockchain activities as the verifier can be codified in smart contracts as opposed to trusted parties or third-party intermediaries.

Zero-knowledge proofs (ZKPs) are an important privacy-enhancing tool from cryptography. They allow proving the veracity of a statement, related to confidential data, without revealing any information beyond the validity of the statement. ZKPs were initially developed by the academic community in the 1980s, and have seen tremendous improvements since then. They are now of practical feasibility in multiple domains of interest to the industry, and to a large community of developers and researchers. ZKPs can have a positive impact in industries, agencies, and for personal use, by allowing privacy-preserving applications where designated private data can be made useful to third parties, despite not being disclosed to them.

ZKP systems involve at least two parties: a prover and a verifier. The goal of the prover is to convince the verifier that a statement is true, without revealing any additional information. For example, suppose the prover holds a birth certificate digitally signed by an authority. In order to access some service, the prover may have to prove being at least 18 years old, that is, that there exists a birth certificate, tied to the identity of the prover and digitally signed by a trusted certification authority, stating a birthdate consistent with the age claim. A ZKP allows this, without the prover having to reveal the birthdate.

1.1 Target audience

This book is accessible for both beginners and experienced developers alike. Concepts are gradually introduced in a logical and steady pace. Nonetheless, the chapters lend themselves rather well to being read in a different order. More experienced developers might get the most benefit by jumping to the chapters that interest them most. If you like to learn by example, then you should go straight to the chapter on Using Clarity.

It is assumed that you have a basic understanding of programming and the underlying logical concepts. The first chapter covers the general syntax of Clarity but it does not delve into what

programming itself is all about. If this is what you are looking for, then you might have a more difficult time working through this book unless you have an (undiscovered) natural affinity for such topics. Do not let that dissuade you though, find an introductory programming book and press on! The straightforward design of Clarity makes it a great first language to pick up.

1.2 The Zoo of Zero-Knowledge Proofs

First, a list of zero-knowledge proof systems:

1. Pinocchio (2013): Paper

– Notes: trusted setup

2. BCGTV (2013): Paper

– Notes: trusted setup, implementation

3. BCTV (2013): Paper

– Notes: trusted setup, implementation

4. Groth16 (2016): Paper

– Notes: trusted setup

– Other resources: Talk in 2019 by Georgios Konstantopoulos

5. GM17 (2017): Paper

– Notes: trusted setup

– Other resources: later Simulation extractability in ROM, 2018

6. Bulletproofs (2017): Paper

– Notes: no trusted setup

– Other resources: Polynomial Commitment Scheme on DL, 2016 and KZG10, Polynomial Commitment Scheme on Pairings, 2010

7. Ligero (2017): Paper

– Notes: no trusted setup

– Other resources:

8. Hyrax (2017): Paper

– Notes: no trusted setup

– Other resources:

9. STARKs (2018): Paper

– Notes: no trusted setup

– Other resources:

10. Aurora (2018): Paper

- Notes: transparent SNARK

- Other resources:

11. Sonic (2019): Paper

- Notes: SNORK - SNARK with universal and updateable trusted setup, PCS-based

- Other resources: Blog post by Mary Maller from 2019 and work on updateable and universal setup from 2018

12. Libra (2019): Paper

- Notes: trusted setup

- Other resources:

13. Spartan (2019): Paper

- Notes: transparent SNARK

- Other resources:

14. PLONK (2019): Paper

- Notes: SNORK, PCS-based

- Other resources: Discussion on Plonk systems and Awesome Plonk list

15. Halo (2019): Paper

- Notes: no trusted setup, PCS-based, recursive

- Other resources:

16. Marlin (2019): Paper

- Notes: SNORK, PCS-based

- Other resources: Rust Github

17. Fractal (2019): Paper

- Notes: Recursive, transparent SNARK

- Other resources:

18. SuperSonic (2019): Paper

- Notes: transparent SNARK, PCS-based

- Other resources: Attack on DARK compiler in 2021

19. Redshift (2019): Paper

- Notes: SNORK, PCS-based

- Other resources:

Other resources on the zoo: Awesome ZKP list on Github, ZKP community with the reference document

To Do List

- Make table for prover time, verifier time, and proof size
- Think of categories - *Achieved Goals*: Trusted setup or not, Post-quantum or not, ...
- Think of categories - *Mathematical background*: Polynomial commitment scheme, ...
- ... while we discuss the points above, we should also discuss a common notation/language for all these things. (E.g. transparent SNARK/no trusted setup/STARK)

Points to cover while writing

- Make a historical overview over the "discovery" of the different ZKP systems
- Make reader understand what paper is build on what result etc. - the tree of publications!
- Make reader understand the different terminology, e.g. SNARK/SNORK/STARK, PCS, R1CS, updateable, universal, ...
- Make reader understand the mathematical assumptions - and what this means for the zoo.
- Where will the development/evolution go? What are bottlenecks?

Other topics I fell into while compiling this list

- Vector commitments: <https://eprint.iacr.org/2020/527.pdf>
- Snark1: <http://ace.cs.ohio.edu/~gstewart/papers/snaark1.pdf>
- Virgo?: https://people.eecs.berkeley.edu/~kubitron/courses/cs262a-F19/projects/reports/project5_report_ver2.pdf

Chapter 2

Preliminaries

2.1 Preface and Acknowledgements

This book began as a set of lecture and notes accompanying the zk-Summit 0x and 0xx It arose from the desire to collect the scattered information of snarks [] and present them to an audience that does not have a strong background in cryptography []

2.2 Purpose of the book

The first version of this book is written by security auditors at Least Authority where we audited quite a few snark based systems. Its included "what we have learned" destilate of the time we spend on various audits.

We intend to let illustrative examples drive the discussion and present the key concepts of pairing computation with as little machinery as possible. For those that are fresh to pairing-based cryptography, it is our hope that this chapter might be particularly useful as a first read and prelude to more complete or advanced expositions (e.g. the related chapters in [Gal12]).

On the other hand, we also hope our beginner-friendly intentions do not leave any sophisticated readers dissatisfied by a lack of formality or generality, so in cases where our discussion does sacrifice completeness, we will at least endeavour to point to where a more thorough exposition can be found.

One advantage of writing a survey on pairing computation in 2012 is that, after more than a decade of intense and fast-paced research by mathematicians and cryptographers around the globe, the field is now racing towards full maturity. Therefore, an understanding of this text will equip the reader with most of what they need to know in order to tackle any of the vast literature in this remarkable field, at least for a while yet.

Since we are aiming the discussion at active readers, we have matched every example with a corresponding snippet of (hyperlinked) Magma [BCP97] code 1 , where we take inspiration from the helpful Magma pairing tutorial by Dominguez Perez et al. [DKS09].

Early in the book we will develop examples that we then later extend with most of the things we learn in each chapter. This way we incrementally build a few real world snarks but over full fledged cryptographic systems that are nevertheless simple enough to be computed by pen and paper to illustrate all steps in great detail.

2.3 How to read this book

Books and papers to read: XXXXXXXXXXXXX

Software to try: XXXXXXXXXXXXXXXXXXXXX

Correctly prescribing the best reading route for a beginner naturally requires individual diagnosis that depends on their prior knowledge and technical preparation.

2.4 Cryptological Systems

The science of information security is referred to as *cryptology*. In the broadest sense, it deals with encryption and decryption processes, with digital signatures, identification protocols, cryptographic hash functions, secrets sharing, electronic voting procedures and electronic money.
EXPAND

2.5 SNARKS

2.6 complexity theory

Before we deal with the mathematics behind zero knowledge proof systems, we must first clarify what is meant by the runtime of an algorithm or the time complexity of an entire mathematical problem. This is particularly important for us when we analyze the various snark systems...

For the reader who is interested in complexity theory, we recommend, or example or , as well as the references contained therein.

2.6.1 Runtime complexity

The runtime complexity of an algorithm describes, roughly speaking, the amount of elementary computation steps that this algorithm requires in order to solve a problem, depending on the size of the input data.

Of course, the exact amount of arithmetic operations required depends on many factors such as the implementation, the operating system used, the CPU and many more. However, such accuracy is seldom required and is mostly meaningful to consider only the asymptotic computational effort.

In computer science, the runtime of an algorithm is therefore not specified in individual calculation steps, but instead looks for an upper limit which approximates the runtime as soon as the input quantity becomes very large. This can be done using the so-called *Landau notation* (also called big - \mathcal{O} -notation) A precise definition would, however, go beyond the scope of this work and we therefore refer the reader to .

For us, only a rough understanding of transit times is important in order to be able to talk about the security of cryptographic systems. For example, $\mathcal{O}(n)$ means that the running time of the algorithm to be considered is linearly dependent on the size of the input set n , $\mathcal{O}(n^k)$ means that the running time is polynomial and $\mathcal{O}(2^n)$ stands for an exponential running time (chapter 2.4).

An algorithm which has a running time that is greater than a polynomial is often simply referred to as *slow*.

A generalization of the runtime complexity of an algorithm is the so-called *time complexity of a mathematical problem*, which is defined as the runtime of the fastest possible algorithm that can still solve this problem (chapter 3.1).

Since the time complexity of a mathematical problem is concerned with the runtime analysis of all possible (and thus possibly still undiscovered) algorithms, this is often a very difficult and deep-seated question .

For us, the time complexity of the so-called discrete logarithm problem will be important. This is a problem for which we only know slow algorithms on classical computers at the moment, but for which at the same time we cannot rule out that faster algorithms also exist.

STUFF ON CRYPTOGRAPHIC HASH FUNCTIOND

2.7 Software Used in This Book

2.7.1 Sagemath

It order to provide an interactive learning experience, and to allow getting hands-on with the concepts described in this book, we give examples for how to program them in the Sage programming language. Sage is a dialect of the learning-friendly programming language Python, which was extended and optimized for computing with, in and over algebraic objects. Therefore, we recommend installing Sage before diving into the following chapters.

The installation steps for various system configurations are described on the sage websit ¹. Note however that we use Sage version 9, so if you are using Linux and your package manager only contains version 8, you may need to choose a different installation path, such as using prebuilt binaries.

We recommend the interested reader, who is not familiar with sagemath to read on the many tutorial before starting this book. For example

¹<https://doc.sagemath.org/html/en/installation/index.html>

Chapter 3

arithmetic

3.1 Introduction

3.1.1 Aims and target audience

Sylvia: This subsection should be in the introduction of the book as it applies to the entire math part

How much mathematics do you need to understand **zero-knowledge proofs**? The answer, of course, depends on the level of understanding you aim for. It is possible to describe zero-knowledge proofs without using mathematics at all; however, to read a foundational paper like ? and to understand the internals of snark implementations, some knowledge of mathematics is needed to be able to follow the discussion.

The goal of this chapter is therefore to enable a reader who is starting out with nothing more than basic high school algebra to be able to solve simple tasks in the mathematics underlying most zero knowledge proofs without the need of a computer.

Without a solid grounding in mathematics, someone who is interested in learning the concepts of zero-knowledge proofs, but who has never seen or dealt with, say, a prime field 4.3.1, or an elliptic curve 5, may quickly become overwhelmed. This is not so much due to the complexity of the mathematics needed, but rather because of the vast amount of technical jargon, unknown terms, and obscure symbols that quickly makes a text unreadable, even though the concepts themselves are not actually that complicated. As a result, the reader might either lose interest, or pick up some incoherent bits and pieces of knowledge that, in the worst case scenario, result in immature and unsecure code.

This is why we dedicated this chapter to explaining the mathematical foundations needed to understand the basic concepts underlying snark development. We encourage the reader who is not familiar with basic number theory and elliptic curves to take the time and read this and the following chapters, until they are able to solve at least a few exercises in each chapter.

If, on the other hand, you are already skilled in elliptic curve cryptography, feel free to skip this chapter and only come back to it for reference and comparison. Maybe the most interesting parts are XXX .

We start our explanations at a very basic level, and only assume pre-existing knowledge of fundamental concepts like high school integer arithmetic. At the same time, we'll attempt to teach you to "think mathematically", and to show you that there are numbers and mathematical structures out there that appear to be very different from the things you learned about in high school, but on a deeper level, they are actually quite similar, as we will see in various examples below in this chapter.

Sylvia:
This subsection should be in the introduction of the book as it applies to the entire math part

zero-knowledge proofs

add references

To make it easier to memorize new concepts and symbols, we might frequently link to definitions in the beginning, but as too many links render a text unreadable, we will assume the reader will become familiar with definitions as the text proceeds at which point we will not link them anymore.

We want to stress, however that this introduction is informal, incomplete and optimized to enable the reader to understand zero-knowledge concepts as efficiently as possible. Our focus and design choices are to include as little theory as necessary, focusing on a wealth of numerical examples. We believe that such an informal, example-driven approach to learning mathematics may make it easier for beginners to digest the material in the initial stages.

For instance, as a beginner, you would probably find it more beneficial to first compute a simple toy **snark** with pen and paper all the way through, before actually developing real-world production-ready systems. In addition, it's useful to have a few simple examples in your head before getting started with reading actual academic papers.

However, in order to be able to derive these toy examples, some mathematical groundwork is needed. This chapter therefore will help the inexperienced reader to focus on what we believe is important, accompanied by exercises that you are encouraged to recompute yourself. Every section usually ends with a list of additional exercises in increasing order of difficulty, to help the reader memorize and apply the concepts.

3.1.2 The structure of this chapter

Sylvia: This subsection should be in the introduction of the book as it applies to the entire math part

We start with a brief recapitulation of basic integer arithmetic like long division, the greatest common divisor and Euclid's algorithm. After that, we introduce modular arithmetic as **the most important skill** to compute our pen-and-paper examples. We then introduce polynomials, compute their analogs to integer arithmetic and introduce the important concept of Lagrange interpolation.

After this practical warm up, we introduce some basic algebraic terms like groups and fields, because those terms are used very frequently in academic papers relating to zero-knowledge proofs. The beginner is advised to memorize those terms and think about them: Why are they defined the way they are? Can you come up with a better definition? How and why is every rule important and what happens if that rule is dropped?

We define these terms in the general abstract way of mathematics, hoping that the non mathematical trained reader will gradually learn to become comfortable with this style. We then give basic examples and do basic computations with these examples to get familiar with the concepts.

Sylvia: This subsection should be in the introduction of the book as it applies to the entire math part

3.2 Integer arithmetic

In a sense, integer arithmetic is at the heart of large parts of modern cryptography. Fortunately, most readers will probably remember integer arithmetic from school. It is, however, important that you can confidently apply those concepts to understand and execute computations in the many pen-and-paper examples that form an integral part of the MoonMath Manual. We will therefore recapitulate basic arithmetic concepts to refresh your memory and fill any knowledge gaps.

In what follows, we use many mathematical notations, which we summarized in the following table 3.2:

Symbol	Meaning of Symbol
$=$	equals
$:=$	defining the symbol on the r
\in	element from a set
\Leftrightarrow	logical equivalence
$\sum_{j=n}^k a_j$	summation

Sylvia: We should put this table into the same introduction as 3.1.1

In this book, we use the symbol \mathbb{Z} as a short description for the set of all **integers**, that is we write:

$$\mathbb{Z} := \{\dots, -3, -2, -1, 0, 1, 2, 3, \dots\} \quad (3.1)$$

Integers are also known as **whole numbers**, that is, numbers that can be written without fractional parts. Examples of numbers that are **not** integers are $\frac{2}{3}$, 1.2 and -1280.006 .

If $a \in \mathbb{Z}$ is an integer, then we write $|a|$ for the **absolute value** of a , that is, the non-negative value of a without regard to its sign:

$$|4| = 4 \quad (3.2)$$

$$|-4| = 4 \quad (3.3)$$

We use the symbol \mathbb{N} for the set of all positive integers, usually called the set of **natural numbers** and \mathbb{N}_0 for the set of all non negative integers. So whenever you see the symbol \mathbb{N} , think of the set of all positive integers excluding the number 0:

$$\mathbb{N} := \{1, 2, 3, \dots\} \quad \mathbb{N}_0 := \{0, 1, 2, 3, \dots\}$$

Let $n \in \mathbb{N}_0$ be a non negative integer and (b_0, b_1, \dots, b_k) a string of **bits** $b_j \in \{0, 1\} \subset \mathbb{N}_0$ for some non negative integer $k \in \mathbb{N}$, such that the following equation holds:

$$n = \sum_{j=0}^k b_j \cdot 2^j \quad (3.4)$$

In this case, we call $\text{Bits}(n) := \langle b_0, b_1, \dots, b_k \rangle$ the **binary representation** of n , say that n is a k -bit number and call $k := |n|_2$ the **bit length** of n . It can be shown, that the binary representation of any non negative integer is unique. We call b_0 the **least significant bit** and b_k the **most significant bit** and define the **Hamming weight** of an integer as the number of 1s in its binary representation.

In addition, we use the symbol \mathbb{Q} for the set of all **rational numbers**, which can be represented as the set of all fractions $\frac{n}{m}$, where $n \in \mathbb{Z}$ is an integer and $m \in \mathbb{N}$ is a natural number, such that there is no other fraction $\frac{n'}{m'}$ and natural number $k \in \mathbb{N}$ with $k \neq 1$ and

$$\frac{n}{m} = \frac{k \cdot n'}{k \cdot m'} \quad (3.5)$$

The sets \mathbb{N} , \mathbb{Z} and \mathbb{Q} have a notion of addition and multiplication defined on them. Most of us are probably able to do many integer computations in our head, but this gets more and

Sylvia:
We should
put this
table into
the same
introduc-
tion as
3.1.1

more difficult as these increase in complexity. We will frequently invoke the SageMath system (2.7.1) for more complicated computations (We define rings and fields later in this book):

```

sage: ZZ # A sage notation for the integers      1
Integer Ring                                     2
sage: NN # A sage notation for the natural numbers 3
Non negative integer semiring                   4
sage: QQ # A sage notation for the rational numbers 5
Rational Field                                  6
sage: ZZ(5) # Get an element from the integers   7
5                                                8
sage: ZZ(5) + ZZ(3)                             9
8                                              10
sage: ZZ(5) * NN(3)                             11
15                                             12
sage: ZZ.random_element(10**50)                13
16893726593249394733186881187934468674672175982558 14
sage: ZZ(27713).str(2) # Binary string representation 15
110110001000001                               16
sage: NN(27713).str(2) # Binary string representation 17
110110001000001                               18
sage: ZZ(27713).str(16) # Hexadecimal string representation 19
6c41                                           20

```

One set of numbers that is of particular interest to us is the set of **prime numbers**, which are natural numbers $p \in \mathbb{N}$ with $p \geq 2$, which are only divisible by themselves and by 1. All prime numbers apart from the number 2 are called **odd prime numbers**. We write \mathbb{P} for the set of all prime numbers and $\mathbb{P}_{\geq 3}$ for the set of all odd prime numbers. The set of prime numbers \mathbb{P} is an infinite set and can be ordered according to size, which means that for any prime number $p \in \mathbb{P}$ one can always find another prime number $p' \in \mathbb{P}$ with $p < p'$. It follows that there is no largest prime number. Since prime numbers can be ordered by size, we can write them as follows:

$$2, 3, 5, 7, 11, 13, 17, 19, 23, 29, 31, 37, 41, 43, 47, 53, 59, 61, 67, \dots \quad (3.6)$$

As the **fundamental theorem of arithmetic** tells us, prime numbers are, in a certain sense, the basic building blocks from which all other natural numbers are composed. To see that, let $n \in \mathbb{N}$ be any natural number with $n > 1$. Then there are always prime numbers $p_1, p_2, \dots, p_k \in \mathbb{P}$, such that

$$n = p_1 \cdot p_2 \cdot \dots \cdot p_k. \quad (3.7)$$

This representation is unique for each natural number (except for the order of the factors) and is called the **prime factorization** of n .

Example 1 (Prime Factorization). To see what we mean by prime factorization of a number, let's look at the number $504 \in \mathbb{N}$. To get its prime factors, we can successively divide it by all prime numbers in ascending order starting with 2:

$$504 = 2 \cdot 2 \cdot 2 \cdot 3 \cdot 3 \cdot 7$$

We can double check our findings invoking Sage, which provides an algorithm to factor natural numbers:

654	sage: <code>n = NN(504)</code>	21
655	sage: <code>factor(n)</code>	22
656	<code>2^3 * 3^2 * 7</code>	23

657 The computation from the previous example reveals an important observation: Computing
 658 the factorization of an integer is computationally expensive, because we have to divide repeatedly
 659 by all prime numbers smaller than the number itself until all factors are prime numbers themselves.
 660 From this, an important question arises: How fast can we compute the prime factorization of a
 661 natural number? This question is the famous **integer factorization problem** and, as far as we
 662 know, there is currently no method known that can factor integers much faster than the naive
 663 approach that just divides the given number by all prime numbers in ascending order.

664 On the other hand computing the product of a given set of prime numbers, is fast (just
 665 multiply all factors) and this simple observation implies that the two processes "prime number
 666 multiplication" on the one side and its inverse process "natural number factorization" have very
 667 different computational costs. The factorization problem is therefore an example of a so-called
 668 **one-way function**: An invertible function that is easy to compute in one direction, but hard to
 669 compute in the other direction.

670 It should be pointed out, however, that the American mathematician Peter W. Shor devel-
 671 oped an algorithm in ? which can calculate the prime factorization of a natural number in
 672 polynomial time on a quantum computer. The consequence of this is that cryptosystems, which
 673 are based on the prime factor problem, are unsafe as soon as practically usable quantum com-
 674 puters become available .

Do we
even need
this quan-
tum com-
puting
excuse?

675 *Exercise 1.* What is the absolute value of the integers -123 , 27 and 0 ?

676 *Exercise 2.* Compute the factorization of 30030 and double check your results using Sage.

677 *Exercise 3.* Consider the following equation $4 \cdot x + 21 = 5$. Compute the set of all solutions for
 678 x under the following alternative assumptions:

679 1. The equation is defined over the natural numbers.

680 2. The equation is defined over the integers.

681 *Exercise 4.* Consider the following equation $2x^3 - x^2 - 2x = -1$. Compute the set of all solu-
 682 tions x under the following assumptions:

683 1. The equation is defined over the natural numbers.

684 2. The equation is defined over the integers.

685 3. The equation is defined over the rational numbers.

686 **Euclidean Division** As we know from high school mathematics, integers can be added, sub-
 687 tracted and multiplied and the result is guaranteed to always be an integer again. On the contrary
 688 division in the commonly understood sense is not defined for integers, as, for example, 7 divided
 689 by 3 will not be an integer again. However it is always possible to divide any two integers if we
 690 consider division with remainder. So for example 7 divided by 3 is equal to 2 with a remainder
 691 of 1 , since $7 = 2 \cdot 3 + 1$.

692 It is the content of this section to introduce division with remainder for integers which is
 693 usually called **Euclidean division**. It is an essential technique underlying many concepts in this
 694 book. The precise definition is as follows:

Let $a \in \mathbb{Z}$ and $b \in \mathbb{Z}$ be two integers with $b \neq 0$. Then there is always another integer $m \in \mathbb{Z}$ and a natural number $r \in \mathbb{N}$, with $0 \leq r < |b|$ such that

$$a = m \cdot b + r \quad (3.8)$$

This decomposition of a given b is called **Euclidean division**, where a is called the **dividend**, b is called the **divisor**, m is called the **quotient** and r is called the **remainder**. It can be shown that both the quotient and the remainder always exist and are unique, as long as the divisor is different from 0.

Notation and Symbols 1. Suppose that the numbers a, b, m and r satisfy equation (3.8). Then we often write

$$a \operatorname{div} b := m, \quad a \operatorname{mod} b := r \quad (3.9)$$

to describe the quotient and the remainder of the Euclidean division. We also say that an integer a is divisible by another integer b if $a \operatorname{mod} b = 0$ holds. In this case we also write $b|a$ and call the integer $a \operatorname{div} b$ the **cofactor** of b in a .

So, in a nutshell Euclidean division is a process of dividing one integer by another in a way that produces a quotient and a non-negative remainder, the latter of which is smaller than the absolute value of the divisor.

A special situation occurs whenever the remainder is zero, because in this case the dividend is divisible by the divisor. Our notation $b|a$ reflects that.

Example 2. Applying Euclidean division and our previously defined notation 3.9 to the dividend -17 and the divisor 4, we get

$$-17 \operatorname{div} 4 = -5, \quad -17 \operatorname{mod} 4 = 3$$

because $-17 = -5 \cdot 4 + 3$ is the Euclidean division of -17 and 4 (the remainder is, by definition, a non-negative number). In this case 4 does not divide -17 , as the remainder is not zero. The truth value of the expression $4|-17$ therefore is FALSE. On the other hand, the truth value of $4|12$ is TRUE, since 4 divides 12, as $12 \operatorname{mod} 4 = 0$. We can invoke sage to do the computation for us. We get the following:

```
sage: ZZ(-17) // ZZ(4) # Integer quotient      24
-5                                              25
sage: ZZ(-17) % ZZ(4) # remainder             26
3                                              27
sage: ZZ(4).divides(ZZ(-17)) # self divides other 28
False                                          29
sage: ZZ(4).divides(ZZ(12))                    30
True                                           31
```

Remark 1. In 3.9 we defined the notation of $a \operatorname{div} b$ and $a \operatorname{mod} b$, in terms of Euclidean division. It should be noted however that many programming languages like Python and Sage, implement both the operator ($/$) as well as the operator ($\%$) differently. Programmers should be aware of this, as the discrepancy between the mathematical notation and the implementation in programming languages might become the source of subtle bugs in implementations of cryptographic primitives.

To give an example consider the the dividend -17 and the divisor -4 . Note that in contrast to the previous example 2, we have a negative divisor. According to our definition we have

$$-17 \operatorname{div} -4 = 5, \quad -17 \operatorname{mod} -4 = 3$$

because $-17 = 5 \cdot (-4) + 3$ is the Euclidean division of -17 and -4 (the remainder is, by definition, a non-negative number). However using the operators $(/)$ and $(\%)$ in Sage we get

```

sage: ZZ(-17) // ZZ(-4) # Integer quotient      32
4                                              33
sage: ZZ(-17) % ZZ(-4) # remainder             34
-1                                              35
sage: ZZ(-17).quo_rem(ZZ(-4)) # not Euclidean division 36
(4, -1)                                         37

```

Methods to compute Euclidean division for integers are called **integer division algorithms**. Probably the best known algorithm is the so-called **long division**, which most of us might have learned in school.

As long division is the standard method used for pen-and-paper division of multi-digit numbers expressed in decimal notation, the reader should become familiar with it as we use it throughout this book when we do simple pen-and-paper computations. However, instead of defining the algorithm formally, we rather give some examples that will hopefully make the process clear.

In a nutshell, the algorithm loops through the digits of the dividend from the left to right, subtracting the largest possible multiple of the divisor (at the digit level) at each stage; the multiples then become the digits of the quotient, and the remainder is the first digit of the dividend.

Example 3 (Integer Long Division). To give an example of integer long division algorithm, let's divide the integer $a = 143785$ by the number $b = 17$. Our goal is therefore to find solutions to equation 3.8, that is, we need to find the quotient $m \in \mathbb{Z}$ and the remainder $r \in \mathbb{N}$ such that $143785 = m \cdot 17 + r$. Using a notation that is mostly used in Commonwealth countries, we compute as follows:

$$\begin{array}{r}
 8457 \\
 17 \overline{) 143785} \\
 \underline{136} \\
 77 \\
 \underline{68} \\
 98 \\
 \underline{85} \\
 135 \\
 \underline{119} \\
 16
 \end{array} \tag{3.10}$$

We therefore get $m = 8457$ as well as $r = 16$ and indeed we have $143785 = 8457 \cdot 17 + 16$, which we can double check invoking Sage:

```

sage: ZZ(143785).quo_rem(ZZ(17))              38
(8457, 16)                                     39
sage: ZZ(143785) == ZZ(8457)*ZZ(17) + ZZ(16) # check 40
True                                           41

```

Exercise 5 (Integer Long Division). Find an $m \in \mathbb{Z}$ as well as an $r \in \mathbb{N}$ with $0 \leq r < |b|$ such that $a = m \cdot b + r$ holds for the following pairs $(a, b) = (27, 5)$, $(a, b) = (27, -5)$, $(a, b) = (127, 0)$, $(a, b) = (-1687, 11)$ and $(a, b) = (0, 7)$. In which cases are your solutions unique?

Exercise 6 (Long Division Algorithm). Write an algorithm that computes integer long division and handling all edge cases properly.

Exercise 7 (Binary Representation). Write an algorithm that computes the binary representation 3.4 of any non-negative integer.

The Extended Euclidean Algorithm One of the most critical parts in this book is the so called modular arithmetic which we will define in 3.3 and its application in the computations of **prime fields** as defined in 4.3.1. To be able to do computations in modular arithmetic, we have to get familiar with the so-called **extended Euclidean algorithm**. We therefore introduce this algorithm here.

The **greatest common divisor** (GCD) of two non-zero integers a and b , is defined as the greatest non-zero natural number d such that d divides both a and b , that is, $d|a$ as well as $d|b$. We write $\gcd(a, b) := d$ for this number. Since the natural number 1 divides any other integer, 1 is always a common divisor of any two non-zero integers. However it must not be the greatest.

A common method to compute the greatest common divisor is the so called Euclidean algorithm. However since we don't need that algorithm in this book, we will introduce the Extended Euclidean algorithm which is a method to calculate the greatest common divisor of two natural numbers a and $b \in \mathbb{N}$, as well as two additional integers $s, t \in \mathbb{Z}$, such that the following equation holds:

$$\gcd(a, b) = s \cdot a + t \cdot b \quad (3.11)$$

The pseudocode in algorithm 1 shows in detail how to calculate the greatest common divisor and the numbers s and t with the extended Euclidean algorithm:

Algorithm 1 Extended Euclidean Algorithm

Require: $a, b \in \mathbb{N}$ with $a \geq b$

procedure EXT-EUCLID(a, b)

$r_0 \leftarrow a$ and $r_1 \leftarrow b$

$s_0 \leftarrow 1$ and $s_1 \leftarrow 0$

$t_0 \leftarrow 0$ and $t_1 \leftarrow 1$

$k \leftarrow 2$

while $r_{k-1} \neq 0$ **do**

$q_k \leftarrow r_{k-2} \text{ div } r_{k-1}$

$r_k \leftarrow r_{k-2} \text{ mod } r_{k-1}$

$s_k \leftarrow s_{k-2} - q_k \cdot s_{k-1}$

$t_k \leftarrow t_{k-2} - q_k \cdot t_{k-1}$

$k \leftarrow k + 1$

end while

return $\gcd(a, b) \leftarrow r_{k-2}$, $s \leftarrow s_{k-2}$ and $t \leftarrow t_{k-2}$

end procedure

Ensure: $\gcd(a, b) = s \cdot a + t \cdot b$

The algorithm is simple enough to be done effectively in pen-and-paper examples, where it is common to write it as a table where the rows represent the while-loop and the columns represent the values of the the array r , s and t with index k . The following example provides a simple execution:

Example 4. To illustrate algorithm 1, we apply it to the numbers $a = 12$ and $b = 5$. Since $12, 5 \in \mathbb{N}$ as well as $12 \geq 5$ all requirements are met and we compute as follows:

k	r_k	s_k	t_k
0	12	1	0
1	5	0	1
2	2	1	-2
3	1	-2	5
4	0		

From this we can see that the greatest common divisor of 12 and 5 is $\gcd(12, 5) = 1$ and that the equation $1 = (-2) \cdot 12 + 5 \cdot 5$ holds. We can also invoke sage to double check our findings:

```
sage: ZZ(12).xgcd(ZZ(5)) # (gcd(a,b), s, t)
(1, -2, 5)
```

42

43

Exercise 8 (Extended Euclidean Algorithm). Find integers $s, t \in \mathbb{Z}$ such that $\gcd(a, b) = s \cdot a + t \cdot b$ holds for the following pairs $(a, b) = (45, 10)$, $(a, b) = (13, 11)$, $(a, b) = (13, 12)$. What pairs (a, b) are coprime?

Exercise 9 (Towards Prime fields). Let $n \in \mathbb{N}$ be a natural number and p a prime number, such that $n < p$. What is the greatest common divisor $\gcd(p, n)$?

Exercise 10. Find all numbers $k \in \mathbb{N}$ with $0 \leq k \leq 100$ such that $\gcd(100, k) = 5$.

Exercise 11. Show that $\gcd(n, m) = \gcd(n + m, m)$ for all $n, m \in \mathbb{N}$.

Coprime Integers Coprime integers are integers that do not have a common prime number as a factor. As we will see in 3.3 those numbers are important for our purposes because in modular arithmetic, computation that involve coprime numbers are substantially different from computations on non-coprime numbers 3.3.

The naive way to decide if two integers are coprime would be to divide both number suces- sively by all prime numbers smaller then those numbers to see if they share a common prime factor. However two integers are coprime if and only if their greatest common divisor is 1 and hence computing the \gcd is the preferred method.

Example 5. Consider example 4 again. As we have seen, the greatest common divisor of 12 and 5 is 1. This implies that the integers 12 and 5 are coprime, since they share no divisor other then 1, which is not a prime number.

Exercise 12. Consider exercise 8 again. Which pairs (a, b) from that exercise are coprime?

3.3 Modular arithmetic

Modular arithmetic is a system of integer arithmetic, where numbers “wrap around” when reaching a certain value, much like calculations on a clock wrap around whenever the value exceeds the number 12. For example, if the clock shows that it is 11 o’clock, then 20 hours later it will be 7 o’clock, not 31 o’clock. The number 31 has no meaning on a normal clock that shows hours.

The number at which the wrap occurs is called the **modulus**. Modular arithmetic general- izes the clock example to arbitrary moduli and studies equations and phenomena that arise in this new kind of arithmetic. It is of central importance for understanding most modern crypto systems, in large parts because modular arithmetic provides the computational infrastrutute for algebraic types that have cryptographically useful examples of one-way functions.

Although modular arithmetic appears very different from ordinary integer arithmetic that we are all familiar with, we encourage the interested reader to work through the example and to discover that, once they get used to the idea that this is a new kind of calculations, it will seem much less daunting.

Congruence In what follows, let $n \in \mathbb{N}$ with $n \geq 2$ be a fixed natural number that we will call the **modulus** of our modular arithmetic system. With such an n given, we can then group integers into classes, by saying that two integers are in the same class, whenever their Euclidean division 3.2 by n will give the same remainder. We then say that two numbers are **congruent** whenever they are in the same class.

Example 6. If we choose $n = 12$ as in our clock example, then the integers $-7, 5, 17$ and 29 are all congruent with respect to 12 , since all of them have the remainder 5 if we perform Euclidean division on them by 12 . In the picture of an analog 12-hour clock, starting at 5 o'clock, when we add 12 hours we are again at 5 o'clock, representing the number 17 . On the other hand, when we subtract 12 hours, we are at 5 o'clock again, representing the number -7 .

We can formalize this intuition of what congruence should be into a proper definition utilizing Euclidean division (as explained previously in 3.2): Let $a, b \in \mathbb{Z}$ be two integers and $n \in \mathbb{N}$ a natural number, such that $n \geq 2$. Then a and b are said to be **congruent with respect to the modulus n** , if and only if the following equation holds

$$a \bmod n = b \bmod n \quad (3.12)$$

If, on the other hand, two numbers are not congruent with respect to a given modulus n , we call them **incongruent** w.r.t. n .

A **congruence** is then nothing but an equation "up to congruence", which means that the equation only needs to hold if we take the modulus on both sides. In which case we write

$$a \equiv b \pmod{n} \quad (3.13)$$

Exercise 13. Which of the following pairs of numbers are congruent with respect to the modulus 13: $(5, 19), (13, 0), (-4, 9), (0, 0)$.

Exercise 14. Find all integers x , such that the congruence $x \equiv 4 \pmod{6}$ is satisfied.

Computational Rules Having defined the notion of a congruence as an equation "up to a modulus", a follow up question is if we can manipulate a congruence similar to an equation. Indeed we can almost apply the same substitution rules to a congruency then to an equation, with the main difference being that for some non-zero integer $k \in \mathbb{Z}$, the congruence $a \equiv b \pmod{n}$ is equivalent to the congruence $k \cdot a \equiv k \cdot b \pmod{n}$ only, if k and the modulus n are coprime 3.2. The following list gives a set of useful rules:

Suppose that integers $a_1, a_2, b_1, b_2, k \in \mathbb{Z}$ are given. Then the following arithmetic rules hold for congruencies:

- $a_1 \equiv b_1 \pmod{n} \Leftrightarrow a_1 + k \equiv b_1 + k \pmod{n}$ (compatibility with translation)
- $a_1 \equiv b_1 \pmod{n} \Rightarrow k \cdot a_1 \equiv k \cdot b_1 \pmod{n}$ (compatibility with scaling)
- $\gcd(k, n) = 1$ and $k \cdot a_1 \equiv k \cdot b_1 \pmod{n} \Rightarrow a_1 \equiv b_1 \pmod{n}$
- $k \cdot a_1 \equiv k \cdot b_1 \pmod{k \cdot n} \Rightarrow a_1 \equiv b_1 \pmod{n}$

• $a_1 \equiv b_1 \pmod{n}$ and $a_2 \equiv b_2 \pmod{n} \Rightarrow a_1 + a_2 \equiv b_1 + b_2 \pmod{n}$ (compatibility with addition)

• $a_1 \equiv b_1 \pmod{n}$ and $a_2 \equiv b_2 \pmod{n} \Rightarrow a_1 \cdot a_2 \equiv b_1 \cdot b_2 \pmod{n}$ (compatibility with multiplication)

Other rules, such as compatibility with subtraction, follow from the rules above. For example, compatibility with subtraction follows from compatibility with scaling by $k = -1$ and compatibility with addition.

Another property of congruencies, not known in the traditional arithmetic of integers is **Fermat's Little Theorem**. In simple words, it states that, in modular arithmetic, every number raised to the power of a prime number modulus is congruent to the number itself. Or, to be more precise, if $p \in \mathbb{P}$ is a prime number and $k \in \mathbb{Z}$ is an integer, then:

$$k^p \equiv k \pmod{p}, \quad (3.14)$$

If k is coprime to p , then we can divide both sides of this congruence by k and rewrite the expression into the equivalent form

$$k^{p-1} \equiv 1 \pmod{p} \quad (3.15)$$

The following sage code computes example effects of Fermat's little theorem and highlights the effects of the exponent k being coprime and not coprime to p :

```
sage: ZZ(137).gcd(ZZ(64))      44
1                                45
sage: ZZ(64)^ZZ(137)%ZZ(137) == ZZ(64)%ZZ(137)  46
True                             47
sage: ZZ(64)^ZZ(137-1)%ZZ(137) == ZZ(1)%ZZ(137)  48
True                             49
sage: ZZ(1918).gcd(ZZ(137))    50
137                             51
sage: ZZ(1918)^ZZ(137)%ZZ(137) == ZZ(1918)%ZZ(137)  52
True                             53
sage: ZZ(1918)^ZZ(137-1)%ZZ(137) == ZZ(1)%ZZ(137)  54
False                            55
```

Let's compute an example that contains most of the concepts described in this section:

Example 7. Assume that we consider the modulus 6 and that our task is to solve the following congruence for $x \in \mathbb{Z}$

$$7 \cdot (2x + 21) + 11 \equiv x - 102 \pmod{6}$$

As many rules for congruencies are more or less same as for integers, we can proceed in a similar way as we would if we had an equation to solve. Since both sides of a congruence contain ordinary integers, we can rewrite the left side as follows: $7 \cdot (2x + 21) + 11 = 14x + 147 + 11 = 14x + 158$. We can therefore rewrite the congruence into the equivalent form

$$14x + 158 \equiv x - 102 \pmod{6}$$

In the next step we want to shift all instances of x to left and every other term to the right. So we apply the "compatibility with translation" rules two times. In a first step we choose $k = -x$

and in a second step we choose $k = -158$. Since “compatibility with translation” transforms a congruence into an equivalent form, the solution set will not change and we get

$$\begin{aligned} 14x + 158 &\equiv x - 102 \pmod{6} \Leftrightarrow \\ 14x - x + 158 - 158 &\equiv x - x - 102 - 158 \pmod{6} \Leftrightarrow \\ 13x &\equiv -260 \pmod{6} \end{aligned}$$

If our congruence would just be a normal integer equation, we would divide both sides by 13 to get $x = -20$ as our solution. However, in case of a congruence, we need to make sure that the modulus and the number we want to divide by are coprime first – only then will we get an equivalent expression (See rule XXX). So we need to find the greatest common divisor $\gcd(13, 6)$. Since 13 is prime and 6 is not a multiple of 13, we know that $\gcd(13, 6) = 1$, so these numbers are indeed coprime. We therefore compute

$$13x \equiv -260 \pmod{6} \Leftrightarrow x \equiv -20 \pmod{6}$$

Our task is now to find all integers x , such that x is congruent to -20 with respect to the modulus 6. So we have to find all x such

$$x \bmod 6 = -20 \bmod 6$$

Since $-4 \cdot 6 + 4 = -20$ we know $-20 \bmod 6 = 4$ and hence we know that $x = 4$ is a solution to this congruence. However, 22 is another solution since $22 \bmod 6 = 4$ as well, and so is -20 . In fact, there are infinitely many solutions given by the set

$$\{\dots, -8, -2, 4, 10, 16, \dots\} = \{4 + k \cdot 6 \mid k \in \mathbb{Z}\}$$

Putting all this together, we have shown that the every x from the set $\{x = 4 + k \cdot 6 \mid k \in \mathbb{Z}\}$ is a solution to the congruence $7 \cdot (2x + 21) + 11 \equiv x - 102 \pmod{6}$. We double check for, say, $x = 4$ as well as $x = 4 + 12 \cdot 6 = 76$ using sage:

```

893 sage: (ZZ(7) * (ZZ(2) * ZZ(4) + ZZ(21)) + ZZ(11)) % ZZ(6) == (ZZ 56
894         (4) - ZZ(102)) % ZZ(6)
895 True 57
896 sage: (ZZ(7) * (ZZ(2) * ZZ(76) + ZZ(21)) + ZZ(11)) % ZZ(6) == ( 58
897         ZZ(76) - ZZ(102)) % ZZ(6)
898 True 59

```

Readers who had not been familiar with modular arithmetic until now and who might be discouraged by how complicated modular arithmetic seems at this point, should keep two things in mind. First, computing congruencies in modular arithmetic is not really more complicated than computations in more familiar number systems (e.g. rational numbers), it is just a matter of getting used to it. Second, once we introduce the idea of remainder class representations 3.3, computations become conceptually cleaner and more easy to handle.

Exercise 15. Consider the modulus 13 and find all solutions $x \in \mathbb{Z}$ to the following congruence $5x + 4 \equiv 28 + 2x \pmod{13}$

Exercise 16. Consider the modulus 23 and find all solutions $x \in \mathbb{Z}$ to the following congruence $69x \equiv 5 \pmod{23}$

Exercise 17. Consider the modulus 23 and find all solutions $x \in \mathbb{Z}$ to the following congruence $69x \equiv 46 \pmod{23}$

- 911 *Exercise 18.* Let a, b, k be integers, such that $a \equiv b \pmod{n}$ holds. Show $a^k \equiv b^k \pmod{n}$.
 912 *Exercise 19.* Let a, n be integers, such that a and n are not coprime. For which $b \in \mathbb{Z}$ does the
 913 congruence $a \cdot x \equiv b \pmod{n}$ have a solution x and how does the solution set look in that
 914 case?

915 **The Chinese Remainder Theorem** We have seen how to solve congruencies in modular
 916 arithmetic. However, one question that remains is how to solve systems of congruencies with
 917 different moduli? The answer is given by the **Chinese remainder theorem**, which states that
 918 for any $k \in \mathbb{N}$ and coprime natural numbers $n_1, \dots, n_k \in \mathbb{N}$ as well as integers $a_1, \dots, a_k \in \mathbb{Z}$, the
 919 so-called **simultaneous congruences**

$$\begin{aligned} x &\equiv a_1 \pmod{n_1} \\ x &\equiv a_2 \pmod{n_2} \\ &\dots \\ x &\equiv a_k \pmod{n_k} \end{aligned} \tag{3.16}$$

920 has a solution, and all possible solutions of this congruence system are congruent modulo the
 product $N = n_1 \cdot \dots \cdot n_k$.¹ In fact, the following algorithm computes the solution set:

check
algorithm
floating

Algorithm 2 Chinese Remainder Theorem

Require: $k \in \mathbb{Z}$, $j \in \mathbb{N}_0$ and $n_0, \dots, n_{k-1} \in \mathbb{N}$ coprime

procedure CONGRUENCE-SYSTEMS-SOLVER(a_0, \dots, a_{k-1})

$N \leftarrow n_0 \cdot \dots \cdot n_{k-1}$

while $j < k$ **do**

$N_j \leftarrow N / n_j$

$(-, s_j, t_j) \leftarrow EXT - EUCLID(N_j, n_j)$

$$\triangleright 1 = s_j \cdot N_j + t_j \cdot n_j$$

end while

$x' \leftarrow \sum_{j=0}^{k-1} a_j \cdot s_j \cdot N_j$

$x \leftarrow x' \bmod N$

return $\{x + m \cdot N \mid m \in \mathbb{Z}\}$

end procedure

Ensure: $\{x + m \cdot N \mid m \in \mathbb{Z}\}$ is the complete solution set to 3.16.

921

Example 8. To illustrate how to solve simultaneous congruences using the Chinese remainder theorem, let's look at the following system of congruencies:

$$\begin{aligned} x &\equiv 4 \pmod{7} \\ x &\equiv 1 \pmod{3} \\ x &\equiv 3 \pmod{5} \\ x &\equiv 0 \pmod{11} \end{aligned}$$

Clearly all moduli are coprime and we have $N = 7 \cdot 3 \cdot 5 \cdot 11 = 1155$, as well as $N_1 = 165$, $N_2 = 385$, $N_3 = 231$ and $N_4 = 105$. From this we calculate with the extended Euclidean algorithm

$$\begin{aligned} 1 &= 2 \cdot 165 + -47 \cdot 7 \\ 1 &= 1 \cdot 385 + -128 \cdot 3 \\ 1 &= 1 \cdot 231 + -46 \cdot 5 \\ 1 &= 2 \cdot 105 + -19 \cdot 11 \end{aligned}$$

¹This is the classical Chinese remainder theorem as it was already known in ancient China. Under certain circumstances, the theorem can be extended to non-coprime moduli n_1, \dots, n_k but this is beyond the scope of this book. Interested readers should consult XXX [add references](#)

so we have $x = 4 \cdot 2 \cdot 165 + 1 \cdot 1 \cdot 385 + 3 \cdot 1 \cdot 231 + 0 \cdot 2 \cdot 105 = 2398$ as one solution. Because $2398 \bmod 1155 = 88$ the set of all solutions is $\{\dots, -2222, -1067, 88, 1243, 2398, \dots\}$. We can invoke Sage's computation of the Chinese Remainder Theorem (CRT) to double check our findings:

```
sage: CRT_list([4,1,3,0], [7,3,5,11])
88
```

60

61

Remainder Class Representation As we have seen in various examples before, computing congruencies can be cumbersome and solution sets are large in general. It is therefore advantageous to find some kind of simplification for modular arithmetic.

Fortunately, this is possible and relatively straightforward once we identify each set of numbers with equal remainder with that remainder itself and call it the **remainder class** or **residue class** representation in modulo n arithmetic.

It then follows from the properties of Euclidean division that there are exactly n different remainder classes for every modulus n and that integer addition and multiplication can be projected to a new kind of addition and multiplication on those classes.

Roughly speaking, the new rules for addition and multiplication are then computed by taking any element of the first remainder class and some element of the second, then add or multiply them in the usual way and see which remainder class the result is contained in. The following example makes this abstract description more concrete:

Example 9 (Arithmetic modulo 6). Choosing the modulus $n = 6$, we have six remainder classes of integers which are congruent modulo 6 (they have the same remainder when divided by 6) and when we identify each of those remainder classes with the remainder, we get the following identification:

$$\begin{aligned} 0 &:= \{\dots, -6, 0, 6, 12, \dots\} \\ 1 &:= \{\dots, -5, 1, 7, 13, \dots\} \\ 2 &:= \{\dots, -4, 2, 8, 14, \dots\} \\ 3 &:= \{\dots, -3, 3, 9, 15, \dots\} \\ 4 &:= \{\dots, -2, 4, 10, 16, \dots\} \\ 5 &:= \{\dots, -1, 5, 11, 17, \dots\} \end{aligned}$$

Now to compute the new addition law of those remainder class representatives, say $2 + 5$, one chooses arbitrary elements from both classes, say 14 and -1 , adds those numbers in the usual way and then looks at the remainder class of the result.

So we get $14 + (-1) = 13$, and 13 is in the remainder class (of) 1. Hence we find that $2 + 5 = 1$ in modular 6 arithmetic, which is a more readable way to write the congruence $2 + 5 \equiv 1 \pmod{6}$.

Applying the same reasoning to all remainder classes, addition and multiplication can be transferred to the representatives of the remainder classes. The results for modulus 6 arithmetic are summarized in the following addition and multiplication tables:

+	0	1	2	3	4	5	·	0	1	2	3	4	5
0	0	1	2	3	4	5	0	0	0	0	0	0	0
1	1	2	3	4	5	0	1	0	1	2	3	4	5
2	2	3	4	5	0	1	2	0	2	4	0	2	4
3	3	4	5	0	1	2	3	0	3	0	3	0	3
4	4	5	0	1	2	3	4	0	4	2	0	4	2
5	5	0	1	2	3	4	5	0	5	4	3	2	1

This way, we have defined a new arithmetic system that contains just 6 numbers and comes with its own definition of addition and multiplication. We call it **modular 6 arithmetic** and write the associated type as \mathbb{Z}_6 .

To see why such an identification of a remainder class with its remainder is useful and actually simplifies congruence computations a lot, let's go back to the congruence from example 7 again:

$$7 \cdot (2x + 21) + 11 \equiv x - 102 \pmod{6} \quad (3.17)$$

As shown in example 7, the arithmetic of congruencies can deviate from ordinary arithmetic: For example, division needs to check whether the modulus and the dividend are coprimes, and solutions are not unique in general.

We can rewrite this congruence as an **equation** over our new arithmetic type \mathbb{Z}_6 by **projecting onto the remainder classes**. In particular, since $7 \bmod 6 = 1$, $21 \bmod 6 = 3$, $11 \bmod 6 = 5$ and $102 \bmod 6 = 0$ we have

$$\begin{aligned} 7 \cdot (2x + 21) + 11 &\equiv x - 102 \pmod{6} \text{ over } \mathbb{Z} \\ &\Leftrightarrow 1 \cdot (2x + 3) + 5 = x \text{ over } \mathbb{Z}_6 \end{aligned}$$

We can use the multiplication and addition table above to solve the equation on the right like we would solve normal integer equations:

$$\begin{array}{ll} 1 \cdot (2x + 3) + 5 = x & \\ 2x + 3 + 5 = x & \# \text{ addition-table: } 3 + 5 = 2 \\ 2x + 2 = x & \# \text{ add 4 and } -x \text{ on both sides} \\ 2x + 2 + 4 - x = x + 4 - x & \# \text{ addition-table: } 2 + 4 = 0 \\ x = 4 & \end{array}$$

As we can see, despite the somewhat unfamiliar rules of addition and multiplication, solving congruencies this way is very similar to solving normal equations. And, indeed, the solution set is identical to the solution set of the original congruence, since 4 is identified with the set $\{4 + 6 \cdot k \mid k \in \mathbb{Z}\}$.

We can invoke Sage to do computations in our modular 6 arithmetic type. This is particularly useful to double-check our computations:

```
sage: Z6 = Integers(6)          62
sage: Z6(2) + Z6(5)             63
1                                64
sage: Z6(7) * (Z6(2) * Z6(4) + Z6(21)) + Z6(11) == Z6(4) - Z6(102) 65
True                             66
```

Remark 2 (k-bit modulus). In cryptographic papers, we sometimes read phrases like “[...] using a 4096-bit modulus”. This means that the underlying modulus n of the modular arithmetic used in the system has a binary representation with a length of 4096 bits. In contrast, the number 6 has the binary representation 110 and hence our example 9 describes a 3-bit modulus arithmetic system.

Exercise 20. Define \mathbb{Z}_{13} as the the arithmetic modulo 13 analog to example 9. Then consider the congruence from exercise 15 and rewrite it into an equation in \mathbb{Z}_{13}

Modular Inverses As we know, integers can be added, subtracted and multiplied so that the result is also an integer, but this is not true for the division of integers in general: for example, $3/2$ is not an integer anymore. To see why this is, from a more theoretical perspective, let us consider the definition of a multiplicative inverse first. When we have a set that has some kind of multiplication defined on it and we have a distinguished element of that set that behaves neutrally with respect to that multiplication (doesn't change anything when multiplied with any other element), then we can define **multiplicative inverses** in the following way:

Let S be our set that has some notion $a \cdot b$ of multiplication and a **neutral element** $1 \in S$, such that $1 \cdot a = a$ for all elements $a \in S$. Then a **multiplicative inverse** a^{-1} of an element $a \in S$ is defined as follows:

$$a \cdot a^{-1} = 1 \quad (3.18)$$

Informally speaking, the definition of a multiplicative inverse means that it “cancels” the original element to give 1 when they are multiplied.

Numbers that have multiplicative inverses are of particular interest, because they immediately lead to the definition of division by those numbers. In fact, if a is number such that the multiplicative inverse a^{-1} exists, then we define **division** by a simply as multiplication by the inverse:

$$\frac{b}{a} := b \cdot a^{-1} \quad (3.19)$$

Example 10. Consider the set of rational numbers, also known as fractions, \mathbb{Q} . For this set, the neutral element of multiplication is 1, since $1 \cdot a = a$ for all rational numbers. For example, $1 \cdot 4 = 4$, $1 \cdot \frac{1}{4} = \frac{1}{4}$, or $1 \cdot 0 = 0$ and so on.

Every rational number $a \neq 0$ has a multiplicative inverse, given by $\frac{1}{a}$. For example, the multiplicative inverse of 3 is $\frac{1}{3}$, since $3 \cdot \frac{1}{3} = 1$, the multiplicative inverse of $\frac{5}{7}$ is $\frac{7}{5}$, since $\frac{5}{7} \cdot \frac{7}{5} = 1$, and so on.

Example 11. Looking at the set \mathbb{Z} of integers, we see that with respect to multiplication the neutral element is the number 1 and we notice that no integer other than 1 or -1 has a multiplicative inverse, since the equation $a \cdot x = 1$ has no integer solutions for $a \neq 1$ or $a \neq -1$.

The definition of multiplicative inverse works verbatim for addition as well where it is called the additive inverse. In the case of integers, the neutral element with respect to addition is 0, since $a + 0 = a$ for all integers $a \in \mathbb{Z}$. The additive inverse always exist and is given by the negative number $-a$, since $a + (-a) = 0$.

Example 12. Looking at the set \mathbb{Z}_6 of residual classes modulo 6 from example 9, we can use the multiplication table to find multiplicative inverses. To do so, we look at the row of the element and then find the entry equal to 1. If such an entry exists, the element of that column is the multiplicative inverse. If, on the other hand, the row has no entry equal to 1, we know that the element has no multiplicative inverse.

For example in \mathbb{Z}_6 the multiplicative inverse of 5 is 5 itself, since $5 \cdot 5 = 1$. We can also see that 5 and 1 are the only elements that have multiplicative inverses in \mathbb{Z}_6 .

Now, since 5 has a multiplicative inverse in modulo 6 arithmetic, we can divide by 5 in \mathbb{Z}_6 , since we have a notation of multiplicative inverse and division is nothing but multiplication by the multiplicative inverse. For example

$$\frac{4}{5} = 4 \cdot 5^{-1} = 4 \cdot 5 = 2$$

From the last example, we can make the interesting observation that while 5 has no multiplicative inverse as an integer, it has a multiplicative inverse in modular 6 arithmetic.

1018 This raises the question which numbers have multiplicative inverses in modular arithmetic.
 1019 The answer is that, in modular n arithmetic, a number r has a multiplicative inverse, if and only
 1020 if n and r are coprime. Since $\gcd(n, r) = 1$ in that case, we know from the extended Euclidean
 1021 algorithm that there are numbers s and t , such that

$$1 = s \cdot n + t \cdot r \quad (3.20)$$

1022 If we take the modulus n on both sides, the term $s \cdot n$ vanishes, which tells us that $t \bmod n$ is the
 1023 multiplicative inverse of r in modular n arithmetic.

1024 *Example 13* (Multiplicative inverses in \mathbb{Z}_6). In the previous example, we looked up multiplica-
 1025 tive inverses in \mathbb{Z}_6 from the lookup-table in Example 9. In real world examples, it is usually
 1026 impossible to write down those lookup tables, as the modulus is way too large, and the sets
 1027 occasionally contain more elements than there are atoms in the observable universe.

1028 Now, trying to determine that $2 \in \mathbb{Z}_6$ has no multiplicative inverse in \mathbb{Z}_6 without using the
 1029 lookup table, we immediately observe that 2 and 6 are not coprime, since their greatest common
 1030 divisor is 2. It follows that equation 3.20 has no solutions s and t , which means that 2 has no
 1031 multiplicative inverse in \mathbb{Z}_6 .

1032 The same reasoning works for 3 and 4, as neither of these are coprime with 6. The case
 1033 of 5 is different, since $\gcd(6, 5) = 1$. To compute the multiplicative inverse of 5, we use the
 1034 extended Euclidean algorithm and compute the following:

k	r_k	s_k	$t_k = (r_k - s_k \cdot a) \div b$
0	6	1	0
1	5	0	1
2	1	1	-1
3	0	.	.

1036 We get $s = 1$ as well as $t = -1$ and have $1 = 1 \cdot 6 - 1 \cdot 5$. From this, it follows that $-1 \bmod 6 =$
 1037 5 is the multiplicative inverse of 5 in modular 6 arithmetic. We can double check using Sage:

1038 **sage:** `ZZ(6).xgcd(ZZ(5))` 67
 1039 `(1, 1, -1)` 68

At this point, the attentive reader might notice that the situation where the modulus is a prime number is of particular interest, because we know from exercise 9 that in these cases all remainder classes must have modular inverses, since $\gcd(r, n) = 1$ for prime n and any $r < n$. In fact, Fermat's little theorem provides a way to compute multiplicative inverses in this situation, since in case of a prime modulus p and $r < p$, we get the following:

$$\begin{aligned} r^p &\equiv r \pmod{p} \Leftrightarrow \\ r^{p-1} &\equiv 1 \pmod{p} \Leftrightarrow \\ r \cdot r^{p-2} &\equiv 1 \pmod{p} \end{aligned}$$

1040 This tells us that the multiplicative inverse of a residue class r in modular p arithmetic is pre-
 1041 cisely r^{p-2} .

Example 14 (Modular 5 arithmetic). To see the unique properties of modular arithmetic when the modulus is a prime number, we will replicate our findings from example 9, but this time for the prime modulus 5. For $n = 5$ we have five equivalence classes of integers which are

congruent modulo 5. We write this as follows:

$$\begin{aligned} 0 &:= \{\dots, -5, 0, 5, 10, \dots\} \\ 1 &:= \{\dots, -4, 1, 6, 11, \dots\} \\ 2 &:= \{\dots, -3, 2, 7, 12, \dots\} \\ 3 &:= \{\dots, -2, 3, 8, 13, \dots\} \\ 4 &:= \{\dots, -1, 4, 9, 14, \dots\} \end{aligned}$$

1042 Addition and multiplication can be transferred to the equivalence classes, in a way exactly
1043 parallel to Example 9. This results in the following addition and multiplication tables:

	+	0	1	2	3	4		·	0	1	2	3	4
	0	0	1	2	3	4		0	0	0	0	0	0
	1	1	2	3	4	0		1	0	1	2	3	4
1044	2	2	3	4	0	1		2	0	2	4	1	3
	3	3	4	0	1	2		3	0	3	1	4	2
	4	4	0	1	2	3		4	0	4	3	2	1

1045 Calling the set of remainder classes in modular 5 arithmetic with this addition and multiplication
1046 \mathbb{Z}_5 , we see some subtle but important differences to the situation in \mathbb{Z}_6 . In particular, we see
1047 that in the multiplication table, every remainder $r \neq 0$ has the entry 1 in its row and therefore
1048 has a multiplicative inverse. In addition, there are no non-zero elements such that their product
1049 is zero.

1050 To use Fermat's little theorem in \mathbb{Z}_5 for computing multiplicative inverses (instead of using
1051 the multiplication table), let's consider $3 \in \mathbb{Z}_5$. We know that the multiplicative inverse is given
1052 by the remainder class that contains $3^{5-2} = 3^3 = 3 \cdot 3 \cdot 3 = 4 \cdot 3 = 2$. And indeed $3^{-1} = 2$, since
1053 $3 \cdot 2 = 1$ in \mathbb{Z}_5 .

1054 We can invoke Sage to do computations in our modular 5 arithmetic type to double-check
1055 our computations:

```

1056 sage: Z5 = Integers(5)                                     69
1057 sage: Z5(3) ** (5-2)                                       70
1058 2                                                         71
1059 sage: Z5(3) ** (-1)                                       72
1060 2                                                         73
1061 sage: Z5(3) ** (5-2) == Z5(3) ** (-1)                   74
1062 True                                                       75

```

Example 15. To understand one of the principal differences between prime number modular arithmetic and non-prime number modular arithmetic, consider the linear equation $a \cdot x + b = 0$ defined over both types \mathbb{Z}_5 and \mathbb{Z}_6 . Since in \mathbb{Z}_5 every non-zero element has a multiplicative inverse, we can always solve these equations in \mathbb{Z}_5 , which is not true in \mathbb{Z}_6 . To see that, consider the equation $3x + 3 = 0$. In \mathbb{Z}_5 we have the following:

$$\begin{aligned} 3x + 3 &= 0 && \# \text{ add 2 and on both sides} \\ 3x + 3 + 2 &= 2 && \# \text{ addition-table: } 2 + 3 = 0 \\ 3x &= 2 && \# \text{ divide by 3 (which equals multiplication by 2)} \\ 2 \cdot (3x) &= 2 \cdot 2 && \# \text{ multiplication-table: } 2 \cdot 2 = 4 \\ x &= 4 \end{aligned}$$

So in the case of our prime number modular arithmetic, we get the unique solution $x = 4$. Now consider \mathbb{Z}_6 :

$$\begin{array}{ll} 3x + 3 = 0 & \# \text{ add 3 and on both sides} \\ 3x + 3 + 3 = 3 & \# \text{ addition-table: } 3 + 3 = 0 \\ 3x = 3 & \# \text{ division not possible (no multiplicative inverse of 3 exists)} \end{array}$$

So, in this case, we cannot solve the equation for x by dividing by 3. And, indeed, when we look at the multiplication table of \mathbb{Z}_6 (Example 9), we find that there are three solutions $x \in \{1, 3, 5\}$, such that $3x + 3 = 0$ holds true for all of them.

Exercise 21. Consider the modulus $n = 24$. Which of the integers 7, 1, 0, 805, -4255 have multiplicative inverses in modular 24 arithmetic? Compute the inverses, in case they exist.

Exercise 22. Find the set of all solutions to the congruence $17(2x + 5) - 4 \equiv 2x + 4 \pmod{5}$. Then project the congruence into \mathbb{Z}_5 and solve the resulting equation in \mathbb{Z}_5 . Compare the results.

Exercise 23. Find the set of all solutions to the congruence $17(2x + 5) - 4 \equiv 2x + 4 \pmod{6}$. Then project the congruence into \mathbb{Z}_6 and try to solve the resulting equation in \mathbb{Z}_6 .

3.4 Polynomial arithmetic

A polynomial is an expression consisting of variables (also called indeterminates) and coefficients that involves only the operations of addition, subtraction and multiplication. All coefficients of a polynomial must have the same type, e.g. being integers or rational numbers etc. To be more precise an *univariate polynomial* is an expression

$$P(x) := \sum_{j=0}^m a_j x^j = a_m x^m + a_{m-1} x^{m-1} + \cdots + a_1 x + a_0, \quad (3.21)$$

where x is called the **indeterminate**, each a_j is called a **coefficient**. If R is the type of the coefficients, then the set of all **univariate² polynomials with coefficients in R** is written as $R[x]$. We often simply use **polynomial** instead of univariate polynomial, write $P(x) \in R[x]$ for a polynomial and denote the constant term a_0 as $P(0)$.

A polynomial is called the **zero polynomial** if all coefficients are zero and a polynomial is called the **one polynomial** if the constant term is 1 and all other coefficients are zero.

Given an univariate polynomial $P(x) = \sum_{j=0}^m a_j x^j$ that is not the zero polynomial, we call the non-negative integer $\deg(P) := m$ the *degree* of P and define the degree of the zero polynomial to be $-\infty$, where $-\infty$ (negative infinity) is a symbol with the properties that $-\infty + m = -\infty$ and $-\infty < m$ for all non-negative integers $m \in \mathbb{N}_0$. In addition, we write

$$Lc(P) := a_m \quad (3.22)$$

and call it the **leading coefficient** of the polynomial P . We can restrict the set $R[x]$ of all polynomials with coefficients in R , to the set of all such polynomials that have a degree that does not exceed a certain value. If m is the maximum degree allowed, we write $R_{\leq m}[x]$ for the set of all polynomials with a degree less than or equal to m .

²in our context the term univariate means that the polynomial contains a single variable only

Example 16 (Integer Polynomials). The coefficients of a polynomial must all have the same type. The set of polynomials with integer coefficients is written as $\mathbb{Z}[x]$. Examples of such polynomials are:

$$\begin{array}{ll}
 P_1(x) = 2x^2 - 4x + 17 & \# \text{ with } \deg(P_1) = 2 \text{ and } Lc(P_1) = 2 \\
 P_2(x) = x^{23} & \# \text{ with } \deg(P_2) = 23 \text{ and } Lc(P_2) = 1 \\
 P_3(x) = x & \# \text{ with } \deg(P_3) = 1 \text{ and } Lc(P_3) = 1 \\
 P_4(x) = 174 & \# \text{ with } \deg(P_4) = 0 \text{ and } Lc(P_4) = 174 \\
 P_5(x) = 1 & \# \text{ with } \deg(P_5) = 0 \text{ and } Lc(P_5) = 1 \\
 P_6(x) = 0 & \# \text{ with } \deg(P_6) = -\infty \text{ and } Lc(P_6) = 0 \\
 P_7(x) = (x-2)(x+3)(x-5)
 \end{array}$$

In particular, every integer can be seen as an integer polynomial of degree zero. P_7 is a polynomial, because we can expand its definition into $P_7(x) = x^3 - 4x^2 - 11x + 30$, which is a polynomial of degree 3 and leading coefficient 1. The following expressions are not integer polynomials:

$$\begin{aligned}
 Q_1(x) &= 2x^2 + 4 + 3x^{-2} \\
 Q_2(x) &= 0.5x^4 - 2x \\
 Q_3(x) &= 2^x
 \end{aligned}$$

In particular Q_1 is not an integer polynomial, because the expression x^{-2} has a negative exponent, Q_2 is not an integer polynomial because the coefficient 0.5 is not an integer and Q_3 is not an integer polynomial because the indeterminate appears in the exponent of a coefficient.

We can invoke Sage to do computations with polynomials. To do so, we have to specify the symbol for the indeterminate and the type for the coefficients (For the definition of rings see 4.2). Note, however that Sage defines the degree of the zero polynomial to be -1 .

```

1097 sage: Zx = ZZ['x'] # integer polynomials with indeterminate x 76
1098 sage: Zt.<t> = ZZ[] # integer polynomials with indeterminate t 77
1099 sage: Zx 78
1100 Univariate Polynomial Ring in x over Integer Ring 79
1101 sage: Zt 80
1102 Univariate Polynomial Ring in t over Integer Ring 81
1103 sage: p1 = Zx([17,-4,2]) 82
1104 sage: p1 83
1105 2*x^2 - 4*x + 17 84
1106 sage: p1.degree() 85
1107 2 86
1108 sage: p1.leading_coefficient() 87
1109 2 88
1110 sage: p2 = Zt(t^23) 89
1111 sage: p2 90
1112 t^23 91
1113 sage: p6 = Zx([0]) 92
1114 sage: p6.degree() 93
1115 -1 94

```

Example 17 (Polynomials over \mathbb{Z}_6). Recall the definition of modular 6 arithmetics \mathbb{Z}_6 as defined in example 9. The set of all polynomials with indeterminate x and coefficients in \mathbb{Z}_6 is symbolized as $\mathbb{Z}_6[x]$. Example of polynomials from $\mathbb{Z}_6[x]$ are:

$$\begin{array}{ll}
 P_1(x) = 2x^2 - 4x + 5 & \# \text{ with } \deg(P_1) = 2 \text{ and } Lc(P_1) = 2 \\
 P_2(x) = x^{23} & \# \text{ with } \deg(P_2) = 23 \text{ and } Lc(P_2) = 1 \\
 P_3(x) = x & \# \text{ with } \deg(P_3) = 1 \text{ and } Lc(P_3) = 1 \\
 P_4(x) = 3 & \# \text{ with } \deg(P_4) = 0 \text{ and } Lc(P_4) = 3 \\
 P_5(x) = 1 & \# \text{ with } \deg(P_5) = 0 \text{ and } Lc(P_5) = 1 \\
 P_6(x) = 0 & \# \text{ with } \deg(P_5) = -\infty \text{ and } Lc(P_6) = 0 \\
 P_7(x) = (x-2)(x+3)(x-5) &
 \end{array}$$

Just like in the previous example, P_7 is a polynomial. However, since we are working with coefficients from \mathbb{Z}_6 now the expansion of P_7 is computed differently, as we have to invoke addition and multiplication in \mathbb{Z}_6 as defined in XXX. We get the following:

$$\begin{aligned}
 (x-2)(x+3)(x-5) &= (x+4)(x+3)(x+1) && \# \text{ additive inverses in } \mathbb{Z}_6 \\
 &= (x^2 + 4x + 3x + 3 \cdot 4)(x+1) && \# \text{ bracket expansion} \\
 &= (x^2 + 1x + 0)(x+1) && \# \text{ computation in } \mathbb{Z}_6 \\
 &= x^3 + x^2 + x^2 + x && \# \text{ bracket expansion} \\
 &= x^3 + 2x^2 + x
 \end{aligned}$$

1116 Again, we can use Sage to do computations with polynomials that have their coefficients in \mathbb{Z}_6
 1117 (For the definition of rings see 4.2). To do so, we have to specify the symbol for the indertemi-
 1118 nate and the type for the coefficients:

```

1119 sage: Z6 = Integers(6)                                     95
1120 sage: Z6x = Z6['x']                                         96
1121 sage: Z6x                                                    97
1122 Univariate Polynomial Ring in x over Ring of integers modulo 6 98
1123 sage: p1 = Z6x([5,-4,2])                                     99
1124 sage: p1                                                    100
1125 2*x^2 + 2*x + 5                                             101
1126 sage: p1 = Z6x([17,-4,2])                                    102
1127 sage: p1                                                    103
1128 2*x^2 + 2*x + 5                                             104
1129 sage: Z6x(x-2)*Z6x(x+3)*Z6x(x-5) == Z6x(x^3 + 2*x^2 + x) 105
1130 True                                                         106

```

1131 Given some element from the same type as the coefficients of a polynomial, the poly-
 1132 nomial can be evaluated at that element, which means that we insert the given element for every
 1133 occurrence of the indeterminate x in the polynomial expression.

1134 To be more precise, let $P \in R[x]$, with $P(x) = \sum_{j=0}^m a_j x^j$ be a polynomial with a coefficient
 1135 of type R and let $b \in R$ be an element of that type. Then the **evaluation** of P at b is given as
 1136 follows:

$$P(b) = \sum_{j=0}^m a_j b^j \quad (3.23)$$

Example 18. Consider the integer polynomials from example 16 again. To evaluate them at given points, we have to insert the point for all occurrences of x in the polynomial expression. Inserting arbitrary values from \mathbb{Z} , we get:

$$\begin{aligned} P_1(2) &= 2 \cdot 2^2 - 4 \cdot 2 + 17 = 17 \\ P_2(3) &= 3^{23} = 94143178827 \\ P_3(-4) &= -4 = -4 \\ P_4(15) &= 174 \\ P_5(0) &= 1 \\ P_6(1274) &= 0 \\ P_7(-6) &= (-6-2)(-6+3)(-6-5) = -264 \end{aligned}$$

1137 Note, however, that it is not possible to evaluate any of those polynomial on values of different
1138 type. For example, it is not strictly correct to write $P_1(0.5)$, since 0.5 is not an integer. We can
1139 verify our computations using Sage:

```
1140 sage: Zx = ZZ['x'] 107
1141 sage: p1 = Zx([17, -4, 2]) 108
1142 sage: p7 = Zx(x-2)*Zx(x+3)*Zx(x-5) 109
1143 sage: p1(ZZ(2)) 110
1144 17 111
1145 sage: p7(ZZ(-6)) == ZZ(-264) 112
1146 True 113
```

Example 19. Consider the polynomials with coefficients in \mathbb{Z}_6 from example again. To evaluate them at given values from \mathbb{Z}_6 , we have to insert the point for all occurrences of x in the polynomial expression. We get the following:

$$\begin{aligned} P_1(2) &= 2 \cdot 2^2 - 4 \cdot 2 + 5 = 2 - 2 + 5 = 5 \\ P_2(3) &= 3^{23} = 3 \\ P_3(-4) &= P_3(2) = 2 \\ P_5(0) &= 1 \\ P_6(4) &= 0 \end{aligned}$$

```
1147
1148 sage: Z6 = Integers(6) 114
1149 sage: Z6x = Z6['x'] 115
1150 sage: p1 = Z6x([5, -4, 2]) 116
1151 sage: p1(Z6(2)) == Z6(5) 117
1152 True 118
```

1153 *Exercise 24.* Compare both expansions of P_7 from $\mathbb{Z}[x]$ and from $\mathbb{Z}_6[x]$ in example 16 and
1154 example 19 ,and consider the definition of \mathbb{Z}_6 as given in example 9. Can you see how the
1155 definition of P_7 over \mathbb{Z} projects to the definition over \mathbb{Z}_6 if you consider the residue classes of
1156 \mathbb{Z}_6 ?

Polynomial arithmetic Polynomials behave like integers in many ways. In particular, they can be added, subtracted and multiplied. In addition, they have their own notion of Euclidean division. Informally speaking, we can add two polynomials by simply adding the coefficients of the same index, and we can multiply them by applying the distributive property, that is, by multiplying every term of the left factor with every term of the right factor and adding the results together.

To be more precise let $\sum_{n=0}^{m_1} a_n x^n$ and $\sum_{n=0}^{m_2} b_n x^n$ be two polynomials from $R[x]$. Then the **sum** and the **product** of these polynomials is defined as follows:

$$\sum_{n=0}^{m_1} a_n x^n + \sum_{n=0}^{m_2} b_n x^n = \sum_{n=0}^{\max(\{m_1, m_2\})} (a_n + b_n) x^n \quad (3.24)$$

$$\left(\sum_{n=0}^{m_1} a_n x^n \right) \cdot \left(\sum_{n=0}^{m_2} b_n x^n \right) = \sum_{n=0}^{m_1+m_2} \sum_{i=0}^n a_i b_{n-i} x^n \quad (3.25)$$

A rule for polynomial subtraction can be deduced from these two rules by first multiplying the **subtrahend** with (the polynomial) -1 and then add the result to the **minuend**.

Regarding the definition of the degree of a polynomial, we see that the degree of the sum is always the maximum of the degrees of both summands, and the degree of the product is always the degree of the sum of the factors, since we defined $-\infty + m = -\infty$ for every integer $m \in \mathbb{Z}$.

Example 20. To give an example of how polynomial arithmetic works, consider the following two integer polynomials $P, Q \in \mathbb{Z}[x]$ with $P(x) = 5x^2 - 4x + 2$ and $Q(x) = x^3 - 2x^2 + 5$. The sum of these two polynomials is computed by adding the coefficients of each term with equal exponent in x . This gives the following:

$$\begin{aligned} (P + Q)(x) &= (0 + 1)x^3 + (5 - 2)x^2 + (-4 + 0)x + (2 + 5) \\ &= x^3 + 3x^2 - 4x + 7 \end{aligned}$$

The product of these two polynomials is computed by multiplication of each term in the first factor with each term in the second factor. We get the following:

$$\begin{aligned} (P \cdot Q)(x) &= (5x^2 - 4x + 2) \cdot (x^3 - 2x^2 + 5) \\ &= (5x^5 - 10x^4 + 25x^2) + (-4x^4 + 8x^3 - 20x) + (2x^3 - 4x^2 + 10) \\ &= 5x^5 - 14x^4 + 10x^3 + 21x^2 - 20x + 10 \end{aligned}$$

```

sage: Zx = ZZ['x']
sage: P = Zx([2, -4, 5])
sage: Q = Zx([5, 0, -2, 1])
sage: P+Q == Zx(x^3 +3*x^2 -4*x +7)
True
sage: P*Q == Zx(5*x^5 -14*x^4 +10*x^3+21*x^2-20*x +10)
True

```

Example 21. Let us consider the polynomials of the previous example but interpreted in modular 6 arithmetic. So we consider $P, Q \in \mathbb{Z}_6[x]$ again with $P(x) = 5x^2 - 4x + 2$ and $Q(x) = x^3 - 2x^2 +$

5. This time we get the following:

$$\begin{aligned}(P + Q)(x) &= (0 + 1)x^3 + (5 - 2)x^2 + (-4 + 0)x + (2 + 5) \\ &= (0 + 1)x^3 + (5 + 4)x^2 + (2 + 0)x + (2 + 5) \\ &= x^3 + 3x^2 + 2x + 1\end{aligned}$$

$$\begin{aligned}(P \cdot Q)(x) &= (5x^2 - 4x + 2) \cdot (x^3 - 2x^2 + 5) \\ &= (5x^2 + 2x + 2) \cdot (x^3 + 4x^2 + 5) \\ &= (5x^5 + 2x^4 + 1x^2) + (2x^4 + 2x^3 + 4x) + (2x^3 + 2x^2 + 4) \\ &= 5x^5 + 4x^4 + 4x^3 + 3x^2 + 4x + 4\end{aligned}$$

1179

1180	<code>sage: Z6x = Integers(6) ['x']</code>	126
1181	<code>sage: P = Z6x([2, -4, 5])</code>	127
1182	<code>sage: Q = Z6x([5, 0, -2, 1])</code>	128
1183	<code>sage: P+Q == Z6x(x^3 +3*x^2 +2*x +1)</code>	129
1184	<code>True</code>	130
1185	<code>sage: P*Q == Z6x(5*x^5 +4*x^4 +4*x^3+3*x^2+4*x +4)</code>	131
1186	<code>True</code>	132

1187 *Exercise 25.* Compare the sum $P + Q$ and the product $P \cdot Q$ from the previous two examples
 1188 20 and 21 and consider the definition of \mathbb{Z}_6 as given in example 9. How can we derive the
 1189 computations in $\mathbb{Z}_6[x]$ from the computations in $\mathbb{Z}[x]$?

1190 **Euklidean Division** The arithmetic of polynomials share a lot of properties with the arith-
 1191 metic of integers and as a consequence the concept of Euclidean division and the algorithm of
 1192 long division is also defined for polynomials. Recalling the Euclidean division of integers 3.2,
 1193 we know that, given two integers a and $b \neq 0$, there is always another integer m and a natural
 1194 number r with $r < |b|$ such that $a = m \cdot b + r$ holds.

1195 We can generalize this to polynomials whenever the leading coefficient of the dividend
 1196 polynomial has a notion of multiplicative inverse. In fact, given two polynomials A and $B \neq 0$
 1197 from $R[x]$ such that $Lc(B)^{-1}$ exists in R , there exist two polynomials Q (the quotient) and P (the
 1198 remainder), such that the following equation holds:

$$A = Q \cdot B + P \tag{3.26}$$

1199 and $\deg(P) < \deg(B)$. Similarly to integer Euclidean division, both Q and P are uniquely
 1200 defined by these relations.

1201 *Notation and Symbols 2.* Suppose that the polynomials A, B, Q and P satisfy equation 3.26. We
 1202 often use the following notation to describe the quotient and the remainder polynomials of the
 1203 Euclidean division:

$$A \operatorname{div} B := Q, \quad A \operatorname{mod} B := P \tag{3.27}$$

1204 We also say that a polynomial A is divisible by another polynomial B if $A \operatorname{mod} B = 0$ holds. In
 1205 this case, we also write $B|A$ and call B a *factor* of A .

Algorithm 3 Polynomial Euclidean Algorithm

Require: $A, B \in R[x]$ with $B \neq 0$, such that $Lc(B)^{-1}$ exists in R

procedure POLY-LONG-DIVISION(A, B)

$$Q \leftarrow 0$$
$$P \leftarrow A$$
$$d \leftarrow \deg(B)$$
$$c \leftarrow Lc(B)$$
while $\deg(P) \geq d$ **do**
$$S := Lc(P) \cdot c^{-1} \cdot x^{\deg(P)-d}$$
$$Q \leftarrow Q + S$$
$$P \leftarrow P - S \cdot B$$
end while**return** (Q, P)

end procedure

Ensure: $A = Q \cdot B + P$

Analogously to integers, methods to compute Euclidean division for polynomials are called **polynomial division algorithms**. Probably the best known algorithm is the so called **polynomial long division**.

This algorithm works only when there is a notion of division by the leading coefficient of B . It can be generalized, but we will only need this somewhat simpler method in what follows.

Example 22 (Polynomial Long Division). To give an example of how the previous algorithm works, let us divide the integer polynomial $A(x) = x^5 + 2x^3 - 9 \in \mathbb{Z}[x]$ by the integer polynomial $B(x) = x^2 + 4x - 1 \in \mathbb{Z}[x]$. Since B is not the zero polynomial and the leading coefficient of B is 1, which is invertible as an integer, we can apply algorithm 1. Our goal is to find solutions to equation XXX, that is, we need to find the quotient polynomial $Q \in \mathbb{Z}[x]$ and the remainder polynomial $P \in \mathbb{Z}[x]$ such that $x^5 + 2x^3 - 9 = Q(x) \cdot (x^2 + 4x - 1) + P(x)$. Using a notation that is mostly used in anglophone countries, we compute as follows:

algorithm-floating

$$X^2 + 4X - 1) \overline{\begin{array}{r} X^3 - 4X^2 + 19X - 80 \\ X^5 + 2X^3 - 9 \\ -X^5 - 4X^4 + X^3 \\ \hline -4X^4 + 3X^3 \\ 4X^4 + 16X^3 - 4X^2 \\ \hline 19X^3 - 4X^2 \\ -19X^3 - 76X^2 + 19X \\ \hline -80X^2 + 19X - 9 \\ 80X^2 + 320X - 80 \\ \hline 339X - 89 \end{array}} \quad (3.28)$$

We therefore get $Q(x) = x^3 - 4x^2 + 19x - 80$ as well as $P(x) = 339x - 89$ and indeed we have $x^5 + 2x^3 - 9 = (x^3 - 4x^2 + 19x - 80) \cdot (x^2 + 4x - 1) + (339x - 89)$, which we can double check invoking Sage:

```
sage: Zx = ZZ['x']
```

```
sage: A = Zx([-9, 0, 0, 2, 0, 1])
```

```
sage: B = Zx([-1, 4, 1])
```

```

1224 sage: Q = Zx([-80, 19, -4, 1]) 136
1225 sage: P = Zx([-89, 339]) 137
1226 sage: A == Q*B + P 138
1227 True 139

```

Example 23. In the previous example, polynomial division gave a non-trivial (non-vanishing, i.e non-zero) remainder. Of special interest are divisions that don't give a remainder. Such divisors are called factors of the dividend.

For example, consider the integer polynomial P_7 from example 16 again. As we have shown, it can be written both as $x^3 - 4x^2 - 11x + 30$ and as $(x - 2)(x + 3)(x - 5)$. From this, we can see that the polynomials $F_1(x) = (x - 2)$, $F_2(x) = (x + 3)$ and $F_3(x) = (x - 5)$ are all factors of $x^3 - 4x^2 - 11x + 30$, since division of P_7 by any of these factors will result in a zero remainder.

Exercise 26. Consider the polynomial expressions $A(x) := -3x^4 + 4x^3 + 2x^2 + 4$ and $B(x) = x^2 - 4x + 2$. Compute the Euclidean division of A by B in the following types:

1. $A, B \in \mathbb{Z}[x]$
2. $A, B \in \mathbb{Z}_6[x]$
3. $A, B \in \mathbb{Z}_5[x]$

Now consider the result in $\mathbb{Z}[x]$ and in $\mathbb{Z}_6[x]$. How can we compute the result in $\mathbb{Z}_6[x]$ from the result in $\mathbb{Z}[x]$?

Exercise 27. Show that the polynomial $B(x) = 2x^4 - 3x + 4 \in \mathbb{Z}_5[x]$ is a factor of the polynomial $A(x) = x^7 + 4x^6 + 4x^5 + x^3 + 2x^2 + 2x + 3 \in \mathbb{Z}_5[x]$ that is show $B|A$. What is $B \text{ div } A$?

Prime Factors Recall that the fundamental theorem of arithmetic 3.7 tells us that every natural number is the product of prime numbers. In this chapter we will see that something similar holds for univariate polynomials $R[x]$, too³.

The polynomial analog to a prime number is a so called an **irreducible polynomial**, which is defined as a polynomial that cannot be factored into the product of two non-constant polynomials using Euclidean division. Irreducible polynomials are for polynomials what prime numbers are for integer: They are the basic building blocks from which all other polynomials can be constructed. To be more precise, let $P \in R[x]$ be any polynomial. Then there are always irreducible polynomials $F_1, F_2, \dots, F_k \in R[x]$, such that the following holds:

$$P = F_1 \cdot F_2 \cdot \dots \cdot F_k . \quad (3.29)$$

This representation is unique, except for permutations in the factors and is called the **prime factorization** of P . Moreover each factor F_i is called a **prime factor** of P .

Example 24. Consider the polynomial expression $P = x^2 - 3$. When we interpret P as an integer polynomial $P \in \mathbb{Z}[x]$, we find that this polynomial is irreducible, since any factorization other than $1 \cdot (x^2 - 3)$, must look like $(x - a)(x + a)$ for some integer a , but there is no integers a with $a^2 = 3$.

```

1259 sage: Zx = ZZ['x'] 140
1260 sage: p = Zx(x^2-3) 141

```

³Strictly speaking this is not true for polynomials over arbitrary types R . However in this book we assume R to be a so called unique factorization domain for which the content of this section holds.

```

1261 sage: p.factor()
1262 x^2 - 3

```

On the other hand interpreting P as a polynomial $P \in \mathbb{Z}_6[x]$ in modulo 6 arithmetic, we see that P has two factors $F_1 = (x - 3)$ and $F_2 = (x + 3)$, since $(x - 3)(x + 3) = x^2 - 3x + 3x - 3 \cdot 3 = x^2 - 3$.

Points where a polynomial evaluates to zero are called **roots** of the polynomial. To be more precise, let $P \in R[x]$ be a polynomial. Then a root is a point $x_0 \in R$ with $P(x_0) = 0$ and the set of all roots of P is defined as follows:

$$R_0(P) := \{x_0 \in R \mid P(x_0) = 0\} \quad (3.30)$$

The roots of a polynomial are of special interest with respect to its prime factorization, since it can be shown that for any given root x_0 of P the polynomial $F(x) = (x - x_0)$ is a prime factor of P .

Finding the roots of a polynomial is sometimes called **solving the polynomial**. It is a hard problem and has been the subject of much research throughout history.

It can be shown that if m is the degree of a polynomial P , then P can not have more than m roots. However, in general, polynomials can have less than m roots.

Example 25. Consider the integer polynomial $P_7(x) = x^3 - 4x^2 - 11x + 30$ from example 16 again. We know that its set of roots is given by $R_0(P_7) = \{-3, 2, 5\}$.

On the other hand, we know from example 24 that the integer polynomial $x^2 - 3$ is irreducible. It follows that it has no roots, since every root defines a prime factor.

Example 26. To give another example, consider the integer polynomial $P = x^7 + 3x^6 + 3x^5 + x^4 - x^3 - 3x^2 - 3x - 1$. We can invoke Sage to compute the roots and prime factors of P :

```

1281 sage: Zx = ZZ['x']
1282 sage: p = Zx(x^7 + 3*x^6 + 3*x^5 + x^4 - x^3 - 3*x^2 - 3*x - 1)
1283
1284 sage: p.roots()
1285 [(1, 1), (-1, 4)]
1286 sage: p.factor()
1287 (x - 1) * (x + 1)^4 * (x^2 + 1)

```

We see that P has the root 1 and that the associated prime factor $(x - 1)$ occurs once in P and that it has the root -1 , where the associated prime factor $(x + 1)$ occurs 4 times in P . This gives the following prime factorization:

$$P = (x - 1)(x + 1)^4(x^2 + 1)$$

Exercise 28. Show that if a polynomial $P \in R[x]$ of degree $\deg(P) = m$ has less than m roots, it must have a prime factor F of degree $\deg(F) > 1$.

Exercise 29. Consider the polynomial $P = x^7 + 3x^6 + 3x^5 + x^4 - x^3 - 3x^2 - 3x - 1 \in \mathbb{Z}_6[x]$. Compute the set of all roots of $R_0(P)$ and then compute the prime factorization of P .

Lagrange interpolation One particularly useful property of polynomials is that a polynomial of degree m is completely determined on $m + 1$ evaluation points, which implies that we can uniquely derive a polynomial of degree m from a set S :

$$S = \{(x_0, y_0), (x_1, y_1), \dots, (x_m, y_m) \mid x_i \neq x_j \text{ for all indices } i \text{ and } j\} \quad (3.31)$$

1295 Polynomials therefore have the property that $m + 1$ pairs of points (x_i, y_i) for $x_i \neq x_j$ are enough
 1296 to determine the set of pairs $(x, P(x))$ for all $x \in R$. This “few too many” property of polynomials
 1297 is used in many places, like for example in erasure codes. It is also of importance in snarks and
 1298 we therefore need to understand a method to actually compute a polynomial from a set of points.

1299 If the coefficients of the polynomial we want to find have a notion of multiplicative inverse,
 1300 it is always possible to find such a polynomial using a method called **Lagrange interpolation**,
 1301 which works as follows: Given a set like 3.31, a polynomial P of degree m with $P(x_i) = y_i$ for
 1302 all pairs (x_i, y_i) from S is given by the following algorithm:

check
algorithm
floating

Algorithm 4 Lagrange Interpolation

Require: R must have multiplicative inverses

Require: $S = \{(x_0, y_0), (x_1, y_1), \dots, (x_m, y_m) \mid x_i, y_i \in R, x_i \neq x_j \text{ for all indices } i \text{ and } j\}$

procedure LAGRANGE-INTERPOLATION(S)

for $j \in (0 \dots m)$ **do**

$$l_j(x) \leftarrow \prod_{i=0; i \neq j}^m \frac{x - x_i}{x_j - x_i} = \frac{(x - x_0)}{(x_j - x_0)} \dots \frac{(x - x_{j-1})}{(x_j - x_{j-1})} \frac{(x - x_{j+1})}{(x_j - x_{j+1})} \dots \frac{(x - x_m)}{(x_j - x_m)}$$

end for

$$P \leftarrow \sum_{j=0}^m y_j \cdot l_j$$

return P

end procedure

Ensure: $P \in R[x]$ with $\deg(P) = m$

Ensure: $P(x_j) = y_j$ for all pairs $(x_j, y_j) \in S$

Example 27. Let us consider the set $S = \{(0, 4), (-2, 1), (2, 3)\}$. Our task is to compute a polynomial of degree 2 in $\mathbb{Q}[x]$ with coefficients from the rational numbers \mathbb{Q} . Since \mathbb{Q} has multiplicative inverses, we can use the Lagrange interpolation algorithm from 4, to compute the polynomial.

$$\begin{aligned} l_0(x) &= \frac{x - x_1}{x_0 - x_1} \cdot \frac{x - x_2}{x_0 - x_2} = \frac{x + 2}{0 + 2} \cdot \frac{x - 2}{0 - 2} = -\frac{(x + 2)(x - 2)}{4} \\ &= -\frac{1}{4}(x^2 - 4) \\ l_1(x) &= \frac{x - x_0}{x_1 - x_0} \cdot \frac{x - x_2}{x_1 - x_2} = \frac{x - 0}{-2 - 0} \cdot \frac{x - 2}{-2 - 2} = \frac{x(x - 2)}{8} \\ &= \frac{1}{8}(x^2 - 2x) \\ l_2(x) &= \frac{x - x_0}{x_2 - x_0} \cdot \frac{x - x_1}{x_2 - x_1} = \frac{x - 0}{2 - 0} \cdot \frac{x + 2}{2 + 2} = \frac{x(x + 2)}{8} \\ &= \frac{1}{8}(x^2 + 2x) \\ P(x) &= 4 \cdot \left(-\frac{1}{4}(x^2 - 4)\right) + 1 \cdot \frac{1}{8}(x^2 - 2x) + 3 \cdot \frac{1}{8}(x^2 + 2x) \\ &= -x^2 + 4 + \frac{1}{8}x^2 - \frac{1}{4}x + \frac{3}{8}x^2 + \frac{3}{4}x \\ &= -\frac{1}{2}x^2 + \frac{1}{2}x + 4 \end{aligned}$$

1303 And, indeed, evaluation of P on the x -values of S gives the correct points, since $P(0) = 4$,
 1304 $P(-2) = 1$ and $P(2) = 3$. Sage provides the following function:

```

1305 sage: Qx = QQ['x'] 150
1306 sage: S=[(0,4),(-2,1),(2,3)] 151
1307 sage: Qx.lagrange_polynomial(S) 152
1308 -1/2*x^2 + 1/2*x + 4 153

```

Example 28. To give another example more relevant to the topics of this book, let us consider the same set $S = \{(0,4), (-2,1), (2,3)\}$ as in the previous example. This time, the task is to compute a polynomial $P \in \mathbb{Z}_5[x]$ from this data. Since we know from example 14 that multiplicative inverses exist in \mathbb{Z}_5 , algorithm 4 applies and we can compute a unique polynomial of degree 2 in $\mathbb{Z}_5[x]$ from S . We can use the lookup tables from example 14 for computation in \mathbb{Z}_5 and get the following:

$$\begin{aligned}
l_0(x) &= \frac{x-x_1}{x_0-x_1} \cdot \frac{x-x_2}{x_0-x_2} = \frac{x+2}{0+2} \cdot \frac{x-2}{0-2} = \frac{(x+2)(x-2)}{-4} = \frac{(x+2)(x+3)}{1} \\
&= x^2 + 1 \\
l_1(x) &= \frac{x-x_0}{x_1-x_0} \cdot \frac{x-x_2}{x_1-x_2} = \frac{x-0}{-2-0} \cdot \frac{x-2}{-2-2} = \frac{x}{-2} \cdot \frac{x+3}{1} = 2(x^2 + 3x) \\
&= 2x^2 + x \\
l_2(x) &= \frac{x-x_0}{x_2-x_0} \cdot \frac{x-x_1}{x_2-x_1} = \frac{x-0}{2-0} \cdot \frac{x+2}{2+2} = \frac{x(x+2)}{3} = 2(x^2 + 2x) \\
&= 2x^2 + 4x \\
P(x) &= 4 \cdot (x^2 + 1) + 1 \cdot (2x^2 + x) + 3 \cdot (2x^2 + 4x) \\
&= 4x^2 + 4 + 2x^2 + x + x^2 + 2x \\
&= 2x^2 + 3x + 4
\end{aligned}$$

1309 And, indeed, evaluation of P on the x -values of S gives the correct points, since $P(0) = 4$,
1310 $P(-2) = 1$ and $P(2) = 3$. We can doublecheck our findings using Sage:

```

1311 sage: F5 = GF(5) 154
1312 sage: F5x = F5['x'] 155
1313 sage: S=[(0,4),(-2,1),(2,3)] 156
1314 sage: F5x.lagrange_polynomial(S) 157
1315 2*x^2 + 3*x + 4 158

```

1316 *Exercise 30.* Consider modular 5 arithmetic from example 14 and the set $S = \{(0,0), (1,1), (2,2), (3,2)\}$.
1317 Find a polynomial $P \in \mathbb{Z}_5[x]$ such that $P(x_i) = y_i$ for all $(x_i, y_i) \in S$.

1318 *Exercise 31.* Consider the set S from the previous example. Why is it not possible to apply
1319 algorithm 4 to construct a polynomial $P \in \mathbb{Z}_6[x]$, such that $P(x_i) = y_i$ for all $(x_i, y_i) \in S$?

Chapter 4

Algebra

In the previous chapter, we gave an introduction to the basic computational tools needed for a pen-and-paper approach to SNARKs and in this chapter we provide a more abstract clarification of relevant mathematical terminology such as **groups**, **rings** and **fields**.

Scientific literature on cryptography frequently contain such terms, and it is necessary to get at least some understanding of these terms to be able to follow the literature.

4.1 Commutative Groups

Commutative groups are abstractions that capture the essence of mathematical phenomena, like addition and subtraction, or multiplication and division.

To understand commutative groups, let us think back to when we learned about the addition and subtraction of integers in school. We have learned that, whenever we add two integers, the result is guaranteed to be an integer as well. We have also learned that adding zero to any integer means that “nothing happens”, that is, the result of the addition is the same integer we started with. Furthermore, we have learned that the order in which we add two (or more) integers does not matter, that brackets have no influence on the result of addition, and that, for every integer, there is always another integer (the negative) such that we get zero when we add them together.

These conditions are the defining properties of a commutative group, and mathematicians have realized that the exact same set of rules can be found in very different mathematical structures. It therefore makes sense to abstract from integers and to give a formal definition of what a group should be, detached from any concrete examples. This lets us handle entities of very different mathematical origins in a flexible way, while retaining essential structural aspects of many objects in abstract algebra and beyond.

Distilling these rules to the smallest independent list of properties and making them abstract, we arrive at the following definition of a commutative group:

Sylvia: I would like to have a separate counter for definitions

Definition 4.1.0.1. A **commutative group** (\mathbb{G}, \cdot) is a set \mathbb{G} , together with a **map** $\cdot : \mathbb{G} \times \mathbb{G} \rightarrow \mathbb{G}$ called the **group law**, that combines two elements of the set \mathbb{G} into a third one such that the following properties hold:

- **Commutativity:** For all $g_1, g_2 \in \mathbb{G}$, the equation $g_1 \cdot g_2 = g_2 \cdot g_1$ holds.
- **Associativity:** For every $g_1, g_2, g_3 \in \mathbb{G}$ the equation $g_1 \cdot (g_2 \cdot g_3) = (g_1 \cdot g_2) \cdot g_3$ holds.
- **Existence of a neutral element:** There is a $e \in \mathbb{G}$ for all $g \in \mathbb{G}$, such that $e \cdot g = g$.

Sylvia: I would like to have a separate counter for definitions

• **Existence of an inverse:** For every $g \in \mathbb{G}$ there is a $g^{-1} \in \mathbb{G}$, such that $g \cdot g^{-1} = e$.

If (\mathbb{G}, \cdot) is a group and $\mathbb{G}' \subset \mathbb{G}$ is a subset of \mathbb{G} , such that the restriction of the group law $\cdot : \mathbb{G}' \times \mathbb{G}' \rightarrow \mathbb{G}'$ is a group law on \mathbb{G}' , then (\mathbb{G}', \cdot) is called a **subgroup** of (\mathbb{G}, \cdot) .

Rephrasing the abstract definition in layman's terms, a group is something where we can do computations in a way that resembles the behavior of the addition of integers. Specifically, this means we can combine some element with another element into a new element in a way that is reversible and where the order of combining elements doesn't matter.

Notation and Symbols 3. Since we are exclusively concerned with commutative groups in this book, we often just call them groups, keeping the notation of commutativity implicit. Commutative groups are also called **Abelian groups**. A set \mathbb{G} with a map \cdot that satisfies all previously mentioned rules, except for the commutativity law is called a non-commutative group.

If there is no risk of ambiguity (about what the group law of that group is), we frequently drop the symbol \cdot and simply write \mathbb{G} as notation for the group, keeping the group law implicit. In this case we also say that \mathbb{G} is of group type, indicating that \mathbb{G} is not simply a set but a set together with a group law.

For commutative groups (\mathbb{G}, \cdot) , we sometimes use the so-called **additive notation** $(\mathbb{G}, +)$, that is, we write $+$ instead of \cdot for the group law, 0 for the neutral element and $-g := g^{-1}$ for the inverse of an element $g \in \mathbb{G}$.

As we will see in the following chapters, groups are heavily used in cryptography and in SNARKs. But let us look at some more familiar examples first:

Example 29 (Integer Addition and Subtraction). The set $(\mathbb{Z}, +)$ of integers with integer addition is the archetypical example of a commutative group, where the group law is traditionally written in additive notation 3.

To compare integer addition against the abstract axioms of a commutative group, we first see that integer addition is commutative and associative, since $a + b = b + a$ as well as $(a + b) + c = a + (b + c)$ for all integers $a, b, c \in \mathbb{Z}$. The neutral element e is the number 0 , since $a + 0 = a$ for all integers $a \in \mathbb{Z}$. Furthermore, the inverse of a number is its negative counterpart, since $a + (-a) = 0$, for all $a \in \mathbb{Z}$. This implies that integers with addition are indeed a commutative group in the abstract sense.

To give an example of a subgroup for the group of integers, consider the set $\mathbb{Z}_{\text{even}} := \{\dots, -4, -2, 0, 2, 4, \dots\}$ of even numbers, including 0 . We can see that this set is a subgroup of $(\mathbb{Z}, +)$, since the sum of two even numbers is always an even number again, since the neutral element 0 is a member of \mathbb{Z}_{even} and since the negative of an even number is itself an even number.

Example 30 (The trivial group). The most basic example of a commutative group is the group with just one element $\{\bullet\}$ and the group law $\bullet \cdot \bullet = \bullet$. We call it the **trivial group**.

The trivial group is a subgroup of any group. To see that let (\mathbb{G}, \cdot) be a group with neutral element $e \in \mathbb{G}$. Then $e \cdot e = e$ as well as $e^{-1} = e$ and it follows that the set $\{e\}$ is a subgroup of \mathbb{G} . In particular $\{0\}$ is a subgroup of $(\mathbb{Z}, +)$, since $0 + 0 = 0$.

Example 31. Consider the addition in modulo 6 arithmetics $(\mathbb{Z}_6, +)$ as defined in in example 9. As we see, the remainder 0 is the neutral element in modulo 6 addition and the inverse of a remainder r is given by $6 - r$, because $r + (6 - r) = 6$, which is congruent to 0 , since $6 \bmod 6 = 0$. Moreover, $r_1 + r_2 = r_2 + r_1$ as well as $(r_1 + r_2) + r_3 = r_1 + (r_2 + r_3)$ are inherited from integer addition. We therefore see that $(\mathbb{Z}_6, +)$ is a group.

The previous example of a commutative group is a very important one for this book. Abstracting from this example and considering residue classes $(\mathbb{Z}_n, +)$ for arbitrary moduli n , it can be shown that $(\mathbb{Z}_n, +)$ is a commutative group with the neutral element 0 and the additive

inverse $n - r$ for any element $r \in \mathbb{Z}_n$. We call such a group the **remainder class group** of modulus n .

Exercise 32. Consider example 14 again and let \mathbb{Z}_5^* be the set of all remainder classes from \mathbb{Z}_5 without the class 0. Then $\mathbb{Z}_5^* = \{1, 2, 3, 4\}$. Show that (\mathbb{Z}_5^*, \cdot) is a commutative group.

Exercise 33. Generalizing the previous exercise, consider the general modulus n , and let \mathbb{Z}_n^* be the set of all remainder classes from \mathbb{Z}_n without the class 0. Then $\mathbb{Z}_n^* = \{1, 2, \dots, n - 1\}$. Provide a counter-example to show that (\mathbb{Z}_n^*, \cdot) is not a group in general.

Find a condition such that (\mathbb{Z}_n^*, \cdot) is a commutative group, compute the neutral element, give a closed form for the inverse of any element and prove the commutative group axioms.

Finite groups As we have seen in the previous examples, groups can either contain infinitely many elements (such as integers) or finitely many elements (as for example the remainder class groups $(\mathbb{Z}_n, +)$). To capture this distinction, a group is called a **finite group** if the underlying set of elements is finite. In that case, the number of elements of that group is called its **order**.

Notation and Symbols 4. Let \mathbb{G} be a finite group. We write $\text{ord}(\mathbb{G})$ or $|\mathbb{G}|$ for the order of \mathbb{G} .

Example 32. Consider the remainder class groups $(\mathbb{Z}_6, +)$ from example 9, the group $(\mathbb{Z}_5, +)$ from example 14, and the group (\mathbb{Z}_5^*, \cdot) from exercise 32. We can easily see that the order of $(\mathbb{Z}_6, +)$ is 6, the order of $(\mathbb{Z}_5, +)$ is 5 and the order of (\mathbb{Z}_5^*, \cdot) is 4.

Exercise 34. Let $n \in \mathbb{N}$ with $n \geq 2$ be some modulus. What is the order of the remainder class group $(\mathbb{Z}_n, +)$.

Generators The set of elements of a group can be complicated and it is not always obvious how to actually compute elements of a given group. From a practical point of view it is therefore desirable, if a group has a small subset of elements, such that all other elements can be generated by applying the group law repeatedly to the elements of that subset or their inverses only. Sets with these properties are called **generator sets**.

Of course, every group \mathbb{G} has a trivial set of generators, when we just consider every element of the group to be in the generator set. The more interesting question is to find smallest possible sets of generators for a given group. Of particular interest in this regard are groups that have a generator set that contains a single element only. In this case, there exists a (not necessarily unique) element $g \in \mathbb{G}$ such that every other element from \mathbb{G} can be computed by the repeated combination of g and its inverse g^{-1} only. Groups with single, not necessarily unique, generators are called **cyclic groups** and any element $g \in \mathbb{G}$ that is able to generate \mathbb{G} is called a **generator**.

Example 33. The most basic example of a cyclic group is the group of integers $(\mathbb{Z}, +)$ with integer addition. In this case, the number 1 is a generator of \mathbb{Z} , since every integer can be obtained by repeatedly adding either 1 or its inverse -1 to itself. For example -4 is generated by 1, since $-4 = -1 + (-1) + (-1) + (-1)$. Another generator of \mathbb{Z} is the number -1 .

Example 34. Consider the group (\mathbb{Z}_5^*, \cdot) from exercise 32. Since $2^1 = 2$, $2^2 = 4$, $2^3 = 3$ and $2^4 = 1$, the element 2 is a generator of (\mathbb{Z}_5^*, \cdot) . Moreover since $3^1 = 3$, $3^2 = 4$, $3^3 = 2$ and $3^4 = 1$, the element 3 is another generator of (\mathbb{Z}_5^*, \cdot) . Cyclic groups can therefore have more than one generator. However since $4^1 = 4$, $4^2 = 1$, $4^3 = 4$ and in general $4^k = 4$ for k odd and $4^k = 1$ for k even the element 4 is not a generator of (\mathbb{Z}_5^*, \cdot) . It follows that in general not every element of a finite cyclic group is a generator.

Example 35. Consider a modulus n and the remainder class groups $(\mathbb{Z}_n, +)$ from exercise 34. These groups are cyclic, with generator 1, since every other element of that group can be constructed by repeatedly adding the remainder class 1 to itself. Since \mathbb{Z}_n is also finite, we know that $(\mathbb{Z}_n, +)$ is a finite cyclic group of order n .

Exercise 35. Consider the group $(\mathbb{Z}_6, +)$ of modular 6 addition from example 9. Show that $5 \in \mathbb{Z}_6$ is a generator and then show that $2 \in \mathbb{Z}_6$ is not a generator.

Exercise 36. Let $p \in \mathbb{P}$ be prime number and (\mathbb{Z}_p^*, \cdot) the finite group from exercise 33. Show that (\mathbb{Z}_p^*, \cdot) is cyclic.

The exponential map Observe that, when \mathbb{G} is a cyclic group of order n and $g \in \mathbb{G}$ is a generator of \mathbb{G} , then there is the following map with respect to the generator g :

$$g^{(\cdot)} : \mathbb{Z}_n \rightarrow \mathbb{G} \quad x \mapsto g^x \quad (4.1)$$

In the map above, g^x means “multiply g x -times by itself” and $g^0 = e_{\mathbb{G}}$. This map, called the **exponential map**, has the remarkable property that it maps the additive group law of the remainder class group $(\mathbb{Z}_n, +)$ in a one-to-one correspondence to the group law of \mathbb{G} .

To see this, first observe that, since $g^0 := e_{\mathbb{G}}$ by definition, the neutral element of \mathbb{Z}_n is mapped to the neutral element of \mathbb{G} , and, since $g^{x+y} = g^x \cdot g^y$, the map respects the group law.

Remark 3 (Scalar multiplication). If a group $(\mathbb{G}, +)$ is written in additive notation 3, then the exponential map is often called **scalar multiplication** and written as

$$(\cdot) \cdot g : \mathbb{Z}_n \rightarrow \mathbb{G} ; x \mapsto x \cdot g \quad (4.2)$$

In this notation the symbol $x \cdot g$ is defined as “add the generator g x -times to itself” and the symbol $0 \cdot g$ is defined to be the neutral element in \mathbb{G} .

Cryptographic applications often utilize finite cyclic groups of very large order n and computing the exponential map by repeated multiplication of the generator with itself is infeasible, for very large remainder classes. The following so called **square and multiply** algorithm solves this problem as it computes the exponential map in approximately k steps, where k is the bit length of the exponent 3.4:

Because the exponential map respects the group law, it doesn’t matter if we do our computation in \mathbb{Z}_n before we write the result into the exponent of g or afterwards: the result will be the same in both cases. This is usually referred to as doing computations “in the exponent”. In cryptography in general, and in SNARK development in particular, we often perform computations “in the exponent” of a generator.

Example 36. Consider the multiplicative group (\mathbb{Z}_5^*, \cdot) from exercise 32. We know from 36 that \mathbb{Z}_5^* is a cyclic group of order 4, and that the element $3 \in \mathbb{Z}_5^*$ is a generator. We then know that the following map respects the group law of addition in \mathbb{Z}_4 and the group law of multiplication in \mathbb{Z}_5^* :

$$3^{(\cdot)} : \mathbb{Z}_4 \rightarrow \mathbb{Z}_5^* ; x \mapsto 3^x$$

To do an example computation “in the exponent” of 3, let’s perform the calculation $1 + 3 + 2$ in the exponent of the generator 3:

$$\begin{aligned} 3^{1+3+2} &= 3^2 \\ &= 4 \end{aligned}$$

Algorithm 5 Cyclic Group Exponentiation**Require:** g group generator of order n **Require:** $x \in \mathbb{Z}_n$ **procedure** EXPONENTIATION(g, x)Let (b_0, \dots, b_k) be a binary representation of x

▷ see example XXX

 $h \leftarrow g$ $y \leftarrow e_{\mathbb{G}}$ **for** $0 \leq j < k$ **do** **if** $b_j = 1$ **then** $y \leftarrow y \cdot h$

▷ multiply

end if $h \leftarrow h \cdot h$

▷ square

end for**return** y **end procedure****Ensure:** $y = g^x$

1469 What we did is, we first performed the computation $1 + 3 + 2 = 1$ in the remainder class group
 1470 $(\mathbb{Z}_4, +)$ and then applied the exponential map $3^{(\cdot)}$ to the result.

1471 However since the exponential map 4.1 "respects the group law" we also could map each
 1472 summand into (\mathbb{F}_5^*, \cdot) first and then apply the group law of (\mathbb{F}_5^*, \cdot) . The result is guranteed to be
 1473 the same:

$$\begin{aligned} 3^1 \cdot 3^3 \cdot 3^2 &= 3 \cdot 2 \cdot 4 \\ &= 1 \cdot 4 \\ &= 4 \end{aligned}$$

1474 Since the exponential map is a one-to-one correspondence that respects the group law, it
 1475 can be shown that this map has an inverse with respect to the base g , called the **base g discrete**
 1476 **logarithm map**:

$$\log_g(\cdot) : \mathbb{G} \rightarrow \mathbb{Z}_n \quad x \mapsto \log_g(x) \quad (4.3)$$

1477 Discrete logarithms are highly important in cryptography, because there are finite cyclic groups
 1478 where the exponential map and its inverse, the discrete logarithm map, are believed to be one-
 1479 way functions, which informally means that computing the exponential map is fast, while com-
 1480 puting the logarithm map is slow (We will look into a more precise definition in 4.1.1).

Example 37. Consider the exponential map $3^{(\cdot)}$ from example 36. Its inverse is the discrete logarithm to the base 3 and it is given by the map

$$\log_3(\cdot) : \mathbb{Z}_5^* \rightarrow \mathbb{Z}_4 \quad x \mapsto \log_3(x)$$

In contrast to the exponential map $3^{(\cdot)}$, we have no way to actually compute this map, other than by trying all elements of the group until we find the correct one. For example in order to compute $\log_3(4)$, we have to find some $x \in \mathbb{Z}_4$, such that $3^x = 4$ and all we can do is repeatedly insert elements x into the exponent of 3 until the result is 4. To do this let's write down all the images of $3^{(\cdot)}$:

$$3^0 = 1, \quad 3^1 = 3, \quad 3^2 = 4, \quad 3^3 = 2$$

Since the discrete logarithm $\log_3(\cdot)$ is defined as the inverse to this function, we can use those images to compute the discrete logarithm:

$$\log_3(1) = 0, \quad \log_3(2) = 3, \quad \log_3(3) = 1, \quad \log_3(4) = 2$$

Note that this computation was only possible, because we were able to write down all images of the exponential map. However, in real world applications the groups in consideration are too large to write down the images of the exponential map.

Exercise 37 (Efficient Scalar Multiplication). Let $(\mathbb{G}, +)$ be a finite cyclic group of order n . Consider algorithm 5 and define it's analog for groups in additive notation.

Factor Groups As we know from the fundamental theorem of arithmetics 3.7, every natural number n is a product of factors, the most basic of which are prime numbers. This reflects into subgroups of a finite cyclic group in an interesting way: If \mathbb{G} , is a finite cyclic group of order n , then every subgroup \mathbb{G}' of \mathbb{G} , is finite and cyclic and the order of \mathbb{G}' , is a factor of n . Moreover for each factor k of n , \mathbb{G} has exactly one subgroup of order k . This is known as the **fundamental theorem of finite cyclic groups**.

Notation and Symbols 5. If \mathbb{G} is a finite cyclic group of order n and k is a factor of n , then we write $\mathbb{G}[k]$ for the unique finite cyclic group, which is the order k subgroup of \mathbb{G} and call it a **factor group** of \mathbb{G} .

One particular interesting situation occurs if the order of a given finite cyclic group is a prime number. As we know from the fundamental theorem of arithmetics 3.7, prime numbers have only two factors, given by the number 1 and the prime number itself. It then follows from the fundamental theorem of finite cyclic groups 4.1, that those groups have no subgroups other than the trivial group 30 and the group itself.

Cryptographic protocols often assume the existence of finite cyclic groups of prime order but sometimes real world implementations of those protocols are not defined on prime order groups, but on groups where the order consist of a (usually large) prime number that has small cofactors 1. In this case a method called **cofactor clearing** has to be applied to ensure that the computations are not done in the group itself but in its (large) prime order subgroup.

To understand cofactor clearing in detail, let \mathbb{G} be a finite cyclic group of order n and let k be a factor of n with associated factor group $\mathbb{G}[k]$. We can project any element $g \in \mathbb{G}[k]$ onto the neutral element e of \mathbb{G} by multiplying g k -times with itself:

$$g^k = e \tag{4.4}$$

From this follows that if $c := n \div k$ is the cofactor 1 of k in n then any element from the full group $g \in \mathbb{G}$ can be projected into the factor group $\mathbb{G}[k]$ by multiplying g c -times with itself. This defines the following map, which is often called **cofactor clearing** in the cryptographic literature:

$$(\cdot)^c : \mathbb{G} \rightarrow \mathbb{G}[k] : g \mapsto g^c \tag{4.5}$$

Example 38. Consider the finite cyclic group (\mathbb{Z}_5^*, \cdot) from example 34. Since the order of \mathbb{Z}_5^* is 4 and 4 has the factors 1, 2 and 4, it follows from the fundamental theorem of finite cyclic groups, that \mathbb{Z}_5^* has 3 unique subgroups. In fact the unique subgroup $\mathbb{Z}_5^*[1]$ of order 1 is given by the trivial group $\{1\}$ that contains only the multiplicative neutral element 1 and the unique subgroup $\mathbb{Z}_5^*[4]$ of order 4 is \mathbb{Z}_5^* itself, since by definition every group is trivially a subgroup of itself. The unique subgroup $\mathbb{Z}_5^*[2]$ of order 2 is more interesting and is given by the set $\mathbb{Z}_5^*[2] = \{1, 4\}$.

Since \mathbb{Z}_5^* is not a prime order group and since the only prime factor of 4 is 2, the "large" prime order subgroup of \mathbb{Z}_5^* is $\mathbb{Z}_5^*[2]$. Moreover since the cofactor of 2 in 4 is also 2, we have the cofactor clearing map $(\cdot)^2 : \mathbb{Z}_5^* \rightarrow \mathbb{Z}_5^*[2]$ and indeed applying this map to all elements from \mathbb{Z}_5^* we see that it maps onto the elements of $\mathbb{Z}_5^*[2]$ only:

$$1^2 = 1, \quad 2^2 = 4, \quad 3^2 = 4, \quad 4^2 = 1$$

1518 We can therefore use this map to "clear the cofactor" of any element from \mathbb{Z}_5^* which means that
1519 the element is projected into the "large" prime order subgroup $\mathbb{Z}_5^*[2]$.

1520 *Exercise 38.* Consider the previous example 38 and show that $\mathbb{Z}_5^*[2]$ is a commutative group.

1521 *Exercise 39.* Consider the finite cyclic group $(\mathbb{Z}_6, +)$ of modular 6 addition from example 35.
1522 Describe all subgroups of $(\mathbb{Z}_6, +)$. Identify the large prime order subgroup of \mathbb{Z}_6 , define its
1523 cofactor clearing map and apply that map to all elements of \mathbb{Z}_6 .

1524 *Exercise 40.* Let (\mathbb{Z}_p^*, \cdot) be the cyclic group from exercise 36. Show that for $p \geq 5$, not every
1525 element $x \in \mathbb{F}_p^*$ is a generator of \mathbb{F}_p^* .

1526 **Pairings** Of particular importance for the development of SNARKs are so-called pairing maps
1527 on commutative groups. To see the definition, let $\mathbb{G}_1, \mathbb{G}_2$ and \mathbb{G}_3 be three commutative groups.
1528 Then a **pairing map** is a function

$$e(\cdot, \cdot) : \mathbb{G}_1 \times \mathbb{G}_2 \rightarrow \mathbb{G}_3 \quad (4.6)$$

1529 This function takes pairs (g_1, g_2) of elements from \mathbb{G}_1 and \mathbb{G}_2 , and maps them to elements
1530 from \mathbb{G}_3 , such that the **bilinearity** property holds, which means that for all $g_1, g'_1 \in \mathbb{G}_1$ and
1531 $g_2, g'_2 \in \mathbb{G}_2$ the following two identities are satisfied:

$$e(g_1 \cdot g'_1, g_2) = e(g_1, g_2) \cdot e(g'_1, g_2) \quad \text{and} \quad e(g_1, g_2 \cdot g'_2) = e(g_1, g_2) \cdot e(g_1, g'_2) \quad (4.7)$$

1532 Informally speaking, bilinearity means that it doesn't matter if we first execute the group law
1533 on one side and then apply the bilinear map, or if we first apply the bilinear map and then apply
1534 the group law in \mathbb{G}_3 .

1535 A pairing map is called **non-degenerate** if, whenever the result of the pairing is the neutral
1536 element in \mathbb{G}_3 , one of the input values is the neutral element of \mathbb{G}_1 or \mathbb{G}_2 . To be more precise,
1537 $e(g_1, g_2) = e_{\mathbb{G}_3}$ implies $g_1 = e_{\mathbb{G}_1}$ or $g_2 = e_{\mathbb{G}_2}$.

Example 39. One of the most basic examples of a non-degenerate pairing involves $\mathbb{G}_1, \mathbb{G}_2$ and
 \mathbb{G}_3 all to be the group of integers with addition $(\mathbb{Z}, +)$. Then the following map defines a
non-degenerate pairing:

$$e(\cdot, \cdot) : \mathbb{Z} \times \mathbb{Z} \rightarrow \mathbb{Z} \quad (a, b) \mapsto a \cdot b$$

1538 Note that bilinearity follows from the distributive law of integers, since for $a, b, c \in \mathbb{Z}$, we have
1539 $e(a + b, c) = (a + b) \cdot c = a \cdot c + b \cdot c = e(a, c) + e(b, c)$ and the same reasoning is true for the
1540 second argument.

1541 To see that $e(\cdot, \cdot)$ is non-degenerate, assume that $e(a, b) = 0$. Then $a \cdot b = 0$ implies that a or
1542 b must be zero.

1543 *Exercise 41* (Arithmetic laws for pairing maps). Let $\mathbb{G}_1, \mathbb{G}_2$ as well as \mathbb{G}_3 be finite cyclic groups
1544 of the same order n and let $e(\cdot, \cdot) : \mathbb{G}_1 \times \mathbb{G}_2 \rightarrow \mathbb{G}_3$ be a pairing map. Show that for given $g_1 \in \mathbb{G}_1$
1545 and $g_2 \in \mathbb{G}_2$ and all $a, b \in \mathbb{Z}_n$ the following identity holds:

$$e(g_1^a, g_2^b) = e(g_1, g_2)^{a \cdot b} \quad (4.8)$$

Exercise 42. Consider the remainder class groups $(\mathbb{Z}_n, +)$ from example 34 for some modulus n . Show that the map

$$e(\cdot, \cdot) : \mathbb{Z}_n \times \mathbb{Z}_n \rightarrow \mathbb{Z}_n (a, b) \mapsto a \cdot b$$

is a pairing map. Why is the pairing not non-degenerate in general and what condition must be imposed on n , such that the pairing will be non-degenerate?

4.1.1 Cryptographic Groups

In this section, we will look at classes of groups that are believed to satisfy certain **computational hardness assumptions**, namely that it is not feasible to solve a particular problem.

Example 40. To give an example for a well-known computational hardness assumption, consider the problem of factorization, i.e. computing the prime factors of a composite integer. If the prime factors are very large, this is infeasible to do, and is expected to remain infeasible. We assume the problem is **computationally hard** or **infeasible**.

Note that in the example, we say that the problem is infeasible to solve *if the prime factors are large enough*. In the cryptographic standard model we have a security parameter and we say that "there exists a security parameter, such that it is not feasible to compute a solution to the problem". In the following examples, the security parameter roughly correlates with the order of the group in consideration. In this book, we do not include the security parameter in our definitions, since we only aim to provide an intuitive understanding of the cryptographic assumptions, not teach the ability to perform rigorous analysis.

Furthermore, understand that these are *assumptions*. Academics have been looking for efficient prime factorization algorithms for a long time, and they have been getting better and better and computers have become faster and faster - but there always was a higher security parameter for which the problem still was infeasible.

In what follows, we will describe a few problems that are assumed to be infeasible that arise in the context of groups in cryptography. We will refer to them throughout the book.

The discrete logarithm assumption The so-called **discrete logarithm problem (DLP)** is one of the most fundamental assumptions in cryptography. To define it, let \mathbb{G} be a finite cyclic group of order r and let g be a generator of \mathbb{G} . We know from 4.1 that there is an exponential map $g^{(\cdot)} : \mathbb{Z}_r \rightarrow \mathbb{G} ; x \mapsto g^x$ that maps the residue classes from modulo r arithmetic onto the group in a 1 : 1 correspondence. The **discrete logarithm problem** is the task of finding an inverse to this map, that is, to find a solution $x \in \mathbb{Z}_r$ to the following equation for some given $h, g \in \mathbb{G}$:

$$h = g^x \tag{4.9}$$

There are groups in which the DLP is assumed to be infeasible to solve, and there are groups in which it isn't. We call the former group **DL-secure** groups.

Rephrasing the previous definition, it is believed that in DL-secure groups there is a number n (as that corresponds to the security parameter), such that it is infeasible to compute some number x that solves the equation $h = g^x$ for a given h and g , assuming that the order of the group n is large enough.

Example 41 (Public key cryptography). One the most basic examples of an application for DL-secure groups is in public key cryptography, where the parties publicly agree on some pair (\mathbb{G}, g) such that \mathbb{G} is a finite cyclic group of appropriate order n , where \mathbb{G} is believed to be a DL-secure group, and g is a generator of \mathbb{G} .

In this setting, a secret key is some number $sk \in \mathbb{Z}_r$ and the associated public key pk is the group element $pk = g^{sk}$. Since discrete logarithms are assumed to be hard, it is infeasible for an attacker to compute the secret key from the public key, since it is believed to be infeasible to find solutions x to the following equation:

$$pk = g^x \quad (4.10)$$

As the previous example shows, identifying DL-secure groups is an important practical problem. Unfortunately, it is easy to see that it does not make sense to assume the hardness of the discrete logarithm problem in all finite cyclic groups: Counterexamples are common and easy to construct.

The decisional Diffie–Hellman assumption Let \mathbb{G} be a finite cyclic group of order n and let g be a generator of \mathbb{G} . The decisional Diffie–Hellman (DDH) problem is to distinguish (g^a, g^b, g^{ab}) from the triple (g^a, g^b, g^c) for uniformly random values $a, b, c \in \mathbb{Z}_r$. If we assume the DDH problem is infeasible to solve in \mathbb{G} , we call \mathbb{G} a **DDH-secure** group.

DDH-security is a stronger assumption than DL-security 4.1.1, in the sense that if the DDH problem is infeasible, so is the DLP, but not necessarily the other way around.

To see why this is the case, assume that the discrete logarithm assumption does not hold. In that case, given a generator g and a group element h , it is easy to compute some element $x \in \mathbb{Z}_p$ with $h = g^x$. Then the decisional Diffie–Hellman assumption cannot hold, since given some triple (g^a, g^b, z) , one could efficiently decide whether $z = g^{ab}$ is true by first computing the discrete logarithm b of g^b , then computing $g^{ab} = (g^a)^b$ and deciding whether or not $z = g^{ab}$.

On the other hand, the following example shows that there are groups where the discrete logarithm assumption holds but the decisional Diffie–Hellman assumption does not.

Example 42 (Efficiently computable bilinear pairings). Let \mathbb{G} be a DL-secure, finite, cyclic group of order r with generator g and \mathbb{G}_T another group, such that there is an efficiently computable pairing map $e(\cdot, \cdot) : \mathbb{G} \times \mathbb{G} \rightarrow \mathbb{G}_T$ that is bilinear and non degenerate 4.6.

In a setting like this, it is easy to show that solving DDH cannot be infeasible, since given some triple (g^a, g^b, z) , it is possible to efficiently check whether $z = g^{ab}$ by making use of the pairing:

$$e(g^a, g^b) \stackrel{?}{=} e(g, z) \quad (4.11)$$

Since the bilinearity properties of $e(\cdot, \cdot)$ imply $e(g^a, g^b) = e(g, g)^{ab} = e(g, g^{ab})$, and $e(g, y) = e(g, y')$ implies $y = y'$ due to the non-degenerate property, the equality means $z = g^{ab}$.

It follows that the DDH assumption is indeed stronger than the discrete log assumption, and groups with efficient pairings cannot be DDH-secure groups.

The computational Diffie–Hellman assumption Let \mathbb{G} be a finite cyclic group of order n and let g be a generator of \mathbb{G} . The computational Diffie–Hellman assumption stipulates that, given randomly and independently chosen elements $a, b \in \mathbb{Z}_r$, it is not possible to compute g^{ab} if only g, g^a and g^b (but not a and b) are known. If this is the case for \mathbb{G} , we call \mathbb{G} a **CDH-secure** group.

In general, we don't know if CDH-security is a stronger assumption than DL-security, or if both assumptions are equivalent. We know that DL-security is necessary for CDH-security, but the other direction is currently not well understood. In particular, there are no DL-security groups known that are not also CDH-secure

To see why the discrete logarithm assumption is necessary, assume that it does not hold. So, given a generator g and a group element h , it is easy to compute some element $x \in \mathbb{Z}_p$ with $h = g^x$. In that case, the computational Diffie–Hellman assumption cannot hold, since, given g, g^a and g^b , one can efficiently compute b and hence is able to compute $g^{ab} = (g^a)^b$ from this data.

The computational Diffie–Hellman assumption is a weaker assumption than the decisional Diffie–Hellman assumption. This means that there are groups where CDH holds and DDH does not hold, while there cannot be groups in which DDH holds but CDH does not hold. To see that, assume that it is efficiently possible to compute g^{ab} from g, g^a and g^b . Then, given (g^a, g^b, z) it is easy to decide whether $z = g^{ab}$ holds or not.

Several variations and special cases of CDH exist. For example, the **square computational Diffie–Hellman assumption** assumes that, given g and g^x , it is computationally hard to compute g^{x^2} . The **inverse computational Diffie–Hellman assumption** assumes that, given g and g^x , it is computationally hard to compute $g^{x^{-1}}$.

4.1.2 Hashing to Groups

Hash functions Generally speaking, a hash function is any function that can be used to map data of arbitrary size to fixed-size values. Since binary strings of arbitrary length are a way to represent data in general, we can understand a **hash function** as the following map where $\{0, 1\}^*$ represents the set of all binary strings of arbitrary but finite length and $\{0, 1\}^k$ represents the set of all binary strings that have a length of exactly k bits:

$$H : \{0, 1\}^* \rightarrow \{0, 1\}^k \quad (4.12)$$

The **images** of H , that is, the values returned by the hash function H , are called **hash values**, **digests**, or simply **hashes**.

Notation and Symbols 6. In what follows we call an element $b \in \{0, 1\}$ a **bit**. If $s \in \{0, 1\}^*$ is a binary string, we write $|s| = k$ for its **length**, that is for the number of bits in s . We write $\langle \rangle$ for the empty binary string and $s = \langle b_1, b_2, \dots, b_k \rangle$ for a binary string of length k .

If two binary strings $s = \langle b_1, b_2, \dots, b_k \rangle$ and $s' = \langle b'_1, b'_2, \dots, b'_l \rangle$ are given then we write $s||s'$ for the **concatenation** that is the string $s||s' = \langle b_1, b_2, \dots, b_k, b'_1, b'_2, \dots, b'_l \rangle$.

If H is a hash function that maps binary strings of arbitrary length onto binary strings of length k and if $s \in \{0, 1\}^*$ is a binary string, we write $H(s)_j$ for the bit at position j in the image $H(s)$.

Example 43 (k -truncation hash). One of the most basic hash functions $H_k : \{0, 1\}^* \rightarrow \{0, 1\}^k$ is given by simply truncating every binary string s of size $|s| > k$ to a string of size k and by filling any string s' of size $|s'| < k$ with zeros. To make this hash function deterministic, we define that both truncation and filling should happen “on the left”.

For example, if the parameter k is given by $k = 3$ and $s_1 = \langle 0, 0, 0, 0, 1, 0, 1, 0, 1, 1, 1, 0 \rangle$ as well as $s_2 = 1$, then $H_3(s_1) = \langle 1, 1, 0 \rangle$ and $H_3(s_2) = \langle 0, 0, 1 \rangle$.

A desirable property of a hash function is **uniformity**, which means that it should map input values as evenly as possible over its output range. In mathematical terms, every string of length k from $\{0, 1\}^k$ should be generated with roughly the same probability.

Of particular interest are so-called **cryptographic** hash functions, which are hash functions that are also **one-way functions**, which essentially means that, given a string y from $\{0, 1\}^k$ it is infeasible to find a string $x \in \{0, 1\}^*$ such that $H(x) = y$ holds. This property is usually called **preimage-resistance**.

Moreover, if a string $x_1 \in \{0, 1\}^*$ is given, then it should be infeasible to find another string $x_2 \in \{0, 1\}^*$ with $x_1 \neq x_2$ and $H(x_1) = H(x_2)$

In addition, it should be infeasible to find two strings $x_1, x_2 \in \{0, 1\}^*$, such that $H(x_1) = H(x_2)$, which is called **collision resistance**. It is important to note, though, that collisions always exist, since a function $H : \{0, 1\}^* \rightarrow \{0, 1\}^k$ inevitably maps infinitely many values onto the same hash. In fact, for any hash function with digests of length k , finding a preimage to a given digest can always be done using a brute force search in 2^k evaluation steps. It should just be practically impossible to compute those values, and statistically very unlikely to generate two of them by chance.

A third property of a cryptographic hash function is that small changes in the input string, like changing a single bit, should generate hash values that look completely different from each other. This is called **diffusion** or the avalanche effect.

Because cryptographic hash functions map tiny changes in input values onto large changes in the output, implementation errors that change the outcome are usually easy to spot by comparing them to expected output values. The definitions of cryptographic hash functions are therefore usually accompanied by some test vectors of common inputs and expected digests. Since the empty string $<>$ is the only string of length 0, a common test vector is the expected digest of the empty string.

Example 44 (k -truncation hash). Consider the k -truncation hash from example 43. Since the empty string has length 0, it follows that the digest of the empty string is the string of length k that only contains 0's:

$$H_k(<>) = <0, 0, \dots, 0, 0> \quad (4.13)$$

It is pretty obvious from the definition of H_k that this simple hash function is not a cryptographic hash function. In particular, every digest is its own preimage, since $H_k(y) = y$ for every string of size exactly k . Finding preimages is therefore easy, so the property of preimage resistance does not hold.

In addition, it is easy to construct collisions as all strings s of size $|s| > k$ that share the same k -bits “on the right” are mapped to the same hash value, so this function is not collision resistant, either.

Finally, this hash function does not have a lot of diffusion, as changing bits that are not part of the k right-most bits don't change the digest at all.

Computing cryptographically secure hash functions in pen-and-paper style is possible but tedious. Fortunately, Sage can import the **hashlib** library, which is intended to provide a reliable and stable base for writing Python programs that require cryptographic functions. The following examples explain how to use hashlib in Sage.

Example 45. An example of a hash function that is generally believed to be a cryptographically secure hash function is the so-called **SHA256** hash, which, in our notation, is a function that maps binary strings of arbitrary length onto binary strings of length 256:

$$SHA256 : \{0, 1\}^* \rightarrow \{0, 1\}^{256} \quad (4.14)$$

To evaluate a proper implementation of the *SHA256* hash function, the digest of the empty string is supposed to be

$$SHA256(<>) = e3b0c44298fc1c149afb4c8996fb92427ae41e4649b934ca495991b7852b855 \quad (4.15)$$

For better human readability, it is common practice to represent the digest of a string not in its binary form, but in a hexadecimal representation. We can use Sage to compute *SHA256* and

freely transit between binary, hexadecimal and decimal representations. To do so, we import hashlib's implementation of SHA256:

```

1711 sage: import hashlib
1712 sage: test = 'e3b0c44298fc1c149afbf4c8996fb92427ae41e4649b934
1713         ca495991b7852b855'
1714 sage: empty_string = ""
1715 sage: binary_string = empty_string.encode()
1716 sage: hasher = hashlib.sha256(binary_string)
1717 sage: result = hasher.hexdigest()
1718 sage: type(result) # sage represents digests as strings
1719 <class 'str'>
1720 sage: d = ZZ('0x'+ result) # conversion to an integer
1721 sage: d.str(16) == test # hash is equal to test vector
1722 True
1723 sage: d.str(16) # hexadecimal representation
1724 e3b0c44298fc1c149afbf4c8996fb92427ae41e4649b934ca495991b7852b8
1725 55
1726 sage: d.str(2) # binary representation
1727 11100011101100001100010001000010100110001111110000011100000101
1728 0010011010111110111110100110010001001100101101111101110010
1729 01001000010011110101110010000011110010001100100100110111001
1730 00110100110010100100100101011001100100011011011110000101001
1731 01011100001010101
1732 sage: d.str(10) # decimal representation
1733 10298733624955409702953521232258132278979990064819803499337939
1734 7001115665086549

```

Hashing to cyclic groups As we have seen in the previous paragraph, general hash functions map binary strings of arbitrary length onto binary strings of some fixed length. However, it is desirable in various cryptographic primitives to not simply hash to binary strings of fixed length but to hash into algebraic structures like groups, while keeping (some of) the properties like preimage resistance or collision resistance.

Hash functions like this can be defined for various algebraic structures, but, in a sense, the most fundamental ones are hash functions that map into groups, because they can be easily extended to map into other structures like rings or fields.

To give a more precise definition, let \mathbb{G} be a group and $\{0, 1\}^*$ the set of all finite, binary strings, then a **hash-to-group** function is a deterministic map

$$H : \{0, 1\}^* \rightarrow \mathbb{G} \quad (4.16)$$

As the following example shows, hashing to finite cyclic groups can be trivially achieved for the price of some undesirable properties of the hash function:

Example 46 (Naive cyclic group hash). Let \mathbb{G} be a finite cyclic group of order n . If the task is to implement a hash-to-group function, one immediate approach can be based on the observation that binary strings of size k can be interpreted as integers $z \in \mathbb{Z}$ in the range $0 \leq z < 2^k$ using equation 3.4.

1751 To be more precise, let $H : \{0, 1\}^* \rightarrow \{0, 1\}^k$ be a hash function for some parameter k , g a
 1752 generator of \mathbb{G} and $s \in \{0, 1\}^*$ a binary string. Using equation 3.4 and notation 6 the following
 1753 expression is a non negative integer:

$$z_{H(s)} = H(s)_0 \cdot 2^0 + H(s)_1 \cdot 2^1 + \dots + H(s)_k \cdot 2^k \quad (4.17)$$

1754 A hash-to-group function for the group \mathbb{G} can then be defined as a composition of the expo-
 1755 nential map $g^{(\cdot)}$ of g with the interpretation of $H(s)$ as an integer:

$$H_g : \{0, 1\}^* \rightarrow \mathbb{G} : s \mapsto g^{z_{H(s)}} \quad (4.18)$$

1756 Constructing a hash-to-group function like this is easy for cyclic groups, and it might be
 1757 good enough in certain applications. It is, however, almost never adequate in cryptographic
 1758 applications, as a discrete log relation might be constructible between some hash values $H_g(s)$
 1759 and $H_g(t)$, regardless of whether or not \mathbb{G} is DL-secure 4.1.1.

a few ex-
amples?

To be more precise a discrete log relation between the group elements $H_g(s)$ and $H_g(t)$ is
 any element $x \in \mathbb{Z}_n$, such that $H_g(s) = H_g(t)^x$. To see how such an x can be constructed, assume
 that $z_{H(s)}$ has a multiplicative inverse in \mathbb{Z}_n . In this case, the element $x = z_{H(t)} \cdot z_{H(s)}^{-1}$ from \mathbb{Z}_n is
 a discrete log relation between $H_g(s)$ and $H_g(t)$ since:

$$\begin{aligned} g^{z_{H(t)}} &= g^{z_{H(t)}} && \Leftrightarrow \\ g^{z_{H(t)}} &= g^{z_{H(t)} \cdot z_{H(s)} \cdot z_{H(s)}^{-1}} && \Leftrightarrow \\ g^{z_{H(t)}} &= g^{z_{H(s)} \cdot x} && \Leftrightarrow \\ H_g(t) &= (H_g(s))^x \end{aligned}$$

1760 Therefore applications where discrete log relations between hash values are undesirable
 1761 need different approaches. Many of these approaches start with a way to hash into the set \mathbb{Z}_r of
 1762 modular r arithmetics.

1763 **Pedersen Hashes** The so-called **Pedersen hash function** [?] provides a way to map fixed
 1764 size tuples of elements from modular arithmetics onto elements of finite cyclic groups in such
 1765 a way that discrete log relations 46 between different images are avoidable. Compositions of
 1766 a Pedersen hash with a general hash function 4.12, then provide hash-to-group functions that
 1767 maps strings of arbitrary length onto group elements.

1768 To be more precise, let j be an integer, \mathbb{G} a finite cyclic group of order n and $\{g_1, \dots, g_j\} \subset \mathbb{G}$
 1769 a uniform and randomly generated set of generators of \mathbb{G} . Then **Pedersen's hash function** is
 1770 defined as follows:

$$H_{\{g_1, \dots, g_j\}} : (\mathbb{Z}_r)^j \rightarrow \mathbb{G} : (x_1, \dots, x_j) \mapsto \prod_{i=1}^j g_i^{x_i} \quad (4.19)$$

1771 It can be shown that Pedersen's hash function is collision-resistant under the assumption that \mathbb{G}
 1772 is DL-secure 4.1.1. It is important to note though, that the following familie of functions does
 1773 not qualify as a **pseudorandom function family**.

pseudorandom
function
family

$$\{H_{\{g_1, \dots, g_j\}} \mid g_1, \dots, g_j \in \mathbb{G}\} \quad (4.20)$$

1774 From an implementation perspective, it is important to derive the set of generators $\{g_1, \dots, g_k\}$
 1775 in such a way that they are as uniform and random as possible. In particular, any known discrete
 1776 log relation between two generators, that is, any known $x \in \mathbb{Z}_n$ with $g_h = (g_i)^x$ must be avoided.

Example 47. To compute an actual Pedersen's hash, consider the cyclic group \mathbb{Z}_5^* from example 34. We know from example 38, that the elements 2 and 3 are generators of \mathbb{Z}_5^* and it follows that the following map is a Pedersen's hash function:

$$H_{\{2,3\}} : \mathbb{Z}_4 \times \mathbb{Z}_4 \rightarrow \mathbb{Z}_5^* ; (x, y) \mapsto 2^x \cdot 3^y$$

1777 To see how this map can be calculated, we choose the input value $(1, 3)$ from $\mathbb{Z}_4 \times \mathbb{Z}_4$. Then
 1778 $H_{\{2,3\}}(1, 3) = 2^1 \cdot 3^3 = 2 \cdot 2 = 4$.

To see how the composition of a hash function with $H_{\{2,3\}}$ defines a hash-to-group function, consider the *SHA256* hash function from example 45. Given some binary string $s \in \{0, 1\}^*$, we can insert the two least significant bits $SHA256(s)_0$ and $SHA256(s)_1$ from the image $SHA256(s)$ into $H_{\{2,3\}}$ to get an element in \mathbb{F}_5^* . This defines the following hash-to-group function

$$SHA256_H_{\{2,3\}} : \{0, 1\}^* \rightarrow \mathbb{Z}_5^* ; s \mapsto 2^{SHA256(s)_0} \cdot 3^{SHA256(s)_1}$$

1779 To see how this hash function can be calculated, consider the empty string $<>$. Since we know
 1780 from the sage computation in example 45, that $SHA256(<>)_0 = 1$ as well as $SHA256(<>)_1 =$
 1781 0 , we get $SHA_256H_{\{2,3\}}(<>) = 2^1 \cdot 3^0 = 2$.

1782 Of course computing $SHA256_H_{\{2,3\}}$ in a pen and paper style is difficult. However we can
 1783 easily implement this function in sage in the following way:

```

1784 sage: import hashlib                                     176
1785 sage: def SHA256_H(x) :                                  177
1786     ....:     Z5 = Integers(5) # define the group type    178
1787     ....:     hasher = hashlib.sha256(x) # Compute SHA256 179
1788     ....:     digest = hasher.hexdigest()                 180
1789     ....:     z = ZZ(digest, 16) # cast into integer       181
1790     ....:     z_bin = z.digits(base=2, padto=256) # cast to 256 182
1791     bits
1792     ....:     return Z5(2)^z_bin[0] * Z5(3)^z_bin[1]      183
1793 sage: SHA256_H(b'') # evaluate on empty string           184
1794 2                                                         185
1795 sage: SHA256_H(b'SHA') # possible images are {1,2,3}    186
1796 3                                                         187
1797 sage: SHA256_H(b'Math')                                  188
1798 1                                                         189

```

1799 *Exercise 43.* Consider the multiplicative group \mathbb{Z}_{13}^* of modular 13 arithmetic from example 33.
 1800 Choose a set of 3 generators of \mathbb{Z}_{13}^* , define its associated Pedersen hash function and compute
 1801 the Pedersen hash of $(3, 7, 11) \in \mathbb{Z}_{12}$.

1802 *Exercise 44.* Consider the Pedersen hash from exercise 43. Compose it with the *SHA256* hash
 1803 function from example 45 to define a hash-to-group function. Implement that function in sage.

1804 **Pseudorandom Function Families in DDH-secure groups** As noted in 4.1.2, the family of
 1805 Pederson's hash functions, parameterized by a set of generators $\{g_1, \dots, g_j\}$ does not qualify
 1806 as a family of pseudorandom functions and should therefore not be instantiated as such. To
 1807 see an example of a proper family of pseudorandom functions in groups where the decisional
 1808 Diffie–Hellman assumption 4.1.1 is assumed to hold true, let \mathbb{G} be a DDH-secure cyclic group of
 1809 order n with generator g and $\{a_0, a_1, \dots, a_k\} \subset \mathbb{Z}_n^*$ a uniform randomly generated set of numbers

invertible in modular n arithmetics. Then a family of pseudorandom functions, parameterized by the seed $\{a_0, a_1, \dots, a_k\}$ is given as follows:

$$F_{\{a_0, a_1, \dots, a_k\}} : \{0, 1\}^{k+1} \rightarrow \mathbb{G} : (b_0, \dots, b_k) \mapsto g^{b_0 \cdot \prod_{i=1}^k a_i^{b_i}} \quad (4.21)$$

Exercise 45. Consider the multiplicative group \mathbb{Z}_{13}^* of modular 13 arithmetic from example 33 and the parameter $k = 3$. Choose a generator of \mathbb{Z}_{13}^* , a seed and instantiate a member of the familie 4.21 for that seed. Evaluate that member on the binary string $\langle 1, 0, 1 \rangle$.

4.2 Commutative Rings

In the previous section we have seen that integers are a commutative group with respect to integer addition, but as we know there are in fact two arithmetic operations defined on integers: addition and multiplication. However, in contrast to addition, multiplication does not define a group structure, given that integers generally don't have multiplicative inverses. Configurations like these constitute so-called **commutative rings with unit** and the following definition will make the structure explicit:

Definition 4.2.0.1 (Commutative ring with unit). A **commutative ring with unit** $(R, +, \cdot, 1)$ is a set R provided with two maps $+: R \times R \rightarrow R$ and $\cdot: R \times R \rightarrow R$, called **addition** and **multiplication** and an element $1 \in R$, called the **unit**, such that the following conditions hold:

- $(R, +)$ is a commutative group, where the neutral element is denoted with 0.
- **Commutativity of multiplication:** $r_1 \cdot r_2 = r_2 \cdot r_1$ for all $r_1, r_2 \in R$.
- **Multiplicative neutral unit** : $1 \cdot g = g$ for all $g \in R$.
- **Associativity:** For every $g_1, g_2, g_3 \in \mathbb{G}$ the equation $g_1 \cdot (g_2 \cdot g_3) = (g_1 \cdot g_2) \cdot g_3$ holds.
- **Distributivity:** For all $g_1, g_2, g_3 \in R$ the distributive law $g_1 \cdot (g_2 + g_3) = g_1 \cdot g_2 + g_1 \cdot g_3$ holds.

If $(R, +, \cdot, 1)$ is a commutative ring with unit and $R' \subset R$ is a subset of R , such that the restriction of addition and multiplication to R' define a commutative ring with addition $+: R' \times R' \rightarrow R'$, multiplication $\cdot: R' \times R' \rightarrow R'$ and unit 1 on R' , then $(R', +, \cdot, 1)$ is called a **subring** of $(R, +, \cdot, 1)$.

Notation and Symbols 7. Since we are exclusively concerned with commutative rings in this book, we often just call them rings, keeping the notation of commutativity implicit. A set R with two maps $+$ and \cdot that satisfies all previously mentioned rules, except for the commutativity law of the multiplication is called a non-commutative ring.

If there is no risk of ambiguity (about what the addition and multiplication maps of a ring are), we frequently drop the symbols $+$ and \cdot and simply write R as notation for the ring, keeping those maps implicit. In this case we also say that R is of ring type, indicating that R is not simply a set but a set together with an addition and a multiplication map.

Example 48 (The ring of integers). The set \mathbb{Z} of integers with the usual addition and multiplication is the archetypical example of a commutative ring with unit 1.

sage: ZZ
Integer Ring

190

191

1846 *Example 49* (Underlying commutative group of a ring). Every commutative ring with unit
1847 $(R, +, \cdot, 1)$ gives rise to a group, if we disregard multiplication.

1848 The following example is somewhat unusual, but we encourage you to think through it
1849 because it helps to detach the mind from familiar styles of computation and concentrate on the
1850 abstract algebraic explanation.

1851 *Example 50.* Let $S := \{\bullet, \star, \odot, \otimes\}$ be a set that contains four elements, and let addition and
1852 multiplication on S be defined as follows:

	\cup	\bullet	\star	\odot	\otimes		\circ	\bullet	\star	\odot	\otimes
	\bullet	\bullet	\star	\odot	\otimes		\bullet	\bullet	\bullet	\bullet	\bullet
1853	\star	\star	\odot	\otimes	\bullet		\star	\bullet	\star	\odot	\otimes
	\odot	\odot	\otimes	\bullet	\star		\odot	\bullet	\odot	\bullet	\odot
	\otimes	\otimes	\bullet	\star	\odot		\otimes	\bullet	\otimes	\odot	\star

Then (S, \cup, \circ, \star) is a ring with unit \star and zero \bullet . It therefore makes sense to ask for solutions to equations like this one: Find $x \in S$ such that

$$\otimes \circ (x \cup \odot) = \star$$

To see how such a “moonmath equation” can be solved, we have to keep in mind that rings behaves mostly like normal numbers when it comes to bracketing and computation rules. The only differences are the symbols, and the actual way to add and multiply them. With this in mind, we solve the equation for x in the “usual way”¹:

$$\begin{aligned}
 \otimes \circ (x \cup \odot) &= \star && \# \text{ apply the distributive law} \\
 \otimes \circ x \cup \otimes \circ \odot &= \star && \# \otimes \circ \odot = \odot \\
 \otimes \circ x \cup \odot &= \star && \# \text{ concatenate the } \cup \text{ inverse of } \odot \text{ to both sides} \\
 \otimes \circ x \cup \odot \cup -\odot &= \star \cup -\odot && \# \odot \cup -\odot = \bullet \\
 \otimes \circ x \cup \bullet &= \star \cup -\odot && \# \bullet \text{ is the } \cup \text{ neutral element} \\
 \otimes \circ x &= \star \cup -\odot && \# \text{ for } \cup \text{ we have } -\odot = \odot \\
 \otimes \circ x &= \star \cup \odot && \# \star \cup \odot = \otimes \\
 \otimes \circ x &= \otimes && \# \text{ concatenate the } \circ \text{ inverse of } \otimes \text{ to both sides} \\
 (\otimes)^{-1} \circ \otimes \circ x &= (\otimes)^{-1} \circ \otimes && \# \text{ multiply with the multiplicative inverse} \\
 \star \circ x &= \star \\
 x &= \star
 \end{aligned}$$

1854 So, even though this equation looked really alien at first glance, we could solve it basically
1855 exactly the way we solve “normal” equations containing numbers.

1856 Note, however, that whenever a multiplicative inverse would be needed to solve an equation
1857 in the usual way in a ring, things can be very different than most of us are used to. For example,
1858 the following equation cannot be solved for x in the usual way, since there is no multiplicative
1859 inverse for \odot in our ring.

$$\odot \circ x = \otimes \tag{4.22}$$

1860 We can confirm this by looking at the multiplication table to see that no such x exists.

¹Note that there are more efficient ways to solve this equation. The point of our computation is to show how the axioms of a ring can be used to solve the equation

1861 As another example, the following equation does not have a single solution but two: $x \in$
 1862 $\{\star, \otimes\}$.

$$\odot \circ x = \odot \quad (4.23)$$

1863 Having no solution or two solutions is certainly not something to expect from types like the
 1864 rational numbers \mathbb{Q} .

1865 *Example 51* (Ring of Polynomials). Considering the definition of polynomials from 3.4 again,
 1866 we notice that what we have informally called the type R of the coefficients must in fact be a
 1867 commutative ring with a unit, since we need addition, multiplication, commutativity and the
 1868 existence of a unit for $R[x]$ to have the properties we expect.

1869 In fact if we consider R to be a ring and we define addition and multiplication of polyno-
 1870 mials as in 3.24, the set $R[x]$ is a commutative ring with a unit, where the polynomial 1 is the
 1871 multiplicative unit. We call this ring the **ring of polynomials with coefficients in R** .

1872 **sage: ZZ['x']** 192
 1873 **Univariate Polynomial Ring in x over Integer Ring** 193

1874 *Example 52* (Ring of modular n arithmetic). Let n be a modulus and $(\mathbb{Z}_n, +, \cdot)$ the set of all re-
 1875 mainder classes of integers modulo n , with the projection of integer addition and multiplication
 1876 as defined in 3.3. Then $(\mathbb{Z}_n, +, \cdot)$ is a commutative ring with unit 1.

1877 **sage: Integers(6)** 194
 1878 **Ring of integers modulo 6** 195

1879 *Example 53* (Binary Representations in Modular Arithmetic). TODO (Non unique)

1880 *Example 54* (Polynomial evaluation in the exponent of group generators). As we show in 6.2.3,
 1881 a key insights in many zero knowledge protocols is the ability to encode computations as poly-
 1882 nomials and then to hide the information of that computation by evaluating the polynomial "in
 1883 the exponent" of certain cryptographic groups 8.2.

To understand the underlying principle of this idea, consider the exponential map 44 again.
 If \mathbb{G} is a finite cyclic group of order n with generator $g \in \mathbb{G}$, then the ring structure of $(\mathbb{Z}_n, +, \cdot)$
 corresponds to the group structure of \mathbb{G} in the following way:

$$g^{x+y} = g^x \cdot g^y \quad g^{x \cdot y} = (g^x)^y \quad \text{for all } x, y \in \mathbb{Z}_n \quad (4.24)$$

This correspondence allows polynomials with coefficients in \mathbb{Z}_n to be evaluated "in the ex-
 ponent" of a group generator. To see what this means, let $p \in \mathbb{Z}_n[x]$ be a polynomial with
 $p(x) = a_m \cdot x^m + a_{m-1}x^{m-1} + \dots + a_1x + a_0$ and let $s \in \mathbb{Z}_n$ be an evaluation point. Then the
 previously defined exponential laws 4.24 imply the following identity:

$$\begin{aligned} g^{p(s)} &= g^{a_m \cdot s^m + a_{m-1}s^{m-1} + \dots + a_1s + a_0} \\ &= (g^{s^m})^{a_m} \cdot (g^{s^{m-1}})^{a_{m-1}} \cdot \dots \cdot (g^s)^{a_1} \cdot g^{a_0} \end{aligned} \quad (4.25)$$

1884 Utilizing these identities, it is possible to evaluate any polynomial p of degree $\deg(p) \leq m$ at a
 1885 "secret" evaluation point s in the exponent of g without any knowledge about s , assuming that
 1886 \mathbb{G} is a DL-group. To see this assume that the set $\{g, g^s, g^{s^2}, \dots, g^{s^m}\}$ is given, but s is unknown.
 1887 Then $g^{p(s)}$ can be computed using 4.25, however it is not feasible to compute s .

Example 55. To give an example of the evaluation of a polynomial in the exponent of a finite cyclic group, consider the exponential map from example 36:

$$3^{(\cdot)} : \mathbb{Z}_4 \rightarrow \mathbb{Z}_5^* ; x \mapsto 3^x$$

Choosing the polynomial $p(x) = 2x^2 + 3x + 1$ from $\mathbb{Z}_4[x]$, we first evaluate the polynomial at the point $s = 2$ and then write the result into the exponent 3 as follows:

$$\begin{aligned} 3^{p(2)} &= 3^{2 \cdot 2^2 + 3 \cdot 2 + 1} \\ &= 3^{2 \cdot 0 + 2 + 1} \\ &= 3^3 \\ &= 2 \end{aligned}$$

This was possible, because we had access to the evaluation point 2. On the other hand, if we only had access to the set $\{3, 4, 1\}$ and we knew that this set represents the set $\{3, 3^s, 3^{s^2}\}$ for some secret value s , we could evaluate p at the point s in the exponent of 3 as

$$\begin{aligned} 3^{p(s)} &= 1^2 \cdot 4^3 \cdot 3^1 \\ &= 1 \cdot 4 \cdot 3 \\ &= 2 \end{aligned}$$

Both computations agree, since the secret point s was equal to 2 in this example. However the second evaluation was possible without any knowledge about s .

Hashing into Modular Arithmetic As we have seen in 4.1.2, various constructions for hashing-to-groups are known and used in applications. As commutative rings are commutative groups, when we disregard the multiplicative structure, hash-to-group constructions can be applied for hashing into commutative rings.

One of the most widely used applications of hash-into-ring constructions are hash functions that map into the ring \mathbb{Z}_n of modular n arithmetics for some modulus n . Different approaches to construct such a function are known, but probably the most widely used ones are based on the insight that the images of general hash functions can be interpreted as binary representations of integers, as explained in example 46.

It follows from this interpretation that one simple method of hashing into \mathbb{Z}_n is constructed by observing that if n is a modulus with a bit-length 3.4 of $k = |n|$, then every binary string $\langle b_0, b_1, \dots, b_{k-2} \rangle$ of length $k - 1$ defines an integer z in the range $0 \leq z \leq 2^{k-1} - 1 < n$:

$$z = b_0 \cdot 2^0 + b_1 \cdot 2^1 + \dots + b_{k-2} \cdot 2^{k-2} \quad (4.26)$$

Now, since $z < n$, we know that z is guaranteed to be in the set $\{0, 1, \dots, n - 1\}$, and hence it can be interpreted as an element of \mathbb{Z}_n . From this it follows that if $H : \{0, 1\}^* \rightarrow \{0, 1\}^{k-1}$ is a hash function, then a hash-to-ring function can be constructed as follows:

$$H_{|n|_2-1} : \{0, 1\}^* \rightarrow \mathbb{Z}_n : s \mapsto H(s)_0 \cdot 2^0 + H(s)_1 \cdot 2^1 + \dots + H(s)_{k-2} \cdot 2^{k-2} \quad (4.27)$$

A drawback of this hash function is that the distribution of the hash values in \mathbb{Z}_n is not necessarily uniform. In fact, if n is larger than 2^{k-1} , then by design $H_{|n|_2-1}$ will never hash onto values $z \geq 2^{k-1}$. Using this hashing method therefore generates approximately uniform hashes only, if n is very close to 2^{k-1} . In the worst case, when $n = 2^k - 1$, it misses almost half of all elements from \mathbb{Z}_n .

An advantage of this approach is that properties like preimage resistance or collision resistance of the original hash function $H(\cdot)$ are preserved.

Example 56. To analyze a particular implementation of a $H_{|n|_2-1}$ hash function, we use a 5-bit truncation of the *SHA256* hash from example 45 and define a hash into \mathbb{Z}_{16} as follows:

$$H_{|16|_2-5} : \{0, 1\}^* \rightarrow \mathbb{Z}_{16} : s \mapsto \text{SHA256}(s)_0 \cdot 2^0 + \text{SHA256}(s)_1 \cdot 2^1 + \dots + \text{SHA256}(s)_4 \cdot 2^4$$

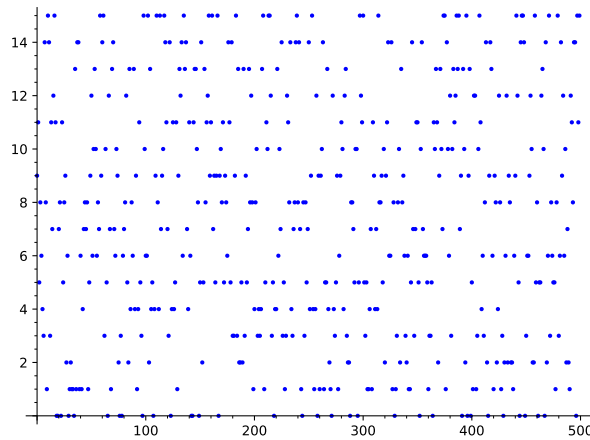
1912 Since $k = |16|_2 = 5$ and $16 - 2^{k-1} = 0$, this hash maps uniformly onto \mathbb{Z}_{16} . We can invoke Sage
1913 to implement it:

```

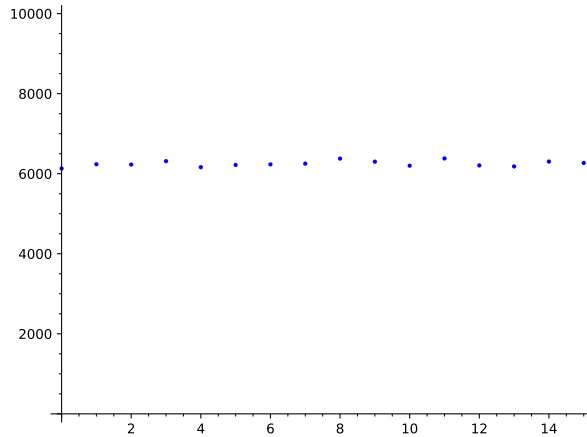
1914 sage: import hashlib                                196
1915 sage: def Hash5(x):                                  197
1916     ....:     Z16 = Integers(16)                     198
1917     ....:     hasher = hashlib.sha256(x) # compute SHA56 199
1918     ....:     digest = hasher.hexdigest()             200
1919     ....:     d = ZZ(digest, base=16) # cast to integer 201
1920     ....:     d = d.str(2)[-4:] # keep 5 least significant bits 202
1921     ....:     d = ZZ(d, base=2) # cast to integer      203
1922     ....:     return Z16(d) # cast to Z16             204
1923 sage: Hash5(b' ')                                     205
1924 5                                                       206

```

1925 We can then use Sage to apply this function to a large set of input values in order to plot a
1926 visualization of the distribution over the set $\{0, \dots, 15\}$. Executing over 500 input values gives
1927 the following plot:

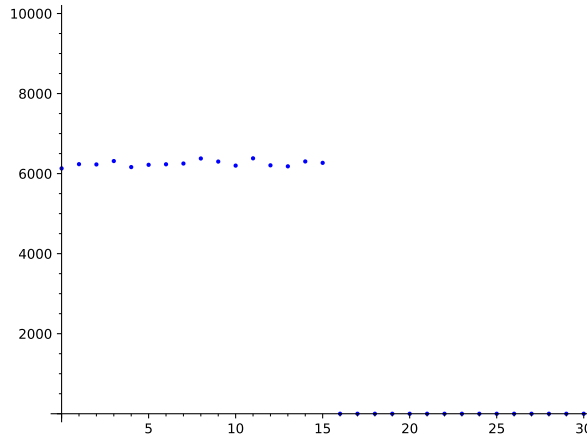


1928
1929 To get an intuition of uniformity, we can count the number of times the hash function $H_{|16|_2-1}$
1930 maps onto each number in the set $\{0, 1, \dots, 15\}$ in a loop of 100000 hashes, and compare that
1931 to the ideal uniform distribution, which would map exactly 6250 samples to each element. This
1932 gives the following result:



1933

1934 The lack of uniformity becomes apparent if we want to construct a similar hash function for \mathbb{Z}_n
 1935 for any other 5 bit integer n in the range $17 \leq n \leq 31$. In this case, the definition of the hash
 1936 function is exactly the same as for \mathbb{Z}_{16} , and hence, the images will not exceed the value 15.
 1937 So, for example, even in the case of hashing to \mathbb{Z}_{31} , the hash function never maps to any value
 1938 larger than 15, leaving almost half of all numbers out of the image range.



1939

1940 A second widely used method of hashing into \mathbb{Z}_n is constructed by observing the following:
 1941 If n is a modulus with a bit-length of $|n|_2 = k_1$ and $H : \{0, 1\}^* \rightarrow \{0, 1\}^{k_2}$ is a hash function that
 1942 produces digests of size k_2 , with $k_2 \geq k_1$, then a hash-to-ring function can be constructed by
 1943 interpreting the image of H as a binary representation of an integer and then taking the modulus
 1944 by n to map into \mathbb{Z}_n .

$$H'_{mod_n} : \{0, 1\}^* \rightarrow \mathbb{Z}_n : s \mapsto \left(H(s)_0 \cdot 2^0 + H(s)_1 \cdot 2^1 + \dots + H(s)_{k_2} \cdot 2^{k_2} \right) \bmod n \quad (4.28)$$

1945

1946 A drawback of this hash function is that computing the modulus requires some computa-
 1947 tional effort. In addition, the distribution of the hash values in \mathbb{Z}_n might not be uniform, depend-
 1948 ing on the number $2^{k_2+1} \bmod n$. An advantage of it is that potential properties of the original
 1949 hash function $H(\cdot)$ (like preimage resistance or collision resistance) are preserved, and the dis-
 1950 tribution can be made almost uniform, with only negligible bias depending on what modulus n
 and images size k_2 are chosen.

Example 57. To give an implementation of the H_{mod_n} hash function, we use k_2 -bit truncation of the SHA256 hash from example 45, and define a hash into \mathbb{Z}_{23} as follows:

$$H_{mod_{23}, k_2} : \{0, 1\}^* \rightarrow \mathbb{Z}_{23} : s \mapsto \left(SHA256(s)_0 \cdot 2^0 + SHA256(s)_1 \cdot 2^1 + \dots + SHA256(s)_{k_2} \cdot 2^{k_2} \right) \bmod 23$$

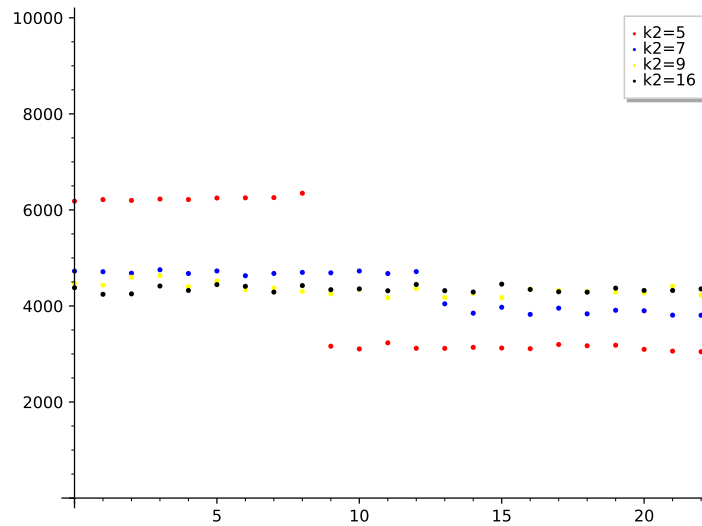
We want to use various instantiations of k_2 to visualize the impact of truncation length on the distribution of the hashes in \mathbb{Z}_{23} . We can invoke Sage to implement it as follows:

```

sage: import hashlib
sage: Z23 = Integers(23)
sage: def Hash_mod23(x, k2):
.....:     hasher = hashlib.sha256(x.encode('utf-8')) # Compute
SHA256
.....:     digest = hasher.hexdigest()
.....:     d = ZZ(digest, base=16) # cast to integer
.....:     d = d.str(2)[-k2:] # keep k2+1 LSB
.....:     d = ZZ(d, base=2) # cast to integer
.....:     return Z23(d) # cast to Z23

```

We can then use Sage to apply this function to a large set of input values in order to plot visualizations of the distribution over the set $\{0, \dots, 22\}$ for various values of k_2 , by counting the number of times it maps onto each number in a loop of 100000 hashes. We get the following plot:



A third method that can sometimes be found in implementations is the so-called “**try-and-increment**” method. To understand this method, we define an integer $z \in \mathbb{Z}$ from any hash value $H(s)$ as we did in the previous methods, that is, we define

$$z = H(s)_0 \cdot 2^0 + H(s)_1 \cdot 2^1 + \dots + H(s)_{k-1} \cdot 2^k$$

Hashing into \mathbb{Z}_n is then achievable by first computing z , and then trying to see if $z \in \mathbb{Z}_n$. If it is, then the hash is done; if not, the string s is modified in a deterministic way and the process is repeated until a suitable element $z \in \mathbb{Z}_n$ is found. A suitable, deterministic modification could be to concatenate the original string by some bit counter. A “try-and-increment” algorithm would then work like in algorithm 6.

Depending on the parameters, this method can be very efficient. In fact, if k is sufficiently large and n is close to 2^{k+1} , the probability for $z < n$ is very high and the repeat loop will almost always be executed a single time only. A drawback is, however, that the probability of having to execute the loop multiple times is not zero.

Algorithm 6 Hash-to- \mathbb{Z}_n **Require:** $n \in \mathbb{Z}$ with $|n|_2 = k$ and $s \in \{0, 1\}^*$ **procedure** TRY-AND-INCREMENT(n, k, s) $c \leftarrow 0$ **repeat** $s' \leftarrow s || c_bits()$ $z \leftarrow H(s')_0 \cdot 2^0 + H(s')_1 \cdot 2^1 + \dots + H(s')_k \cdot 2^k$ $c \leftarrow c + 1$ **until** $z < n$ **return** x **end procedure****Ensure:** $z \in \mathbb{Z}_n$

4.3 Fields

We started this chapter with the definition of a group 4.1, which we then expanded into the definition of a commutative ring with a unit 4.2. Such rings generalize the behavior of integers. In this section, we will look at those special cases of commutative rings where every element other than the neutral element of addition has a multiplicative inverse. Those structures behave very much like the rational numbers \mathbb{Q} . Rational numbers are, in a sense, an extension of the ring of integers, that is, they are constructed by including newly defined multiplicative inverses (fractions) to the integers. The following definition makes the definition of a field precise:

Definition 4.3.0.1 (Field). A **field** $(\mathbb{F}, +, \cdot)$ is a set \mathbb{F} provided with two maps $+: \mathbb{F} \times \mathbb{F} \rightarrow \mathbb{F}$ and $\cdot: \mathbb{F} \times \mathbb{F} \rightarrow \mathbb{F}$, called **addition** and **multiplication**, such that the following conditions hold:

- $(\mathbb{F}, +)$ is a commutative group, where the neutral element is denoted by 0.
- $(\mathbb{F} \setminus \{0\}, \cdot)$ is a commutative group, where the neutral element is denoted by 1.
- (Distributivity) The equation $g_1 \cdot (g_2 + g_3) = g_1 \cdot g_2 + g_1 \cdot g_3$ holds for all $g_1, g_2, g_3 \in \mathbb{F}$.

If $(\mathbb{F}, +, \cdot)$ is a field and $\mathbb{F}' \subset \mathbb{F}$ is a subset of \mathbb{F} , such that the restriction of addition and multiplication to \mathbb{F}' define a field with addition $+: \mathbb{F}' \times \mathbb{F}' \rightarrow \mathbb{F}'$ and multiplication $\cdot: \mathbb{F}' \times \mathbb{F}' \rightarrow \mathbb{F}'$ on \mathbb{F}' , then $(\mathbb{F}', +, \cdot)$ is called a **subfield** of $(\mathbb{F}, +, \cdot)$ and $(\mathbb{F}, +, \cdot)$ is called an **extension field** of $(\mathbb{F}', +, \cdot)$.

Notation and Symbols 8. If there is no risk of ambiguity (about what the addition and multiplication maps of a field are), we frequently drop the symbols $+$ and \cdot and simply write \mathbb{F} as notation for the field, keeping those maps implicit. In this case we also say that \mathbb{F} is of field type, indicating that \mathbb{F} is not simply a set but a set together with an addition and a multiplication map that satisfy the field axioms 4.3.0.1.

We call $(\mathbb{F}, +)$ the **additive group** of the field, write $\mathbb{F}^* := \mathbb{F} \setminus \{0\}$ for the set of all elements excluding the neutral element of addition and call the group (\mathbb{F}^*, \cdot) the **multiplicative group** of the field.

The **characteristic** of a field \mathbb{F} , represented as $\text{char}(\mathbb{F})$, is the smallest natural number $n \geq 1$ for which the n -fold sum of the multiplicative neutral element 1 equals zero, i.e. for which $\sum_{i=1}^n 1 = 0$. If such an $n > 0$ exists, the field is also said to have a **finite characteristic**. If, on the other hand, every finite sum of 1 is such that it is not equal to zero, then the field is defined to have characteristic 0.

S: Tried to disambiguate the scope of negation between 1. “It is true of

Check
change of
wording

every finite sum of 1 that it is not equal to 0” and 2. “It is not true of every finite sum of 1 that it is equal to 0” From the example below, it looks like 1. is the intended meaning here, correct?

Example 58 (Field of rational numbers). Probably the best known example of a field is the set of rational numbers \mathbb{Q} together with the usual definition of addition, subtraction, multiplication and division. Since there is no natural number $n \in \mathbb{N}$, such that $\sum_{j=0}^n 1 = 0$ in the set of rational numbers, the characteristic of the field \mathbb{Q} is given by $\text{char}(\mathbb{Q}) = 0$.

sage: QQ

216

Rational Field

217

Example 59 (Field with two elements). It can be shown that, in any field, the neutral element of addition 0 must be different from the neutral element of multiplication 1, that is, $0 \neq 1$ always holds in a field. From this, it follows that the smallest field must contain at least two elements. As the following addition and multiplication tables show, there is indeed a field with two elements, which is usually called \mathbb{F}_2 :

Let $\mathbb{F}_2 := \{0, 1\}$ be a set that contains two elements and let addition and multiplication on \mathbb{F}_2 be defined as follows:

$$\begin{array}{c|cc} + & 0 & 1 \\ \hline 0 & 0 & 1 \\ 1 & 1 & 0 \end{array} \quad \begin{array}{c|cc} \cdot & 0 & 1 \\ \hline 0 & 0 & 0 \\ 1 & 0 & 1 \end{array}$$

Since $1 + 1 = 0$ in the field \mathbb{F}_2 , we know that the characteristic of \mathbb{F}_2 given by $\text{char}(\mathbb{F}_2) = 2$ and the multiplicative subgroup \mathbb{F}_2^* of \mathbb{F}_2 is given by the trivial group $\{1\}$.

sage: F2 = GF(2)

218

sage: F2(1) # Get an element from GF(2)

219

1

220

sage: F2(1) + F2(1) # Addition

221

0

222

sage: F2(1) / F2(1) # Division

223

1

224

Exercise 46. Consider the ring of modular 5 arithmetics $(\mathbb{Z}_5, +, \cdot)$ from example 14. Show that $(\mathbb{Z}_5, +, \cdot)$ is a field. What is the characteristic of \mathbb{Z}_5 ? Proof that the equation $a \cdot x = b$ has only a single solution $x \in \mathbb{Z}_5$ for any given $a, b \in \mathbb{Z}_5^*$.

Exercise 47. Consider the ring of modular 6 arithmetics $(\mathbb{Z}_6, +, \cdot)$ from example 9. Show that $(\mathbb{Z}_6, +, \cdot)$ is not a field.

4.3.1 Prime fields

As we have seen in the various examples of the previous sections, modular arithmetics behaves similarly to the ordinary arithmetics of integers in many ways. This is due to the fact that remainder class sets \mathbb{Z}_n are commutative rings with units 52.

However, we have also seen in 36 that, whenever the modulus is a prime number, every remainder class other than the zero class has a modular multiplicative inverse. This is an important observation, since it immediately implies that, in case the modulus is a prime number, the remainder class set \mathbb{Z}_n is not just a ring but actually a **field**. Moreover, since $\sum_{j=0}^n 1 = 0$ in \mathbb{Z}_n , we know that those fields have the finite characteristic n .

Notation and Symbols 9 (Prime Fields). Let $p \in \mathbb{P}$ be a prime number and $(\mathbb{Z}_p, +, \cdot)$ the ring of modular p arithmetics 52. To distinguish prime fields from arbitrary modular arithmetic rings, we write $(\mathbb{F}_p, +, \cdot)$ for the ring of modular p arithmetics and call it the **prime field** of characteristic p .

Prime fields are the foundation for many of the contemporary algebra-based cryptographic systems, as they have some desirable properties. One of them is that any prime field of characteristic p contain exactly p elements which can be represented on a computer with not more than $\log_2(p)$ many bits. On the other hand fields like the rational numbers, require a potentially unbounded amount of bits for any full-precision representation.

Since prime fields are special cases of modular arithmetic rings, addition and multiplication can be computed by first doing normal integer addition and multiplication, and then considering the remainder in Eucliden division by p as the result. For any prime field element $x \in \mathbb{F}_p$, its additive inverse (the negative) is given by $-x = p - x \bmod p$. For $x \neq 0$ the multiplicative inverse always exists and is given by $x^{-1} = x^{p-2}$. Division is then defined by multiplication with the multiplicative inverse as explained in 3.3. Alternative the multiplicative inverse can be computed using the Extended Euclidean Algorithm as explained in 3.20.

Example 60. The smallest field is the field \mathbb{F}_2 of characteristic 2 as we have seen in example 59. It is the prime field of the prime number 2.

Example 61. The field \mathbb{F}_5 from example 14 as defined by its addition and multiplication table is a prime field.

Example 62. To summarize the basic aspects of computation in prime fields, let us consider the prime field \mathbb{F}_5 and simplify the following expression:

$$\left(\frac{2}{3} - 2\right) \cdot 2$$

A first thing to note is that since \mathbb{F}_5 is a field, all rules are identical to the rules we learned in school when we where dealing with rational, real or complex numbers. This means we can use e.g. bracketing (distributivity) or addition as usual:

$$\begin{aligned} \left(\frac{2}{3} - 2\right) \cdot 2 &= \frac{2}{3} \cdot 2 - 2 \cdot 2 && \# \text{ distributive law} \\ &= \frac{2 \cdot 2}{3} - 2 \cdot 2 && 4 \bmod 5 = 4 \\ &= \frac{4}{3} - 4 && \# \text{ multiplicative inverse of 3 is } 3^{5-2} \bmod 5 = 2 \\ &= 4 \cdot 2 - 4 && \# \text{ additive inverse of 4 is } 5 - 4 = 1 \\ &= 4 \cdot 2 + 1 && 8 \bmod 5 = 3 \\ &= 3 + 1 && 4 \bmod 5 = 4 \\ &= 4 \end{aligned}$$

In this computation, we computed the multiplicative inverse of 3 using the identity $x^{-1} = x^{p-2}$ in a prime field. This is impractical for large prime numbers. Recall that another way of computing the multiplicative inverse is the Extended Euclidean Algorithm (see 3.11). To refresh our memory, the algorithm solves the equation $x^{-1} \cdot 3 + t \cdot 5 = 1$, for x^{-1} , even though in this case t is irrelevant. We get:

k	r_k	x_k^{-1}	t_k
0	3	1	.
1	5	0	.
2	3	1	.
3	2	-1	.
4	1	2	.

2071

2072 So the multiplicative inverse of 3 in \mathbb{Z}_5 is 2, and, indeed, if we compute the product of 3 with
 2073 its multiplicative inverse 2 we get the neutral element 1 in \mathbb{F}_5 .

2074 *Exercise 48* (Prime field \mathbb{F}_3). Construct the addition and multiplication table of the prime field
 2075 \mathbb{F}_3 .

2076 *Exercise 49* (Prime field \mathbb{F}_{13}). Construct the addition and multiplication table of the prime field
 2077 \mathbb{F}_{13} .

Exercise 50. Consider the prime field \mathbb{F}_{13} from exercise 49. Find the set of all pairs $(x, y) \in \mathbb{F}_{13} \times \mathbb{F}_{13}$ that satisfy the equation

$$x^2 + y^2 = 1 + 7 \cdot x^2 \cdot y^2$$

2078 **Square Roots** As we know from integer arithmetics some integers like 4 or 9 are squares of
 2079 other integers, as for example $4 = 2^2$ and $9 = 3^2$. However we also know that not all integers
 2080 are squares of other integers, as for example there is no integers $x \in \mathbb{Z}$ such that $x^2 = 2$. If an
 2081 integer a is square of another integer b , then it make sense to define the square-root of a to be b .

2082 In the context of prime fields an element that is a square of another element is also called a
 2083 **quadratic residue** and an element that is not a square of another element is called a **quadratic**
 2084 **non-residue**. Those notations are of particular importance in our studies on elliptic curves in
 2085 chapter 5, as only square numbers can actually be points on an elliptic curve.

2086 To make the intuition of quadratic residues and their roots precise, let $p \in \mathbb{P}$ be a prime
 2087 number and \mathbb{F}_p its associated prime field. Then a number $x \in \mathbb{F}_p$ is called a **square root** of
 2088 another number $y \in \mathbb{F}_p$, if x is a solution to the following equation:

$$x^2 = y \tag{4.29}$$

2089 In this case, y is called a **quadratic residue**. On the other hand, if y is given and the quadratic
 2090 equation has no solution x , we call y a **quadratic non-residue**. For any $y \in \mathbb{F}_p$, we denote the
 2091 set of all square roots of y in the prime field \mathbb{F}_p as follows:

$$\sqrt{y} := \{x \in \mathbb{F}_p \mid x^2 = y\} \tag{4.30}$$

2092 Informally speaking, quadratic residues are numbers such that we can take the square root of
 2093 them, while quadratic non-residues are numbers that don't have square roots. The situation
 2094 therefore parallels the familiar case of integers, where some integers like 4 or 9 have square
 2095 roots and others like 2 or 3 don't (as integers).

2096 If y is a quadratic non-residue, then $\sqrt{y} = \emptyset$ (an empty set), and if $y = 0$, then $\sqrt{y} = \{0\}$.
 2097 Moreover if $y \neq 0$ is a quadratic residue then it has precisely two roots $\sqrt{y} = \{x, p - x\}$ for
 2098 some $x \in \mathbb{F}_p$. We adopt the convention to call the smaller one (when interpreted as an integer)
 2099 as the **positive** square root and the larger one as the **negative** square root. If $p \in \mathbb{P}_{\geq 3}$ is an odd
 2100 prime number with associated prime field \mathbb{F}_p , then there are precisely $(p + 1)/2$ many quadratic
 2101 residues and $(p - 1)/2$ quadratic non residues.

Example 63 (Quadratic residues and roots in \mathbb{F}_5). Let us consider the prime field \mathbb{F}_5 again. All square numbers can be found on the main diagonal of the multiplication table in example 14. As you can see, in \mathbb{F}_5 only the numbers 0, 1 and 4 have square roots and we get $\sqrt{0} = \{0\}$, $\sqrt{1} = \{1, 4\}$, $\sqrt{2} = \emptyset$, $\sqrt{3} = \emptyset$ and $\sqrt{4} = \{2, 3\}$. The numbers 0, 1 and 4 are therefore quadratic residues, while the numbers 2 and 3 are quadratic non-residues.

In order to describe whether an element of a prime field is a square number or not, the so-called **Legendre symbol** can sometimes be found in the literature, which is why we will summarize it here:

Let $p \in \mathbb{P}$ be a prime number and $y \in \mathbb{F}_p$ an element from the associated prime field. Then the *Legendre symbol* of y is defined as follows:

$$\left(\frac{y}{p}\right) := \begin{cases} 1 & \text{if } y \text{ has square roots} \\ -1 & \text{if } y \text{ has no square roots} \\ 0 & \text{if } y = 0 \end{cases} \quad (4.31)$$

Example 64. Looking at the quadratic residues and non residues in \mathbb{F}_5 from example 14 again, we can deduce the following Legendre symbols, from example 63.

$$\left(\frac{0}{5}\right) = 0, \quad \left(\frac{1}{5}\right) = 1, \quad \left(\frac{2}{5}\right) = -1, \quad \left(\frac{3}{5}\right) = -1, \quad \left(\frac{4}{5}\right) = 1.$$

The Legendre symbol provides a criterion to decide whether or not an element from a prime field has a quadratic root or not. This, however, is not just of theoretical use: The so-called **Euler criterion** provides a compact way to actually compute the Legendre symbol. To see that, let $p \in \mathbb{P}_{\geq 3}$ be an odd prime number and $y \in \mathbb{F}_p$. Then the Legendre symbol can be computed as follows:

$$\left(\frac{y}{p}\right) = y^{\frac{p-1}{2}}. \quad (4.32)$$

Example 65. Looking at the quadratic residues and non residues in \mathbb{F}_5 from example 63 again, we can compute the following Legendre symbols using the Euler criterion:

$$\begin{aligned} \left(\frac{0}{5}\right) &= 0^{\frac{5-1}{2}} = 0^2 = 0 \\ \left(\frac{1}{5}\right) &= 1^{\frac{5-1}{2}} = 1^2 = 1 \\ \left(\frac{2}{5}\right) &= 2^{\frac{5-1}{2}} = 2^2 = 4 = -1 \\ \left(\frac{3}{5}\right) &= 3^{\frac{5-1}{2}} = 3^2 = 4 = -1 \\ \left(\frac{4}{5}\right) &= 4^{\frac{5-1}{2}} = 4^2 = 1 \end{aligned}$$

Exercise 51. Consider the prime field \mathbb{F}_{13} from exercise 49. Compute the Legendre symbol $\left(\frac{x}{13}\right)$ and the set of roots \sqrt{x} for all elements $x \in \mathbb{F}_{13}$.

2121 Hashing into prime fields

An important problem in cryptography is the ability to hash to (various subsets) of elliptic curves. As we will see in chapter 5, those curves are often defined over prime fields, and hashing

to a curve might start with hashing to the prime field. It is therefore important to understand how to hash into prime fields.

In 4.2, we looked at a few methods of hashing into the modular arithmetic rings \mathbb{Z}_n for arbitrary $n > 1$. As prime fields are just special instances of those rings, all methods for hashing into \mathbb{Z}_n functions can be used for hashing into prime fields, too.

4.3.2 Prime Field Extensions

Prime fields, as defined in the previous section, are basic building blocks in cryptography. However, as we will see in chapter 8 so-called pairing-based SNARK systems are crucially dependent on certain group pairings 4.6 defined on elliptic curves over **prime field extensions**. In this section we therefore introduce those extensions.

Given some prime number $p \in \mathbb{P}$, a natural number $m \in \mathbb{N}$ and an irreducible polynomial $P \in \mathbb{F}_p[x]$ of degree m with coefficients from the prime field \mathbb{F}_p , then a prime field extension $(\mathbb{F}_{p^m}, +, \cdot)$ is defined as follows:

The set \mathbb{F}_{p^m} of the prime field extension is given by the set of all polynomials with a degree less than m :

$$\mathbb{F}_{p^m} := \{a_{m-1}x^{m-1} + a_{m-2}x^{m-2} + \dots + a_1x + a_0 \mid a_i \in \mathbb{F}_p\} \quad (4.33)$$

The addition law of the prime field extension \mathbb{F}_{p^m} is given by the usual addition of polynomials as defined in 3.24:

$$+ : \mathbb{F}_{p^m} \times \mathbb{F}_{p^m} \rightarrow \mathbb{F}_{p^m}, (\sum_{j=0}^m a_j x^j, \sum_{j=0}^m b_j x^j) \mapsto \sum_{j=0}^m (a_j + b_j) x^j \quad (4.34)$$

The multiplication law of the prime field extension \mathbb{F}_{p^m} is given by first multiplying the two polynomials as defined in 3.25 and then divided the result by the irreducible polynomial P and keep the remainder:

$$\cdot : \mathbb{F}_{p^m} \times \mathbb{F}_{p^m} \rightarrow \mathbb{F}_{p^m}, (\sum_{j=0}^m a_j x^j, \sum_{j=0}^m b_j x^j) \mapsto (\sum_{n=0}^{2m} \sum_{i=0}^n a_i b_{n-i} x^n) \bmod P \quad (4.35)$$

The neutral element of the additive group $(\mathbb{F}_{p^m}, +)$ is given by the zero polynomial 0 and the additive inverse is given by the polynomial with all negative coefficients. The neutral element of the multiplicative group $(\mathbb{F}_{p^m}^*, \cdot)$ is given by the unit polynomial 1 and the multiplicative inverse can be computed by the extended Euclidean algorithm.

We can see from the definition of \mathbb{F}_{p^m} that the field is of characteristic p , since the multiplicative neutral element 1 is equivalent to the multiplicative element 1 from the underlying prime field, and hence $\sum_{j=0}^p 1 = 0$. Moreover, \mathbb{F}_{p^m} is finite and contains p^m many elements, since elements are polynomials of degree $< m$, and every coefficient a_j can have p many different values. In addition, we see that the prime field \mathbb{F}_p is a subfield of \mathbb{F}_{p^m} that occurs when we restrict the elements of \mathbb{F}_{p^m} to polynomials of degree zero.

One key point is that the construction of \mathbb{F}_{p^m} depends on the choice of an irreducible polynomial, and, in fact, different choices will give different multiplication tables, since the remainders from dividing a polynomial product by those polynomials will be different.

It can, however, be shown that the fields for different choices of P are **isomorphic**, which means that there is a one-to-one correspondence between all of them. Consequently, from an abstract point of view, they are the same thing. From an implementations point of view, however, some choices are preferable to others because they allow for faster computations.

Remark 4. Similar to the way prime fields \mathbb{F}_p are generated by starting with the ring of integers and then dividing by a prime number p and keeping the remainder, prime field extensions \mathbb{F}_{p^m}

are generated by starting with the ring $\mathbb{F}_p[x]$ of polynomials and then dividing them by an irreducible polynomial of degree m and keeping the remainder.

In fact it can be shown that \mathbb{F}_{p^m} is the set of all remainders when dividing any polynomial $Q \in \mathbb{F}_p[x]$ by an irreducible polynomial P of degree m . This is analogous to how \mathbb{F}_p is the set of all remainders when dividing integers by p .

Any field \mathbb{F}_{p^m} constructed in the above manner is a field extension of \mathbb{F}_p . To be more general, a field $\mathbb{F}_{p^{m_2}}$ is a field extension of a field $\mathbb{F}_{p^{m_1}}$, if and only if m_1 divides m_2 . From this, we can deduce that, for any given fixed prime number, there are nested sequences of subfields whenever the power m_j divides the power m_{j+1} :

$$\mathbb{F}_p \subset \mathbb{F}_{p^{m_1}} \subset \cdots \subset \mathbb{F}_{p^{m_k}} \quad (4.36)$$

To get a more intuitive picture of this, we construct an extension field of the prime field \mathbb{F}_3 in the following example, and we can see how \mathbb{F}_3 sits inside that extension field.

Example 66 (The Extension field \mathbb{F}_{3^2}). In exercise 48 we have constructed the prime field \mathbb{F}_3 . In this example, we apply the definition of a field extension 4.33 to construct the extension field \mathbb{F}_{3^2} . We start by choosing an irreducible polynomial of degree 2 with coefficients in \mathbb{F}_3 . We try $P(t) = t^2 + 1$. Possibly the fastest way to show that P is indeed irreducible is to just insert all elements from \mathbb{F}_3 to see if the result is ever zero. We compute as follows:

$$\begin{aligned} P(0) &= 0^2 + 1 = 1 \\ P(1) &= 1^2 + 1 = 2 \\ P(2) &= 2^2 + 1 = 1 + 1 = 2 \end{aligned}$$

This implies that P is irreducible, since all factors must be of the form $(t - a)$ for a being a root of P . The set \mathbb{F}_{3^2} contains all polynomials of degrees lower than two, with coefficients in \mathbb{F}_3 , which are precisely as listed below:

$$\mathbb{F}_{3^2} = \{0, 1, 2, t, t+1, t+2, 2t, 2t+1, 2t+2\}$$

As expected, our extension field contains 9 elements. Addition is defined as addition of polynomials; for example $(t+2) + (2t+2) = (1+2)t + (2+2) = 1$. Doing this computation for all elements gives the following addition table

+	0	1	2	t	t+1	t+2	2t	2t+1	2t+2
0	0	1	2	t	t+1	t+2	2t	2t+1	2t+2
1	1	2	0	t+1	t+2	t	2t+1	2t+2	2t
2	2	0	1	t+2	t	t+1	2t+2	2t	2t+1
t	t	t+1	t+2	2t	2t+1	2t+2	0	1	2
t+1	t+1	t+2	t	2t+1	2t+2	2t	1	2	0
t+2	t+2	t	t+1	2t+2	2t	2t+1	2	0	1
2t	2t	2t+1	2t+2	0	1	2	t	t+1	t+2
2t+1	2t+1	2t+2	2t	1	2	0	t+1	t+2	t
2t+2	2t+2	2t	2t+1	2	0	1	t+2	t	t+1

As we can see, the group $(\mathbb{F}_3, +)$ is a subgroup of the group $(\mathbb{F}_{3^2}, +)$, obtained by only considering the first three rows and columns of this table.

We can use the addition table to deduce the additive inverse (the negative) of any element from \mathbb{F}_{3^2} . For example, in \mathbb{F}_{3^2} we have $-(2t+1) = t+2$, since $(2t+1) + (t+2) = 0$

Multiplication needs a bit more computation, as we first have to multiply the polynomials, and whenever the result has a degree ≥ 2 , we have to apply a polynomial division algorithm like 3 to divide the product by the polynomial P and keep the remainder. To see how this works, let us compute the product of $t + 2$ and $2t + 2$ in \mathbb{F}_{3^2} :

$$\begin{aligned}(t + 2) \cdot (2t + 2) &= (2t^2 + 2t + t + 1) \bmod (t^2 + 1) \\ &= (2t^2 + 1) \bmod (t^2 + 1) & \# 2t^2 + 1 : t^2 + 1 = 2 + \frac{2}{t^2 + 1} \\ &= 2\end{aligned}$$

2182 This means that the product of $t + 2$ and $2t + 2$ in \mathbb{F}_{3^2} is 2. Performing this computation for all
2183 elements gives the following multiplication table:

·	0	1	2	t	t+1	t+2	2t	2t+1	2t+2
0	0	0	0	0	0	0	0	0	0
1	0	1	2	t	t+1	t+2	2t	2t+1	2t+2
2	0	2	1	2t	2t+2	2t+1	t	t+2	t+1
t	0	t	2t	2	t+2	2t+2	1	t+1	2t+1
t+1	0	t+1	2t+2	t+2	2t	1	2t+1	2	t
t+2	0	t+2	2t+1	2t+2	1	t	t+1	2t	2
2t	0	2t	t	1	2t+1	t+1	2	2t+2	t+2
2t+1	0	2t+1	t+2	t+1	2	2t	2t+2	t	1
2t+2	0	2t+2	t+1	2t+1	t	2	t+2	1	2t

2185 As it was the case in previous examples, we can use the table to deduce the multiplicative
2186 inverse of any non-zero element from \mathbb{F}_{3^2} . For example, in \mathbb{F}_{3^2} we have $(2t + 1)^{-1} = 2t + 2$,
2187 since $(2t + 1) \cdot (2t + 2) = 1$.

2188 From the multiplication table, we can also see that the only quadratic residues in \mathbb{F}_{3^2} are
2189 from the set $\{0, 1, 2, t, 2t\}$, with $\sqrt{0} = \{0\}$, $\sqrt{1} = \{1, 2\}$, $\sqrt{2} = \{t, 2t\}$, $\sqrt{t} = \{t + 2, 2t + 1\}$ and
2190 $\sqrt{2t} = \{t + 1, 2t + 2\}$.

Since \mathbb{F}_{3^2} is a field, we can solve equations as we would for other fields, (such as rational numbers). To see that, let us find all $x \in \mathbb{F}_{3^2}$ that solve the quadratic equation $(t + 1)(x^2 + (2t + 2)) = 2$. We compute as follows:

$$\begin{aligned}(t + 1)(x^2 + (2t + 2)) &= 2 & \# 2 \text{ distributive law} \\ (t + 1)x^2 + (t + 1)(2t + 2) &= 2 \\ (t + 1)x^2 + (t) &= 2 & \# 2 \text{ add the additive inverse of } t \\ (t + 1)x^2 + (t) + (2t) &= (2) + (2t) \\ (t + 1)x^2 &= 2t + 2 & \# \text{ multiply with the multiplicative invers of } t + 1 \\ (t + 2)(t + 1)x^2 &= (t + 2)(2t + 2) & \# \text{ multiply with the multiplicative invers of } t + 1 \\ x^2 &= 2 & \# 2 \text{ is quadratic residue. Take the roots.} \\ x &\in \{t, 2t\}\end{aligned}$$

2191 Computations in extension fields are arguably on the edge of what can reasonably be done with
2192 pen and paper. Fortunately, Sage provides us with a simple way to do the computations.

2193 `sage: Z3 = GF(3) # prime field` 225
2194 `sage: Z3t.<t> = Z3[] # polynomials over Z3` 226

```

2195 sage: P = Z3t(t^2+1) 227
2196 sage: P.is_irreducible() 228
2197 True 229
2198 sage: F3_2.<t> = GF(3^2, name='t', modulus=P) # Extension 230
2199 field F_3^2
2200 sage: F3_2 231
2201 Finite Field in t of size 3^2 232
2202 sage: F3_2(t+2)*F3_2(2*t+2) == F3_2(2) 233
2203 True 234
2204 sage: F3_2(2*t+2)^(-1) # multiplicative inverse 235
2205 2*t + 1 236
2206 sage: # verify our solution to (t+1)(x^2 + (2t+2)) = 2 237
2207 sage: F3_2(t+1)*(F3_2(t)**2 + F3_2(2*t+2)) == F3_2(2) 238
2208 True 239
2209 sage: F3_2(t+1)*(F3_2(2*t)**2 + F3_2(2*t+2)) == F3_2(2) 240
2210 True 241

```

2211 *Exercise 52.* Consider the extension field \mathbb{F}_{3^2} from the previous example and find all pairs of
 2212 elements $(x, y) \in \mathbb{F}_{3^2}$, for which the following equation holds:

$$y^2 = x^3 + 4 \quad (4.37)$$

2213 *Exercise 53.* Show that the polynomial $Q = x^2 + x + 2$ from $\mathbb{F}_3[x]$ is irreducible. Construct the
 2214 multiplication table of \mathbb{F}_{3^2} with respect to Q and compare it to the multiplication table of \mathbb{F}_{3^2}
 2215 from example 66.

2216 *Exercise 54.* Show that the polynomial $P = t^3 + t + 1$ from $\mathbb{F}_5[t]$ is irreducible. Then consider the
 2217 extension field \mathbb{F}_{5^3} defined relative to P . Compute the multiplicative inverse of $(2t^2 + 4) \in \mathbb{F}_{5^3}$
 2218 using the extended Euclidean algorithm. Then find all $x \in \mathbb{F}_{5^3}$ that solve the following equation:

$$(2t^2 + 4)(x - (t^2 + 4t + 2)) = (2t + 3) \quad (4.38)$$

2219 *Exercise 55.* Consider the prime field \mathbb{F}_5 . Show that the polynomial $P = x^2 + 2$ from $\mathbb{F}_5[x]$ is
 2220 irreducible. Implement the finite field \mathbb{F}_{5^2} in sage.

2221 4.4 Projective Planes

2222 Projective planes are particular geometric constructs defined over a given field. In a sense,
 2223 projective planes extend the concept of the ordinary Euclidean plane by including “points at
 2224 infinity.”

2225 To understand the idea of constructing of projective planes, note that in an ordinary Eu-
 2226 clidean plane, two lines either intersect in a single point or are parallel. In the latter case, both
 2227 lines are either the same, that is, they intersect in all points, or do not intersect at all. A projec-
 2228 tive plane can then be thought of as an ordinary plane, but equipped with additional “point at
 2229 infinity” such that two different lines always intersect in a single point. Parallel lines intersect
 2230 “at infinity”.

2231 Such an inclusion of infinity points makes projective planes particularly useful in the de-
 2232 scription of elliptic curves, as the description of such a curve in an ordinary plane needs an
 2233 additional symbol “the point at infinity” to give the set of points on the curve the structure of a

group 5.1. Translating the curve into projective geometry includes this “point at infinity” more naturally into the set of all points on a projective plane.

To be more precise, let \mathbb{F} be a field, $\mathbb{F}^3 := \mathbb{F} \times \mathbb{F} \times \mathbb{F}$ the set of all tuples of three elements over \mathbb{F} and $x \in \mathbb{F}^3$ with $x = (X, Y, Z)$. Then there is exactly one *line* L_x in \mathbb{F}^3 that intersects both $(0, 0, 0)$ and x , given by the set $L_x = \{(k \cdot X, k \cdot Y, k \cdot Z) \mid k \in \mathbb{F}\}$. A point in the **projective plane** over \mathbb{F} can then be defined as such a **line** if we exclude the intersection of that line with $(0, 0, 0)$. This leads to the following definition of a **point** in projective geometry:

$$[X : Y : Z] := \{(k \cdot X, k \cdot Y, k \cdot Z) \mid k \in \mathbb{F}^*\} \quad (4.39)$$

Points in projective geometry are therefore lines in \mathbb{F}^3 where the intersection with $(0, 0, 0)$ is excluded. Given a field \mathbb{F} the **projective plane** of that field is then defined as the set of all points, excluding the point $[0 : 0 : 0]$:

$$\mathbb{FP}^2 := \{[X : Y : Z] \mid (X, Y, Z) \in \mathbb{F}^3 \text{ with } (X, Y, Z) \neq (0, 0, 0)\} \quad (4.40)$$

It can be shown that a projective plane over a finite field \mathbb{F}_{p^m} contains $p^{2m} + p^m + 1$ number of elements.

To understand why the projective point $[X : Y : Z]$ is also a line, consider the situation where the underlying field \mathbb{F} is the set of rational numbers \mathbb{Q} . In this case, \mathbb{Q}^3 can be seen as the three-dimensional space, and $[X : Y : Z]$ is an ordinary line in this 3-dimensional space that intersects zero and the point with coordinates X, Y and Z , such that the intersection with zero is excluded.

The key observation here is that points in the projective plane \mathbb{FP}^2 are lines in the 3-dimensional space \mathbb{F}^3 . However it should be kept in mind that, for finite fields, the terms **space** and **line** share very little visual similarity with their counterparts over the set of rational numbers.

It follows from this that points $[X : Y : Z] \in \mathbb{FP}^2$ are not simply described by fixed coordinates (X, Y, Z) , but by **sets of coordinates**, where two different coordinates (X_1, Y_1, Z_1) and (X_2, Y_2, Z_2) describe the same point if and only if there is some non-zero field element $k \in \mathbb{F}^*$ such that $(X_1, Y_1, Z_1) = (k \cdot X_2, k \cdot Y_2, k \cdot Z_2)$. Points $[X : Y : Z]$ are called **projective coordinates**.

Notation and Symbols 10 (Projective coordinates). Projective coordinates of the form $[X : Y : 1]$ are descriptions of so-called **affine points**. Projective coordinates of the form $[X : Y : 0]$ are descriptions of so-called **points at infinity**. In particular, the projective coordinate $[1 : 0 : 0]$ describes the so-called **line at infinity**.

Example 67. Consider the field \mathbb{F}_3 from exercise 48. As this field only contains three elements, it does not take too much effort to construct its associated projective plane $\mathbb{F}_3\mathbb{P}^2$, as we know that it only contains 13 elements.

To find $\mathbb{F}_3\mathbb{P}^2$, we have to compute the set of all lines in $\mathbb{F}_3 \times \mathbb{F}_3 \times \mathbb{F}_3$ that intersect $(0, 0, 0)$, excluding their intersection with $(0, 0, 0)$. Since those lines are parameterized by tuples (x_1, x_2, x_3) ,

we compute as follows:

$$\begin{aligned}
[0 : 0 : 1] &= \{(k \cdot x_1, k \cdot x_2, k \cdot x_3) \mid k \in \mathbb{F}_3^*\} = \{(0, 0, 1), (0, 0, 2)\} \\
[0 : 0 : 2] &= \{(k \cdot x_1, k \cdot x_2, k \cdot x_3) \mid k \in \mathbb{F}_3^*\} = \{(0, 0, 2), (0, 0, 1)\} = [0 : 0 : 1] \\
[0 : 1 : 0] &= \{(k \cdot x_1, k \cdot x_2, k \cdot x_3) \mid k \in \mathbb{F}_3^*\} = \{(0, 1, 0), (0, 2, 0)\} \\
[0 : 1 : 1] &= \{(k \cdot x_1, k \cdot x_2, k \cdot x_3) \mid k \in \mathbb{F}_3^*\} = \{(0, 1, 1), (0, 2, 2)\} \\
[0 : 1 : 2] &= \{(k \cdot x_1, k \cdot x_2, k \cdot x_3) \mid k \in \mathbb{F}_3^*\} = \{(0, 1, 2), (0, 2, 1)\} \\
[0 : 2 : 0] &= \{(k \cdot x_1, k \cdot x_2, k \cdot x_3) \mid k \in \mathbb{F}_3^*\} = \{(0, 2, 0), (0, 1, 0)\} = [0 : 1 : 0] \\
[0 : 2 : 1] &= \{(k \cdot x_1, k \cdot x_2, k \cdot x_3) \mid k \in \mathbb{F}_3^*\} = \{(0, 2, 1), (0, 1, 2)\} = [0 : 1 : 2] \\
[0 : 2 : 2] &= \{(k \cdot x_1, k \cdot x_2, k \cdot x_3) \mid k \in \mathbb{F}_3^*\} = \{(0, 2, 2), (0, 1, 1)\} = [0 : 1 : 1] \\
[1 : 0 : 0] &= \{(k \cdot x_1, k \cdot x_2, k \cdot x_3) \mid k \in \mathbb{F}_3^*\} = \{(1, 0, 0), (2, 0, 0)\} \\
[1 : 0 : 1] &= \{(k \cdot x_1, k \cdot x_2, k \cdot x_3) \mid k \in \mathbb{F}_3^*\} = \{(1, 0, 1), (2, 0, 2)\} \\
[1 : 0 : 2] &= \{(k \cdot x_1, k \cdot x_2, k \cdot x_3) \mid k \in \mathbb{F}_3^*\} = \{(1, 0, 2), (2, 0, 1)\} \\
[1 : 1 : 0] &= \{(k \cdot x_1, k \cdot x_2, k \cdot x_3) \mid k \in \mathbb{F}_3^*\} = \{(1, 1, 0), (2, 2, 0)\} \\
[1 : 1 : 1] &= \{(k \cdot x_1, k \cdot x_2, k \cdot x_3) \mid k \in \mathbb{F}_3^*\} = \{(1, 1, 1), (2, 2, 2)\} \\
[1 : 1 : 2] &= \{(k \cdot x_1, k \cdot x_2, k \cdot x_3) \mid k \in \mathbb{F}_3^*\} = \{(1, 1, 2), (2, 2, 1)\} \\
[1 : 2 : 0] &= \{(k \cdot x_1, k \cdot x_2, k \cdot x_3) \mid k \in \mathbb{F}_3^*\} = \{(1, 2, 0), (2, 1, 0)\} \\
[1 : 2 : 1] &= \{(k \cdot x_1, k \cdot x_2, k \cdot x_3) \mid k \in \mathbb{F}_3^*\} = \{(1, 2, 1), (2, 1, 2)\} \\
[1 : 2 : 2] &= \{(k \cdot x_1, k \cdot x_2, k \cdot x_3) \mid k \in \mathbb{F}_3^*\} = \{(1, 2, 2), (2, 1, 1)\} \\
[2 : 0 : 0] &= \{(k \cdot x_1, k \cdot x_2, k \cdot x_3) \mid k \in \mathbb{F}_3^*\} = \{(2, 0, 0), (1, 0, 0)\} = [1 : 0 : 0] \\
[2 : 0 : 1] &= \{(k \cdot x_1, k \cdot x_2, k \cdot x_3) \mid k \in \mathbb{F}_3^*\} = \{(2, 0, 1), (1, 0, 2)\} = [1 : 0 : 2] \\
[2 : 0 : 2] &= \{(k \cdot x_1, k \cdot x_2, k \cdot x_3) \mid k \in \mathbb{F}_3^*\} = \{(2, 0, 2), (1, 0, 1)\} = [1 : 0 : 1] \\
[2 : 1 : 0] &= \{(k \cdot x_1, k \cdot x_2, k \cdot x_3) \mid k \in \mathbb{F}_3^*\} = \{(2, 1, 0), (1, 2, 0)\} = [1 : 2 : 0] \\
[2 : 1 : 1] &= \{(k \cdot x_1, k \cdot x_2, k \cdot x_3) \mid k \in \mathbb{F}_3^*\} = \{(2, 1, 1), (1, 2, 2)\} = [1 : 2 : 2] \\
[2 : 1 : 2] &= \{(k \cdot x_1, k \cdot x_2, k \cdot x_3) \mid k \in \mathbb{F}_3^*\} = \{(2, 1, 2), (1, 2, 1)\} = [1 : 2 : 1] \\
[2 : 2 : 0] &= \{(k \cdot x_1, k \cdot x_2, k \cdot x_3) \mid k \in \mathbb{F}_3^*\} = \{(2, 2, 0), (1, 1, 0)\} = [1 : 1 : 0] \\
[2 : 2 : 1] &= \{(k \cdot x_1, k \cdot x_2, k \cdot x_3) \mid k \in \mathbb{F}_3^*\} = \{(2, 2, 1), (1, 1, 2)\} = [1 : 1 : 2] \\
[2 : 2 : 2] &= \{(k \cdot x_1, k \cdot x_2, k \cdot x_3) \mid k \in \mathbb{F}_3^*\} = \{(2, 2, 2), (1, 1, 1)\} = [1 : 1 : 1]
\end{aligned}$$

These lines define the 13 points in the projective plane $\mathbb{F}_3\mathbb{P}$:

$$\begin{aligned}
\mathbb{F}_3\mathbb{P} = \{ & [0 : 0 : 1], [0 : 1 : 0], [0 : 1 : 1], [0 : 1 : 2], [1 : 0 : 0], [1 : 0 : 1], \\
& [1 : 0 : 2], [1 : 1 : 0], [1 : 1 : 1], [1 : 1 : 2], [1 : 2 : 0], [1 : 2 : 1], [1 : 2 : 2] \}
\end{aligned}$$

2265 This projective plane contains 9 affine points, three points at infinity and one line at infinity.

2266 To understand the ambiguity in projective coordinates a bit better, let us consider the point
 2267 $[1 : 2 : 2]$. As this point in the projective plane is a line in $\mathbb{F}_3^3 \setminus \{(0, 0, 0)\}$, it has the projective
 2268 coordinates $(1, 2, 2)$ as well as $(2, 1, 1)$, since the former coordinate gives the latter when multi-
 2269 plied in \mathbb{F}_3 by the factor 2. In addition, note that, for the same reasons, the points $[1 : 2 : 2]$ and
 2270 $[2 : 1 : 1]$ are the same, since their underlying sets are equal.

2271 *Exercise 56.* Construct the so-called **Fano plane**, that is, the projective plane over the finite
 2272 field \mathbb{F}_2 .

Chapter 5

Elliptic Curves

Generally speaking, elliptic curves are nothing but geometric objects in projective planes over some given field, made up of points that satisfy certain equations. One of their key features from the point of view of cryptography is that if the underlying field is of positive characteristic, elliptic curves are finite, cyclic groups and it is believed that the discrete logarithm problem on many elliptic curve groups is hard, given that the underlying characteristic is large enough.

A special class of elliptic curves are so-called pairing-friendly curves, which have a notation of a group pairing attached to them, that have cryptographically advantageous properties.

In this chapter, we introduce elliptic curves as they are used in pairing-based approaches to the construction of SNARKs. The elliptic curves we consider are all defined over prime fields or prime field extensions and the reader should be familiar with the content of the previous chapter on those notations.

5.1 Short Weierstrass Curves

In this section, we introduce **short Weierstrass** curves, which are the most general types of curves over finite fields of characteristics greater than 3 and start with their so called affine representation. Introducing elliptic curves in their affine representation is probably not the most common and conceptually cleanest way, but has the advantage that in the affine representation an elliptic curve is just a set of pairs of numbers. We believe that such an introduction makes elliptic curves more accessible to the beginner, since potential unfamiliarity with projective coordinates can be avoided. However, the affine representation has the disadvantage that a special “point at infinity”, that is not a point on the curve, is necessary to describe the curve’s group structure.

We then introduce the elliptic curve group law and describe elliptic curve scalar multiplication, which is an instantiation of the exponential map of general cyclic groups. After that, we look at the projective representation of elliptic curves, which has the advantage that no special symbol is necessary to represent the point at infinity. As this representation is conceptually more straight forward, this is how elliptic curves are usually introduced in math classes. We believe that the major drawback from a beginners point of view is that in the projective representation, points are elements from projective planes, which are classes of numbers.

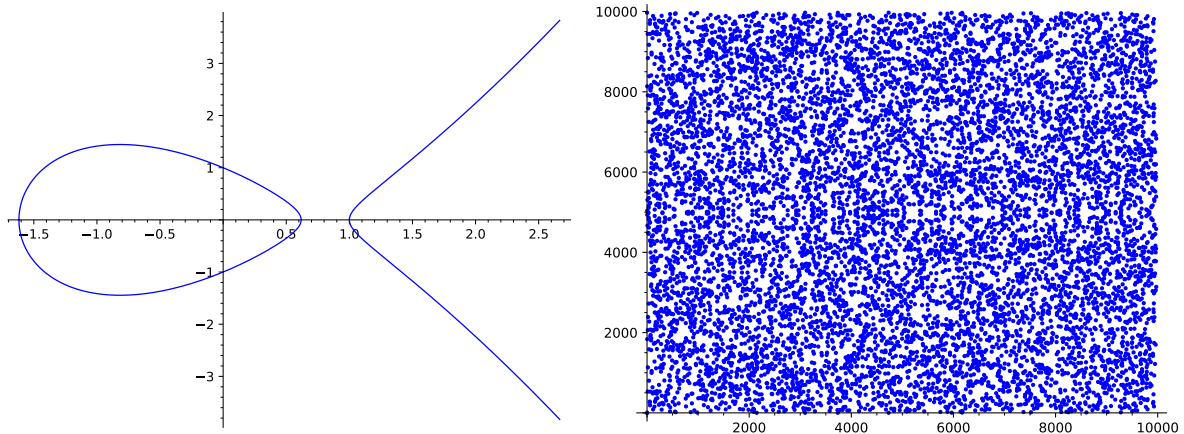
We finish this section with an explicit equivalence that transforms affine representations into projective representations and vice versa.

5.1.1 Affine Short Weierstrass form

Probably the least abstract and most straight-forward way to introduce elliptic curves for non-mathematicians and beginners is the so-called affine representation of a short Weierstrass curve. To see what this is, let \mathbb{F} be a finite field of characteristic q with $q > 3$ and $a, b \in \mathbb{F}$ two field elements such that the so called **discriminant** $4a^3 + 27b^2$ is not equal to zero. Then a **short Weierstrass elliptic curve** $E_{a,b}(\mathbb{F})$ over \mathbb{F} in its affine representation is the set of all pairs of field elements $(x, y) \in \mathbb{F} \times \mathbb{F}$ that satisfy the short Weierstrass cubic equation $y^2 = x^3 + a \cdot x + b$, together with a distinguished symbol \mathcal{O} , called the **point at infinity**:

$$E_{a,b}(\mathbb{F}) = \{(x, y) \in \mathbb{F} \times \mathbb{F} \mid y^2 = x^3 + a \cdot x + b\} \cup \{\mathcal{O}\} \quad (5.1)$$

The term “curve” is used here because, if an elliptic curve is defined over a characteristic zero field, like the field \mathbb{Q} of rational numbers, the set of all points $(x, y) \in \mathbb{Q} \times \mathbb{Q}$ that satisfy $y^2 = x^3 + a \cdot x + b$ looks like a curve. We should note however that visualizing elliptic curves over finite fields as “curves” has its limitations, and we will therefore not stress the geometric picture too much, but focus on the computational properties instead. To understand the visual difference, consider the following two elliptic curves:



Both elliptic curves are defined by the same short Weierstrass equation $y^2 = x^3 - 2x + 1$, but the first curve is defined over the rational numbers \mathbb{Q} , that is, the pair (x, y) contains rational numbers, while the second one is defined over the prime field \mathbb{F}_{9973} , which means that both coordinates x and y are from the prime field \mathbb{F}_{9973} . Every blue dot represents a pair (x, y) , that is a solution to $y^2 = x^3 - 2x + 1$. As we can see, the second curve hardly looks like a geometric structure one would naturally call a curve. This shows that our geometric intuitions from \mathbb{Q} are obfuscated in curves over finite fields.

The equation $4a^3 + 27b^2 \neq 0$ ensures that the curve is non-singular, which loosely means that the curve has no cusps or self-intersections in the geometric sense, if seen as an actual curve. As we will see in 5.1.2, cusps and self-intersections would make the group law potentially ambiguous.

Throughout this book, the reader is advised to do as many computations in a pen-and-paper fashion as possible, as this helps getting a deeper understanding of the details. However, when dealing with elliptic curves, computations can quickly become cumbersome and tedious, and one might get lost in the details. Fortunately, Sage is very helpful in dealing with elliptic curves. The following snippet shows a way to define elliptic curves and how to work with them in Sage:

```
sage: F5 = GF(5) # define the base field
```

242


```

2339 sage: a = F5(2) # parameter a                243
2340 sage: b = F5(4) # parameter b                244
2341 sage: # check discriminant                    245
2342 sage: F5(6)*(F5(4)*a^3+F5(27)*b^2) != F5(0)    246
2343 True                                           247
2344 sage: # short Weierstrass curve over field F5   248
2345 sage: E = EllipticCurve(F5,[a,b]) # y^2 == x^3 + ax +b  249
2346 sage: # point on a curve                      250
2347 sage: P = E(0,2) # 2^2 == 0^3 + 2*0 + 4         251
2348 sage: P.xy() # affine coordinates             252
2349 (0, 2)                                         253
2350 sage: INF = E(0) # point at infinity           254
2351 sage: try: # point at infinity has no affine coordinates 255
2352 .....:     INF.xy()                           256
2353 .....: except ZeroDivisionError:               257
2354 .....:     pass                               258
2355 sage: P = E.plot() # create a plotted version  259

```

2356 The following three examples give a more practical understanding of what an elliptic curve is
 2357 and how we can compute it. The reader is advised to read these examples carefully, and ideally,
 2358 to also carry out the computation themselves. We will repeatedly build on these examples in
 2359 this chapter, and use the second example throughout the entire book.

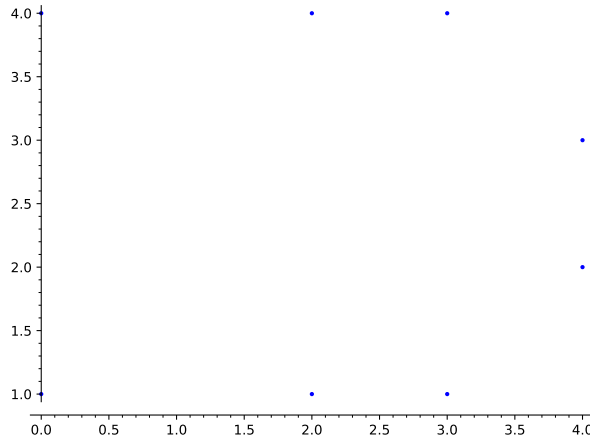
2360 *Example 68.* Consider the prime field \mathbb{F}_5 from example 14. To define an elliptic curve over
 2361 \mathbb{F}_5 , we have to choose two numbers a and b from that field. Assuming we choose $a = 1$ and
 2362 $b = 1$ then $4a^3 + 27b^2 \equiv 1 \pmod{5}$ from which follows that the corresponding elliptic curve
 2363 $E_{1,1}(\mathbb{F}_5)$ is given by the set of all pairs (x, y) from \mathbb{F}_5 that satisfy the equation $y^2 = x^3 + x + 1$,
 2364 together with the special symbol \mathcal{O} , which represents the “point at infinity”.

2365 To get a better understanding of that curve, observe that if we choose arbitrarily the pair
 2366 $(x, y) = (1, 1)$, we see that $1^2 \neq 1^3 + 1 + 1$ and hence $(1, 1)$ is not a point on the curve $E_{1,1}(\mathbb{F}_5)$.
 2367 On the other hand choosing for example $(x, y) = (2, 1)$ gives $1^2 = 2^3 + 2 + 1$ and hence the pair
 2368 $(2, 1)$ is a point on the curve $E_{1,1}(\mathbb{F}_5)$ (Remember that all computations are done in modulo 5
 2369 arithmetics).

Now since the set $\mathbb{F}_5 \times \mathbb{F}_5$ of all pairs (x, y) from \mathbb{F}_5 contains only $5 \cdot 5 = 25$ pairs, we can
 compute the curve, by just inserting every possible pair (x, y) into the short Weierstrass equation
 $y^2 = x^3 + x + 1$. If the equation holds, the pair is a curve point, if not that means that the point
 is not on the curve. Combining the result of this computation with the point at infinity gives the
 curve as follows:

$$E_{1,1}(\mathbb{F}_5) = \{\mathcal{O}, (0, 1), (2, 1), (3, 1), (4, 2), (4, 3), (0, 4), (2, 4), (3, 4)\}$$

2370 This means that the elliptic curve is a set of 9 elements, 8 of which are pairs of elements from
 2371 \mathbb{F}_5 and one special symbol \mathcal{O} . Visualizing $E_{1,1}(\mathbb{F}_5)$ gives the following plot:



In the development of SNARKs, it is sometimes necessary to do elliptic curve cryptography “in a circuit”, which basically means that the elliptic curve needs to be implemented in a certain SNARK-friendly way. We will look at what this means in chapter 7. To be able to do this efficiently, it is desirable to have curves with special properties. The following example is a pen-and-paper version of such a curve, called Tiny-jubjub. We design this curve especially to resemble a well known cryptographically secure curve, called Baby-jubjub, the latter of which is extensively used in real-world SNARKs.

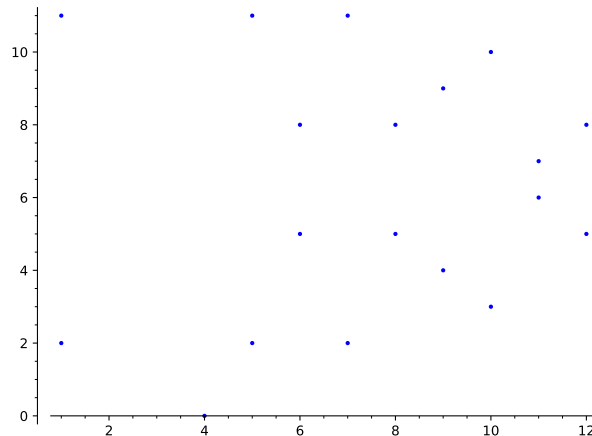
In the literature the Baby-jubjub curve is commonly introduced as a so called twisted Edwards curve, which we will introduce in 5.3. However as we will see in 5.3, every twisted Edwards curve is equivalent to a short Weierstrass curve and hence we start with an introduction of Tiny-Jubjub in its short Weierstrass incarnation. The interested reader is advised to study this example carefully, as we will use it and build on it in various places throughout the book.

Example 69 (The Tiny-jubjub curve). Consider the prime field \mathbb{F}_{13} from exercise 49. If we choose $a = 8$ and $b = 8$, then $4a^3 + 27b^2 \equiv 6 \pmod{13}$ and the corresponding elliptic curve is given by all pairs (x, y) from \mathbb{F}_{13} such that $y^2 = x^3 + 8x + 8$ holds. We call this curve the **Tiny-jubjub** curve (in its affine short Weierstrass representation), or *TJJ_13* for short.

Since the set $\mathbb{F}_{13} \times \mathbb{F}_{13}$ of all pairs (x, y) from \mathbb{F}_{13} contains only $13 \cdot 13 = 169$ pairs, we can compute the curve by just inserting every possible pair (x, y) into the short Weierstrass equation $y^2 = x^3 + 8x + 8$. We get the following result:

$$TJJ_{13} = \{\mathcal{O}, (1, 2), (1, 11), (4, 0), (5, 2), (5, 11), (6, 5), (6, 8), (7, 2), (7, 11), (8, 5), (8, 8), (9, 4), (9, 9), (10, 3), (10, 10), (11, 6), (11, 7), (12, 5), (12, 8)\} \quad (5.2)$$

As we can see, the curve consists of 20 points; 19 pairs of elements from \mathbb{F}_{13} and the point at infinity. To get a visual impression of the *TJJ_13* curve, we might plot all of its points (except the point at infinity):



As we will see in what follows, this curve is rather special, as it is possible to represent it in two alternative forms called the **Montgomery** and the **twisted Edwards form** (See sections 5.2 and 5.3, respectively).

Now that we have seen two pen-and-paper friendly elliptic curves, let us look at a curve, that is used in actual cryptography. Cryptographically secure elliptic curves are not **qualitatively** different from the curves we looked at so far, but the prime number modulus of their prime field is much larger. Typical examples use prime numbers that have binary representations in the magnitude of more than double the size of the desired security level. If, for example, a security of 128 bits is desired, a prime modulus of binary size ≥ 256 is chosen. The following example provides such a curve.

Example 70 (Bitcoin's secp256k1 curve). To give an example of a real-world, cryptographically secure curve, let us look at curve secp256k1, which is famous for being used in the public key cryptography of Bitcoin. The prime field \mathbb{F}_p of secp256k1 is defined by the following prime number:

$$p = 115792089237316195423570985008687907853269984665640564039457584007908834671663$$

The binary representation of this number needs 256 bits, which implies that the prime field \mathbb{F}_p contains approximately 2^{256} many elements, which is considered quite large. To get a better impression of how large the base field is, consider that the number 2^{256} is approximately in the same order of magnitude as the estimated number of atoms in the observable universe.

The curve secp256k1 is defined by the parameters $a, b \in \mathbb{F}_p$ with $a = 0$ and $b = 7$. Since $4 \cdot 0^3 + 27 \cdot 7^2 \bmod p = 1323$, those parameters indeed define an elliptic curve given as follows:

$$\text{secp256k1} = \{(x, y) \in \mathbb{F}_p \times \mathbb{F}_p \mid y^2 = x^3 + 7\}$$

Clearly, the secp256k1 curve is too large to be useful in pen and paper computations, since it can be shown that the number of its elements is a prime number r that also has a binary representation of 256 bits:

$$r = 115792089237316195423570985008687907852837564279074904382605163141518161494337$$

Cryptographically secure elliptic curves are therefore not useful in pen-and-paper computations, but fortunately, Sage handles large curves efficiently:

```
sage: p = 1157920892373161954235709850086879078532699846656405 260
      64039457584007908834671663 2410
```

```

2411 sage: # Hexadecimal representation                261
2412 sage: p.str(16)                                    262
2413 ffffffffffffffffffffffffffffffffffffffffffffffeffffc 263
2414 2f
2415 sage: p.is_prime()                                264
2416 True                                              265
2417 sage: p.nbits()                                    266
2418 256                                              267
2419 sage: Fp = GF(p)                                    268
2420 sage: secp256k1 = EllipticCurve(Fp, [0, 7])        269
2421 sage: r = secp256k1.order() # number of elements  270
2422 sage: r.str(16)                                    271
2423 fffffffffffffffffffffffffffffffffffebaaedce6af48a03bbfd25e8cd03641 272
2424 41
2425 sage: r.is_prime()                                273
2426 True                                              274
2427 sage: r.nbits()                                    275
2428 256                                              276

```

2429 *Exercise 57.* Consider the curve $E_1(\mathbb{F})$ from example 68 and compute the set of all curve points
 2430 $(x, y) \in E_1(\mathbb{F})$.

2431 *Exercise 58.* Consider the curve TJJ_13 from example 69 and compute the set of all curve
 2432 points $(x, y) \in TJJ_13$.

2433 *Exercise 59.* Look up the definition of curve BLS12-381, implement it in Sage and compute the
 2434 number of all curve points.

2435 **Isomorphic affine short Weierstrass curves** As explained in the previous part, elliptic curves
 2436 are defined by pairs of parameters $(a, b) \in \mathbb{F} \times \mathbb{F}$ for some field \mathbb{F} . An important question in
 2437 classifying elliptic curves is then the task to decide which pairs of parameters (a, b) and (a', b')
 2438 instantiate equivalent curves in the sense that there is a 1:1 correspondence between the set of
 2439 curve points.

2440 To be more precise let \mathbb{F} be a field and (a, b) as well as (a', b') two pairs of parameters, such
 2441 that there is an invertible field element $c \in \mathbb{F}^*$ with $a' = a \cdot c^4$ and $b' = b \cdot c^6$. Then the elliptic
 2442 curves $E_{a,b}(\mathbb{F})$ and $E_{a',b'}(\mathbb{F})$ are called **isomorphic** and there is a map that maps curve points
 2443 onto curve points

$$I : E_{a,b}(\mathbb{F}) \rightarrow E_{a',b'}(\mathbb{F}) : \begin{cases} (x, y) \\ \mathcal{O} \end{cases} \mapsto \begin{cases} (c^2 \cdot x, c^2 \cdot y) \\ \mathcal{O} \end{cases} \quad (5.3)$$

2444 This map is a 1:1 correspondence and its inverse map is given by mapping the point at infinity
 2445 onto the point at infinity and each curve point (x, y) onto the curve point $(c^{-2}x, c^{-2}y)$.

Example 71. Consider the short Weierstrass elliptic curve $E_{1,1}(\mathbb{F}_5)$ from example 68 and the elliptic curve

$$E_{1,4}(\mathbb{F}_5) := \{(x, y) \in \mathbb{F}_5 \times \mathbb{F}_5 \mid y^3 = x^3 + x + 4\}$$

Inserting all pairs of elements $(x, y) \in \mathbb{F}_5 \times \mathbb{F}_5$ into the short Weierstrass equation $y^3 = x^3 + x + 4$ of $E_{1,4}(\mathbb{F}_5)$ results in the following set of points:

$$E_{1,4}(\mathbb{F}_5) = \{\mathcal{O}, (0, 2), (0, 3), (1, 1), (1, 4), (2, 2), (2, 3), (3, 2), (3, 3)\}$$

As we can see, both curves are of the same order and indeed since 2 is an invertible element from \mathbb{F}_5 with $1 = 2^4 \cdot 1$ and $4 = 2^6 \cdot 1$, $E_{1,4}(\mathbb{F})$ and $E_{1,1}(\mathbb{F})$ are isomorphic and the map $I : E_{1,1}(\mathbb{F}_5) \rightarrow E_{1,4}(\mathbb{F}_5) : (x, y) \mapsto (4x, 4y)$ from 5.3 defines a 1:1 correspondence. For example the point $(4, 3) \in E_{1,1}(\mathbb{F})$ is mapped onto the point $I(4, 3) = (4 \cdot 4, 4 \cdot 3) = (1, 2) \in E_{1,4}(\mathbb{F})$.

Exercise 60. Let \mathbb{F} be a finite field and (a, b) as well as (a', b') two pairs of parameters, and $c \in \mathbb{F}^*$ an invertible field element with $a' = a \cdot c^4$ and $b' = b \cdot c^6$. Show that in this case function I 5.3 maps curve points onto curve points.

Exercise 61. Consider the tiny-jubjub curve from example 69 and the elliptic curve $E_{5,12}(\mathbb{F}_{13})$ defined as follows:

$$E_{5,12}(\mathbb{F}_{13}) = \{(x, y) \in \mathbb{F}_{13} \times \mathbb{F}_{13} \mid y^2 = x^3 + 5x + 12\}$$

Show that TJJ_13 and $E_{5,12}(\mathbb{F}_{13})$ are isomorphic. Then compute the set of all points from $E_{5,12}(\mathbb{F}_{13})$, construct I and map all points of TJJ_13 onto $E_{5,12}(\mathbb{F}_{13})$.

Affine compressed representation As we have seen in example 70, cryptographically secure elliptic curves are defined over large prime fields, where elements of those fields typically need more than 255 bits of storage on a computer. Since elliptic curve points consist of pairs of those field elements, they need double that amount of storage.

However, we can reduce the amount of space needed to represent a curve point by using a technique called **point compression**. To understand this, note that for each given $x \in \mathbb{F}$, there are only 2 possible $y \in \mathbb{F}$, such that the pair (x, y) is a point on an affine short Weierstrass curve, since x and y have to satisfy the equation $y^2 = x^3 + a \cdot x + b$. From this follows that y can be computed from x , since it is an element from the set $\sqrt{x^3 + a \cdot x + b}$ of square roots 4.30, which contains exactly two elements for $x^3 + a \cdot x + b \neq 0$ and exactly one element for $x^3 + a \cdot x + b = 0$.

This implies that we can represent a curve point in **compressed form** by simply storing the x coordinate together with a single bit called the **sign bit**, the latter of which deterministically decides which of the two roots to choose. One convention could be to always choose the root closer to 0 when the sign bit is 0, and the root closer to the order of \mathbb{F} when the sign bit is 1. In case the y coordinate is zero, both sign bits give the same result.

Example 72 (Tiny-jubjub). To understand the concept of compressed curve points a bit better, consider the TJJ_13 curve from example 69 again. Since this curve is defined over the prime field \mathbb{F}_{13} , and numbers between 0 and 13 need approximately 4 bits to be represented, each TJJ_13 point on this curve needs 8 bits of storage in uncompressed form. The following set represents the uncompressed form of the points on this curve:

$$TJJ_13 = \{\mathcal{O}, (1, 2), (1, 11), (4, 0), (5, 2), (5, 11), (6, 5), (6, 8), (7, 2), (7, 11), (8, 5), (8, 8), (9, 4), (9, 9), (10, 3), (10, 10), (11, 6), (11, 7), (12, 5), (12, 8)\}$$

Using the technique of point compression, we can reduce the bits needed to represent the points on this curve to 5 per point. To achieve this, we can replace the y coordinate in each (x, y) pair by a sign bit indicating whether or not y is closer to 0 or to 13. As a result y values in the range $[0, \dots, 6]$ will have the sign bit 0, while y -values in the range $[7, \dots, 12]$ will have the sign bit 1. Applying this to the points in TJJ_13 gives the compressed representation as follows:

$$TJJ_13 = \{\mathcal{O}, (1, 0), (1, 1), (4, 0), (5, 0), (5, 1), (6, 0), (6, 1), (7, 0), (7, 1), (8, 0), (8, 1), (9, 0), (9, 1), (10, 0), (10, 1), (11, 0), (11, 1), (12, 0), (12, 1)\}$$

2470 Note that the numbers $7, \dots, 12$ are the negatives (additive inverses) of the numbers $1, \dots, 6$ in
 2471 modular 13 arithmetics and that $-0 = 0$.

2472 To recover the uncompressed counterpart of, say, the compressed point $(5, 1)$, we insert the
 2473 x coordinate 5 into the short Weierstrass equation and get $y^2 = 5^3 + 8 \cdot 5 + 8 = 4$. As expected,
 2474 4 is a quadratic residue in \mathbb{F}_{13} with roots $\sqrt{4} = \{2, 11\}$. Since the sign bit of the point is 1,
 2475 we have to choose the root closer to the modulus 13, which is 11. The uncompressed point is
 2476 therefore $(5, 11)$.

2477 5.1.2 Affine Group Law

2478 One of the key properties of an elliptic curve is that it is possible to define a group law on the
 2479 set of its points such that the point at infinity serves as the neutral element and inverses are
 2480 reflections on the x -axis. The origin of this law can be understood in a geometric picture and is
 2481 known as the **chord-and-tangent rule**. In the affine representation of a short Weierstrass curve,
 2482 the rule can be described in the following way, using the symbol \oplus for the group law:

- 2483 • (Point at infinity) We define the point at infinity \mathcal{O} as the neutral element of addition, that
 2484 is, we define $P \oplus \mathcal{O} = P$ for all points $P \in E(\mathbb{F})$.
- 2485 • (Chord Rule) Let $P, Q \in E(\mathbb{F}) \setminus \{\mathcal{O}\}$ with $P \neq Q$ be two distinct points on an elliptic curve,
 2486 neither of them the point at infinity. The sum of P and Q is defined as follows:
 2487 Consider the line l which intersects the curve in P and Q . If l intersects the elliptic curve
 2488 at a third point R' , define the sum $R = P \oplus Q$ of P and Q as the reflection of R' at the x -axis.
 2489 If the line l does not intersect the curve at a third point, define the sum to be the point at
 2490 infinity \mathcal{O} . Calling such a line a **chord**, it can be shown that no chord will intersect the
 2491 curve in more than three points. This implies that addition is not ambiguous.
- 2492 • (Tangent Rule) Let $P \in E(\mathbb{F}) \setminus \{\mathcal{O}\}$ be a point on an elliptic curve, that is not the point at
 2493 infinity. The sum of P with itself (the doubling of P) is defined as follows:
 2494 Consider the line which is tangential to the elliptic curve at P , in the sense that it "just
 2495 touches" the curve at that point. If this line intersects the elliptic curve at a second point
 2496 R' , the sum $P \oplus P$ is the reflection of R' at the x -axis. If it does not intersect the curve at
 2497 a third point define the sum to be the point at infinity \mathcal{O} . Calling such a line a **tangent**, it
 2498 can be shown that no such tangent will intersect the curve in more than two points. This
 2499 implies that doubling is not ambiguous.

2500 It can be shown that the points of an elliptic curve form a commutative group with respect to the
 2501 previously stated chord-and-tangent rule such that \mathcal{O} acts the neutral element, and the inverse
 2502 of any element $P \in E(\mathbb{F})$ is the reflection of P on the x -axis.

2503 The chord-and-tangent rule defines the group law of an elliptic curve geometrically and we
 2504 just stated it informally as an intuition. In order to apply those rules on a computer we have to
 2505 translate it into algebraic equations. To do so first observe that for any two given curve points
 2506 $(x_1, y_1), (x_2, y_2) \in E(\mathbb{F})$ the identity $x_1 = x_2$ implies $y_2 = \pm y_1$ as explained in 5.1.1. This shows
 2507 that the following rules are a complete description of elliptic curve group $(E(\mathbb{F}), \oplus)$:

- 2508 • (The neutral element) The point at infinity \mathcal{O} is the neutral element.
- 2509 • (The inverse element) The inverse of \mathcal{O} is \mathcal{O} . For any other curve point $(x, y) \in E(\mathbb{F}) \setminus \{\mathcal{O}\}$,
 2510 the inverse is given by $(x, -y)$.

- (The group law) For any two curve points $P, Q \in E(\mathbb{F})$, the group law is defined by one of the following cases:

1. (Neutral element) If $Q = \mathcal{O}$, then the group law is defined as $P \oplus Q = P$.

2. (Inverse elements) If $P = (x, y)$ and $Q = (x, -y)$, the group law is defined as $P \oplus Q = \mathcal{O}$.

3. (Tangent Rule) If $P = (x, y)$ with $y \neq 0$, the group law $P \oplus P = (x', y')$ is defined as follows:

$$x' = \left(\frac{3x^2 + a}{2y} \right)^2 - 2x \quad , \quad y' = \left(\frac{3x^2 + a}{2y} \right)^2 (x - x') - y$$

4. (Chord Rule) If $P = (x_1, y_1)$ and $Q = (x_2, y_2)$ such that $x_1 \neq x_2$, the group law $R = P \oplus Q$ with $R = (x_3, y_3)$ is defined as follows:

$$x_3 = \left(\frac{y_2 - y_1}{x_2 - x_1} \right)^2 - x_1 - x_2 \quad , \quad y_3 = \left(\frac{y_2 - y_1}{x_2 - x_1} \right) (x_1 - x_3) - y_1$$

Notation and Symbols 11. Let \mathbb{F} be a field and $E(\mathbb{F})$ an elliptic curve over \mathbb{F} . We write \oplus for the group law on $E(\mathbb{F})$, $(E(\mathbb{F}), \oplus)$ for the commutative group of elliptic curve points and use the additive notation 3 on this group. If P is a point on a short Weierstrass curve with $P = (x, 0)$ then P is called **self-inverse**.

As we can see, it is very efficient to compute inverses on elliptic curves. However, computing the addition of elliptic curve points in the affine representation needs to consider many cases and involves extensive finite field divisions. As we will see in 5.1.3, the addition law is simplified in projective coordinates.

To get some practical impression of how the group law on an elliptic curve is computed, let's look at some actual cases:

Example 73. Consider the elliptic curve $E_{1,1}(\mathbb{F}_5)$ from example 68 again. As we have seen, the curve consists of the following 9 elements:

$$E_{1,1}(\mathbb{F}_5) = \{\mathcal{O}, (0, 1), (2, 1), (3, 1), (4, 2), (4, 3), (0, 4), (2, 4), (3, 4)\}$$

We know that this set defines a group, so we can add any two elements from $E_{1,1}(\mathbb{F}_5)$ to get a third element.

To give an example, consider the elements $(0, 1)$ and $(4, 2)$. Neither of these elements is the neutral element \mathcal{O} , and since, the x coordinate of $(0, 1)$ is different from the x coordinate of $(4, 2)$, we know that we have to use the chord rule from definition 5.1.2 to compute the sum

$(0, 1) \oplus (4, 2)$:

$$\begin{aligned} x_3 &= \left(\frac{y_2 - y_1}{x_2 - x_1} \right)^2 - x_1 - x_2 && \# \text{ insert points} \\ &= \left(\frac{2 - 1}{4 - 0} \right)^2 - 0 - 4 && \# \text{ simplify in } \mathbb{F}_5 \\ &= \left(\frac{1}{4} \right)^2 + 1 = 4^2 + 1 = 1 + 1 = 2 \end{aligned}$$

$$\begin{aligned} y_3 &= \left(\frac{y_2 - y_1}{x_2 - x_1} \right) (x_1 - x_3) - y_1 && \# \text{ insert points} \\ &= \left(\frac{2 - 1}{4 - 0} \right) (0 - 2) - 1 && \# \text{ simplify in } \mathbb{F}_5 \\ &= \left(\frac{1}{4} \right) \cdot 3 + 4 = 4 \cdot 3 + 4 = 2 + 4 = 1 \end{aligned}$$

So, in the elliptic curve $E_{1,1}(\mathbb{F}_5)$ we get $(0, 1) \oplus (4, 2) = (2, 1)$, and, indeed, the pair $(2, 1)$ is an element of $E_{1,1}(\mathbb{F}_5)$ as expected. On the other hand, $(0, 1) \oplus (0, 4) = \mathcal{O}$, since both points have equal x coordinates and inverse y coordinates, rendering them inverses of each other. Adding the point $(4, 2)$ to itself, we have to use the tangent rule from definition 5.1.2:

$$\begin{aligned} x' &= \left(\frac{3x^2 + a}{2y} \right)^2 - 2x && \# \text{ insert points} \\ &= \left(\frac{3 \cdot 4^2 + 1}{2 \cdot 2} \right)^2 - 2 \cdot 4 && \# \text{ simplify in } \mathbb{F}_5 \\ &= \left(\frac{3 \cdot 1 + 1}{4} \right)^2 + 3 \cdot 4 = \left(\frac{4}{4} \right)^2 + 2 = 1 + 2 = 3 \end{aligned}$$

$$\begin{aligned} y' &= \left(\frac{3x^2 + a}{2y} \right)^2 (x - x') - y && \# \text{ insert points} \\ &= \left(\frac{3 \cdot 4^2 + 1}{2 \cdot 2} \right)^2 (4 - 3) - 2 && \# \text{ simplify in } \mathbb{F}_5 \\ &= 1 \cdot 1 + 3 = 4 \end{aligned}$$

2528 So, in the elliptic curve $E_{1,1}(\mathbb{F}_5)$, we get the doubling of $(4, 2)$, that is, $(4, 2) \oplus (4, 2) = (3, 4)$,
 2529 and, indeed the pair $(3, 4)$ is an element of $E_{1,1}(\mathbb{F}_5)$ as expected. The group $E_{1,1}(\mathbb{F}_5)$ has no
 2530 self-inverse points other than the neutral element \mathcal{O} , since no point has 0 as its y coordinate. We
 2531 can invoke Sage to double-check the computations.

2532	sage: <code>F5 = GF(5)</code>	277
2533	sage: <code>E1 = EllipticCurve(F5, [1, 1])</code>	278
2534	sage: <code>INF = E1(0) # point at infinity</code>	279
2535	sage: <code>P1 = E1(0, 1)</code>	280
2536	sage: <code>P2 = E1(4, 2)</code>	281
2537	sage: <code>P3 = E1(0, 4)</code>	282


```

2538 sage: R1 = E1(2, 1) 283
2539 sage: R2 = E1(3, 4) 284
2540 sage: R1 == P1+P2 285
2541 True 286
2542 sage: INF == P1+P3 287
2543 True 288
2544 sage: R2 == P2+P2 289
2545 True 290
2546 sage: R2 == 2*P2 291
2547 True 292
2548 sage: P3 == P3 + INF 293
2549 True 294

```

Example 74 (Tiny-jubjub). Consider the *TJJ_13*-curve from example 69 again and recall that its group of points is given as follows:

$$TJJ_13 = \{\mathcal{O}, (1, 2), (1, 11), (4, 0), (5, 2), (5, 11), (6, 5), (6, 8), (7, 2), (7, 11), (8, 5), (8, 8), (9, 4), (9, 9), (10, 3), (10, 10), (11, 6), (11, 7), (12, 5), (12, 8)\}$$

In contrast to the group from the previous example, this group contains a self-inverse point, which is different from the neutral element, defined by $(4, 0)$. To see what this means, observe that we cannot add $(4, 0)$ to itself using the tangent rule 3 from definition 5.1.2, as the y coordinate is zero. Instead, we have to use the rule for additive inverses, since $0 = -0$. We get $(4, 0) \oplus (4, 0) = \mathcal{O}$ in *TJJ_13* and the point $(4, 0)$ is therefore the inverse of itself, as adding it to itself results in the neutral element.

```

2556 sage: F13 = GF(13) 295
2557 sage: TJJ = EllipticCurve(F13, [8, 8]) 296
2558 sage: P = TJJ(4, 0) 297
2559 sage: INF = TJJ(0) # Point at infinity 298
2560 sage: INF == P+P 299
2561 True 300
2562 sage: INF == 2*P 301
2563 True 302

```

Example 75. Consider the *secp256k1* curve from example 70 again. The following code invokes Sage to generate two random affine curve points and to add these points together:

```

2566 sage: P = secp256k1.random_point() 303
2567 sage: Q = secp256k1.random_point() 304
2568 sage: R = P + Q 305
2569 sage: P.xy() 306
2570 (2018192404838541489620861076888137165249049545263176717990132 307
2571      2903216517073948, 74501364833437599029661288628497454591062
2572      698749060648397859359417219929252983)
2573 sage: Q.xy() 308
2574 (1140745707232855006890276861633302689894901906675586043226993 309
2575      59835745161978566, 6040406944906933766190230199715993287960
2576      4687656285721910801349140834095137590)
2577 sage: R.xy() 310

```

2578 (9129180938045147914609720891105690095836321624680267698118192 311
 2579 1440156530365053, 91878271939541575585805520955859772299238
 2580 006887591917424374347555775414482121)

2581 *Exercise 62.* Consider the commutative group (TJJ_13, \oplus) of the Tiny-jubjub-curve from ex-
 2582 ample 69.

- 2583 1. Compute the inverse of $(10, 10)$, \mathcal{O} , $(4, 0)$ and $(1, 2)$.
- 2584 2. Solve the equation $x \oplus (9, 4) = (5, 2)$ for some $x \in TJJ_13$

2585 **Scalar multiplication** As we have seen in the previous section, elliptic curves $E(\mathbb{F})$ have the
 2586 structure of a commutative group associated to them. It can be shown that this group is finite
 2587 and cyclic whenever the underlying field \mathbb{F} is finite and as we know from 4.2 this implies, that
 2588 there is a notation of scalar multiplication associated to any elliptic curve over finite fields.

2589 To understand this scalar multiplication, recall from 4.3 that every finite cyclic group of
 2590 order n has a generator g and an associated exponential map $g^{(\cdot)} : \mathbb{Z}_n \rightarrow \mathbb{G}$, where g^x is the
 2591 x -fold product of g with itself.

Elliptic curve scalar multiplication is the exponential map written in additive notation. To
 be more precise, let \mathbb{F} be a finite field, $E(\mathbb{F})$ an elliptic curve of order n , and P a generator of
 $E(\mathbb{F})$. Then the **elliptic curve scalar multiplication** with base P is defined as follows (where
 $[0]P = \mathcal{O}$ and $[m]P = P + P + \dots + P$ is the m -fold sum of P with itself):

$$[\cdot]P : \mathbb{Z}_n \rightarrow E(\mathbb{F}) ; m \mapsto [m]P$$

2592 Therefore, elliptic curve scalar multiplication is an instantiation of the general exponential map
 2593 using additive instead of multiplicative notation.

2594 **Logarithmic Ordering** As explained in 4.3 the inverse of the exponential map exists and
 2595 is usually called the **elliptic curve discrete logarithm map**. However we don't know of any
 2596 efficient way to actually compute this map, which is one reason why some elliptic curves are
 2597 believed to be DL-secure 4.1.1.

2598 One useful property of the exponential map in regard to the examples in this book is that
 2599 it can be used to greatly simplify pen-and-paper computations. As we have seen in example
 2600 73, computing the elliptic curve addition law takes quite a bit of effort when done without a
 2601 computer. However, when g is a generator of a small pen-and-paper elliptic curve group of
 2602 order n , we can use the exponential map to write the elements of the group in the following
 2603 way, which we call its **logarithmic order** with respect to the generator g :

$$\mathbb{G} = \{[1]g \rightarrow [2]g \rightarrow [3]g \rightarrow \dots \rightarrow [n-1]g \rightarrow \mathcal{O}\} \quad (5.4)$$

2604 For small pen and paper groups, the logarithmic order greatly simplifies complicated elliptic
 2605 curve addition to the much simpler case of modular n arithmetic. In order to add two curve
 2606 points P and Q , we only have to look up their discrete log relations with the generator $P = [l]g$
 2607 and $Q = [m]g$, and compute the group law as $P \oplus Q = [l + m]g$, where $l + m$ is addition in
 2608 modular n arithmetics.

2609 The reader should keep in mind though, that many elliptic curves are believed to be DL-
 2610 secure 4.1.1, which implies that in those cases the logarithmic order can not be computed effi-
 2611 ciently.

2612 In the following example, we will look at some implications of the fact that elliptic curves
 2613 are finite cyclic groups and apply the logarithmic order:

2614 *Example 76.* Consider the elliptic curve group $E_{1,1}(\mathbb{F}_5)$ from example 68. Since it is a finite
 2615 cyclic group of order 9, and the prime factorization of 9 is $3 \cdot 3$, we can use the fundamental
 2616 theorem of finite cyclic groups 4.1 to reason about all its subgroups. In fact, since the only
 2617 factors of 9 are 1, 3 and 9, we know that $E_{1,1}(\mathbb{F}_5)$ has the following subgroups:

- 2618 • $E_{1,1}(\mathbb{F}_5)[9]$ is a subgroup of order 9. By definition, any group is a subgroup of itself.
- 2619 • $E_{1,1}(\mathbb{F}_5)[3] = \{(2, 1), (2, 4), \mathcal{O}\}$ is a subgroup of order 3. This is the subgroup associated
 2620 to the prime factor 3.
- 2621 • $E_{1,1}(\mathbb{F}_5)[1] = \{\mathcal{O}\}$ is a subgroup of order 1. This is the trivial subgroup.

Moreover, since $E_{1,1}(\mathbb{F}_5)$ and all its subgroups are cyclic, we know from 4.3 that they must have generators. For example, the curve point $(2, 1)$ is a generator of the order 3 subgroup $E_{1,1}(\mathbb{F}_5)[3]$, since every element of $E_{1,1}(\mathbb{F}_5)[3]$ can be generated by repeatedly adding $(2, 1)$ to itself:

$$\begin{aligned} [1](2, 1) &= (2, 1) \\ [2](2, 1) &= (2, 4) \\ [3](2, 1) &= \mathcal{O} \end{aligned}$$

Since $(2, 1)$ is a generator, we know from 4.1 that it gives rise to an exponential map from the finite field \mathbb{F}_3 onto \mathbb{G}_2 defined by scalar multiplication:

$$[\cdot](2, 1) : \mathbb{F}_3 \rightarrow E_{1,1}(\mathbb{F}_5)[3] : x \mapsto [x](2, 1)$$

To give an example of a generator that generates the entire group $E_{1,1}(\mathbb{F}_5)$, consider the point $(0, 1)$. Applying the tangent rule repeatedly, we compute as follows:

$$\begin{array}{ll} [0](0, 1) = \mathcal{O} & [1](0, 1) = (0, 1) \\ [2](0, 1) = (4, 2) & [3](0, 1) = (2, 1) \\ [4](0, 1) = (3, 4) & [5](0, 1) = (3, 1) \\ [6](0, 1) = (2, 4) & [7](0, 1) = (4, 3) \\ [8](0, 1) = (0, 4) & [9](0, 1) = \mathcal{O} \end{array}$$

Again, since $(0, 1)$ is a generator, we know from 4.1 that it gives rise to an exponential map. However, since the group order is not a prime number, the exponential map does not map from any field, but from the ring \mathbb{Z}_9 of modular 9 arithmetics:

$$[\cdot](0, 1) : \mathbb{Z}_9 \rightarrow E_{1,1}(\mathbb{F}_5) : x \mapsto [x](0, 1)$$

Using the generator $(0, 1)$ and its associated exponential map, we can write $E(\mathbb{F}_1)$ in logarithmic order with respect to $(0, 1)$ as explained in 5.1.2. We get the following:

$$E_{1,1}(\mathbb{F}_5) = \{(0, 1) \rightarrow (4, 2) \rightarrow (2, 1) \rightarrow (3, 4) \rightarrow (3, 1) \rightarrow (2, 4) \rightarrow (4, 3) \rightarrow (0, 4) \rightarrow \mathcal{O}\}$$

2622 This indicates that the first element is a generator, and the n -th element is the scalar product of
 2623 n and the generator. To see how logarithmic orders like this simplify the computations in small
 2624 elliptic curve groups, consider example 73 again. In that example, we use the chord-and-tangent
 2625 rule to compute $(0, 1) \oplus (4, 2)$. Now, in the logarithmic order of $E_1(\mathbb{F})$, we can compute that
 2626 sum much easier, since we can directly see that $(0, 1) = [1](0, 1)$ and $(4, 2) = [2](0, 1)$. We can
 2627 then deduce $(0, 1) \oplus (4, 2) = (2, 1)$ immediately, since $[1](0, 1) \oplus [2](0, 1) = [3](0, 1) = (2, 1)$.

2628 To give another example, we can immediately see that $(3, 4) \oplus (4, 3) = (4, 2)$, without do-
 2629 ing any expensive elliptic curve addition, since we know $(3, 4) = [4](0, 1)$ as well as $(4, 3) =$
 2630 $[7](0, 1)$ from the logarithmic ordering of $E_{1,1}(\mathbb{F}_5)$. Since $4 + 7 = 2$ in \mathbb{Z}_9 , the result must be
 2631 $[2](0, 1) = (4, 2)$.

2632 Finally we can use $E_{1,1}(\mathbb{F}_5)$ as an example to understand the concept of cofactor clearing
 2633 from 4.5. Since the order of $E_{1,1}(\mathbb{F}_5)$ is 9, we only have a single factor, which happen to be the
 2634 cofactor as well. Cofactor clearing then implies that we can map any element from $E_{1,1}(\mathbb{F}_5)$
 2635 onto its prime factor group $E_{1,1}(\mathbb{F}_5)[3]$ by scalar multiplication with 3. For example, taking the
 2636 element $(3, 4)$, which is not in $E_{1,1}(\mathbb{F}_5)[3]$, and multiplying it with 3, we get $[3](3, 4) = (2, 1)$,
 2637 which is an element of $E_{1,1}(\mathbb{F}_5)[3]$ as expected.

2638 In the following example, we will look at the subgroups of the tiny-jubjub curve, define
 2639 generators, and compute the logarithmic order for pen-and-paper computations. Then we take
 2640 another look at the principle of cofactor clearing.

2641 *Example 77.* Consider the tiny-jubjub curve TJJ_13 from example 69 again. Since the order of
 2642 TJJ_13 is 20, and the prime factorization of 20 is $2^2 \cdot 5$, we know that the TJJ_13 contains a
 2643 “large” prime-order subgroup of size 5 and a small prime order subgroup of size 2.

2644 To compute those groups, we can apply the technique of cofactor clearing in a try-and-repeat
 2645 loop. We start the loop by arbitrarily choosing an element $P \in TJJ_13$, then multiplying that
 2646 element with the cofactor of the group that we want to compute. If the result is \mathcal{O} , we try a
 2647 different element and repeat the process until the result is different from the point at infinity \mathcal{O} .

To compute a generator for the small prime-order subgroup $(TJJ_13)[2]$, first observe that
 the cofactor is 10, since $20 = 2 \cdot 10$. We then arbitrarily choose the curve point $(5, 11) \in TJJ_13$
 and compute $[10](5, 11) = \mathcal{O}$. Since the result is the point at infinity, we have to try another
 curve point, say $(9, 4)$. We get $[10](9, 4) = (4, 0)$ and we can deduce that $(4, 0)$ is a generator of
 $(TJJ_13)[2]$. Logarithmic order then gives the following order:

$$(TJJ_13)[2] = \{(4, 0) \rightarrow \mathcal{O}\}$$

2648 This is expected, since we know from example 74 that $(4, 0)$ is self-inverse, with $(4, 0) \oplus (4, 0) =$
 2649 \mathcal{O} . We double check the computations using Sage:

2650	sage: <code>F13 = GF(13)</code>	312
2651	sage: <code>TJJ = EllipticCurve(F13, [8, 8])</code>	313
2652	sage: <code>P = TJJ(5, 11)</code>	314
2653	sage: <code>INF = TJJ(0)</code>	315
2654	sage: <code>10*P == INF</code>	316
2655	True	317
2656	sage: <code>Q = TJJ(9, 4)</code>	318
2657	sage: <code>R = TJJ(4, 0)</code>	319
2658	sage: <code>10*Q == R</code>	320
2659	True	321

We can apply the same reasoning to the “large” prime-order subgroup $(TJJ_13)[5]$, which
 contains 5 elements. To compute a generator for this group, first observe that the associ-
 ated cofactor is 4, since $20 = 5 \cdot 4$. We choose the curve point $(9, 4) \in TJJ_13$ again, and
 compute $[4](9, 4) = (7, 11)$. Since the result is not the point at infinity, we know that $(7, 11)$
 is a generator of $(TJJ_13)[5]$. Using the generator $(7, 11)$, we compute the exponential map

$[\cdot](7, 11) : \mathbb{F}_5 \rightarrow TJJ_13[5]$ and get the following:

$$\begin{aligned} [0](7, 11) &= \mathcal{O} \\ [1](7, 11) &= (7, 11) \\ [2](7, 11) &= (8, 5) \\ [3](7, 11) &= (8, 8) \\ [4](7, 11) &= (7, 2) \end{aligned}$$

We can use this computation to write the large-order prime group $(TJJ_13)[5]$ of the tiny-jubjub curve in logarithmic order, which we will use quite frequently in what follows. We get the following:

$$(TJJ_13)[5] = \{(7, 11) \rightarrow (8, 5) \rightarrow (8, 8) \rightarrow (7, 2) \rightarrow \mathcal{O}\} \quad (5.5)$$

From this, we can immediately see, for example that $(8, 8) \oplus (7, 2) = (8, 5)$, since $3 + 4 = 2$ in \mathbb{F}_5 .

From the previous two examples, the reader might get the impression that elliptic curve computation can be largely replaced by modular arithmetics. This however, is not true in general, but only an artifact of small groups, where it is possible to write the entire group in a logarithmic order.

Exercise 63. Consider example 76 and compute the set $\{[1](0, 1), [2](0, 1), \dots, [8](0, 1), [9](0, 1)\}$ using the tangent rule only.

Exercise 64. Consider example 77 and compute the scalar multiplications $[10](5, 11)$ as well as $[10](9, 4)$ and $[4](9, 4)$ with pen and paper using the algorithm from exercise 37.

5.1.3 Projective short Weierstrass form

As we have seen in the previous section, describing elliptic curves as pairs of points that satisfy a certain equation is relatively straight-forward. However, in order to define a group structure on the set of points, we had to add a special point at infinity to act as the neutral element.

Recalling from the definition of projective planes 4.4, we know that points at infinity are handled as ordinary points in projective geometry. Therefore, it makes sense to look at the definition of a short Weierstrass curve in projective geometry.

To see what a short Weierstrass curve in projective coordinates is, let \mathbb{F} be a finite field of order q and characteristic > 3 , let $a, b \in \mathbb{F}$ be two field elements such that $4a^3 + 27b^2 \bmod q \neq 0$ and let \mathbb{FP}^2 be the projective plane over \mathbb{F} as introduced in 4.4. Then a **projective short Weierstrass elliptic curve** over \mathbb{F} is the set of all points $[X : Y : Z] \in \mathbb{FP}^2$ from the projective plane that satisfy the cubic equation $Y^2 \cdot Z = X^3 + a \cdot X \cdot Z^2 + b \cdot Z^3$:

$$E(\mathbb{FP}^2) = \{[X : Y : Z] \in \mathbb{FP}^2 \mid Y^2 \cdot Z = X^3 + a \cdot X \cdot Z^2 + b \cdot Z^3\} \quad (5.6)$$

To understand how the point at infinity is unified in this definition, recall from 4.4 that, in projective geometry, points at infinity are given by projective coordinates $[X : Y : 0]$. Inserting representatives $(x_1, y_1, 0) \in [X : Y : 0]$ from those coordinates into the defining cubic equation 5.6 results in the following identity:

$$\begin{aligned} y_1^2 \cdot 0 &= x_1^3 + a \cdot x_1 \cdot 0^2 + b \cdot 0^3 \\ 0 &= x_1^3 \end{aligned} \quad \Leftrightarrow$$

This implies $X = 0$ and shows that the only projective point at infinity, that is also a point on a projective short Weierstrass curve is the class $[0, 1, 0] = \{(0, y, 0) \mid y \in \mathbb{F}\}$. The point $[0 : 1 : 0]$ is the projective representation of the point at infinity \mathcal{O} in the affine representation. The projective representation of a short Weierstrass curve, therefore, has the advantage that it does not need a special symbol to represent the point at infinity from the affine definition.

Example 78. To get an intuition of how an elliptic curve in projective geometry looks, consider curve $E_{1,1}(\mathbb{F}_5)$ from example 68. We know that, in its affine representation, the set of points on the affine short Weierstrass curve is given as follows:

$$E_{1,1}(\mathbb{F}_5) = \{\mathcal{O}, (0, 1), (2, 1), (3, 1), (4, 2), (4, 3), (0, 4), (2, 4), (3, 4)\} \quad (5.7)$$

This is defined as the set of all pairs $(x, y) \in \mathbb{F}_5 \times \mathbb{F}_5$ such that the affine short Weierstrass equation $y^2 = x^3 + ax + b$ with $a = 1$ and $b = 1$ is satisfied.

To find the set of elements of $E_{1,1}(\mathbb{F}_5)$ in the projective representation of a short Weierstrass curve with the same parameters $a = 1$ and $b = 1$, we have to compute the set of projective points $[X : Y : Z]$ from the projective plane $\mathbb{F}_5\mathbb{P}^2$ that satisfy the following homogenous cubic equation for any representative $(x_1, y_1, z_1) \in [X : Y : Z]$:

$$y_1^2 z_1 = x_1^3 + 1 \cdot x_1 z_1^2 + 1 \cdot z_1^3 \quad (5.8)$$

We know from 4.4 that the projective plane $\mathbb{F}_5\mathbb{P}^2$ contains $5^2 + 5 + 1 = 31$ elements, so we can take the effort and insert all elements into equation 5.8 and see if both sides match.

For example, consider the projective point $[0 : 4 : 1]$. We know from 4.39 that this point in the projective plane represents the following line in $\mathbb{F}_5^3 \setminus \{(0, 0, 0)\}$:

$$[0 : 4 : 1] = \{(0, 4, 1), (0, 3, 2), (0, 2, 3), (0, 1, 4)\} \quad (5.9)$$

To check whether or not $[0 : 4 : 1]$ satisfies 5.8, we can insert any representative, in other words, any element from 5.9. Each element satisfies the equation if and only if all other elements satisfy the equation. So, we insert $(0, 3, 2)$ and get the following result:

$$3^2 \cdot 2 = 0^3 + 1 \cdot 0 \cdot 2^2 + 1 \cdot 2^3 \Leftrightarrow 3 = 3$$

This tells us that the affine point $[0 : 4 : 1]$ is indeed a solution to the equation 5.8, but we could just as well have inserted any other representative. For example, inserting $(0, 1, 4)$ also satisfies 5.8:

$$1^2 \cdot 4 = 0^3 + 1 \cdot 0 \cdot 4^2 + 1 \cdot 4^3 \Leftrightarrow 4 = 4$$

To find the projective representation of $E_{1,1}(\mathbb{F}_5)$, we first observe that the projective line at infinity $[1 : 0 : 0]$ is not a curve point on any projective short Weierstrass curve, since it cannot satisfy the defining equation in 5.6 for any parameter a and b . Therefore, we can exclude it from our consideration.

Moreover, a point at infinity $[X : Y : 0]$ can only satisfy the equation in 5.6 for any a and b , if $X = 0$, which implies that the only point at infinity relevant for short Weierstrass elliptic curves is $[0 : 1 : 0]$, since $[0 : k : 0] = [0 : 1 : 0]$ for all $k \in \mathbb{F}^*$. Therefore, we can exclude all points at infinity except the point $[0 : 1 : 0]$.

All points that remain are the affine points $[X : Y : 1]$. Inserting all of them into 5.8 we get the set of all projective curve points as follows:

$$E_1(\mathbb{F}_5\mathbb{P}^2) = \{[0 : 1 : 0], [0 : 1 : 1], [2 : 1 : 1], [3 : 1 : 1], [4 : 2 : 1], [4 : 3 : 1], [0 : 4 : 1], [2 : 4 : 1], [3 : 4 : 1]\}$$

If we compare this with the affine representation, we see that there is a 1:1 correspondence between the points in the affine representation in 5.7 and the affine points in projective geometry, and that the projective point $[0 : 1 : 0]$ represents the additional point \mathcal{O} in the affine representation.

Exercise 65. Consider example 78 and compute the set $??$ by inserting all points from the projective plane $\mathbb{F}_5\mathbb{P}^2$ into the defining projective short Weierstrass equation.

Exercise 66. Compute the projective representation of the tiny-jubjub curve and the logarithmic order of its large prime-order subgroup with respect to the generator $[7 : 11 : 1]$ in projective coordinates.

Projective Group law As we have seen in section 5.1.2, one of the key properties of an elliptic curve is that it comes with a definition of a group law on the set of its points, described geometrically by the chord-and-tangent rule 5.1.2. This rule was kind of intuitive, with the exception of the distinguished point at infinity, which appeared whenever the chord or the tangent did not have a third intersection point with the curve.

One of the key features of projective coordinates is that, in projective space, it is guaranteed that any chord will always intersect the curve in three points, and any tangent will intersect it in two points. So, the geometric picture simplifies, as we don't need to consider external symbols and associated cases. The price to pay for this mathematical simplification is of course that for a beginner, projective coordinates might be less intuitive.

It can be shown that the points of an elliptic curve in projective space form a commutative group with respect to the tangent-and-chord rule such that the projective point $[0 : 1 : 0]$ is the neutral element, and the additive inverse of a point $[X : Y : Z]$ is given by $[X : -Y : Z]$. The addition law is usually described by the following algorithm, minimizing the number of necessary additions and multiplications in the base field.

Exercise 67. Consider example 78 again. Compute the following expression for projective points on $E_1(\mathbb{F}_5\mathbb{P}^2)$ using algorithm 7:

- $[0 : 1 : 0] \oplus [4 : 3 : 1]$
- $[0 : 3 : 0] \oplus [3 : 1 : 2]$
- $-[0 : 4 : 1] \oplus [3 : 4 : 1]$
- $[4 : 3 : 1] \oplus [4 : 2 : 1]$

and then solve the equation $[X : Y : Z] \oplus [0 : 1 : 1] = [2 : 4 : 1]$ for some point $[X : Y : Z]$ from the projective short Weierstrass curve $E_1(\mathbb{F}_5\mathbb{P}^2)$.

Exercise 68. Compare the affine addition law for short Weierstrass curves with the projective addition rule. Which branch in the projective rule corresponds to which case in the affine law?

Coordinate Transformations As we can see by comparing the examples 78 and 78, there is a close relation between the affine and the projective representation of a short Weierstrass curve. This is not a coincidence. In fact, from a mathematical point of view, projective and affine short Weierstrass curves describe the same thing, as there is a one-to-one correspondence (an isomorphism) between both representations for any parameters a and b .

To specify the correspondence, let $E(\mathbb{F})$ and $E(\mathbb{F}\mathbb{P}^2)$ be an affine and a projective short Weierstrass curve defined for the same parameters a and b . Then the following function maps

Check if
following
Alg is
floated
too far

Algorithm 7 Projective short Weierstrass Addition Law

Require: $[X_1 : Y_1 : Z_1], [X_2 : Y_2 : Z_2] \in E(\mathbb{F}_{\mathbb{P}^2})$

procedure ADD-RULE($[X_1 : Y_1 : Z_1], [X_2 : Y_2 : Z_2]$)

if $[X_1 : Y_1 : Z_1] == [0 : 1 : 0]$ **then**

$[X_3 : Y_3 : Z_3] \leftarrow [X_2 : Y_2 : Z_2]$

else if $[X_2 : Y_2 : Z_2] == [0 : 1 : 0]$ **then**

$[X_3 : Y_3 : Z_3] \leftarrow [X_1 : Y_1 : Z_1]$

else

$U_1 \leftarrow Y_2 \cdot Z_1$

$U_2 \leftarrow Y_1 \cdot Z_2$

$V_1 \leftarrow X_2 \cdot Z_1$

$V_2 \leftarrow X_1 \cdot Z_2$

if $V_1 == V_2$ **then**

if $U_1 \neq U_2$ **then** $[X_3 : Y_3 : Z_3] \leftarrow [0 : 1 : 0]$

else

if $Y_1 == 0$ **then** $[X_3 : Y_3 : Z_3] \leftarrow [0 : 1 : 0]$

else

$W \leftarrow a \cdot Z_1^2 + 3 \cdot X_1^2$

$S \leftarrow Y_1 \cdot Z_1$

$B \leftarrow X_1 \cdot Y_1 \cdot S$

$H \leftarrow W^2 - 8 \cdot B$

$X' \leftarrow 2 \cdot H \cdot S$

$Y' \leftarrow W \cdot (4 \cdot B - H) - 8 \cdot Y_1^2 \cdot S^2$

$Z' \leftarrow 8 \cdot S^3$

$[X_3 : Y_3 : Z_3] \leftarrow [X' : Y' : Z']$

end if

end if

else

$U = U_1 - U_2$

$V = V_1 - V_2$

$W = Z_1 \cdot Z_2$

$A = U^2 \cdot W - V^3 - 2 \cdot V^2 \cdot V_2$

$X' = V \cdot A$

$Y' = U \cdot (V^2 \cdot V_2 - A) - V^3 \cdot U_2$

$Z' = V^3 \cdot W$

$[X_3 : Y_3 : Z_3] \leftarrow [X' : Y' : Z']$

end if

end if

return $[X_3 : Y_3 : Z_3]$

end procedure

Ensure: $[X_3 : Y_3 : Z_3] == [X_1 : Y_1 : Z_1] \oplus [X_2 : Y_2 : Z_2]$

points from the affine representation to points from the projective representation of a short Weierstrass curve. In other words, if the pair of field elements (x, y) satisfies the affine short Weierstrass equation $y^2 = x^3 + ax + b$, then all homogeneous coordinates $(x_1, y_1, z_1) \in [x : y : 1]$ satisfy the projective short Weierstrass equation $y_1^2 \cdot z_1 = x_1^3 + ay_1 \cdot z_1^2 + b \cdot z_1^3$.

$$I : E(\mathbb{F}) \rightarrow E(\mathbb{FP}^2) : \begin{array}{ll} (x, y) & \mapsto [x : y : 1] \\ \mathcal{O} & \mapsto [0 : 1 : 0] \end{array} \quad (5.10)$$

This map is a 1 : 1 correspondence, which means that it maps exactly one point from the affine representation onto one point from the projective representation. It is therefore possible to invert this map in order to map points from the projective representation to points from the affine representation of a short Weierstrass curve. The inverse is given by the following map:

$$I^{-1} : E(\mathbb{FP}^2) \rightarrow E(\mathbb{F}) : [X : Y : Z] \mapsto \begin{cases} (\frac{X}{Z}, \frac{Y}{Z}) & \text{if } Z \neq 0 \\ \mathcal{O} & \text{if } Z = 0 \end{cases} \quad (5.11)$$

Note that the only projective point $[X : Y : Z]$ with $Z = 0$ that satisfies the equation in 5.6 is given by the class $[0 : 1 : 0]$. A key feature of I and its inverse is that both maps respect the group structure, which means that the neutral element is mapped to the neutral element, i.e. $I(\mathcal{O}) = [0 : 1 : 0]$ and that $I((x_1, y_1) \oplus (x_2, y_2))$ is equal to $I(x_1, y_1) \oplus I(x_2, y_2)$ and the same holds true for the inverse map I^{-1} .

Maps with these properties are called **group isomorphisms**, and, from a mathematical point of view, the existence of function I implies that the affine and the projective definition of short Weierstrass elliptic curves are equivalent and represent the same mathematical thing in just two different views. Implementations can therefore choose freely between both representations.

5.2 Montgomery Curves

Both the affine and the projective short Weierstrass forms are the most general ways to describe elliptic curves over fields of characteristics larger than 3. However in certain situations it might be advantageous to consider more specialized representations of elliptic curves for example to get faster algorithms for the group law or the scalar multiplication.

As we will see in this section so called Montgomery curves are a subset of all elliptic curves that can be written in the **Montgomery form**. Those curves allow for constant time algorithms for (specializations of) the elliptic curve scalar multiplication.

To see what a Montgomery curve in its affine representation is, let \mathbb{F} be a finite field of characteristic $p > 3$, and let $A, B \in \mathbb{F}$ be two field elements such that $B \neq 0$ and $A^2 \neq 4$. A **Montgomery elliptic curve** $M(\mathbb{F})$ over \mathbb{F} in its affine representation is then the set of all pairs of field elements $(x, y) \in \mathbb{F} \times \mathbb{F}$ that satisfy the **Montgomery cubic equation** $B \cdot y^2 = x^3 + A \cdot x^2 + x$, together with a distinguished symbol \mathcal{O} , called the **point at infinity**.

$$M(\mathbb{F}) = \{(x, y) \in \mathbb{F} \times \mathbb{F} \mid B \cdot y^2 = x^3 + A \cdot x^2 + x\} \cup \{\mathcal{O}\} \quad (5.12)$$

Despite the fact that Montgomery curves look different from short Weierstrass curves, they are just a special way to describe certain short Weierstrass curves. In fact, every curve in affine Montgomery form can be transformed into an elliptic curve in short Weierstrass form. To see that, assume that a curve is given in Montgomery form $By^2 = x^3 + Ax^2 + x$. The associated short Weierstrass form is then defined as follows:

$$y^2 = x^3 + \frac{3 - A^2}{3 \cdot B^2} \cdot x + \frac{2 \cdot A^3 - (9 \bmod q) \cdot A}{(27 \bmod q) \cdot B^3} \quad (5.13)$$

2789 On the other hand, not every elliptic curve $E(\mathbb{F})$ over base field \mathbb{F} given in short Weierstrass
 2790 form $y^2 = x^3 + ax + b$ can be converted into Montgomery form. For a short Weierstrass curve
 2791 to be a Montgomery curve the following conditions need to hold:

- 2792 • The number of points on $E(\mathbb{F})$ is divisible by 4
- 2793 • The polynomial $z^3 + az + b \in \mathbb{F}[z]$ has at least one root $z_0 \in \mathbb{F}$
- 2794 • $3z_0^2 + a$ is a quadratic residue in \mathbb{F}^* .

2795 When these conditions are satisfied, then for $s = (\sqrt{3z_0^2 + a})^{-1}$, a Montgomery curve is
 2796 defined by the following equation:

$$sy^2 = x^3 + (3z_0s)x^2 + x \quad (5.14)$$

2797 In the following example we will look at the tiny-jubjub curve again, and show that it is
 2798 actually a Montgomery curve.

2799 *Example 79.* Consider the prime field \mathbb{F}_{13} and the tiny-jubjub curve TJJ_13 from example 69.
 2800 To see that it is a Montgomery curve, we have to check the requirements from 5.2:

Since the order of TJJ_13 is 20, which is divisible by 4, the first requirement is met. Moreover, since $a = 8$ and $b = 8$, we have to check that the polynomial $P(z) = z^3 + 8z + 8$ has a root in \mathbb{F}_{13} . To see this we simply evaluate P at all numbers $z \in \mathbb{F}_{13}$, and find that $P(4) = 0$, so a root is given by $z_0 = 4$. In the last step, we have to check that $3 \cdot z_0^2 + a$ has a root in \mathbb{F}_{13}^* . We compute as follows:

$$\begin{aligned} 3z_0^2 + a &= 3 \cdot 4^2 + 8 \\ &= 3 \cdot 3 + 8 \\ &= 9 + 8 \\ &= 4 \end{aligned}$$

2801 To see that 4 is a quadratic residue in \mathbb{F}_{13} , we use Euler's criterion (4.32) to compute the
 2802 Legendre symbol of 4. We get the following:

$$\left(\frac{4}{13} \right) = 4^{\frac{13-1}{2}} = 4^6 = 1$$

2803 This means that 4 does have a root in \mathbb{F}_{13} . In fact, computing a root of 4 in \mathbb{F}_{13} is easy, since
 2804 the integer root 2 of 4 is also one of its roots in \mathbb{F}_{13} . The other root is given by $13 - 4 = 9$.

Since all requirements are met, we have shown that TJJ_13 is indeed a Montgomery curve, and we can use 5.14 to compute its associated Montgomery form. We compute as follows:

$$\begin{aligned} s &= \left(\sqrt{3 \cdot z_0^2 + 8} \right)^{-1} \\ &= 2^{-1} && \# \text{ Fermat's little theorem} \\ &= 2^{13-2} && \# 2048 \bmod 13 = 7 \\ &= 7 \end{aligned}$$

The defining equation for the Montgomery form of the tiny-jubjub curve is then given by the following equation:

$$\begin{aligned} sy^2 &= x^3 + (3z_0s)x^2 + x && \Rightarrow \\ 7 \cdot y^2 &= x^3 + (3 \cdot 4 \cdot 7)x^2 + x && \Leftrightarrow \\ 7 \cdot y^2 &= x^3 + 6x^2 + x \end{aligned}$$

2805 So, we get the defining parameters as $B = 7$ and $A = 6$, and we can write the tiny-jubjub curve
2806 in its affine Montgomery representation as follows:

$$TJJ_13 = \{(x, y) \in \mathbb{F}_{13} \times \mathbb{F}_{13} \mid 7 \cdot y^2 = x^3 + 6x^2 + x\} \cup \{\mathcal{O}\} \quad (5.15)$$

Now that we have the abstract definition of the tiny-jubjub curve in Montgomery form, we can compute the set of points by inserting all pairs $(x, y) \in \mathbb{F}_{13} \times \mathbb{F}_{13}$ similarly to how we computed the curve points in its short Weierstrass representation. We get the following:

$$M_TJJ_13 = \{\mathcal{O}, (0, 0), (1, 4), (1, 9), (2, 4), (2, 9), (3, 5), (3, 8), (4, 4), (4, 9), (5, 1), (5, 12), (7, 1), (7, 12), (8, 1), (8, 12), (9, 2), (9, 11), (10, 3), (10, 10)\}$$

2807

```

2808 sage: F13 = GF(13)                                     322
2809 sage: L_MTJJ = []                                       323
2810 .....: for x in F13:                                     324
2811 .....:     for y in F13:                                 325
2812 .....:         if F13(7)*y^2 == x^3 + F13(6)*x^2 + x:  326
2813 .....:             L_MTJJ.append((x, y))                327
2814 sage: MTJJ = Set(L_MTJJ)                                328
2815 sage: # does not compute the point at infinity          329

```

2816 *Exercise 69.* Consider example 79 and compute the set ?? by inserting every pair of field ele-
2817 ments $(x, y) \in \mathbb{F}_{13} \times \mathbb{F}_{13}$ into the defining Montgomery equation.

2818 *Exercise 70.* Consider the elliptic curve $E_1(\mathbb{F})$ from example 68 and show that $E_1(\mathbb{F})$ is not a
2819 Montgomery curve.

2820 *Exercise 71.* Consider the elliptic curve *secp256k1* from example 70 and show that *secp256k1*
2821 is not a Montgomery curve.

2822 **Affine Montgomery coordinate transformation** Comparing the Montgomery representa-
2823 tion of the previous example 5.15 with the short Weierstrass representation of the same curve
2824 5.2, we see that there is a 1:1 correspondence between the curve points in both examples. This
2825 is no accident. In fact, if $M_{A,B}$ is a Montgomery curve, and $E_{a,b}$ a short Weierstrass curve with
2826 $a = \frac{3-A^2}{3B^2}$ and $b = \frac{2A^2-9A}{27B^3}$ then the following function maps all points in Montgomery represen-
2827 tation onto the points in short Weierstrass representation:

$$I : M_{A,B} \rightarrow E_{a,b} : (x, y) \mapsto \left(\frac{3x+A}{3B}, \frac{y}{B} \right) \quad (5.16)$$

2828 The point at infinity of the Montgomery form is mapped to the point at infinity of the short
2829 Weierstrass form. This map is a 1:1 correspondence (an isomorphism), and its inverse map is

2830 given by the following equation (where z_0 is a root of the polynomial $z^3 + az + b \in \mathbb{F}[z]$ and
 2831 $s = (\sqrt{3z_0^2 + a})^{-1}$).

$$I^{-1} : E_{a,b} \rightarrow M_{A,B} : (x, y) \mapsto (s \cdot (x - z_0), s \cdot y) \quad (5.17)$$

2832 The point at infinity of the short Weierstrass form is mapped to the point at infinity of the
 2833 Montgomery form. Using this map, it is therefore possible for implementations of Montgomery
 2834 curves to freely transit between the short Weierstrass and the Montgomery form.

2835 *Example 80.* Consider the tiny-jubjub curve again. In 5.2 we defined its short Weierstrass
 2836 representation and in example 5.15, we derived its Montgomery representation.

To see how the coordinate transformation I works in this example, let's map points from the Montgomery representation onto points from the short Weierstrass representation. Inserting, for example, the point $(0, 0)$ from the Montgomery representation 5.15 into I gives the following:

$$\begin{aligned} I(0, 0) &= \left(\frac{3 \cdot 0 + A}{3B}, \frac{0}{B} \right) \\ &= \left(\frac{3 \cdot 0 + 6}{3 \cdot 7}, \frac{0}{7} \right) \\ &= \left(\frac{6}{8}, 0 \right) \\ &= (4, 0) \end{aligned}$$

As we can see, the Montgomery point $(0, 0)$ maps to the self-inverse point $(4, 0)$ of the short Weierstrass representation. On the other hand, we can use our computations of $s = 7$ and $z_0 = 4$ from example 79 to compute the inverse map I^{-1} , which maps points on the short Weierstrass representation to points on the Montgomery form. Inserting, for example, $(4, 0)$ we get the following:

$$\begin{aligned} I^{-1}(4, 0) &= (s \cdot (4 - z_0), s \cdot 0) \\ &= (7 \cdot (4 - 4), 0) \\ &= (0, 0) \end{aligned}$$

2837 As expected, the inverse map maps the short Weierstrass point back to where it originated
 2838 in the Montgomery form. We can invoke Sage to check that our computation of I is correct:

```

2839 sage: # Compute I of Montgomery form: 330
2840 sage: L_I_MTJJ = [] 331
2841 sage: for (x,y) in L_MTJJ: # LMTJJ as defined previously 332
2842     ....:     v = (F13(3)*x + F13(6))/(F13(3)*F13(7)) 333
2843     ....:     w = y/F13(7) 334
2844     ....:     L_I_MTJJ.append((v,w)) 335
2845 sage: I_MTJJ = Set(L_I_MTJJ) 336
2846 sage: # Computation short Weierstrass form 337
2847 sage: C_WTJJ = EllipticCurve(F13,[8,8]) 338
2848 sage: L_WTJJ = [P.xy() for P in C_WTJJ.points() if P.order() > 339
2849     1]
2850 sage: WTJJ = Set(L_WTJJ) 340
```

```

2851 sage: # check I(Montgomery) == Weierstrass 341
2852 sage: WTJJ == I_MTJJ 342
2853 True 343
2854 sage: # check the inverse map I^(-1) 344
2855 sage: L_IINV_WTJJ = [] 345
2856 sage: for (v,w) in L_WTJJ: 346
2857     ....:     x = F13(7)*(v-F13(4)) 347
2858     ....:     y = F13(7)*w 348
2859     ....:     L_IINV_WTJJ.append((x,y)) 349
2860 sage: IINV_WTJJ = Set(L_IINV_WTJJ) 350
2861 sage: MTJJ == IINV_WTJJ 351
2862 True 352

```

2863 5.2.1 Montgomery group law

2864 We have seen that Montgomery curves are special cases of short Weierstrass curves. As such,
 2865 they have a group structure defined on the set of their points, which can also be derived from the
 2866 chord-and-tangent rule. In accordance with short Weierstrass curves, it can be shown that the
 2867 identity $x_1 = x_2$ implies $y_2 = \pm y_1$, meaning that the following rules are a complete description
 2868 of the elliptic curve group law:

- 2869 • (The neutral element) The point at infinity \mathcal{O} is the neutral element.
- 2870 • (The inverse element) The inverse of \mathcal{O} is \mathcal{O} . For any other curve point $(x, y) \in M(\mathbb{F}_q) \setminus \{\mathcal{O}\}$,
 2871 the inverse is given by $(x, -y)$.
- 2872 • (The group law) For any two curve points $P, Q \in M(\mathbb{F}_q)$, the group law is defined by one
 2873 of the following cases:

- 2874 1. (Neutral element) If $Q = \mathcal{O}$, then the sum is defined as $P \oplus Q = P$.
- 2875 2. (Inverse elements) If $P = (x, y)$ and $Q = (x, -y)$, the group law is defined as $P \oplus Q =$
 2876 \mathcal{O} .
- 2877 3. (Tangent rule) If $P = (x, y)$ with $y \neq 0$, the group law $P \oplus P = (x', y')$ is defined as
 2878 follows:

$$x' = \left(\frac{3x_1^2 + 2Ax_1 + 1}{2By_1}\right)^2 \cdot B - (x_1 + x_2) - A, \quad y' = \frac{3x_1^2 + 2Ax_1 + 1}{2By_1}(x_1 - x') - y_1$$

- 2879 4. (Chord rule) If $P = (x_1, y_1)$ and $Q = (x_2, y_2)$ such that $x_1 \neq x_2$, the group law $R =$
 2880 $P \oplus Q$ with $R = (x_3, y_3)$ is defined as follows:

$$x' = \left(\frac{y_2 - y_1}{x_2 - x_1}\right)^2 B - (x_1 + x_2) - A, \quad y' = \frac{y_2 - y_1}{x_2 - x_1}(x_1 - x') - y_1$$

2877 *Exercise 72.* Consider the commutative group (M_TJJ_13, \oplus) of the Tiny-jubjub-curve in its
 2878 Montgomery form from example ??.

- 2879 1. Compute the inverse of $(1, 9)$, \mathcal{O} , $(7, 12)$ and $(4, 9)$.
- 2880 2. Solve the equation $x \oplus (3, 8) = (10, 3)$ for some $x \in M_TJJ_13$

2881 Choose some element $x \in M_TJJ_13$ and test if x is a generator of M_TJJ_13 . If x is not a
 2882 generator repeat until you find some generator x . Write M_TJJ_13 in logarithmic order with
 2883 respect to x .

5.3 Twisted Edwards Curves

As we have seen in 5.1.2 and 5.2.1 both short Weierstrass and Montgomery curves have somewhat complicated group laws, as many cases have to be distinguished. Cases which translate to branches in computer programs. However in the context of SNARK development, computational models for bounded computations are used 6.2.2, 6.2.1 in which program branches are undesirably costly. To make elliptic curves "SNARK friendly", it is therefore advantageous to look for curves with a group law that requires no branches and utilizes as few field operations as possible.

So called **Snark friendly Twisted Edwards curves** are particularly useful here, as these curves have a compact and easily implementable group law that works for all points including the point at infinity. Implementing this law needs no branching.

To see what a **twisted Edwards curve** in its affine form looks like, let \mathbb{F} be a finite field of characteristic > 3 , and let $a, d \in \mathbb{F} \setminus \{0\}$ be two non-zero field elements with $a \neq d$. A **twisted Edwards elliptic curve** in its affine representation is then the set of all pairs (x, y) from $\mathbb{F} \times \mathbb{F}$ that satisfy the twisted Edwards equation $a \cdot x^2 + y^2 = 1 + d \cdot x^2 y^2$:

$$E(\mathbb{F}) = \{(x, y) \in \mathbb{F} \times \mathbb{F} \mid a \cdot x^2 + y^2 = 1 + d \cdot x^2 y^2\} \quad (5.18)$$

A twisted Edwards curve is called a **SNARK-friendly twisted Edwards curve** if the parameter a is a quadratic residue and the parameter d is a quadratic non-residue.

As we can see from the definition, affine twisted Edwards curves look somewhat different from short Weierstrass curves, as their affine representation does not need a special symbol to represent the point at infinity. In fact, the pair $(0, 1)$ is always a point on any twisted Edwards curve, and it takes the role of the point at infinity.

Despite their different appearances however, twisted Edwards curves are equivalent to Montgomery curves in the sense that, for every twisted Edwards curve, there is a Montgomery curve, and a way to map the points of one curve in a 1:1 correspondence onto the other and vice versa. To see that, assume that a curve in twisted Edwards form is given. The associated Montgomery curve is then defined by the Montgomery equation:

$$\frac{4}{a-d} y^2 = x^3 + \frac{2(a+d)}{a-d} \cdot x^2 + x \quad (5.19)$$

On the other hand, a Montgomery curve $By^2 = x^3 + Ax^2 + x$ with $B \neq 0$ and $A^2 \neq 4$ gives rise to a twisted Edwards curve defined by the following equation:

$$\left(\frac{A+2}{B}\right)x^2 + y^2 = 1 + \left(\frac{A-2}{B}\right)x^2 y^2 \quad (5.20)$$

Example 81. Consider the tiny-jubjub curve from example 69 again. We know from example 79 that it is a Montgomery curve, and, since Montgomery curves are equivalent to twisted Edwards curves, we want to write this curve in twisted Edwards form. We use equation 5.20 and compute

the parameters a and d as follows:

$$\begin{aligned} a &= \frac{A+2}{B} && \# \text{ insert } A=6 \text{ and } B=7 \\ &= \frac{8}{7} = 3 && \# 7^{-1} = 2 \\ \\ d &= \frac{A-2}{B} \\ &= \frac{4}{7} = 8 \end{aligned}$$

Thus, we get the defining parameters as $a = 3$ and $d = 8$. Since our goal is to use this curve later on in implementations of pen-and-paper SNARKs, let us show that tiny-jubjub is also a SNARK-friendly twisted Edwards curve. To see that, we have to show that a is a quadratic residue and d is a quadratic non-residue. We therefore compute the Legendre symbols of a and d using Euler's criterion. We get the following:

$$\begin{aligned} \left(\frac{3}{13} \right) &= 3^{\frac{13-1}{2}} \\ &= 3^6 = 1 \end{aligned}$$

$$\begin{aligned} \left(\frac{8}{13} \right) &= 8^{\frac{13-1}{2}} \\ &= 8^6 = 12 = -1 \end{aligned}$$

2912 This proves that tiny-jubjub is SNARK-friendly. We can write the tiny-jubjub curve in its
2913 affine twisted Edwards representation as follows:

$$TJJ_{13} = \{(x, y) \in \mathbb{F}_{13} \times \mathbb{F}_{13} \mid 3 \cdot x^2 + y^2 = 1 + 8 \cdot x^2 \cdot y^2\} \quad (5.21)$$

2914 Now that we have the abstract definition of our tiny-jubjub curve in twisted Edwards form,
2915 we can compute the set of points by inserting all pairs $(x, y) \in \mathbb{F}_{13} \times \mathbb{F}_{13}$, similarly to how
2916 we computed the curve points in its short Weierstrass or Edwards representation. We get the
2917 following:

$$\begin{aligned} TE_TJJ_{13} &= \{(0, 1), (0, 12), (1, 2), (1, 11), (2, 6), (2, 7), (3, 0), (5, 5), (5, 8), (6, 4), \\ &\quad (6, 9), (7, 4), (7, 9), (8, 5), (8, 8), (10, 0), (11, 6), (11, 7), (12, 2), (12, 11)\} \end{aligned} \quad (5.22)$$

2918

```

2919 sage: F13 = GF(13)                                     353
2920 sage: L_ETJJ = []                                       354
2921 ....: for x in F13:                                     355
2922 ....:     for y in F13:                                 356
2923 ....:         if F13(3)*x^2 + y^2 == 1+ F13(8)*x^2*y^2: 357
2924 ....:             L_ETJJ.append((x, y))                 358
2925 sage: ETJJ = Set(L_ETJJ)                               359

```

5.3.1 Twisted Edwards group law

As we have seen, twisted Edwards curves are equivalent to Montgomery curves, and, as such, also have a group law. However, in contrast to Montgomery and short Weierstrass curves, the group law of SNARK-friendly twisted Edwards curves can be described by a single computation that works in all cases, no matter if we add the neutral element, the inverse, or if we have to double a point.

To see what the twisted Edwards group law looks like let $(x_1, y_1), (x_2, y_2)$ be two points on an Edwards curve $E(\mathbb{F})$. The sum of those points is then given by the following equation:

$$(x_1, y_1) \oplus (x_2, y_2) = \left(\frac{x_1 y_2 + y_1 x_2}{1 + d x_1 x_2 y_1 y_2}, \frac{y_1 y_2 - a x_1 x_2}{1 - d x_1 x_2 y_1 y_2} \right) \quad (5.23)$$

In order to see what the neutral element of the group law is, first observe that the point $(0, 1)$ is a solution to the twisted Edwards equation $a \cdot x^2 + y^2 = 1 + d \cdot x^2 \cdot y^2$ for any parameters a and d and hence $(0, 1)$ is a point on any twisted Edwards curve. It can be shown that $(0, 1)$ serves as the neutral element and that the inverse of a point (x_1, y_1) is given by the point $(-x_1, y_1)$.

Example 82. Lets look at the tiny-jubjub curve in Edwards form from example 5.21 again. As we have seen, this curve is given by

$$TE_TJJ_13 = \{(0, 1), (0, 12), (1, 2), (1, 11), (2, 6), (2, 7), (3, 0), (5, 5), (5, 8), (6, 4), (6, 9), (7, 4), (7, 9), (8, 5), (8, 8), (10, 0), (11, 6), (11, 7), (12, 2), (12, 11)\}$$

To get an understanding of the twisted Edwards addition law, let's first add the neutral element $(0, 1)$ to itself. We apply the group law 5.23 and get the following:

$$\begin{aligned} (0, 1) \oplus (0, 1) &= \left(\frac{0 \cdot 1 + 1 \cdot 0}{1 + 8 \cdot 0 \cdot 0 \cdot 1 \cdot 1}, \frac{1 \cdot 1 - 3 \cdot 0 \cdot 0}{1 - 8 \cdot 0 \cdot 0 \cdot 1 \cdot 1} \right) \\ &= (0, 1) \end{aligned}$$

So, as expected, the neutral element added to itself gives the neutral element again. Now let's add the neutral element to some other curve point. We get the following:

$$\begin{aligned} (0, 1) \oplus (8, 5) &= \left(\frac{0 \cdot 5 + 1 \cdot 8}{1 + 8 \cdot 0 \cdot 8 \cdot 1 \cdot 5}, \frac{1 \cdot 5 - 3 \cdot 0 \cdot 8}{1 - 8 \cdot 0 \cdot 8 \cdot 1 \cdot 5} \right) \\ &= (8, 5) \end{aligned}$$

Again, as expected, adding the neutral element to any element will result in that element again. Given any curve point (x, y) , we know that its inverse is given by $(-x, y)$. To see how the addition of a point to its inverse works, we compute as follows:

$$\begin{aligned} (5, 5) \oplus (8, 5) &= \left(\frac{5 \cdot 5 + 5 \cdot 8}{1 + 8 \cdot 5 \cdot 8 \cdot 5 \cdot 5}, \frac{5 \cdot 5 - 3 \cdot 5 \cdot 8}{1 - 8 \cdot 5 \cdot 8 \cdot 5 \cdot 5} \right) \\ &= \left(\frac{12 + 1}{1 + 5}, \frac{12 - 3}{1 - 5} \right) \\ &= \left(\frac{0}{6}, \frac{12 + 10}{1 + 8} \right) \\ &= \left(0, \frac{9}{9} \right) \\ &= (0, 1) \end{aligned}$$

Adding a curve point to its inverse gives the neutral element, as expected. As we have seen from these examples, the twisted Edwards addition law handles edge cases particularly well and in a unified way.

Exercise 73. Consider the commutative group (TE_TJJ_13, \oplus) from example 82.

1. Compute the inverse of $(1, 11)$, $(0, 1)$, $(3, 0)$ and $(5, 8)$.

2. Solve the equation $x \oplus (5, 8) = (1, 11)$ for some $x \in TE_TJJ_13$

Choose some element $x \in TE_TJJ_13$ and test if x is a generator of TE_TJJ_13 . If x is not a generator repeat until you find some generator x . Write TE_TJJ_13 in logarithmic order with respect to x .

5.4 Elliptic Curve Pairings

As introduced in 4.6, some groups come with the notion of a pairing map. In this section, we discuss **pairings on elliptic curves**, which form the basis of several zk-SNARKs and other zero-knowledge proof schemes, essentially because it allows computations "in the exponent" to be split into different parts computable by different parties.

We start out by defining some important subgroups of the so called full torsion group of an elliptic curve. We then introduce the Weil pairing of an elliptic curve and describe Miller's algorithm, which makes these pairings efficiently computable.

Embedding Degrees As we will see in what follows, every elliptic curve gives rise to a pairing map. However, we will also see in example 85 that not every such pairing can be efficiently computed. In order to distinguish curves with efficiently computable pairings from the rest, we need to start with an introduction to the so-called **embedding degree** of a curve.

To see what the embedding degree of an elliptic curve is, let \mathbb{F} be a finite field of order $|\mathbb{F}| = q$, $E(\mathbb{F})$ an elliptic curve over \mathbb{F} , and let r be a prime factor of the order n of $E(\mathbb{F})$. The embedding degree of $E(\mathbb{F})$ with respect to r is then the smallest integer k such that

$$r \mid q^k - 1 \quad (5.24)$$

Fermat's little theorem 3.3 implies that there always exists an embedding degree $k(r)$ for every elliptic curve and any factor r of the curves order n , since $k = r - 1$ is always a solution to the congruency $q^k \equiv 1 \pmod{r}$. This implies that the remainder of the integer division of $q^{r-1} - 1$ by r is 0.

Notation and Symbols 12. Let \mathbb{F} be a finite field of order q and $E(\mathbb{F})$ an elliptic curve over \mathbb{F} , such that r is a prime factor of the order of $E(\mathbb{F})$. We then write $k(r)$ for the embedding degree of $E(\mathbb{F})$ with respect to r .

Example 83. To get a better intuition of the embedding degree, let's consider the elliptic curve $E_{1,1}(\mathbb{F}_5)$ from example 68. We know that the order of $E_{1,1}(\mathbb{F}_5)$ is 9, and, since the only prime factor of 9 is 3, we compute the embedding degree of $E_{1,1}(\mathbb{F}_5)$ with respect to 3.

To find the embedding degree, we have to find the smallest integer k such that 3 divides $q^k - 1 = 5^k - 1$. We try and increment until we find a proper k .

$$k = 1 : 5^1 - 1 = 4$$

not divisible by 3

$$k = 2 : 5^2 - 1 = 24$$

divisible by 3

2974 This shows that the embedding degree of the elliptic curve $E_{1,1}(\mathbb{F}_5)$ is 2 relative to the the
 2975 prime factor 3 of the order of $E_{1,1}(\mathbb{F}_5)$.

2976 *Example 84.* Let us consider the tiny-jubjub curve *TJJ_13* from example 69. We know that the
 2977 order of *TJJ_13* is 20, and that the order therefore has two prime factors. A “large” prime factor
 2978 5 and a small prime factor 2.

We start by computing the embedding degree of *TJJ_13* with respect to the large prime factor 5. To find that embedding degree, we have to find the smallest integer k such that 5 divides $q^k - 1 = 13^k - 1$. We try and increment until we find a proper k .

$k = 1: 13^1 - 1 = 12$	not divisible by 5
$k = 2: 13^2 - 1 = 168$	not divisible by 5
$k = 3: 13^3 - 1 = 2196$	not divisible by 5
$k = 4: 13^4 - 1 = 28560$	divisible by 5

2979 Now we know that the embedding degree of *TJJ_13* relative to the the prime factor 5 is $k(5) = 4$.

2980 In real-world applications, like on pairing-friendly elliptic curves such as BLS_12-381, usu-
 2981 ally only the embedding degree of the large prime factor is relevant, which in the case of our
 2982 tiny-jubjub curve is represented by 5. It should be noted, however that every prime factor of
 2983 a curve’s order has its own notation of embedding degree despite the fact that this is mostly
 2984 irrelevant in applications.

To find the embedding degree of the small prime factor 2, we have to find the smallest integer k such that 2 divides $q^k - 1 = 13^k - 1$. We try and increment until we find a proper k .

$k = 1: 13^1 - 1 = 12$	divisible by 2
------------------------	----------------

2985 Now we know that the embedding degree of *TJJ_13* is 1 relative to the the prime factor 2.

2986 As we have seen, different prime factors can have different embedding degrees in general.

```

2987 sage: p = ZZ(13)                                     360
2988 sage: # large prime factor                             361
2989 sage: r = ZZ(5)                                       362
2990 sage: k = ZZ(1)                                       363
2991 sage: while k < r: # Fermat's little theorem           364
2992     ....:     if (p^k-1)%r == 0:                       365
2993     ....:         break                                 366
2994     ....:         k=k+1                                367
2995 sage: k                                               368
2996 4                                                     369
2997 sage: # small prime factor                             370
2998 sage: r = ZZ(2)                                       371
2999 sage: k = ZZ(1)                                       372
3000 sage: while k < r: # Fermat's little theorem           373
3001     ....:     if (p^k-1)%r == 0:                       374
3002     ....:         break                                 375
3003     ....:         k=k+1                                376
3004 sage: k                                               377
3005 1                                                     378

```

3006 *Example 85.* To give an example of a cryptographically secure real-world elliptic curve that
 3007 does not have a small embedding degree, let's look at curve secp256k1 again. We know from
 3008 70 that the order of this curve is a prime number, so we only have a single embedding degree.

3009 To test potential embedding degrees k , say, in the range $1 \leq k < 1000$, we can invoke Sage
 3010 and compute as follows:

```

3011 sage: p = ZZ(1157920892373161954235709850086879078532699846656 379
3012         40564039457584007908834671663)
3013 sage: r = ZZ(1157920892373161954235709850086879078528375642790 380
3014         74904382605163141518161494337)
3015 sage: k = ZZ(1) 381
3016 sage: while k < 1000: 382
3017     ....:     if (p^k-1)%r == 0: 383
3018     ....:         break 384
3019     ....:     k=k+1 385
3020 sage: k 386
3021 1000 387

```

3022 We see that secp256k1 has at least no embedding degree $k < 1000$, which renders secp256k1 a
 3023 curve that has no small embedding degree. This property will be of importance later on.

3024 **Elliptic Curves over extension fields** Suppose that p is a prime number, and \mathbb{F}_p its associated
 3025 prime field. We know from equation 4.33 that the fields \mathbb{F}_{p^m} are extensions of \mathbb{F}_p in the sense
 3026 that \mathbb{F}_p is a subfield of \mathbb{F}_{p^m} . This implies that we can extend the affine plane that an elliptic
 3027 curve is defined on by changing the base field to any extension field. To be more precise, let
 3028 $E(\mathbb{F}) = \{(x, y) \in \mathbb{F} \times \mathbb{F} \mid y^2 = x^3 + a \cdot x + b\}$ be an affine short Weierstrass curve, with parameters
 3029 a and b taken from \mathbb{F} . If \mathbb{F}' is an extension field of \mathbb{F} , then we extend the domain of the curve
 3030 by defining $E(\mathbb{F}')$ as follows:

$$E(\mathbb{F}') = \{(x, y) \in \mathbb{F}' \times \mathbb{F}' \mid y^2 = x^3 + a \cdot x + b\} \quad (5.25)$$

3031 While we did not change the defining parameters, we consider curve points from the affine
 3032 plane over the extension field now. Since $\mathbb{F} \subset \mathbb{F}'$, it can be shown that the original elliptic curve
 3033 $E(\mathbb{F})$ is a sub-curve of the extension curve $E(\mathbb{F}')$.

Example 86. Consider the prime field \mathbb{F}_5 from example 62 together with the elliptic curve
 $E_{1,1}(\mathbb{F}_5)$ and its definition from example 68 and the construction the extension field \mathbb{F}_{5^2} relative
 to the polynomial $t^2 + 2 \in \mathbb{F}_5[t]$ from exercise 55. In this example we extend the definition of
 $E_{1,1}(\mathbb{F}_5)$ to an elliptic curve over \mathbb{F}_{5^2} and compute its set of points:

$$E_1(\mathbb{F}_{5^2}) = \{(x, y) \in \mathbb{F}_{5^2} \times \mathbb{F}_{5^2} \mid y^2 = x^3 + x + 1\}$$

3034 Since \mathbb{F}_{5^2} contains 25 points, in order to compute the set $E_1(\mathbb{F}_{5^2})$, we have to try $25 \cdot 25 = 625$
 3035 pairs, which is probably a bit tedious. Instead, we invoke Sage to compute the curve for us. To
 3036 do, we choose the representation of \mathbb{F}_{5^2} from 55. We get:

```

3037 sage: F5= GF(5) 388
3038 sage: F5t.<t> = F5[] 389
3039 sage: P_MOD_2 = F5t(t^2+2) 390
3040 sage: P_MOD_2.is_irreducible() 391
3041 True 392

```

TODO:Rewri
 intro
 together
 with Sven

```

3042 sage: F5_2.<t> = GF(5^2, name='t', modulus=P_MOD_2)          393
3043 sage: E1F5_2 = EllipticCurve(F5_2, [1, 1])                  394
3044 sage: E1F5_2.order()                                         395
3045 27                                                            396

```

The curve $E_1(\mathbb{F}_{5^2})$ consist of 27 points, in contrast to curve $E_1(\mathbb{F}_5)$, which consists of 9 points. Writing those points down gives the following:

$$\begin{aligned}
 E_1(\mathbb{F}_{5^2}) = \{ & \mathcal{O}, (0, 4), (0, 1), (3, 4), (3, 1), (4, 3), (4, 2), (2, 4), (2, 1), \\
 & (4t + 3, 3t + 4), (4t + 3, 2t + 1), (3t + 2, t), (3t + 2, 4t), \\
 & (2t + 2, t), (2t + 2, 4t), (2t + 1, 4t + 4), (2t + 1, t + 1), \\
 & (2t + 3, 3), (2t + 3, 2), (t + 3, 2t + 4), (t + 3, 3t + 1), \\
 & (3t + 1, t + 4), (3t + 1, 4t + 1), (3t + 3, 3), (3t + 3, 2), (1, 4t), (1, t) \}
 \end{aligned}$$

3046 As we can see, the set of points from the elliptic curve $E_{1,1}(\mathbb{F}_5)$ is a subset of the sets of points
 3047 from the elliptic curve $E(\mathbb{F}_{5^2})$. This was expected since the prime field \mathbb{F}_5 is a subfield of the
 3048 finite field \mathbb{F}_{5^2} .

3049 *Exercise 74.* Consider the short Weierstrass elliptic curve $E(\mathbb{F}_{5^2})$ from example 86, compute the
 3050 expression $(4t + 3, 2t + 1) \oplus (3t + 3, 2)$ using pen and paper and double check the computation
 3051 using sage. Then solve the equation $x \oplus (3t + 3, 3) = (3, 4)$ for some $x \in E(\mathbb{F}_{5^2})$. After that
 3052 compute the scalar multiplication $[5](2t + 1, 4t + 4)$ using the double-and-add algorithm from
 3053 exercise 37.

3054 *Exercise 75.* Consider the tiny-jubjub curve from example 69. Show that the polynomial $t^4 +$
 3055 $2 \in \mathbb{F}_{13}[t]$ is irreducible. Then write a sage program to implement the finite field extension \mathbb{F}_{13^4} ,
 3056 implement the curve extension $TJJ_{13}(\mathbb{F}_{13^4})$ and compute the number of curve points.

3057 **Full torsion groups** As we will see in what follows, cryptographically interesting pairings
 3058 are defined on so called torsion subgroups of elliptic curves. To define **torsion groups** of an
 3059 elliptic curve, let \mathbb{F} be a finite field, $E(\mathbb{F})$ an elliptic curve of order n and r a factor of n . Then
 3060 the **r -torsion group** of the elliptic curve $E(\mathbb{F})$ is defined as the set

$$E(\mathbb{F})[r] := \{P \in E(\mathbb{F}) \mid [r]P = \mathcal{O}\} \quad (5.26)$$

3061 The fundamental theorem of finite cyclic groups 4.1 states that every factor r of a cyclic group's
 3062 order uniquely defines a subgroup of the size of that factor and those subgroup are important
 3063 examples of r -torsion groups. We have seen examples of those subgroups in 76 and 77.

3064 When we consider elliptic curve extensions as defined in 5.25, we could ask what happens
 3065 to the r -torsion groups in the extension. One might intuitively think that their extension just
 3066 parallels the extension of the curve. For example, when $E(\mathbb{F}_p)$ is a curve over prime field \mathbb{F}_p ,
 3067 with some r -torsion group $E(\mathbb{F}_p)[r]$ and when we extend the curve to $E(\mathbb{F}_{p^m})$, then there might
 3068 be a bigger r -torsion group $E(\mathbb{F}_{p^m})[r]$ such that $E(\mathbb{F}_p)[r]$ is a subgroup of $E(\mathbb{F}_{p^m})[r]$. This might
 3069 make intuitive sense, as $E(\mathbb{F}_p)$ is a subset of $E(\mathbb{F}_{p^m})$.

3070 However, the actual situation is a bit more surprising than that. To see that, let \mathbb{F}_p be a
 3071 prime field and let $E(\mathbb{F}_p)$ be an elliptic curve of order n , such that r is a factor of n , with
 3072 embedding degree $k(r)$ and r -torsion group $E(\mathbb{F}_p)[r]$. Then the r -torsion group $E(\mathbb{F}_{p^m})[r]$ of a
 3073 curve extension is equal to $E(\mathbb{F}_p)[r]$, only as long as the power m is less than the embedding
 3074 degree $k(r)$ of $E(\mathbb{F}_p)$.

For the prime power $p^{k(r)}$, the r -torsion group $E(\mathbb{F}_{p^{k(r)}})[r]$ might then be larger than $E(\mathbb{F}_p)[r]$ and it contains $E(\mathbb{F}_p)[r]$ as a subgroup. We call it the **full r -torsion group** of that elliptic curve and write it as follows

$$E[r] := E(\mathbb{F}_{p^{k(r)}})[r] \quad (5.27)$$

The r -torsion groups $E(\mathbb{F}_{p^m})[r]$ of any curve extensions for $m > k(r)$ are all equal to $E[r]$. In this sense $E[r]$ is already the largest r -torsion group, which justifies the name. The full r -torsion group contains r^2 many elements and consists of $r + 1$ subgroups, one of which is $E(\mathbb{F}_p)[r]$. The following diagram summarizes the situation:

$$\begin{array}{ccccccccccc} E(\mathbb{F}_p) & \subset & \cdots & \subset & E(\mathbb{F}_{p^{k(r)-1}}) & \subset & E(\mathbb{F}_{p^{k(r)}})[r] & \subset & E(\mathbb{F}_{p^{k(r)+1}})[r] & \subset & \cdots \\ E(\mathbb{F}_p)[r] & = & \cdots & = & E(\mathbb{F}_{p^{k(r)-1}})[r] & \subset & E(\mathbb{F}_{p^{k(r)}})[r] & = & E(\mathbb{F}_{p^{k(r)+1}})[r] & = & \cdots \end{array} \quad (5.28)$$

So, when we consider nested elliptic curve extensions as in 5.28, ordered by the prime power m , then the r -torsion group stays constant for every level m that is smaller than the embedding degree $k(r)$, while it suddenly blossoms into a larger group on level $k(r)$ with $r + 1$ subgroups, and then all r -torsion groups on higher levels $m \geq k(r)$ stay the same. In other words, once the extension field is big enough to find one more curve point P with $[r]P = \mathcal{O}$ that is not an element of the curve over the base field, then we actually find all of the points in the full torsion group.

Example 87. Consider curve $E_{1,1}(\mathbb{F}_5)$ again. We know from 76 that it contains a 3-torsion group and that the embedding degree of 3 is $k(3) = 2$. From this we can deduce that we can find the full 3-torsion group $E_1[3]$ in the curve extension $E_1(\mathbb{F}_{5^2})$, the latter of which we computed in example 86.

Since that curve is small, in order to find the full 3-torsion, we can loop through all elements of $E_1(\mathbb{F}_{5^2})$ and check the defining equation $[3]P = \mathcal{O}$. Invoking Sage and using our implementation of $E_1(\mathbb{F}_{5^2})$ in sage from 86, we compute as follows:

```
sage: INF = E1F5_2(0) # Point at infinity          397
sage: L_E1_3 = []                                     398
sage: for p in E1F5_2:                               399
.....:     if 3*p == INF:                             400
.....:         L_E1_3.append(p)                         401
sage: E1_3 = Set(L_E1_3) # Full 3-torsion set        402
```

$$E_1[3] = \{\mathcal{O}, (2, 1), (2, 4), (1, t), (1, 4t), (2t + 1, t + 1), (2t + 1, 4t + 4), (3t + 1, t + 4), (3t + 1, 4t + 1)\}$$

As we can see the group $E_1[3]$ contains $9 = 3^2$ many elements and the 3-torsion group $E_{1,1}(\mathbb{F}_5)[3]$ of the curve over the prime field is a subset of the full torsion group.

Example 88. Consider the tiny-jubjub curve from example 69. We know from example 84 that it contains a 5-torsion group and that the embedding degree of 5 is 4. This implies that we can find the full 5-torsion group $TJJ_13[5]$ in the curve extension $TJJ_13(\mathbb{F}_{13^4})$.

To compute the full torsion, first observe that, since \mathbb{F}_{13^4} contains 28561 elements, computing $TJJ_13(\mathbb{F}_{13^4})$ means checking $28561^2 = 815730721$ elements. From each of these curve points P , we then have to check the equation $[5]P = \mathcal{O}$. Doing this for 815730721 is a bit too slow even on a computer.

Fortunately, Sage has a function that computes all points P , such that $[m]P = Q$ for given integer m and curve point Q . Using the curve extension from exercise 75, the following Sage code provides a way to compute the full torsion group:

```
sage: # define the extension field          403
```

```

3114 sage: F13= GF(13) # prime field 404
3115 sage: F13t.<t> = F13[] # polynomials over t 405
3116 sage: P_MOD_4 = F13t(t^4+2) # degree 4 irreducible polynomial 406
3117 sage: P_MOD_4.is_irreducible() 407
3118 True 408
3119 sage: F13_4.<t> = GF(13^4, name='t', modulus=P_MOD_4) 409
3120 sage: TJJF13_4 = EllipticCurve(F13_4, [8,8]) # TJJ extension 410
3121 sage: # compute the full 5-torsion 411
3122 sage: INF = TJJF13_4(0) # point at infinity 412
3123 sage: L_TJJF13_4_5 = INF.division_points(5) # [5]P == INF 413
3124 sage: TJJF13_4_5 = Set(L_TJJF13_4_5) 414
3125 sage: TJJF13_4_5.cardinality() # number of elements 415
3126 25 416

```

3127 As expected, we get a group that contains $5^2 = 25$ elements. To see that the embedding degree 4
3128 is actually the smallest prime power to find the full 5-torsion group, let's compute the 5-torsion
3129 group over of the tiny-jubjub curve of the extension field \mathbb{F}_{13^3} . We get the following:

```

3130 sage: # define the extension field 417
3131 sage: P_MOD_3 = F13t(t^3+2) # degree 3 irreducible polynomial 418
3132 sage: P_MOD_3.is_irreducible() 419
3133 True 420
3134 sage: F13_3.<t> = GF(13^3, name='t', modulus=P_MOD_3) 421
3135 sage: TJJF13_3 = EllipticCurve(F13_3, [8,8]) # TJJ extension 422
3136 sage: # compute the 5-torsion 423
3137 sage: INF = TJJF13_3(0) 424
3138 sage: L_TJJF13_3_5 = INF.division_points(5) # [5]P == INF 425
3139 sage: TJJF13_3_5 = Set(L_TJJF13_3_5) # 5$-torsion 426
3140 sage: TJJF13_3_5.cardinality() # number of elements 427
3141 5 428

```

3142 As we can see, the 5-torsion group of tiny-jubjub over \mathbb{F}_{13^3} is equal to the 5-torsion group
3143 of tiny-jubjub over \mathbb{F}_{13} itself.

3144 *Example 89.* Let's look at the curve secp256k1. We know from example 70 that the curve is of
3145 some prime order r . Because of this, the only torsion group to consider is the curve itself, so
3146 the curve group is the r -torsion.

In order to find the full r -torsion of secp256k1, we need to compute the embedding degree k . And as we have seen in 85 it is at least not small. However, we know from Fermat's little theorem 3.3 that a finite embedding degree must exist. It can be shown that it is given by the following 256-bit number:

$$k = 192986815395526992372618308347813175472927379845817397100860523586360249056$$

3147 This means that the embedding degree is very large, which implies that the field extension \mathbb{F}_{p^k}
3148 is very large too. To understand how big \mathbb{F}_{p^k} is, recall that an element of \mathbb{F}_{p^m} can be represented
3149 as a string $\langle x_0, \dots, x_m \rangle$ of m elements, each containing a number from the prime field \mathbb{F}_p .
3150 Now, in the case of secp256k1, such a representation has k -many entries, each of them 256 bits
3151 in size. So, without any optimizations, representing such an element would need $k \cdot 256$ bits,
3152 which is too much to be representable in the observable universe. It follows that it is not only
3153 infeasible to compute the full r -torsion group of secp256k1, but moreover to even write down
3154 single elements of that group in general.

3155 *Exercise 76.* Consider the full 5-torsion group $TJJ_13[5]$ from example 88. Write down the set
 3156 of all elements from this group and identify the subset of all elements from $TJJ_13(\mathbb{F}_{13})[5]$ as
 3157 well as $TJJ_13(\mathbb{F}_{13^2})[5]$. Then compute the 5-torsion group $TJJ_13(\mathbb{F}_{13^8})[5]$.

3158 *Exercise 77.* Consider the curve `secp256k1` from example 70 and its full r -torsion group as
 3159 introduced in example 89. Write down a single element from the curves full torsion group that
 3160 is not the point at infinity.

3161 **Pairing groups** As we have stated above, any full r -torsion group contains $r + 1$ cyclic sub-
 3162 groups, two of which are of particular interest in pairing-based elliptic curve cryptography. To
 3163 characterize these groups, we need to consider the so-called **Frobenius endomorphism** of an
 3164 elliptic curve $E(\mathbb{F})$ over some finite field \mathbb{F} of characteristic p :

$$\pi : E(\mathbb{F}) \rightarrow E(\mathbb{F}) : \begin{array}{ccc} (x, y) & \mapsto & (x^p, y^p) \\ \mathcal{O} & \mapsto & \mathcal{O} \end{array} \quad (5.29)$$

3165 It can be shown that π maps curve points to curve points. The first thing to note is that, in case
 3166 \mathbb{F} is a prime field, the Frobenius endomorphism acts as the identity map, since $(x^p, y^p) = (x, y)$
 3167 on prime fields due to Fermat's little theorem 3.3. This means that the Frobenius map is more
 3168 interesting on elliptic curves over prime field extensions.

3169 With the Frobenius map at hand, we can characterize two important subgroups of the full r -
 3170 torsion group $E[r]$ of an elliptic curve. The first subgroup is the group of elements from the full
 3171 r -torsion group, on which the Frobenius map acts trivially. Since in pairing-based cryptography,
 3172 this group is usually written as \mathbb{G}_1 , assuming that the prime factor r in the definition is implicitly
 3173 given, we define \mathbb{G}_1 as follows:

$$\mathbb{G}_1[r] := \{(x, y) \in E[r] \mid \pi(x, y) = (x, y)\} \quad (5.30)$$

3174 It can be shown that \mathbb{G}_1 is precisely the r -torsion group $E(\mathbb{F}_p)[r]$ of the unextended elliptic
 3175 curve defined over the prime field. There is another subgroup of the full r -torsion group that
 3176 can be characterized by the Frobenius map and in the context of pairing-based cryptography,
 3177 this subgroup is often called \mathbb{G}_2 . This group is defined as follows:

$$\mathbb{G}_2[r] := \{(x, y) \in E[r] \mid \pi(x, y) = [p](x, y)\} \quad (5.31)$$

3178 *Notation and Symbols 13.* If $E(\mathbb{F})$ is an elliptic curve and r is the largest prime factor of the
 3179 curves order, we call $\mathbb{G}_1[r]$ and $\mathbb{G}_2[r]$ **pairing groups**. If the prime factor r is clear from the
 3180 context, we sometimes simply write \mathbb{G}_1 and \mathbb{G}_2 to mean $\mathbb{G}_1[r]$ and $\mathbb{G}_2[r]$, respectively.

3181 It should be noted that other definitions of \mathbb{G}_2 exists in the literature, too. However, in
 3182 the context of pairing-based cryptography, this is a common choice as it is particularly useful
 3183 because we can define efficient hash functions that map into \mathbb{G}_2 , which is not possible for all
 3184 subgroups of the full r -torsion.

Example 90. Consider the curve $E_{1,1}(\mathbb{F}_5)$ from example 68 again. As we have seen, this curve
 has the embedding degree $k = 2$, and a full 3-torsion group is given as follows:

$$E_1[3] = \{\mathcal{O}, (2, 1), (2, 4), (1, t), (1, 4t), (2t + 1, t + 1), \\ (2t + 1, 4t + 4), (3t + 1, t + 4), (3t + 1, 4t + 1)\} \quad (5.32)$$

3185 According to the general theory, $E_1[3]$ contains 4 subgroups, and we can characterize the
 3186 subgroups \mathbb{G}_1 and \mathbb{G}_2 using the Frobenius endomorphism. Unfortunately, at the time of writing,

3187 Sage does not have a predefined Frobenius endomorphism for elliptic curves, so we have to use
 3188 the Frobenius endomorphism of the underlying field as a temporary workaround. Using our
 3189 implementation of $E_1[3]$ in sage from example 87, we compute \mathbb{G}_1 as follows:

```

3190 sage: L_G1 = []                                     429
3191 sage: for P in E1_3:                                430
3192     ....:     PiP = E1F5_2([a.frobenius() for a in P]) # pi(P) 431
3193     ....:     if P == PiP:                             432
3194     ....:         L_G1.append(P)                        433
3195 sage: G1 = Set(L_G1)                                434

```

3196 As expected, the group $\mathbb{G}_1 = \{\mathcal{O}, (2, 4), (2, 1)\}$ is identical to the 3-torsion group of the (unex-
 3197 tended) curve over the prime field $E_{1,1}(\mathbb{F}_5)$.

3198 In order to compute the group \mathbb{G}_2 for the curve $E_{1,1}(\mathbb{F}_5)$, we can use almost the same algo-
 3199 rithm as we used for the computation of \mathbb{G}_1 . Since $p = 5$ we get the following:

```

3200 sage: L_G2 = []                                     435
3201 sage: for P in E1_3:                                436
3202     ....:     PiP = E1F5_2([a.frobenius() for a in P]) # pi(P) 437
3203     ....:     pP = 5*P # [5]P                        438
3204     ....:     if pP == PiP:                             439
3205     ....:         L_G2.append(P)                        440
3206 sage: G2 = Set(L_G2)                                441

```

3207 Thus, we have computed the pairing group \mathbb{G}_2 of the full 3-torsion group of curve $E_{1,1}(\mathbb{F}_5)$
 3208 as the set $\mathbb{G}_2 = \{\mathcal{O}, (1, t), (1, 4t)\}$.

3209 *Example 91.* Consider the tiny-jubjub curve *TJJ_13* from example 69. In example 88 we com-
 3210 puted its full 5 torsion, which is a group that has 6 subgroups. We compute \mathbb{G}_1 using Sage as
 3211 follows:

```

3212 sage: L_TJJ_G1 = []                                 442
3213 sage: for P in TJJF13_4_5:                           443
3214     ....:     PiP = TJJF13_4([a.frobenius() for a in P]) # pi(P) 444
3215     ....:     if P == PiP:                             445
3216     ....:         L_TJJ_G1.append(P)                    446
3217 sage: TJJ_G1 = Set(L_TJJ_G1)                         447

```

3218 We get $\mathbb{G}_1 = \{\mathcal{O}, (7, 2), (8, 8), (8, 5), (7, 11)\}$ and as expected, \mathbb{G}_1 is identical to the 5-torsion
 3219 group of the (unextended) curve over the prime field *TJJ_13* as computed in example 5.5.

3220 In order to compute the group \mathbb{G}_2 for the tiny jubjub curve, we can use almost the same
 3221 algorithm as we used for the computation of \mathbb{G}_1 . Since $p = 13$ we get the following:

```

3222 sage: L_TJJ_G2 = []                                 448
3223 sage: for P in TJJF13_4_5:                           449
3224     ....:     PiP = TJJF13_4([a.frobenius() for a in P]) # pi(P) 450
3225     ....:     pP = 13*P # [13]P                      451
3226     ....:     if pP == PiP: # pi(P) == [13]P          452
3227     ....:         L_TJJ_G2.append(P)                    453
3228 sage: TJJ_G2 = Set(L_TJJ_G2)                         454

```

3229 $\mathbb{G}_2 = \{\mathcal{O}, (9t^2 + 7, t^3 + 11t), (9t^2 + 7, 12t^3 + 2t), (4t^2 + 7, 5t^3 + 10t), (4t^2 + 7, 8t^3 + 3t)\}$

Example 92. Consider Bitcoin’s curve `secp256k1` again. Since the group \mathbb{G}_1 is identical to the torsion group of the unextended curve, and since `secp256k1` has prime order, we know that, in this case, \mathbb{G}_1 is identical to `secp256k1` itself. However it is infeasible to compute elements from \mathbb{G}_2 , since according to example 89 we can not store average curve points from the extension curve `secp256k1`(\mathbb{F}_{p^k}) on any computer, let alone compute their images under the Frobenius map.

Exercise 78. Consider the small prime factor 2 of the tiny-jubjub curve. Compute the full 2-torsion group of `TJJ_13` and then compute the groups $\mathbb{G}_1[2]$ and $\mathbb{G}_2[2]$.

The Weil pairing Recall the definition of a non-degenerate group pairing from 4.6. In this part, we consider a pairing function defined on the subgroups $\mathbb{G}_1[r]$ and $\mathbb{G}_2[r]$ of the full r -torsion $E[r]$ of a short Weierstrass elliptic curve. To be more precise, let $E(\mathbb{F}_p)$ be an elliptic curve of embedding degree k such that r is a prime factor of its order. Then the **Weil pairing** is defined as the following bilinear, non-degenerate map:

$$e(\cdot, \cdot) : \mathbb{G}_1[r] \times \mathbb{G}_2[r] \rightarrow \mathbb{F}_{p^k}^* ; (P, Q) \mapsto (-1)^r \cdot \frac{f_{r,P}(Q)}{f_{r,Q}(P)} \quad (5.33)$$

The extension field elements $f_{r,P}(Q), f_{r,Q}(P) \in \mathbb{F}_{p^k}$ in the definition of the Weil pairing are computed by **Miller’s algorithm**:

Understanding the details of how and why this algorithm works requires the concept of **divisors**, which is outside of the scope this book. The interested reader might look at XXX. As we can see the algorithm is more efficient on prime numbers r , that have a low Hamming weight 3.4.

We call an elliptic curve $E(\mathbb{F}_p)$ **pairing-friendly** if there is a prime factor of the groups order such that the Weil pairing is efficiently computable with respect to that prime factor. In real-world applications of pairing-friendly elliptic curves, the embedding degree is usually a small number like 2, 4, 6 or 12, and the number r is the largest prime factor of the curve’s order.

Example 93. Consider curve $E_{1,1}(\mathbb{F}_5)$ from example 68. Since the only prime factor of the group’s order is 3, we cannot compute the Weil pairing on this group using our definition of Miller’s algorithm. In fact, since \mathbb{G}_1 is of order 3, executing the algorithm will lead to a “division by zero”.

Example 94. Consider the tiny-jubjub curve `TJJ_13`(\mathbb{F}_{13}) from example 69 and its associated pairing groups from example 91:

$$\begin{aligned} \mathbb{G}_1[5] &= \{\mathcal{O}, (7, 2), (8, 8), (8, 5), (7, 11)\} \\ \mathbb{G}_2[5] &= \{\mathcal{O}, (9t^2 + 7, t^3 + 11t), (9t^2 + 7, 12t^3 + 2t), (4t^2 + 7, 5t^3 + 10t), (4t^2 + 7, 8t^3 + 3t)\} \end{aligned}$$

Since we know from example 84 that the embedding degree of 5 is 4, we can instantiate the general definition of the Weil pairing for this example as follows:

$$e(\cdot, \cdot) : \mathbb{G}_1[5] \times \mathbb{G}_2[5] \rightarrow \mathbb{F}_{13^4}$$

The first if-statement in Miller’s algorithm, implies that $e(\mathcal{O}, Q) = 1$ as well as $e(P, \mathcal{O}) = 1$ for all arguments $P \in \mathbb{G}_1[5]$ and $Q \in \mathbb{G}_2[5]$. In order to compute a non-trivial Weil pairing, we choose the argument $P = (7, 2) \in \mathbb{G}_1$ and $Q = (9t^2 + 7, 12t^3 + 2t) \in \mathbb{G}_2$. Invoking sage we get the following computation of the Weil pairing:

sage: `F13 = GF(13)`

check
floating of
algorithm

add refer-
ences

Algorithm 8 Miller's algorithm for short Weierstrass curves $y^2 = x^3 + ax + b$

Require: $r > 3$, $P \in E[r]$, $Q \in E[r]$ and

$b_0, \dots, b_t \in \{0, 1\}$ with $r = b_0 \cdot 2^0 + b_1 \cdot 2^1 + \dots + b_t \cdot 2^t$ and $b_t = 1$

procedure MILLER'S ALGORITHM(P, Q)

if $P = \mathcal{O}$ or $Q = \mathcal{O}$ or $P = Q$ **then**

return $f_{r,P}(Q) \leftarrow (-1)^r$

end if

$(x_T, y_T) \leftarrow (x_P, y_P)$

$f_1 \leftarrow 1$

$f_2 \leftarrow 1$

for $j \leftarrow t - 1, \dots, 0$ **do**

$m \leftarrow \frac{3 \cdot x_T^2 + a}{2 \cdot y_T}$

$f_1 \leftarrow f_1^2 \cdot (y_Q - y_T - m \cdot (x_Q - x_T))$

$f_2 \leftarrow f_2^2 \cdot (x_Q + 2x_T - m^2)$

$x_{2T} \leftarrow m^2 - 2x_T$

$y_{2T} \leftarrow -y_T - m \cdot (x_{2T} - x_T)$

$(x_T, y_T) \leftarrow (x_{2T}, y_{2T})$

if $b_j = 1$ **then**

$m \leftarrow \frac{y_T - y_P}{x_T - x_P}$

$f_1 \leftarrow f_1 \cdot (y_Q - y_T - m \cdot (x_Q - x_T))$

$f_2 \leftarrow f_2 \cdot (x_Q + (x_P + x_T) - m^2)$

$x_{T+P} \leftarrow m^2 - x_T - x_P$

$y_{T+P} \leftarrow -y_T - m \cdot (x_{T+P} - x_T)$

$(x_T, y_T) \leftarrow (x_{T+P}, y_{T+P})$

end if

end for

$f_1 \leftarrow f_1 \cdot (x_Q - x_T)$

return $f_{r,P}(Q) \leftarrow \frac{f_1}{f_2}$

end procedure

```

3262 sage: F13t.<t> = F13[] 456
3263 sage: P_MOD_4 = F13t (t^4+2) 457
3264 sage: F13_4.<t> = GF(13^4, name='t', modulus=P_MOD_4) 458
3265 sage: TJJF13_4 = EllipticCurve(F13_4, [8, 8]) 459
3266 sage: P=TJJF13_4([7, 2]) 460
3267 sage: Q=TJJF13_4([9*t^2+7, 12*t^3+2*t]) 461
3268 sage: P.weil_pairing(Q, 5) 462
3269 7*t^3 + 7*t^2 + 6*t + 3 463

```

3270 *Example 95.* Consider Bitcoin's curve secp256k1 again. As we have seen in example 92, it is
 3271 infeasible to compute elements from the pairing group \mathbb{G}_2 and as we know from example 89
 3272 it is moreover infeasible to do calculations in the extension field \mathbb{F}_{p^k} . It follows that the Weil
 3273 pairing is not efficiently computable and that secp256k1 is not pairing friendly.

3274 5.5 Hashing to Curves

3275 Elliptic curve cryptography frequently requires the ability to hash data onto elliptic curves. If
 3276 the order of the curve is not a prime number, hashing to prime order subgroups is of importance,
 3277 too and in the context of pairing-friendly curves, it is sometimes necessary to hash specifically
 3278 onto the pairing group \mathbb{G}_1 or \mathbb{G}_2 as introduced in 5.4.

3279 As we have seen in section 4.1.2, some general methods are known for hashing into fi-
 3280 nite cyclic groups and since elliptic curves over finite fields are finite and cyclic groups, those
 3281 methods can be utilized in this case, too. However, in what follows we want to describe some
 3282 methods specific to elliptic curves that are frequently used in real-world applications.

3283 **Try-and-increment hash functions** One of the most straight-forward ways of hashing onto
 3284 an elliptic curve point in a secure way is to use a cryptographic hash function together with one
 3285 of the hashing into modular arithmetics methods as described in section 4.2.

3286 Both constructions can be combined in such a way that the image provides an element of
 3287 the base field of the elliptic curve together with a single auxiliary bit. The base field element
 3288 can then be interpreted as the x -coordinate of a potential curve point, and the auxiliary bit can
 3289 be used to determine one of the two possible y coordinates of that curve point as explained in
 3290 5.1.1.

3291 Such an approach would be deterministic and easy to implement, and it would conserve the
 3292 cryptographic properties of the original hash function. However, not all x coordinates generated
 3293 in such a way will result in quadratic residues when inserted into the defining equation. It
 3294 follows that not all field elements give rise to actual curve points.

3295 In fact, on a prime field, only half of the field elements are quadratic residues. Hence,
 3296 assuming an even distribution of the hash values in the field, this method would fail to generate
 3297 a curve point in about half of the attempts.

3298 One way to account for this problem is the following so-called **try-and-increment** method.
 3299 Instead of simply hashing a binary string s to the field, this method use a try-and-increment hash
 3300 to the base field as described in 4.2 in combination with a single auxiliary bit derived from the
 3301 underlying cryptographic hash function.

3302 If any try of hashing to the field does not result in a field element or a valid curve point, the
 3303 counter is incremented, and the hashing is repeated. This is done until a valid curve point is
 3304 found.

check if
the algo-
rithm is
floated
properly

Algorithm 9 Hash-to- $E(\mathbb{F}_p)$ **Require:** $p \in \mathbb{Z}$ with $|p| = k$ and $s \in \{0, 1\}^*$ **Require:** Curve equation $y^2 = x^3 + ax + b$ over \mathbb{F}_p **procedure** TRY-AND-INCREMENT(r, k, s) $c \leftarrow 0$

▷ Try-and-Increment counter

repeat $s' \leftarrow s || \text{Bits}(c)$ $x \leftarrow H(s')_0 \cdot 2^0 + H(s')_1 \cdot 2^1 + \dots + H(s')_k \cdot 2^k$ ▷ potential x $y^2 \leftarrow z^3 + a \cdot z + b$ ▷ potential y^2 $c \leftarrow c + 1$ **until** $x < p$ and $(y^2)^{\frac{p-1}{2}} \bmod r = 1$ ▷ Check x in field and y^2 has root**if** $H(s')_{k+1} == 0$ **then**

▷ auxiliary bit decides root

 $y \leftarrow y' \in \sqrt{y^2}$ with $0 \leq y' \leq (p-1)/2$ **else** $y \leftarrow y' \in \sqrt{y^2}$ with $(p-1)/2 < y' < p$ **end if****return** (x, y) **end procedure****Ensure:** $(x, y) \in E(\mathbb{F}_r)$

The try-and-increment method is relatively easy to implement, and it maintains the cryptographic properties of the original hash function. It should be noted that if the curve is not of prime order, the image of the try-and-increment hash will be a general curve point that might not be an element from the large prime-order subgroup. To map onto the large prime order subgroup it is therefore necessary to apply the technique of cofactor clearing as explained in 4.5.

Example 96. Consider the tiny-jubjub curve from example 69. We want to construct a try-and-increment hash function that maps a binary string s of arbitrary length onto the large prime-order subgroup of size 5 from example 5.5.

Since the curve TJJ_{13} is defined over the field \mathbb{F}_{13} , and the binary representation of 13 is $\text{Bits}(13) = \langle 1, 1, 0, 1 \rangle$, one way to implement a try-and-increment function is to apply SHA256 from Sage's hashlib library on the concatenation $s || c$ for some binary counter string c , and use the first 4 bits of the image to try to hash into \mathbb{F}_{13} . In case we are able to hash to a value x such that $x^3 + 8 \cdot x + 8$ is a quadratic residue in \mathbb{F}_{13} , we use the fifth bit to decide which of the two possible roots of $x^3 + 8 \cdot x + 8$ we will choose as the y coordinate. The result is a curve point different from the point at infinity. To project it onto the large prime order subgroup $TJJ_{13}[5]$, we multiply it with the cofactor 4. If the result is not the point at infinity, it is the result of the hash.

To make this concrete, let $s = \langle 1, 1, 1, 0, 0, 1, 0, 0, 0, 0 \rangle$ be our binary string that we want to hash onto $TJJ_{13}[5]$. We use a binary counter string starting at zero, that is, we choose $c = \langle 0 \rangle$. Invoking Sage, we define the try-hash function as follows:

```

sage: import hashlib                                464
sage: def try_hash(s, c):                            465
....:     s_1 = s+c # string concatenation            466
....:     hasher = hashlib.sha256(s_1.encode('utf-8')) # 467
compute SHA256

```

```

3331     ....:     digest = hasher.hexdigest()                                468
3332     ....:     z = ZZ(digest, 16) # cast into integer                      469
3333     ....:     z_bin = z.digits(base=2, padto=256) # cast to 256          470
3334         bits
3335     ....:     x = z_bin[0]*2^0 + z_bin[1]*2^1 + z_bin[2]*2^2+z_bin 471
3336         [3]*2^3
3337     ....:     return (x,z_bin[4])                                         472
3338 sage: try_hash('1110010000', '0')                                       473
3339 (15, 1)                                                                    474

```

As we can see, our first attempt to hash into \mathbb{F}_{13} was not successful, as 15 is not an element in \mathbb{F}_{13} , so we increment the binary counter by 1 and try again:

```

3342 sage: try_hash('1110010000', '1')                                       475
3343 (3, 1)                                                                    476

```

With this try, we found a hash into \mathbb{F}_{13} . However, this point is not guaranteed to define a curve point. To see that, we insert $x = 3$ into the right side of the short Weierstrass equation of the tiny-jubjub curve, and compute $3^3 + 8 \cdot 3 + 8 = 7$. However, 7 is not a quadratic residue in \mathbb{F}_{13} , since $7^{\frac{13-1}{2}} = 7^6 = 12 = -1$. This means that the field element 7 is not suitable as the x -coordinate of any curve point. We therefore have to increment the counter another time:

```

3349 sage: try_hash('1110010000', '10')                                      477
3350 (12, 1)                                                                    478

```

Since $12^3 + 8 \cdot 12 + 8 = 12$, and we have $\sqrt{12} = \{5, 8\}$, we finally found the valid x -coordinate $x = 12$ for a curve point hash. Now, since the auxiliary bit of this hash is 1, we choose the larger root $y = 8$ as the y coordinate and get the following hash which is a valid curve point on the tiny-jubjub curve:

$$H_{TJJ_13}(< 1, 1, 1, 0, 0, 0, 0, 0 >) = (12, 8)$$

In order to project this onto the “large” prime-order subgroup, we have to do cofactor clearing, that is, we have to multiply the point with the cofactor 4. Using sage we get

```

3353 sage: P = TJJ_13(12, 8)                                                  479
3354 sage: (4*P).xy()                                                         480
3355 (8, 8)                                                                    481

```

This implies that hashing the binary string $< 1, 1, 1, 0, 0, 0, 0, 0 >$ onto the large prime order subgroup $TJJ_13[5]$ gives the hash value $(8, 8)$ as a result.

$$H_{TJJ_13[5]}(< 1, 1, 1, 0, 0, 0, 0, 0 >) = (8, 8)$$

3356 *Exercise 79.* Use our definition of the *try_hash* algorithm to implement a hash function $H_{TJJ_13[5]} : \{0, 1\}^* \rightarrow TJJ_13(\mathbb{F}_{13})[5]$ that maps binary strings of arbitrary length onto the 5-torsion group of $TJJ13(\mathbb{F}_{13})$.

3359 *Exercise 80.* Implement a cryptographic hash function $H_{secp256k1} : \{0, 1\}^* \rightarrow secp256k1$ that maps binary strings of arbitrary length onto the elliptic curve *secp256k1*.

5.6 Constructing elliptic curves

Cryptographically secure elliptic curves like secp256k1 70 have been known for quite some time. Given the latest advancements of cryptography, however, it is often necessary to design and instantiate elliptic curves from scratch that satisfy certain very specific properties.

For example, in the context of SNARK development, it became necessary to design elliptic curves that can be efficiently implemented inside of a so-called **circuit** in order to enable primitives like elliptic curve **signature schemes** in a zero-knowledge proof. Such a curve is given by the Baby-jubjub curve in XXX, and we have paralleled its definition by introducing the tiny-jubjub curve from example 69. As we have seen, those curves are instances of so-called twisted Edwards curves, and as such have easy to implement addition laws that work without branching. However, we introduced the tiny-jubjub curve out of thin air, as we just gave the curve parameters without explaining how we came up with them.

Another requirement in the context of many so-called **pairing-based zero-knowledge proofing systems** is the existence of a suitable, pairing-friendly curve with a specified security level and a low embedding degree as defined in 5.24. Famous examples are the BLS_12 and the NMT curves.

The major goal of this section is to explain the most important method of designing elliptic curves with predefined properties from scratch, called the **complex multiplication method**. We will apply this method in section to synthesize a particular BLS_6 curve, which is one of the most insecure curves, that is particular well suited to serve as the main curve to build our pen-and-paper SNARKs on. As we will see, this curve has a “large” prime factor subgroup of order 13, which implies that we can use our tiny-jubjub curve to implement certain elliptic curve cryptographic primitives in circuits over that BLS_6 curve.

Before we introduce the complex multiplication method, we have to explain a few properties of elliptic curves that are of key importance in understanding that method.

The Trace of Frobenius To understand the complex multiplication method of elliptic curves, we have to define the so-called **trace** of an elliptic curve first.

We know that elliptic curves are cyclic groups of finite order. Therefore, an interesting question is whether it is possible to estimate the number of elements that this curve contains. Since an affine short Weierstrass curve consists of pairs (x, y) of elements from a finite field \mathbb{F}_q plus the point at infinity, and the field \mathbb{F}_q contains q elements, the number of curve points cannot be arbitrarily large, since it can contain at most $q^2 + 1$ many elements.

There is however, a more precise estimation, usually called the **Hasse bound**. To understand it, let $E(\mathbb{F}_q)$ be an affine short Weierstrass curve over a finite field \mathbb{F}_q of order q , and let $|E(\mathbb{F}_q)|$ be the order of the curve. Then there is an integer $t \in \mathbb{Z}$, called the **trace of Frobenius** of the curve, such that $|t| \leq 2\sqrt{q}$ and the following equation holds:

$$|E(\mathbb{F}_q)| = q + 1 - t \quad (5.34)$$

A positive trace, therefore, implies that the curve contains no more points than the underlying field, whereas a non-negative trace means that the curve contains more points. However, the estimation $|t| \leq 2\sqrt{q}$ implies that the difference is not very large in either direction, and the number of elements in an elliptic curve is always approximately in the same order of magnitude as the size of the curve’s base field.

Example 97. Consider the elliptic curve $E_{1,1}(\mathbb{F}_5)$ from example 68. We know that it contains 9 curve points. Since the order of \mathbb{F}_5 is 5, we compute the trace of $E_{1,1}(\mathbb{F}_5)$ to be $t = -3$, since

circuit

signature
schemesadd refer-
enceadd refer-
ences

the Hasse bound is given by the following equation:

$$9 = 5 + 1 - (-3)$$

Indeed, we have $|t| \leq 2\sqrt{q}$, since $\sqrt{5} > 2$ and $|-3| = 3 \leq 4 = 2 \cdot 2 < 2 \cdot \sqrt{5}$.

Example 98. To compute the trace of the tiny-jubjub curve, recall from example 69 that the order of TJJ_13 is 20. Since the order of \mathbb{F}_{13} is 13, we can therefore use the Hasse bound and compute the trace as $t = -6$:

$$20 = 13 + 1 - (-6) \quad (5.35)$$

Again, we have $|t| \leq 2\sqrt{q}$, since $\sqrt{13} > 3$ and $|-6| = 6 = 2 \cdot 3 < 2 \cdot \sqrt{13}$.

Example 99. To compute the trace of secp256k1, recall from example 70 that this curve is defined over a prime field with p elements, and that the order of that group is given by r :

$$p = 115792089237316195423570985008687907853269984665640564039457584007908834671663$$

$$r = 115792089237316195423570985008687907852837564279074904382605163141518161494337$$

Using the Hasse bound $r = p + 1 - t$, we therefore compute $t = p + 1 - r$, which gives the trace of curve secp256k1 as follows:

$$t = 432420386565659656852420866390673177327$$

As we can see, secp256k1 contains less elements than its underlying field. However, the difference is tiny, since the order of secp256k1 is in the same order of magnitude as the order of the underlying field. Compared to p and r , the integer t is tiny.

```
sage: p = 1157920892373161954235709850086879078532699846656405 482
      64039457584007908834671663
sage: r = 1157920892373161954235709850086879078528375642790749 483
      04382605163141518161494337
sage: t = p + 1 - r 484
sage: t.nbits() 485
129 486
sage: abs(RR(t)) <= 2*sqrt(RR(p)) 487
True 488
```

The j -invariant As we have seen in XXX, two elliptic curves $E_1(\mathbb{F})$ defined by $y^2 = x^3 + ax + b$ and $E_2(\mathbb{F})$ defined by $y^2 + a'x + b'$ are strictly isomorphic if and only if there is a quadratic residue $d \in \mathbb{F}$ such that $a' = ad^2$ and $b' = bd^3$.

add reference

There is, however, a more general way to classify elliptic curves over finite fields \mathbb{F}_q , based on the so-called **j -invariant** of an elliptic curve with $j(E(\mathbb{F}_q)) \in \mathbb{F}_q$, as defined below:

$$j(E(\mathbb{F}_q)) = 1728 \cdot \frac{4 \cdot a^3}{4 \cdot a^3 + 27 \cdot b^2} \bmod q \quad (5.36)$$

A detailed description of the j -invariant is beyond the scope of this book. For our present purposes, it is sufficient to note that two elliptic curves $E_1(\mathbb{F})$ and $E_2(\mathbb{F}')$ are isomorphic over the algebraic closures of \mathbb{F} and \mathbb{F}' , if and only if $\overline{\mathbb{F}} = \overline{\mathbb{F}'}$ and $j(E_1) = j(E_2)$.

algebraic closures

So, the j -invariant is an important tool to classify elliptic curves and it is needed in the complex multiplication method to decide on an actual curve instantiation that implements abstractly chosen properties.

Example 100. Consider the elliptic curve $E_{1,1}(\mathbb{F}_5)$ from example 68. We compute its j -invariant as follows:

check
reference

$$\begin{aligned} j(E_{1,1}(\mathbb{F}_5)) &= 1728 \cdot \frac{4 \cdot 1^3}{4 \cdot 1^3 + 27 \cdot 1^2} \bmod 5 \\ &= 3 \frac{4}{4+2} \\ &= 3 \cdot 4 \\ &= 2 \end{aligned}$$

Example 101. Consider the elliptic curve TJJ_13 from example 69. We compute its j -invariant as follows:

check
reference

$$\begin{aligned} j(TJJ_13) &= 1728 \cdot \frac{4 \cdot 8^3}{4 \cdot 8^3 + 27 \cdot 8^2} \bmod 13 \\ &= 12 \cdot \frac{4 \cdot 5}{4 \cdot 5 + 1 \cdot 12} \\ &= 12 \cdot \frac{7}{7+12} \\ &= 12 \cdot 7 \cdot 6^{-1} \\ &= 2 \cdot 7 \\ &= 1 \end{aligned}$$

Example 102. Consider secp256k1 from example secp256k1. We compute its j -invariant using Sage:

```

3430 sage: p = 1157920892373161954235709850086879078532699846656405 489
3431 sage: 64039457584007908834671663
3432
3433 sage: F = GF(p) 490
3434 sage: j = F(1728) * ((F(4) * F(0)^3) / (F(4) * F(0)^3 + F(27) * F(7)^2)) 491
3435 sage: j == F(0) 492
3436 True 493

```

The Complex Multiplication Method As we have seen in the previous sections, elliptic curves have various defining properties, like their order, their prime factors, the embedding degree, or the cardinality (number of elements) of the base field. The **complex multiplication** (CM) method provides a practical way of constructing elliptic curves with pre-defined restrictions on the order and the base field.

The complex multiplication method starts by choosing a base field \mathbb{F}_q of the curve $E(\mathbb{F}_q)$ we want to construct such that $q = p^m$ for some prime number p , and $m \in \mathbb{N}$. We assume $p > 3$ to simplify things in what follows.

Next, the trace of Frobenius $t \in \mathbb{Z}$ of the curve is chosen such that p and t are coprime, that is, $\gcd(p, t) = 1$ holds true and $|t| \leq 2\sqrt{q}$. The choice of t also defines the curve's order r , since $r = p + 1 - t$ by the Hasse bound 5.34, so choosing t will determine the large order subgroup as well as all small cofactors. The resulting r must be such that the curve meets the application's security requirements.

Note that the choice of p and t also determines the embedding degree k of any prime-order subgroup of the curve, since k is defined as the smallest number such that the prime order n divides the number $q^k - 1$.

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$$D < 0$$

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disambiguate

$$S(D) = \{(A, B, C) \mid A, B, C \in \mathbb{Z}, D = B^2 - 4AC, \gcd(A, B, C) = 1,$$

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$$j: \mathbb{H} \rightarrow \mathbb{C}$$

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The following table is guaranteed to define a curve with the correct order $r = q + 1 - t$ for the fields order q and the trace of Frobenius t we initially decided on:

- Case $j_0 \neq 0$ and $j_0 \neq 1728 \bmod q$. A curve with the correct order is defined by one of the following equations:

$$y^2 = x^3 + 3c_1x + 2c_1 \quad \text{or} \quad y^2 = x^3 + 3c_1c_2^2x + 2c_1c_2^3 \quad (5.40)$$

- Case $j_0 = 0$ and $D \neq -3$. A curve with the correct order is defined by one of the following equations:

$$y^2 = x^3 + 1 \quad \text{or} \quad y^2 = x^3 + c_2^3 \quad (5.41)$$

- Case $j_0 = 0$ and $D = -3$. A curve with the correct order is defined by one of the following equations:

$$\begin{aligned} y^2 = x^3 + 1 \quad \text{or} \quad y^2 = x^3 + c_2^3 \quad \text{or} \\ y^2 = x^3 + c_3^2 \quad \text{or} \quad y^2 = c_3^2c_2^3 \quad \text{or} \\ y^2 = x^3 + c_3^{-2} \quad \text{or} \quad y^2 = x^3 + c_3^{-2}c_2^3 \end{aligned}$$

- Case $j_0 = 1728 \bmod q$ and $D \neq -4$. A curve with the correct order is defined by one of the following equations:

$$y^2 = x^3 + x \quad \text{or} \quad y^2 = x^3 + c_2^2x \quad (5.42)$$

- Case $j_0 = 1728 \bmod q$ and $D = -4$. A curve with the correct order is defined by one of the following equations:

$$\begin{aligned} y^2 = x^3 + x \quad \text{or} \quad y^2 = x^3 + c_2x \quad \text{or} \\ y^2 = x^3 + c_2^2x \quad \text{or} \quad y^2 = x^3 + c_2^3x \end{aligned}$$

To decide the proper defining short Weierstrass equation, we therefore have to compute the order of any of the potential curves above, and then choose the one that fits our initial requirements.

To summarize, using the complex multiplication method, it is possible to synthesize elliptic curves with predefined order over predefined base fields from scratch. However, the curves that are constructed this way are just some representatives of a larger class of curves, all of which have the same order. Therefore, in real-world applications, it is sometimes more advantageous to choose a different representative from that class. To do so recall from 5.1.1 that any curve defined by the short Weierstrass equation $y^2 = x^3 + ax + b$ is isomorphic to a curve of the form $y^2 = x^3 + ad^4x + bd^6$ for some invertible field element $d \in \mathbb{F}_q^*$.

In order to find a suitable representative (e.g. with small parameters a and b) in the last step, the curve designer might choose an invertible field element d such that the transformed curve has the properties they wanted.

Example 103. Consider curve $E_{1,1}(\mathbb{F}_5)$ from example 68. We want to use the complex multiplication method to derive that curve from scratch. Since $E_{1,1}(\mathbb{F}_5)$ is a curve of order $r = 9$ over the prime field of order $q = 5$, we know from example 97 that its trace of Frobenius is $t = -3$, which also implies that q and $|t|$ are coprime.

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We then have to find parameters $D, v \in \mathbb{Z}$ such that the criteria in 5.37 hold. We get the following:

$$\begin{aligned} 4q &= t^2 + |D|v^2 && \Rightarrow \\ 20 &= (-3)^2 + |D|v^2 && \Leftrightarrow \\ 11 &= |D|v^2 \end{aligned}$$

3546 Now, since 11 is a prime number, the only solution is $|D| = 11$ and $v = 1$ here. With $D = -11$
 3547 and the Euclidean division of -11 by 4 being $-11 = -3 \cdot 4 + 1$, we have $-11 \bmod 4 = 1$, which
 3548 shows that $D = -11$ is a proper choice.

3549 In the next step, we have to compute the Hilbert class polynomial H_{-11} . To do so, we first
 3550 have to find the set $S(D)$. To compute that set, observe that, since $\sqrt{\frac{|D|}{3}} \approx 1.915 < 2$, we know
 3551 from $A \leq \sqrt{\frac{|D|}{3}}$ and $A \in \mathbb{Z}$ that A must be either 0 or 1.

3552 For $A = 0$, we know $B = 0$ from the constraint $|B| \leq A$. However, in this case, there could be
 3553 no C satisfying $-11 = B^2 - 4AC$. So we try $A = 1$ and deduce $B \in \{-1, 0, 1\}$ from the constraint
 3554 $|B| \leq A$. The case $B = -1$ can be excluded, since then $B < 0$ has to imply $|B| < A$. The case
 3555 $B = 0$ can also be excluded, as there cannot be an integer C with $-11 = -4C$, since 11 is a
 3556 prime number.

This leaves the case $B = 1$, and we compute $C = 3$ from the equation $-11 = 1^2 - 4C$, which gives the solution $(A, B, C) = (1, 1, 3)$:

$$S(D) = \{(1, 1, 3)\}$$

With the set $S(D)$ at hand, we can compute the Hilbert class polynomial of $D = -11$. To do so, we have to insert the term $\frac{-1 + \sqrt{-11}}{2 \cdot 1}$ into the j -function. To do so, first observe that $\sqrt{-11} = i\sqrt{11}$, where i is the imaginary unit, defined by $i^2 = -1$. Using this, we can invoke Sage to compute the j -invariant and get the following:

$$H_{-11}(x) = x - j \left(\frac{-1 + i\sqrt{11}}{2} \right) = x + 32768$$

As we can see, in this particular case, the Hilbert class polynomial is a linear function with a single integer coefficient. In the next step, we have to project it onto a polynomial from $\mathbb{F}_5[x]$ by computing the modular 5 remainder of the coefficients 1 and 32768. We get $32768 \bmod 5 = 3$, from which it follows that the projected Hilbert class polynomial is considered a polynomial from $\mathbb{F}_5[x]$:

$$H_{-11,5}(x) = x + 3$$

As we can see, the only root of this polynomial is $j = 2$, since $H_{-11,5}(2) = 2 + 3 = 0$. We therefore have a situation with $j \neq 0$ and $j \neq 1728$, which tells us that we have to compute the parameter c_1 in modular 5 arithmetics:

$$c_1 = \frac{2}{1728 - 2}$$

3557 Since $1728 \bmod 5 = 3$, we get $c_1 = 2$.

3558 Next, we have to check if the curve $E(\mathbb{F}_5)$ defined by the short Weierstrass equation $y^2 =$
 3559 $x^3 + 3 \cdot 2x + 2 \cdot 2$ has the correct order. We invoke Sage, and find that the order is indeed 9, so it

3560 is a curve with the required parameters. Thus, we have successfully constructed the curve with
 3561 the desired properties.

Note, however, that in real-world applications, it might be useful to choose parameters a and b that have certain properties, e.g. to be as small as possible. As we know from XXX, choosing any quadratic residue $d \in \mathbb{F}_5$ gives a curve of the same order defined by $y^2 = x^2 + ak^2x + bk^3$. Since 4 is a quadratic residue in \mathbb{F}_4 , we can transform the curve defined by $y^2 = x^3 + x + 4$ into the curve $y^2 = x^3 + 4^2 + 4 \cdot 4^3$ which gives the following:

$$y^2 = x^3 + x + 1$$

3562 This is the curve $E_{1,1}(\mathbb{F}_5)$ that we used extensively throughout this book. Thus, using the
 3563 complex multiplication method, we were able to derive a curve with specific properties from
 3564 scratch.

3565 *Example 104.* Consider the tiny-jubjub curve TJJ_13 from example 69. We want to use the
 3566 complex multiplication method to derive that curve from scratch. Since TJJ_13 is a curve of
 3567 order $r = 20$ over the prime field of order $q = 13$, we know from example 98 that its trace of
 3568 Frobenius is $t = -6$, which also implies that q and $|t|$ are coprime.

We then have to find parameters $D, v \in \mathbb{Z}$ such that 5.37 holds. We get the following:

$$\begin{aligned} 4q &= t^2 + |D|v^2 && \Rightarrow \\ 4 \cdot 13 &= (-6)^2 + |D|v^2 && \Rightarrow \\ 52 &= 36 + |D|v^2 && \Leftrightarrow \\ 16 &= |D|v^2 \end{aligned}$$

3569 This equation has two solutions for (D, v) , namely $(-4, \pm 2)$ and $(-16, \pm 1)$. Looking at the
 3570 first solution, we know that $D = -4$ implies $j = 1728$, and the constructed curve is defined by a
 3571 short Weierstrass equation 5.1 that has a vanishing parameter $b = 0$. We can therefore conclude
 3572 that choosing $D = -4$ will not help us reconstructing TJJ_13 . It will produce curves with order
 3573 20, just not the one we are looking for.

So we choose the second solution $D = -16$. In the next step, we have to compute the Hilbert class polynomial H_{-16} . To do so, we first have to find the set $S(D)$. To compute that set, observe that since $\sqrt{\frac{|-16|}{3}} \approx 2.31 < 3$, we know from $A \leq \sqrt{\frac{|-16|}{3}}$ and $A \in \mathbb{Z}$ that A must be in the range $0..2$. So we loop through all possible values of A and through all possible values of B under the constraints $|B| \leq A$, and if $B < 0$ then $|B| < A$. Then we compute potential C 's from $-16 = B^2 - 4AC$. We get the following two solutions for $S(D)$: we get

$$S(D) = \{(1, 0, 4), (2, 0, 2)\}$$

With the set $S(D)$ at hand, we can compute the Hilbert class polynomial of $D = -16$. We can invoke Sage to compute the j -invariant and get the following:

$$\begin{aligned} H_{-16}(x) &= \left(x - j \left(\frac{i\sqrt{16}}{2} \right) \right) \left(x - j \left(\frac{i\sqrt{16}}{4} \right) \right) \\ &= (x - 287496)(x - 1728) \end{aligned}$$

As we can see, in this particular case, the Hilbert class polynomial is a quadratic function with two integer coefficients. In the next step, we have to project it onto a polynomial from $\mathbb{F}_5[x]$ by computing the modular 5 remainder of the coefficients 1, 287496 and 1728. We get

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$287496 \bmod 13 = 1$ and $1728 \bmod 13 = 2$, which means that the projected Hilbert class polynomial is as follows:

$$H_{-11,5}(x) = (x-1)(x-12) = (x+12)(x+1)$$

3574 This is considered a polynomial from $\mathbb{F}_{13}[x]$. Thus, we have two roots, namely $j = 1$ and
 3575 $j = 12$. We already know that $j = 12$ is the wrong root to construct the tiny-jubjub curve, since
 3576 $1728 \bmod 13 = 2$, and that case is not compatible with a curve with $b \neq 0$. So we choose $j = 1$.

Another way to decide the proper root is to compute the j -invariant of the tiny-jubjub curve. We get the following:

$$\begin{aligned} j(TJJ_{13}) &= 12 \frac{4 \cdot 8^3}{4 \cdot 8^3 + 1 \cdot 8^2} \\ &= 12 \frac{4 \cdot 5}{4 \cdot 5 + 12} \\ &= 12 \frac{7}{7 + 12} \\ &= 12 \frac{7}{7 + 12} \\ &= 1 \end{aligned}$$

This is equal to the root $j = 1$ of the Hilbert class polynomial $H_{-16,13}$ as expected. We therefore have a situation with $j \neq 0$ and $j \neq 1728$, which tells us that we have to compute the parameter c_1 in modular 5 arithmetics:

$$c_1 = \frac{1}{12-1} = 6$$

Since $1728 \bmod 13 = 12$, we get $c_1 = 6$. Then we have to check if the curve $E(\mathbb{F}_5)$ defined by the short Weierstrass equation $y^2 = x^3 + 3 \cdot 6x + 2 \cdot 6$, which is equivalent to $y^2 = x^3 + 5x + 12$, has the correct order. We invoke Sage and find that the order is 8, which implies that the trace of this curve is 6, not -6 as required. So we have to consider the second possibility, and choose some quadratic non-residue $c_2 \in \mathbb{F}_{13}$. We choose $c_2 = 5$ and compute the short Weierstrass equation $y^2 = x^3 + 5c_2^2 + 12c_2^3$ as follows:

$$y^2 = x^3 + 8x + 5$$

We invoke Sage and find that the order is 20, which is indeed the correct one. As we know from XXX, choosing any quadratic residue $d \in \mathbb{F}_5$ gives a curve of the same order defined by $y^2 = x^2 + ad^2x + bd^3$. Since 12 is a quadratic residue in \mathbb{F}_{13} , we can transform the curve defined by $y^2 = x^3 + 8x + 5$ into the curve $y^2 = x^3 + 12^2 \cdot 8 + 5 \cdot 12^3$ which gives the following:

$$y^2 = x^3 + 8x + 8$$

3577 This is the tiny-jubjub curve that we used extensively throughout this book. So using the
 3578 complex multiplication method, we were able to derive a curve with specific properties from
 3579 scratch.

Example 105. To consider a real-world example, we want to use the complex multiplication method in combination with Sage to compute secp256k1 from scratch. So based on example 70, we decided to compute an elliptic curve over a prime field \mathbb{F}_p of order r for the following

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security parameters:

$$p = 115792089237316195423570985008687907853269984665640564039457584007908834671663$$

$$r = 115792089237316195423570985008687907852837564279074904382605163141518161494337$$

According to example 99, this gives the following trace of Frobenius:

$$t = 432420386565659656852420866390673177327$$

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We also decided that we want a curve of the form $y^2 = x^3 + b$, that is, we want the parameter a to be zero. This implies that the j -invariant of our curve must be zero.

In a first step, we have to find a CM-discriminant D and some integer v such that the equation $4p = t^2 + |D|v^2$ is satisfied. Since we aim for a vanishing j -invariant, the first thing to try is $D = -3$. In this case, we can compute $v^2 = (4p - t^2)$, and if v^2 happens to be an integer that has a square root v , we are done. Invoking Sage we compute as follows:

```

sage: D = -3
sage: p = 1157920892373161954235709850086879078532699846656405
      64039457584007908834671663
sage: r = 1157920892373161954235709850086879078528375642790749
      04382605163141518161494337
sage: t = p+1-r
sage: v_sqr = (4*p - t^2)/abs(D)
sage: v_sqr.is_integer()
True
sage: v = sqrt(v_sqr)
sage: v.is_integer()
True
sage: 4*p == t^2 + abs(D)*v^2
True
sage: v
303414439467246543595250775667605759171

```

The pair $(D, v) = (-3, 303414439467246543595250775667605759171)$ does indeed solve the equation, which tells us that there is a curve of order r over a prime field of order p , defined by a short Weierstrass equation $y^2 = x^3 + b$ for some $b \in \mathbb{F}_p$. Now we need to compute b .

For $D = -3$, we already know that the associated Hilbert class polynomial is given by $H_{-3}(x) = x$, which gives the projected Hilbert class polynomial as $H_{-3,p} = x$ and the j -invariant of our curve is guaranteed to be $j = 0$. Now, looking at 5.6, we see that there are 6 possible cases to construct a curve with the correct order r . In order to construct the curves in question, we have to choose some arbitrary quadratic and cubic non-residue. So we loop through \mathbb{F}_p to find them, invoking Sage:

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reference

```

sage: F = GF(p)
sage: for c2 in F:
.....:     try: # quadratic residue
.....:         _ = c2.nth_root(2)
.....:     except ValueError: # quadratic non-residue
.....:         break
sage: c2

```



```

3618 3 534
3619 sage: for c3 in F: 535
3620 .....: try: 536
3621 .....:     _ = c3.nth_root(3) 537
3622 .....: except ValueError: 538
3623 .....:     break 539
3624 sage: c3 540
3625 2 541

```

3626 We found the quadratic non-residue $c_2 = 3$ and the cubic non-residue $c_3 = 2$. Using those
 3627 numbers, we check the six cases against the the expected order r of the curve we want to
 3628 synthesize:

```

3629 sage: C1 = EllipticCurve(F, [0, 1]) 542
3630 sage: C1.order() == r 543
3631 False 544
3632 sage: C2 = EllipticCurve(F, [0, c2^3]) 545
3633 sage: C2.order() == r 546
3634 False 547
3635 sage: C3 = EllipticCurve(F, [0, c3^2]) 548
3636 sage: C3.order() == r 549
3637 False 550
3638 sage: C4 = EllipticCurve(F, [0, c3^2*c2^3]) 551
3639 sage: C4.order() == r 552
3640 False 553
3641 sage: C5 = EllipticCurve(F, [0, c3^(-2)]) 554
3642 sage: C5.order() == r 555
3643 False 556
3644 sage: C6 = EllipticCurve(F, [0, c3^(-2)*c2^3]) 557
3645 sage: C6.order() == r 558
3646 True 559

```

As expected, we found an elliptic curve of the correct order r over a prime field of size p . In principle, we are done, as we have found a curve with the same basic properties as secp256k1. However, the curve is defined by the following equation, which uses a very large parameter b_1 , and so it might perform too slowly in certain algorithms.

$$y^2 = x^3 + 86844066927987146567678238756515930889952488499230423029593188005931626003754$$

It is also not very elegant to be written down by hand. It might therefore be advantageous to find an isomorphic curve with the smallest possible parameter b_2 . In order to find such a b_2 , we have to choose a quadratic residue d such that $b_2 = b_1 \cdot d^3$ is as small as possible. To do so, we rewrite the last equation into the following form:

$$d = \sqrt[3]{\frac{b_2}{b_1}}$$

3647 Then we invoke Sage to loop through values $b_2 \in \mathbb{F}_p$ until it finds some number such that
 3648 the quotient $\frac{b_2}{b_1}$ has a cube root d and this cube root itself is a quadratic residue.

```

3649 sage: b1=86844066927987146567678238756515930889952488499230423 560
3650 029593188005931626003754

```

what
does this
mean?
Maybe
just delete
it


```

3651 sage: for b2 in F:
3652     ....:     try:
3653     ....:         d = (b2/b1).nth_root(3)
3654     ....:         try:
3655     ....:             _ = d.nth_root(2)
3656     ....:             if d != 0:
3657     ....:                 break
3658     ....:         except ValueError:
3659     ....:             pass
3660     ....:     except ValueError:
3661     ....:         pass
3662 sage: b2
3663 7

```

Indeed, the smallest possible value is $b_2 = 7$ and the defining short Weierstrass equation of a curve over \mathbb{F}_p with prime order r is $y^2 = x^3 + 7$, which we might call secp256k1. As we have just seen, the complex multiplication method is powerful enough to derive cryptographically secure curves like secp256k1 from scratch.

Exercise 81. Show that the Hilbert class polynomials for the CM-discriminants $D = -3$ and $D = -4$ are given by $H_{-3,q}(x) = x$ and $H_{-4,q} = x - (1728 \bmod q)$.

5.6.1 The BLS6_6 pen-and-paper curve

In this paragraph, we summarize our understanding of elliptic curves to derive our main pen-and-paper example for the rest of the book. To do so, we want to use the complex multiplication method to derive a pairing-friendly elliptic curve that has similar properties to curves that are used in actual cryptographic protocols. However, we design the curve specifically to be useful in pen-and-paper examples, which mostly means that the curve should contain only a few points so that we are able to derive exhaustive addition and pairing tables.

A well-understood family of pairing-friendly curves is the the group of BLS curves (STUFF ABOUT THE HISTORY AND THE NAMING CONVENTION), which are derived in [XXX]. BLS curves are particularly useful in our case if the embedding degree k satisfies $k \equiv 6 \pmod{0}$. Of course, the smallest embedding degree k that satisfies this congruency is $k = 6$ and we therefore aim for a BLS6 curve as our main pen-and-paper example.

To apply the complex multiplication method from page 114 ff., recall that this method starts with a definition of the base field \mathbb{F}_{p^m} , as well as the trace of Frobenius t and the order of the curve. If the order $p^m + 1 - t$ is not a prime number, then the order r of the largest prime factor group needs to be controlled.

In the case of BLS6 curves, the parameter m is chosen to be 1, which means that the curves are defined over prime fields. All relevant parameters p , t and r are then themselves parameterized by the following three polynomials:

$$\begin{aligned}
 r(x) &= \Phi_6(x) \\
 t(x) &= x + 1 \\
 q(x) &= \frac{1}{3}(x-1)^2(x^2 - x + 1) + x
 \end{aligned}
 \tag{5.43}$$

In the equations above, Φ_6 is the 6-th cyclotomic polynomial and $x \in \mathbb{N}$ is a parameter that the designer has to choose in such a way that the evaluation of p , t and r at the point x

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cyclotomic
polyno-
mial

gives integers that have the proper size to meet the security requirements of the curve that they want to design. It is then guaranteed that the complex multiplication method can be used in combination with those parameters to define an elliptic curve with CM-discriminant $D = -3$, embedding degree $k = 6$, and curve equation $y^2 = x^3 + b$ for some $b \in \mathbb{F}_p$.

For example, if the curve should target the 128-bit security level, due to the **Pholaard-rho attack** (TODO) the parameter r should be prime number of at least 256 bits.

In order to design the smallest BLS₆ curve, we therefore have to find a parameter x such that $r(x)$, $t(x)$ and $q(x)$ are the smallest natural numbers that satisfy $q(x) > 3$ and $r(x) > 3$.¹

We therefore initiate the design process of our BLS₆ curve by looking up the 6-th cyclotomic polynomial, which is $\Phi_6 = x^2 - x + 1$, and then insert small values for x into the defining polynomials r, t, q . We get the following results:

$$\begin{array}{lll} x = 1 & (r(x), t(x), q(x)) & (1, 2, 1) \\ x = 2 & (r(x), t(x), q(x)) & (3, 3, 3) \\ x = 3 & (r(x), t(x), q(x)) & (7, 4, \frac{37}{3}) \\ x = 4 & (r(x), t(x), q(x)) & (13, 5, 43) \end{array}$$

Since $q(1) = 1$ is not a prime number, the first x that gives a proper curve is $x = 2$. However, such a curve would be defined over a base field of characteristic 3, and we would rather like to avoid that. We therefore find $x = 4$, which defines a curve over the prime field of characteristic 43 that has a trace of Frobenius $t = 5$ and a larger order prime group of size $r = 13$.

Since the prime field \mathbb{F}_{43} has 43 elements and 43's binary representation is $43_2 = 101011$, which consists of 6 digits, the name of our pen-and-paper curve should be BLS₆_6, since its is common to name a BLS curve by its embedding degree and the bit-length of the modulus in the base field. We call BLS₆_6 the **moon-math-curve**.

Based on 5.34, we know that the Hasse bound implies that BLS₆_6 will contain exactly 39 elements. Since the prime factorization of 39 is $39 = 3 \cdot 13$, we have a “large” prime factor group of size 13, as expected, and a small cofactor group of size 3. Fortunately, a subgroup of order 13 is well suited for our purposes, as 13 elements can be easily handled in the associated addition, scalar multiplication and pairing tables in a pen-and-paper style.

We can check that the embedding degree is indeed 6 as expected, since $k = 6$ is the smallest number k such that $r = 13$ divides $43^k - 1$.

```
sage: for k in range(1, 42): # Fermat's little theorem
.....:     if (43^k - 1) % 13 == 0:
.....:         break
sage: k
6
```

In order to compute the defining equation $y^2 = x^3 + ax + b$ of BLS₆-6, we use the complex multiplication method as described in 5.6. The goal is to find $a, b \in \mathbb{F}_{43}$ representations that are particularly nice to work with. The authors of XXX showed that the CM-discriminant of every BLS curve is $D = -3$ and, indeed, the following equation has the four solutions $(D, v) \in \{(-3, -7), (-3, 7), (-49, -1), (-49, 1)\}$ if D is required to be negative, as expected:

¹The smallest BLS curve will also be the most insecure BLS curve. However, since our goal with this curve is ease of pen-and-paper computation rather than security, it fits the purposes of this book.

Pholaard-rho attack

todo

why? Because in this book elliptic curves are only defined for fields of characteristic > 3

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what does this mean?

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$$\begin{aligned}
4p &= t^2 + |D|v^2 && \Rightarrow \\
4 \cdot 43 &= 5^2 + |D|v^2 && \Rightarrow \\
172 &= 25 + |D|v^2 && \Leftrightarrow \\
49 &= |D|v^2
\end{aligned}$$

This means that $D = -3$ is indeed a proper CM-discriminant, and we can deduce that the parameter a has to be 0, and that the Hilbert class polynomial is given by $H_{-3,43}(x) = x$.

This implies that the j -invariant of $BLS6_6$ is given by $j(BLS6_6) = 0$. We therefore have to look at case XXX in table 5.6 to derive a parameter b . To decide the proper case for $j_0 = 0$ and $D = -3$, we therefore have to choose some arbitrary quadratic non-residue c_2 and cubic non-residue c_3 in \mathbb{F}_{43} . We choose $c_2 = 5$ and $c_3 = 36$. We check these with Sage:

```

sage: F43 = GF(43)
sage: c2 = F43(5)
..... try: # quadratic residue
.....      c2.nth_root(2)
..... except ValueError: # quadratic non-residue
.....      c2
sage: c3 = F43(36)
..... try:
.....      c3.nth_root(3)
..... except ValueError:
.....      c3

```

Using those numbers we check the six possible cases from 5.6 against the the expected order 39 of the curve we want to synthesize:

```

sage: BLS61 = EllipticCurve(F43, [0, 1])
sage: BLS61.order() == 39
False
sage: BLS62 = EllipticCurve(F43, [0, c2^3])
sage: BLS62.order() == 39
False
sage: BLS63 = EllipticCurve(F43, [0, c3^2])
sage: BLS63.order() == 39
True
sage: BLS64 = EllipticCurve(F43, [0, c3^2*c2^3])
sage: BLS64.order() == 39
False
sage: BLS65 = EllipticCurve(F43, [0, c3^(-2)])
sage: BLS65.order() == 39
False
sage: BLS66 = EllipticCurve(F43, [0, c3^(-2)*c2^3])
sage: BLS66.order() == 39
False
sage: BLS6 = BLS63 # our BLS6 curve in the book

```

As expected, we found an elliptic curve of the correct order 39 over a prime field of size 43,

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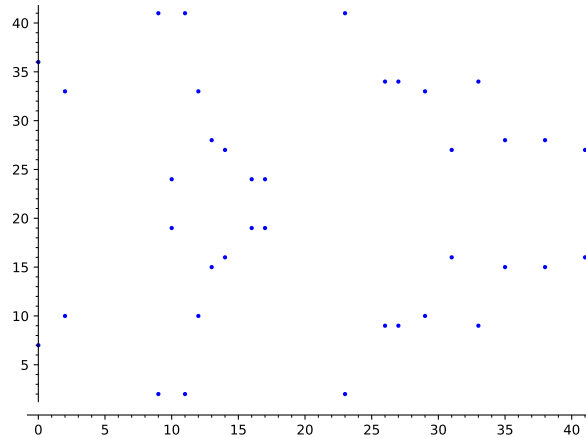
check
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3763 defined by the following equation:

$$BLS6_6 := \{(x, y) \mid y^2 = x^3 + 6 \text{ for all } x, y \in \mathbb{F}_{43}\} \quad (5.44)$$

3764 There are other choices for b , such as $b = 10$ or $b = 23$, but all these curves are isomorphic,
 3765 and hence represent the same curve in a different way. Since BLS6-6 only contains 39 points, it
 3766 is possible to give a visual impression of the curve:



3767

3768 As we can see, our curve has some desirable properties: it does not contain self-inverse
 3769 points, that is, points with $y = 0$. It follows that the addition law can be optimized, since the
 3770 branch for those cases can be eliminated.

3771 Summarizing the previous procedure, we have used the method of Barreto, Lynn and Scott
 3772 to construct a pairing-friendly elliptic curve of embedding degree 6. However, in order to do
 3773 elliptic curve cryptography on this curve, note that, since the order of $BLS6_6$ is 39, its group
 3774 of rational points is not a finite cyclic group of prime order. We therefore have to find a suitable
 3775 subgroup as our main target. Since $39 = 13 \cdot 3$, we know that the curve must contain a “large”
 3776 prime-order group of size 13 and a small cofactor group of order 3.

3777 The following step is to construct this group. One way to do so is to find a generator. We
 3778 can achieve this by choosing an arbitrary element of the group that is not the point at infinity,
 3779 and then multiply that point with the cofactor of the group’s order. If the result is not the point
 3780 at infinity, the result will be a generator. If it is the point at infinity we have to choose a different
 3781 element.

In order to find a generator for the large order subgroup of size 13, we first notice that the cofactor of 13 is 3, since $39 = 3 \cdot 13$. We then need to construct an arbitrary element from $BLS6_6$. To do so in a pen-and-paper style, we can choose some *arbitrary* $x \in \mathbb{F}_{43}$ and see if there is some solution $y \in \mathbb{F}_{43}$ that satisfies the defining short Weierstrass equation $y^2 = x^3 + 6$. We choose $x = 9$, and check that $y = 2$ is a proper solution:

$$\begin{aligned} y^2 &= x^3 + 6 && \Rightarrow \\ 2^2 &= 9^3 + 6 && \Leftrightarrow \\ 4 &= 4 \end{aligned}$$

3782 This implies that $P = (9, 2)$ is therefore a point on $BLS6_6$. To see if we can project this
 3783 point onto a generator of the large order prime group $BLS6_6[13]$, we have to multiply P with
 3784 the cofactor, that is, we have to compute $[3](9, 2)$. After some computation (EXERCISE) we
 3785 get $[3](9, 2) = (13, 15)$. Since this is not the point at infinity, we know that $(13, 15)$ must be a

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3786 generator of $BLS6_6[13]$. The generator $g_{BLS6_6[13]}$, which we will use in pairing computations
 3787 in the remainder of this book, is given as follows:

$$g_{BLS6_6[13]} = (13, 15) \quad (5.45)$$

3788 Since $g_{BLS6_6[13]}$ is a generator, we can use it to construct the subgroup $BLS6_6[13]$ by re-
 3789 peatedly adding the generator to itself. Using Sage, we get the following:

```

3790 sage: P = BLS6(9, 2)                                609
3791 sage: Q = 3*P                                         610
3792 sage: Q.xy()                                          611
3793 (13, 15)                                             612
3794 sage: BLS6_13 = []                                   613
3795 sage: for x in range(0, 13): # cyclic of order 13    614
3796     ....:     P = x*Q                                615
3797     ....:     BLS6_13.append(P)                      616

```

3798 Repeatedly adding a generator to itself, as we just did, will generate small groups in logarithmic
 3799 order with respect to the generator as, explained on page 43 ff. We therefore get the following
 3800 description of the large prime-order subgroup of $BLS6_6$:

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reference

$$\begin{aligned}
 BLS6_6[13] = \\
 \{ (13, 15) \rightarrow (33, 34) \rightarrow (38, 15) \rightarrow (35, 28) \rightarrow (26, 34) \rightarrow (27, 34) \rightarrow \\
 (27, 9) \rightarrow (26, 9) \rightarrow (35, 15) \rightarrow (38, 28) \rightarrow (33, 9) \rightarrow (13, 28) \rightarrow \mathcal{O} \} \quad (5.46)
 \end{aligned}$$

Having a logarithmic description of this group is tremendously helpful in pen-and-paper computations. To see that, observe that we know from XXX that there is an exponential map from the scalar field \mathbb{F}_{13} to $BLS6_6[13]$ with respect to our generator, which generates the group in logarithmic order:

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ence

$$[\cdot]_{(13,15)} : \mathbb{F}_{13} \rightarrow BLS6_6[13] ; x \mapsto [x](13, 15)$$

So, for example, we have $[1]_{(13,15)} = (13, 15)$, $[7]_{(13,15)} = (27, 9)$ and $[0]_{(13,15)} = \mathcal{O}$ and so on. The relevant point here is that we can use this representation to do computations in $BLS6_6[13]$ efficiently in our head using XXX, as in the following example:

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ence

$$\begin{aligned}
 (27, 34) \oplus (33, 9) &= [6](13, 15) \oplus [11](13, 15) \\
 &= [6 + 11](13, 15) \\
 &= [4](13, 15) \\
 &= (35, 28)
 \end{aligned}$$

So XXX is really all we need to do computations in $BLS6_6[13]$ in this book efficiently. How-ever, out of convenience, the following picture lists the entire addition table of that group, as it

add refer-
ence

might be useful in pen-and-paper computations:

\oplus	\mathcal{O}	(13, 15)	(33, 34)	(38, 15)	(35, 28)	(26, 34)	(27, 34)	(27, 9)	(26, 9)	(35, 15)	(38, 28)	(33, 9)	(13, 28)
\mathcal{O}	\mathcal{O}	(13, 15)	(33, 34)	(38, 15)	(35, 28)	(26, 34)	(27, 34)	(27, 9)	(26, 9)	(35, 15)	(38, 28)	(33, 9)	(13, 28)
(13, 15)	(13, 15)	(33, 34)	(38, 15)	(35, 28)	(26, 34)	(27, 34)	(27, 9)	(26, 9)	(35, 15)	(38, 28)	(33, 9)	(13, 28)	\mathcal{O}
(33, 34)	(33, 34)	(38, 15)	(35, 28)	(26, 34)	(27, 34)	(27, 9)	(26, 9)	(35, 15)	(38, 28)	(33, 9)	(13, 28)	\mathcal{O}	(13, 15)
(38, 15)	(38, 15)	(35, 28)	(26, 34)	(27, 34)	(27, 9)	(26, 9)	(35, 15)	(38, 28)	(33, 9)	(13, 28)	\mathcal{O}	(13, 15)	(33, 34)
(35, 28)	(35, 28)	(26, 34)	(27, 34)	(27, 9)	(26, 9)	(35, 15)	(38, 28)	(33, 9)	(13, 28)	\mathcal{O}	(13, 15)	(33, 34)	(38, 15)
(26, 34)	(26, 34)	(27, 34)	(27, 9)	(26, 9)	(35, 15)	(38, 28)	(33, 9)	(13, 28)	\mathcal{O}	(13, 15)	(33, 34)	(38, 15)	(35, 28)
(27, 34)	(27, 34)	(27, 9)	(26, 9)	(35, 15)	(38, 28)	(33, 9)	(13, 28)	\mathcal{O}	(13, 15)	(33, 34)	(38, 15)	(35, 28)	(26, 34)
(27, 9)	(27, 9)	(26, 9)	(35, 15)	(38, 28)	(33, 9)	(13, 28)	\mathcal{O}	(13, 15)	(33, 34)	(38, 15)	(35, 28)	(26, 34)	(27, 34)
(26, 9)	(26, 9)	(35, 15)	(38, 28)	(33, 9)	(13, 28)	\mathcal{O}	(13, 15)	(33, 34)	(38, 15)	(35, 28)	(26, 34)	(27, 34)	(27, 9)
(35, 15)	(35, 15)	(38, 28)	(33, 9)	(13, 28)	\mathcal{O}	(13, 15)	(33, 34)	(38, 15)	(35, 28)	(26, 34)	(27, 34)	(27, 9)	(26, 9)
(38, 28)	(38, 28)	(33, 9)	(13, 28)	\mathcal{O}	(13, 15)	(33, 34)	(38, 15)	(35, 28)	(26, 34)	(27, 34)	(27, 9)	(26, 9)	(35, 15)
(33, 9)	(33, 9)	(13, 28)	\mathcal{O}	(13, 15)	(33, 34)	(38, 15)	(35, 28)	(26, 34)	(27, 34)	(27, 9)	(26, 9)	(35, 15)	(38, 28)
(13, 28)	(13, 28)	\mathcal{O}	(13, 15)	(33, 34)	(38, 15)	(35, 28)	(26, 34)	(27, 34)	(27, 9)	(26, 9)	(35, 15)	(38, 28)	(33, 9)

Now that we have constructed a “large” cyclic prime-order subgroup of $BLS6_6$ suitable for many pen-and-paper computations in elliptic curve cryptography, we have to look at how to do pairings in this context. We know that $BLS6_6$ is a pairing-friendly curve by design, since it has a small embedding degree $k = 6$. It is therefore possible to compute Weil pairings efficiently. However, in order to do so, we have to decide the groups \mathbb{G}_1 and \mathbb{G}_2 as explained in exercise 76.

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reference

Since $BLS6_6$ has two non-trivial subgroups, it would be possible to use any of them as the n -torsion group. However, in cryptography, the only secure choice is to use the large prime-order subgroup, which in our case is $BLS6_6[13]$. We therefore decide to consider the 13-torsion and define $G_1[13]$ as the first argument for the Weil pairing function:

$$\mathbb{G}_1[13] = \{(13, 15) \rightarrow (33, 34) \rightarrow (38, 15) \rightarrow (35, 28) \rightarrow (26, 34) \rightarrow (27, 34) \rightarrow (27, 9) \rightarrow (26, 9) \rightarrow (35, 15) \rightarrow (38, 28) \rightarrow (33, 9) \rightarrow (13, 28) \rightarrow \mathcal{O}\}$$

In order to construct the domain for the second argument, we need to construct $\mathbb{G}_2[13]$, which, according to the general theory, should be defined by those elements P of the full 13-torsion group $BLS6_6[13]$ that are mapped to $43 \cdot P$ under the Frobenius endomorphism (equation 5.29).

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reference

To compute $\mathbb{G}_2[13]$, we therefore have to find the full 13-torsion group first. To do so, we use the technique from XXX, which tells us that the full 13-torsion can be found in the curve extension over the extension field \mathbb{F}_{43^6} , since the embedding degree of $BLS6_6$ is 6:

$$BLS6_6 := \{(x, y) \mid y^2 = x^3 + 6 \text{ for all } x, y \in \mathbb{F}_{43^6}\} \quad (5.47)$$

Thus, we have to construct \mathbb{F}_{43^6} , a field that contains 6321363049 elements. In order to do so, we use the procedure of XXX and start by choosing a non-reducible polynomial of degree 6 from the ring of polynomials $\mathbb{F}_{43}[t]$. We choose $p(t) = t^6 + 6$. Using Sage, we get the following:

add refer-
ence

```
sage: F43 = GF(43) 617
sage: F43t.<t> = F43[] 618
sage: p = F43t(t^6+6) 619
sage: p.is_irreducible() 620
```


3826 **True** 621
 3827 **sage:** `F43_6.<v> = GF(43^6, name='v', modulus=p)` 622

3828 Recall from XXX that elements $x \in \mathbb{F}_{43^6}$ can be seen as polynomials $a_0 + a_1v + a_2v^2 + \dots + a_5v^5$ with the usual addition of polynomials and multiplication modulo $t^6 + 6$. add reference

3830 In order to compute $\mathbb{G}_2[13]$, we first have to extend $BLS6_6$ to \mathbb{F}_{43^6} , that is, we keep the
 3831 defining equation, but expand the domain from \mathbb{F}_{43} to \mathbb{F}_{43^6} . After that, we have to find at least
 3832 one element P from that curve that is not the point at infinity, is in the full 13-torsion and
 3833 satisfies the identity $\pi(P) = [43]P$. We can then use this element as our generator of $\mathbb{G}_2[13]$ and
 3834 construct all other elements by repeatedly adding the generator to itself.

3835 Since $BLS6(\mathbb{F}_{43^6})$ contains 6321251664 elements, it's not a good strategy to simply loop
 3836 through all elements. Fortunately, Sage has a way to loop through elements from the torsion
 3837 group directly:

```
3838 sage: BLS6 = EllipticCurve (F43_6, [0 , 6]) # curve extension 623
3839 sage: INF = BLS6(0) # point at infinity 624
3840 sage: for P in INF.division_points(13): # full 13-torsion 625
3841     ....: # PI(P) == [q]P 626
3842     ....:     if P.order() == 13: # exclude point at infinity 627
3843     ....:         PiP = BLS6([a.frobenius() for a in P]) 628
3844     ....:         qP = 43*P 629
3845     ....:         if PiP == qP: 630
3846     ....:             break 631
3847 sage: P.xy() 632
3848 (7*v^2, 16*v^3) 633
```

3849 We found an element from the full 13-torsion that is in the Eigenspace of the Eigenvalue 43,
 3850 which implies that it is an element of $\mathbb{G}_2[13]$. As $\mathbb{G}_2[13]$ is cyclic of prime order, this element
 3851 must be a generator:

$$g_{\mathbb{G}_2[13]} = (7v^2, 16v^3) \quad (5.48)$$

3852 We can use this generator to compute \mathbb{G}_2 in logarithmic order with respect to $g_{\mathbb{G}_2[13]}$. Using
 3853 Sage we get the following:

```
3854 sage: Q = BLS6(7*v^2, 16*v^3) 634
3855 sage: BLS6_13_2 = [] 635
3856 sage: for x in range(0, 13): 636
3857     ....:     P = x*Q 637
3858     ....:     BLS6_13_2.append(P) 638
```

$$\begin{aligned} \mathbb{G}_2 = \{ & (7v^2, 16v^3) \rightarrow (10v^2, 28v^3) \rightarrow (42v^2, 16v^3) \rightarrow (37v^2, 27v^3) \rightarrow \\ & (16v^2, 28v^3) \rightarrow (17v^2, 28v^3) \rightarrow (17v^2, 15v^3) \rightarrow (16v^2, 15v^3) \rightarrow \\ & (37v^2, 16v^3) \rightarrow (42v^2, 27v^3) \rightarrow (10v^2, 15v^3) \rightarrow (7v^2, 27v^3) \rightarrow \mathcal{O} \} \end{aligned}$$

Again, having a logarithmic description of $\mathbb{G}_2[13]$ is tremendously helpful in pen-and-paper computations, as it reduces complicated computation in the extended curves to modular 13

arithmetics, as in the following example:

$$\begin{aligned}
 (17v^2, 28v^3) \oplus (10v^2, 15v^2) &= [6](7v^2, 16v^3) \oplus [11](7v^2, 16v^3) \\
 &= [6 + 11](7v^2, 16v^3) \\
 &= [4](7v^2, 16v^3) \\
 &= (37v^2, 27v^3)
 \end{aligned}$$

So XXX is really all we need to do computations in $\mathbb{G}_2[13]$ in this book efficiently.

To summarize the previous steps, we have found two subgroups, $\mathbb{G}_1[13]$ and $\mathbb{G}_2[13]$ suitable to do Weil pairings on *BLS6_6* as explained in 5.33. Using the logarithmic order XXX of $\mathbb{G}_1[13]$, the logarithmic order XXX of $\mathbb{G}_2[13]$ and the bilinearity in 5.49, we can do Weil pairings on *BLS6_6* in a pen-and-paper style:

$$e([k_1]g_{BLS6_6[13]}, [k_2]g_{\mathbb{G}_2[13]}) = e(g_{BLS6_6[13]}, g_{\mathbb{G}_2[13]})^{k_1 \cdot k_2} \quad (5.49)$$

Observe that the Weil pairing between our two generators is given by the following identity:

$$e(g_{BLS6_6[13]}, g_{\mathbb{G}_2[13]}) = 5v^5 + 16v^4 + 16v^3 + 15v^2 + 3v + 41 \quad (5.50)$$

sage: `g1 = BLS6([13, 15])`

sage: `g2 = BLS6([7*v^2, 16*v^3])`

sage: `g1.weil_pairing(g2, 13)`

`5*v^5 + 16*v^4 + 16*v^3 + 15*v^2 + 3*v + 41`

Hashing to pairing groups We give various constructions to hash into \mathbb{G}_1 and \mathbb{G}_2 .

We start with hashing to the scalar field... **TO APPEAR**

None of these techniques work for hashing into \mathbb{G}_2 . We therefore implement Pederson's Hash for BLS6.

We start with \mathbb{G}_1 . Our goal is to define an 12-bit bounded hash function:

$$H_1 : \{0, 1\}^{12} \rightarrow \mathbb{G}_1$$

Since $12 = 3 \cdot 4$ we “randomly” select 4 uniformly distributed generators $\{(38, 15), (35, 28), (27, 34), (38, 28)\}$ from \mathbb{G}_1 and use the pseudo-random function from XXX. Therefore, we have to choose a set of 4 randomly generated invertible elements from \mathbb{F}_{13} for every generator. We choose the following:

$$\begin{aligned}
 (38, 15) &: \{2, 7, 5, 9\} \\
 (35, 28) &: \{11, 4, 7, 7\} \\
 (27, 34) &: \{5, 3, 7, 12\} \\
 (38, 28) &: \{6, 5, 1, 8\}
 \end{aligned}$$

Our hash function is then computed as follows:

$$\begin{aligned}
 H_1(x_{11}, x_1, \dots, x_0) &= [2 \cdot 7^{x_{11}} \cdot 5^{x_{10}} \cdot 9^{x_9}](38, 15) + [11 \cdot 4^{x_8} \cdot 7^{x_7} \cdot 7^{x_6}](35, 28) + \\
 &\quad [5 \cdot 3^{x_5} \cdot 7^{x_4} \cdot 12^{x_3}](27, 34) + [6 \cdot 5^{x_2} \cdot 1^{x_1} \cdot 8^{x_0}](38, 28)
 \end{aligned}$$

3874

Note that $a^x = 1$ when $x = 0$. Hence, those terms can be omitted in the computation. In particular, the hash of the 12-bit zero string is given as follows:

3875

correct
computa-
tions

WRONG – ORDERING – REDO

$$H_1(0) = [2](38, 15) + [11](35, 28) + [5](27, 34) + [6](38, 28) = \\ (27, 34) + (26, 34) + (35, 28) + (26, 9) = (33, 9) + (13, 28) = (38, 28)$$

The hash of 011010101100 is given as follows:

fill in
missing
parts

$$H_1(011010101100) = \text{WRONG – ORDERING – REDO} \\ [2 \cdot 7^0 \cdot 5^1 \cdot 9^1](38, 15) + [11 \cdot 4^0 \cdot 7^1 \cdot 7^0](35, 28) + [5 \cdot 3^1 \cdot 7^0 \cdot 12^1](27, 34) + [6 \cdot 5^1 \cdot 1^0 \cdot 8^0](38, 28) = \\ [2 \cdot 5 \cdot 9](38, 15) + [11 \cdot 7](35, 28) + [5 \cdot 3 \cdot 12](27, 34) + [6 \cdot 5](38, 28) = \\ [12](38, 15) + [12](35, 28) + [11](27, 34) + [4](38, 28) =$$

TOAPPEAR

We can use the same technique to define a 12-bit bounded hash function in \mathbb{G}_2 :

$$H_2 : \{0, 1\}^{12} \rightarrow \mathbb{G}_2$$

Again, we “randomly” select 4 uniformly distributed generators $\{(7v^2, 16v^3), (42v^2, 16v^3), (17v^2, 15v^3), (10v^2, 15v^3)\}$ from \mathbb{G}_2 , and use the pseudo-random function from XXX. Therefore, we have to choose a set of 4 randomly generated invertible elements from \mathbb{F}_{13} for every generator:

add refer-
ence

$$\begin{aligned} (7v^2, 16v^3) & : \{8, 4, 5, 7\} \\ (42v^2, 16v^3) & : \{12, 1, 3, 8\} \\ (17v^2, 15v^3) & : \{2, 3, 9, 11\} \\ (10v^2, 15v^3) & : \{3, 6, 9, 10\} \end{aligned}$$

Our hash function is then computed like this:

$$H_1(x_{11}, x_{10}, \dots, x_0) = [8 \cdot 4^{x_{11}} \cdot 5^{x_{10}} \cdot 7^{x_9}](7v^2, 16v^3) + [12 \cdot 1^{x_8} \cdot 3^{x_7} \cdot 8^{x_6}](42v^2, 16v^3) + \\ [2 \cdot 3^{x_5} \cdot 9^{x_4} \cdot 11^{x_3}](17v^2, 15v^3) + [3 \cdot 6^{x_2} \cdot 9^{x_1} \cdot 10^{x_0}](10v^2, 15v^3)$$

We extend this to a hash function that maps unbounded bitstrings to \mathbb{G}_2 by precomposing with an actual hash function like MD5, and feed the first 12 bits of its outcome into our previously defined hash function, with $\text{TinyMD5}_{\mathbb{G}_2}(s) = H_2(\text{MD5}(s)_0, \dots, \text{MD5}(s)_{11})$:

$$\text{TinyMD5}_{\mathbb{G}_2} : \{0, 1\}^* \rightarrow \mathbb{G}_2$$

For example, since $\text{MD5}("") = 0xd41d8cd98f00b204e9800998ecf8427e$, and the binary representation of the hexadecimal number 0x27e is 001001111110, we compute $\text{TinyMD5}_{\mathbb{G}_2}$ of the empty string as follows:

$$\text{TinyMD5}_{\mathbb{G}_2}("") = H_2(\text{MD5}(s)_{11}, \dots, \text{MD5}(s)_0) = H_2(001001111110) =$$

3876

check
equation

Chapter 6

Statements

As we have seen in the informal introduction XXX, a SNARK is a succinct non-interactive argument of knowledge, where the knowledge-proof attests to the correctness of statements like “The prover knows the prime factorization of a given number” or “The prover knows the preimage to a given SHA2 digest value” and similar things. However, human-readable statements like these are imprecise and not very useful from a formal perspective.

In this chapter we therefore look more closely at ways to formalize statements in mathematically rigorous ways, useful for SNARK development. We start by introducing formal languages as a way to define statements properly (section 6.1). We will then look at algebraic circuits and Rank-1 Constraint Systems [R1CS] as two particularly useful ways to define statements in certain formal languages (section 6.2).

Proper statement design should be of high priority in the development of SNARKs, since unintended true statements can lead to potentially severe and almost undetectable security vulnerabilities in the applications of SNARKs.

6.1 Formal Languages

Formal languages provide the theoretical background in which statements can be formulated in a logically rigorous way and where proving the correctness of any given statement can be realized by computing words in that language.

One might argue that the understanding of formal languages is not very important in SNARK development and associated statement design, but terms from that field of research are standard jargon in many papers on zero-knowledge proofs. We therefore believe that at least some introduction to formal languages and how they fit into the picture of SNARK development is beneficial, mostly to give developers a better intuition about where all this is located in the bigger picture of the logic landscape. In addition, formal languages give a better understanding of what a formal proof for a statement actually is.

Roughly speaking, a formal language (or just language for short) is nothing but a set of words and words, in turn, are strings of letters taken from some alphabet and formed according to some defining rules of the language.

To be more precise, let Σ be any set and Σ^* the set of all **strings** of finite length $\langle x_1, \dots, x_n \rangle$ of elements x_j from Σ including the empty string $\langle \rangle \in \Sigma^*$. Then, a **language** L , in its most general definition, is nothing but a subset of the set of all finite strings Σ^* . In this context, the set Σ is called the **alphabet** of the language L , elements from Σ are called letters and elements from L are called **words**. If there are rules that specify which strings from Σ^* belong to the language and which don't, those rules are called the **grammar** of the language. If L_1 and L_2 are

Chapter
1?

two formal languages over the same alphabet, we call L_1 and L_2 **equivalent** if they consist of the same set of words.

While the term language might suggest a deeper relation to the well known **natural languages** like English, formal languages and natural languages differ in many ways. The following two examples will provide some intuition about formal languages and their differences to natural languages:

Example 106 (The English language). To give a better understanding of formal languages consider the natural language English. The English alphabet is given by the following set

$$\Sigma_{\text{English}} = \{A, a, B, b, C, c, D, d, E, e, F, f, G, g, H, h, I, i, J, j, K, k, L, l, M, m, N, n, O, o, P, p, Q, q, R, r, S, s, T, t, U, u, V, v, W, w, X, x, Y, y, Z, z\}$$

The natural language English does not define words by abstract rules, but by something we might call historical human convention as a word in the language English is distinguished from any other string from the English alphabet by human convention not by formal rules. In that regard strings like “tea” or “eat” are words in English, but “aet” and “tae” are not, because people agree on that. So while the set of all English words is a formal language $L_{\text{English}} \subset \Sigma_{\text{English}}$ there is no formal grammar that defines what a word in English is and what not.

It should also be recognized that in such a simple definition, the “grammar” of the natural language English is different from the grammar of the formal language English. The grammar of natural English defines how sentences are generated from words, while sentences have no meaning in our simple formal language English.

In order to express natural English sentences in a formal English language, one has to extend the alphabet by a space character together with the set of all punctuations and then include the grammar of the natural language English into the formal language English. It should be noted however that in such a formal language, sentences like “I drink tea, but I don’t eat meat.” from the natural language English are actually words in the formal language English.

Example 107 (Alternating Binary strings). To consider a very basic formal language with an almost trivial grammar, consider the set of the two letters 0 and 1 as our alphabet Σ :

$$\Sigma = \{0, 1\}$$

Also imply the grammar that a proper word must consist of alternating binary letters of arbitrary length including the empty string. The associated language L_{alt} is the set of all finite binary strings, where a 1 must follow a 0 and vice versa. So, for example, $\langle 1, 0, 1, 0, 1, 0, 1, 0, 1 \rangle \in L_{\text{alt}}$ is a word in this languages as is $\langle 0 \rangle \in L_{\text{alt}}$ or the empty word $\langle \rangle \in L_{\text{alt}}$. However, the binary string $\langle 1, 0, 1, 0, 1, 0, 1, 1, 1 \rangle \in \{0, 1\}^*$ is not a proper word, as it violates the grammar of L_{alt} , since the last 3 letters are all 1. Furthermore, the string $\langle 0, A, 0, A, 0, A, 0 \rangle$ is not a proper word, as not all its letters are from the alphabet Σ .

Decision Functions Our previous definition of formal languages is very general and many subclasses of languages are known in the literature. However, in the context of SNARK development, languages are commonly defined as **decision problems** where a so-called **deciding relation** $R \subset \Sigma^*$ decides whether a given string $x \in \Sigma^*$ is a word in the language or not. If $x \in R$ then x is a word in the associated language L_R and if $x \notin R$ then not. The relation R therefore summarizes the grammar of language L_R .

Unfortunately, in some literature on proof systems, $x \in R$ is often written as $R(x)$, which is misleading since in general R is not a function but a relation in Σ^* . For the sake of this book, we

therefore adopt a different point of view and work with what we might call a **decision function** instead:

$$R : \Sigma^* \rightarrow \{true, false\} \quad (6.1)$$

Decision functions decide if a string $x \in \Sigma^*$ is an element of a language or not. In case a decision function is given, the associated language itself can be written as the set of all strings that are decided by R , i.e as the set:

$$L_R := \{x \in \Sigma^* \mid R(x) = true\} \quad (6.2)$$

In the context of formal languages and decision problems, a **statement** S is the claim that language L contains a word x , i.e a statement claims that there exists some $x \in L$. A constructive **proof** for statement S is given by some string $P \in \Sigma^*$ and a proof is **verified** by checking $R(P) = true$. In this case, P is called an **instance** of the statement S .

Example 108 (Alternating Binary strings). To consider a very basic formal language with a decision function, consider the language L_{alt} from example 107. Attempting to write the grammar of this language in a more formal way, we can define the following decision function:

$$R : \{0, 1\}^* \rightarrow \{true, false\} ; \langle x_0, x_1, \dots, x_n \rangle \mapsto \begin{cases} true & x_{j-1} \neq x_j \text{ for all } 1 \leq j \leq n \\ false & \text{else} \end{cases}$$

We can use this function to decide if given binary strings are words in L_{alt} or not. Some examples are given below:

$$R(\langle 1, 0, 1 \rangle) = true, \quad R(\langle 0 \rangle) = true, \quad R(\langle \rangle) = true, \quad R(\langle 1, 1 \rangle) = false$$

Given language L_{alt} , it makes sense to claim the following statement: “There exists an alternating string.” One way to prove this statement constructively is by providing an actual instance, that is, providing an example of an alternating string like $x = \langle 1, 0, 1 \rangle$. Constructing string $\langle 1, 0, 1 \rangle$ therefore proves the statement “There exists an alternating string.”, because one can verify that $R(\langle 1, 0, 1 \rangle) = true$.

Example 109 (Programming Language). Programming languages are a very important class of formal languages. For these languages, the alphabet is usually (a subset) of the ASCII table, and the grammar is defined by the rules of the programming language’s compiler. Words, then, are nothing but properly written computer programs that the compiler accepts. The compiler can therefore be interpreted as the decision function.

To give an unusual example strange enough to highlight the point, consider the programming language Malbolge as defined in XXX. This language was specifically designed to be almost impossible to use and writing programs in this language is a difficult task. An interesting claim is therefore the statement: “There exists a computer program in Malbolge”. As it turned out, proving this statement constructively, that is, providing an example instance of such a program, is not an easy task, as it took two years after the introduction of Malbolge to write a program that its compiler accepts. So, for two years, no one was able to prove the statement constructively.

To look at the high-level description of Malbolge more formally, we write $L_{Malbolge}$ for the language that uses the ASCII table as its alphabet and its words are strings of ASCII letters that the Malbolge compiler accepts. Proving the statement “There exists a computer program in Malbolge” is then equivalent to the task of finding some word $x \in L_{Malbolge}$. The string

$(=<'9876Z4321UT.-Q+*)M' \& \% \$ H''! \} | B z y ? = | \{ z \} K w Z Y 44 E q 0 / \{ m l k **$

$h K s _ d G 5 [m _ B A \{ ? - Y ; ; V b ' r R 5 4 3 1 M \} / . z H G w E D C B A @ 9 8 \backslash 6 5 4 3 W 1 0 / . R , + O <$

add reference

is an example of such a proof, as it is excepted by the Malbolge compiler and is compiled to an executable binary that displays “Hello, World.” (See XXX). In this example, the Malbolge compiler therefore serves as the verification process.

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Example 110 (The Empty Language). To see that not every language has even a single word, consider the alphabet $\Sigma = \mathbb{Z}_6$, where \mathbb{Z}_6 is the ring of modular 6 arithmetic as derived in example 9. Distinguishing the set \mathbb{Z}_6^* of all elements in modular 6 arithmetic that have multiplicative inverses from the set $(\mathbb{Z}_6)^*$ of all finite strings over the alphabet \mathbb{Z}_6 , we define the following decision function:

$$R_0 : (\mathbb{Z}_6)^* \rightarrow \{true, false\} ; \langle x_1, \dots, x_n \rangle \mapsto \begin{cases} true & n = 1 \text{ and } x \cdot x = 2 \\ false & \text{else} \end{cases}$$

We write L_0 for the associated language. As we can see from the multiplication table of \mathbb{Z}_6 in example 9, the ring \mathbb{Z}_6 does not contain any element x such that $x \cdot x = 2$, which implies $R_0(\langle x_1, \dots, x_n \rangle) = false$ for all strings $\langle x_1, \dots, x_n \rangle \in \Sigma^*$. The language therefore does not contain any words. Proving the statement “There exists a word in L_0 ” constructively by providing an instance is therefore impossible. The verification will never check any string.

Example 111 (3-Factorization). We will use the following simple example repeatedly throughout this book. The task is to develop a SNARK that proves knowledge of three factors of an element from the finite field \mathbb{F}_{13} . There is nothing particularly useful about this example from an application point of view, however, in a sense, it is the most simple example that gives rise to a non trivial SNARK in some of the most common zero-knowledge proof systems.

Formalizing the high-level description, we use $\Sigma := \mathbb{F}_{13}$ as the underlying alphabet of this problem and define the language $L_{3.fac}$ to consists of those strings of field elements from \mathbb{F}_{13} that contain exactly 4 letters x_1, x_2, x_3, x_4 which satisfy the equation $x_1 \cdot x_2 \cdot x_3 = x_4$.

So, for example, the string $\langle 2, 12, 4, 5 \rangle$ is a word in $L_{3.fac}$, while neither $\langle 2, 12, 11 \rangle$, nor $\langle 2, 12, 4, 7 \rangle$ nor $\langle 2, 12, 7, UPS \rangle$ are words in $L_{3.fac}$ as they don’t satisfy the grammar or are not defined over the alphabet \mathbb{F}_{13} .

Distinguishing the set \mathbb{F}_{13}^* of all elements in the multiplicative group of \mathbb{F}_{13} from the set $(\mathbb{F}_{13})^*$ of all finite strings over the alphabet \mathbb{F}_{13} , we can describe the language $L_{3.fac}$ more formally by introducing a decision function:

$$R_{3.fac} : (\mathbb{F}_{13})^* \rightarrow \{true, false\} ; \langle x_1, \dots, x_n \rangle \mapsto \begin{cases} true & n = 4 \text{ and } x_1 \cdot x_2 \cdot x_3 = x_4 \\ false & \text{else} \end{cases}$$

Having defined the language $L_{3.fac}$, it then makes sense to claim the statement “There is a word in $L_{3.fac}$ ”. The way $L_{3.fac}$ is designed, this statement is equivalent to the statement “There are four elements x_1, x_2, x_3, x_4 from the finite field \mathbb{F}_{13} such that the equation $x_1 \cdot x_2 \cdot x_3 = x_4$ holds.”

Proving the correctness of this statement constructively means to actually find some concrete field elements like $x_1 = 2, x_2 = 12, x_3 = 4$ and $x_4 = 5$ that satisfy the decision function $R_{3.fac}$. The string $\langle 2, 12, 4, 5 \rangle$ is therefore a constructive proof for the statement that $L_{3.fac}$ contains words and the computation $R_{3.fac}(\langle 2, 12, 4, 5 \rangle) = true$ is a verification of that proof. In contrast, the string $\langle 2, 12, 4, 7 \rangle$ is not a proof of the statement, since the check $R_{3.fac}(\langle 2, 12, 4, 7 \rangle) = false$ does not verify the proof.

Example 112 (Tiny-jubjub Membership). In one of our main examples, we derive a SNARK that proves a pair (x, y) of field elements from \mathbb{F}_{13} to be a point on the tiny-jubjub curve in its twisted Edwards form as derived in example 5.21.

jubjub

In the first step, we define a language such that points on the tiny-jubjub curve are in 1:1 correspondence with words in that language.

Since the tiny-jubjub curve is an elliptic curve over the field \mathbb{F}_{13} , we choose the alphabet $\Sigma = \mathbb{F}_{13}$. In this case, the set $(\mathbb{F}_{13})^*$ consists of all finite strings of field elements from \mathbb{F}_{13} . To define the grammar, recall from 5.21 that a point on the tiny-jubjub curve is a pair (x, y) of field elements such that $3 \cdot x^2 + y^2 = 1 + 8 \cdot x^2 \cdot y^2$. We can use this equation to derive the following decision function:

$$R_{\text{tiny.jj}} : (\mathbb{F}_{13})^* \rightarrow \{true, false\} ; \langle x_1, \dots, x_n \rangle \mapsto \begin{cases} true & n = 2 \text{ and } 3 \cdot x_1^2 + x_2^2 = 1 + 8 \cdot x_1^2 \cdot x_2^2 \\ false & \text{else} \end{cases}$$

The associated language $L_{\text{tiny.jj}}$ is then given as the set of all strings from $(\mathbb{F}_{13})^*$ that are mapped onto *true* by $R_{\text{tiny.jj}}$. We get

$$L_{\text{tiny.jj}} = \{ \langle x_1, \dots, x_n \rangle \in (\mathbb{F}_{13})^* \mid R_{\text{tiny.jj}}(\langle x_1, \dots, x_n \rangle) = true \}$$

We can claim the statement “There is a word in $L_{\text{tiny.jj}}$ ” and because $L_{\text{tiny.jj}}$ is defined by $R_{\text{tiny.jj}}$, this statement is equivalent to the claim “The tiny-jubjub curve in its twisted Edwards form has a curve point.”

A constructive proof for this statement is a string $\langle x, y \rangle$ of field elements from \mathbb{F}_{13} that satisfies the twisted Edwards equation. Example 5.21 therefore implies that the string $\langle 11, 6 \rangle$ is a constructive proof and the computation $R_{\text{tiny.jj}}(\langle 11, 6 \rangle) = true$ is a proof verification. In contrast, the string $\langle 1, 1 \rangle$ is not a proof of the statement, since the computation $R_{\text{tiny.jj}}(\langle 1, 1 \rangle) = false$ does not verify the proof.

Exercise 82. Define a decision function such that the associated language L_{Exercise_1} consist precisely of all solutions to the equation $5x + 4 = 28 + 2x$ over \mathbb{F}_{13} . Provide a constructive proof for the claim: “There exist a word in L_{Exercise_1} and verify the proof.”

Exercise 83. Consider modular 6 arithmetic \mathbb{Z}_6 from example 9, the alphabet $\Sigma = \mathbb{Z}_6$ and the decision function

$$R_{\text{example}_9} : \Sigma^* \rightarrow \{true, false\} ; \langle x_1, \dots, x_n \rangle \mapsto \begin{cases} true & n = 1 \text{ and } 3 \cdot x_1 + 3 = 0 \\ false & \text{else} \end{cases}$$

Compute all words in the associated language L_{example_9} , provide a constructive proof for the statement “There exist a word in L_{example_9} ” and verify the proof.

Instance and Witness As we have seen in the previous paragraph, statements provide membership claims in formal languages, and instances serve as constructive proofs for those claims. However, in the context of **zero-knowledge** proof systems, our notion of constructive proofs is refined in such a way that it is possible to hide parts of the proof instance and still be able to prove the statement. In this context, it is therefore necessary to split a proof into an unhidden, public part called the **instance** and a hidden, private part called a **witness**.

To account for this separation of a proof instance into an instance and a witness part, our previous definition of formal languages needs a refinement. Instead of a single alphabet, the refined definition considers two alphabets Σ_I and Σ_W , and a decision function defined as follows:

$$R : \Sigma_I^* \times \Sigma_W^* \rightarrow \{true, false\} ; (i; w) \mapsto R(i; w) \quad (6.3)$$

Words are therefore strings $(i; w) \in \Sigma_I^* \times \Sigma_W^*$ with $R(i; w) = true$. The refined definition differentiates between inputs $i \in \Sigma_I$ and inputs $w \in \Sigma_W$. The input i is called an **instance** and the input w is called a **witness** of R .

If a decision function is given, the associated language is defined as the set of all strings from the underlying alphabets that are verified by the decision function:

$$L_R := \{(i; w) \in \Sigma_I^* \times \Sigma_W^* \mid R(i; w) = \text{true}\} \quad (6.4)$$

In this refined context, a **statement** S is a claim that, given an instance $i \in \Sigma_I^*$, there is a witness $w \in \Sigma_W^*$ such that language L contains a word $(i; w)$. A constructive **proof** for statement S is given by some string $P = (i; w) \in \Sigma_I^* \times \Sigma_W^*$ and a proof is **verified** by $R(P) = \text{true}$.

At this point, it is important to note that, while constructive proofs in languages that distinguish between instance and witness as in don't look very different from constructive proofs in languages from 6.1, we will see in 8 that given some instance, there are proof systems able to prove the statement (at least with high probability) without revealing anything about the witness. In this sense the witness is often called the **private input** and the instance is called the **public input**.

It is worth understanding the difference between statements as defined in 6.1 and the refined notion of statements from this paragraph. While statements in the sense of the previous paragraph can be seen as membership claims, statements in the refined definition can be seen as knowledge-claims, where a prover claims knowledge of a witness for a given instance. For a more detailed discussion on this topic see [XXX sec 1.4]

Example 113 (SHA256 – Knowledge of Preimage). One of the most common examples in the context of zero-knowledge proof systems is the **knowledge-of-a-preimage proof** for some cryptographic hash function like *SHA256*, where a publicly known *SHA256* digest value is given, and the task is to prove knowledge of a preimage for that digest under the *SHA256* function, without revealing that preimage.

To understand this problem in detail, we have to introduce a language able to describe the knowledge-of-preimage problem in such a way that the claim “Given digest i , there is a preimage w such that $SHA256(w) = i$ ” becomes a statement in that language. Since *SHA256* is a function

$$SHA256 : \{0, 1\}^* \rightarrow \{0, 1\}^{256}$$

that maps binary strings of arbitrary length onto binary strings of length 256 and we want to prove knowledge of preimages, we have to consider binary strings of size 256 as instances and binary strings of arbitrary length as witnesses.

An appropriate alphabet Σ_I for the set of all instances and an appropriate alphabet Σ_W for the set of all witnesses is therefore given by the set $\{0, 1\}$ of the two binary letters and a proper decision function is given by:

$$R_{SHA256} : \{0, 1\}^* \times \{0, 1\}^* \rightarrow \{\text{true}, \text{false}\};$$

$$(i; w) \mapsto \begin{cases} \text{true} & |i| = 256, i = SHA256(w) \\ \text{false} & \text{else} \end{cases}$$

We write L_{SHA256} for the associated language and note that it consists of words, which are strings $(i; w)$ such that the instance i is the *SHA256* image of the witness w .

Given some instance $i \in \{0, 1\}^{256}$, a statement in L_{SHA256} is the claim “Given digest i , there is a preimage w such that $SHA256(w) = i$ ”, which is exactly what the knowledge-of-preimage problem is about. A constructive proof for this statement is therefore given by a preimage w to the digest i and proof verification is achieved by verifying that $SHA256(w) = i$.

Example 114 (3-factorization). To give another intuition about the implication of refined languages, consider $L_{3.fac}$ from example 111 again. As we have seen, a constructive proof in

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$L_{3, \text{fac}}$ is given by 4 field elements x_1, x_2, x_3 and x_4 from \mathbb{F}_{13} such that the product in modular 13 arithmetic of the first three elements is equal to the 4'th element.

Splitting words from $L_{3, \text{fac}}$ into instance and witness parts, we can reformulate the problem and introduce different levels of knowledge-claims into the problem. For example, we could reformulate the membership statement of $L_{3, \text{fac}}$ into a statement where all factors x_1, x_2, x_3 of x_4 are witnesses and only the product x_4 is the instance. A statement for this reformulation is then expressed by the claim: "Given an instance field element x_4 , there are three witness factors of x_4 ". Assuming some instance x_4 , a constructive proof for the associated knowledge claim is then provided by any string (x_1, x_2, x_3) such that $x_1 \cdot x_2 \cdot x_3 = x_4$.

We can formalize this new language, which we might call $L_{3, \text{fac_zk}}$, by defining the following decision function:

$$R_{3, \text{fac_zk}} : (\mathbb{F}_{13})^* \times (\mathbb{F}_{13})^* \rightarrow \{true, false\};$$

$$(< i_1, \dots, i_n >; < w_1, \dots, w_m >) \mapsto \begin{cases} true & n = 1, m = 3, i_1 = w_1 \cdot w_2 \cdot w_3 \\ false & \text{else} \end{cases}$$

The associated language $L_{3, \text{fac_zk}}$ is defined by all strings from $(\mathbb{F}_{13})^* \times (\mathbb{F}_{13})^*$ that are mapped onto *true* under the decision function $R_{3, \text{fac_zk}}$.

Considering the distinction we made between the instance and the witness part in $L_{3, \text{fac_zk}}$, one might ask why we chose the factors x_1, x_2 and x_3 to be the witness and the product x_4 to be the instance and why we didn't choose another combination? This was an arbitrary choice in the example. Every other combination of instance and witness would be equally valid. For example, it would be possible to declare all variables as witness or to declare all variables as instance. Actual choices are determined by the application only.

Example 115 (The Tiny-Jubjub Curve). Consider the language $L_{\text{tiny.jj}}$ from example 112. As we have seen, a constructive proof in $L_{\text{tiny.jj}}$ is given by a pair (x_1, x_2) of field elements from \mathbb{F}_{13} such that the pair is a point of the tiny-jubjub curve in its Edwards representation.

We look at a reasonable splitting of words from $L_{\text{tiny.jj}}$ into instance and witness parts. The two obvious choices are to either choose both coordinates x_1 as x_2 as instance inputs, or to choose both coordinates x_1 as x_2 as witness inputs.

In case both coordinates are instance, we define the grammar of the associated language by introducing the following decision function:

$$R_{\text{tiny.jj.1}} : (\mathbb{F}_{13})^* \times (\mathbb{F}_{13})^* \rightarrow \{true, false\};$$

$$(< I_1, \dots, I_n >; < W_1, \dots, W_m >) \mapsto \begin{cases} true & n = 2, m = 0 \text{ and } 3 \cdot I_1^2 + I_2^2 = 1 + 8 \cdot I_1^2 \cdot I_2^2 \\ false & \text{else} \end{cases}$$

The language $L_{\text{tiny.jj.1}}$ is defined as the set of all strings from $(\mathbb{F}_{13})^* \times (\mathbb{F}_{13})^*$ that are mapped onto *true* by $R_{\text{tiny.jj.1}}$.

In case both coordinates are witness inputs, we define the grammar of the associated refined language by introducing the following decision function:

$$R_{\text{tiny.jj_zk}} : (\mathbb{F}_{13})^* \times (\mathbb{F}_{13})^* \rightarrow \{true, false\};$$

$$(< I_1, \dots, I_n >; < W_1, \dots, W_m >) \mapsto \begin{cases} true & n = 0, m = m \text{ and } 3 \cdot W_1^2 + W_2^2 = 1 + 8 \cdot W_1^2 \cdot W_2^2 \\ false & \text{else} \end{cases}$$

The language $L_{\text{tiny.jj_zk}}$ is defined as the set of all strings from $(\mathbb{F}_{13})^* \times (\mathbb{F}_{13})^*$ that are mapped onto *true* by $R_{\text{tiny.jj_zk}}$.

Exercise 84. Consider the modular 6 arithmetic \mathbb{Z}_6 from example 9 as alphabets Σ_I and Σ_W and the following decision function

$$R_{linear} : \Sigma^* \times \Sigma^* \rightarrow \{true, false\};$$

$$(i; w) \mapsto \begin{cases} true & |i| = 3 \text{ and } |w| = 1 \text{ and } i_1 \cdot w_1 + i_2 = i_3 \\ false & \text{else} \end{cases}$$

Which of the following instances (i_1, i_2, i_3) has a proof of knowledge in L_{linear} ?

$$(3, 3, 0), \quad (2, 1, 0), \quad (4, 4, 2)$$

4091 *Exercise 85* (Edwards Addition on Tiny-Jubjub). Consider the tiny-jubjub curve together with
 4092 its twisted Edwards addition law from example 69. Define an instance alphabet Σ_I , a witness
 4093 alphabet Σ_W and a decision function R_{add} with associated language L_{add} such that a string
 4094 $(i; w) \in \Sigma_I^* \times \Sigma_W^*$ is a word in L_{add} if and only if i is a pair of curve points on the tiny-jubjub
 4095 curve in Edwards form and w is the sum of those curve points.

4096 Choose some instance $i \in \Sigma_I^*$, provide a constructive proof for the statement “There is a
 4097 witness $w \in \Sigma_W^*$ such that $(i; w)$ is a word in L_{add} ” and verify that proof. Then find some
 4098 instance $i \in \Sigma_I^*$ such that i has no knowledge proof in L_{add} .

4099 **Modularity** From a developers perspective, it is often useful to construct complex statements
 4100 and their representing languages from simple ones. In the context of zero-knowledge proof
 4101 systems, those simple building blocks are often called **gadgets**, and gadget libraries usually
 4102 contain representations of atomic types like booleans, integers, various hash functions, elliptic
 4103 curve cryptography and many more (See chapter 7 for that). In order to synthesize statements,
 4104 developers then combine predefined gadgets into complex logic. We call the ability to combine
 4105 statements into more complex statements **modularity**.

4106 To understand the concept of modularity on the level of formal languages defined by deci-
 4107 sion functions, we need to look at the **intersection** of two languages, which exists whenever
 4108 both languages are defined over the same alphabet. In this case, the intersection is a language
 4109 that consists of strings which are words in both languages.

4110 To be more precise, let L_1 and L_2 be two languages defined over the same instance and
 4111 witness alphabets Σ_I and Σ_W . Then the intersection $L_1 \cap L_2$ of L_1 and L_2 is defined as

$$L_1 \cap L_2 := \{x \mid x \in L_1 \text{ and } x \in L_2\} \quad (6.5)$$

4112 If both languages are defined by decision functions R_1 and R_2 , the following function is a
 4113 decision function for the intersection language $L_1 \cap L_2$:

$$R_{L_1 \cap L_2} : \Sigma_I^* \times \Sigma_W^* \rightarrow \{true, false\}; (i, w) \mapsto R_1(i, w) \text{ and } R_2(i, w) \quad (6.6)$$

4114 Thus, the intersection of two decision-function-based languages is a also decision-function-
 4115 based language. This is important from an implementations point of view: It allows us to
 4116 construct complex decision functions, their languages and associated statements from simple
 4117 building blocks. Given a publicly known instance $i \in \Sigma_I^*$ a statement in an intersection language
 4118 then claims knowledge of a witness that satisfies all relations simultaneously.

6.2 Statement Representations

As we have seen in the previous section, formal languages and their definitions by decision functions are a powerful tool to describe statements in a formally rigorous manner.

However, from the perspective of existing zero-knowledge proof systems, not all ways to actually represent decision functions are equally useful. Depending on the proof system, some are more suitable than others. In this section, will describe two of the most common ways to represent decision functions and their statements.

6.2.1 Rank-1 Quadratic Constraint Systems

Although decision functions are expressible in various ways, many contemporary proving systems require the decision function to be expressed in terms of a system of quadratic equations over a finite field. This is true in particular for pairing-based proving systems like the once we describe in chapter 8, roughly because it is possible to separate instance and witness and then check solutions to those equations “in the exponent” of pairing-friendly cryptographic groups.

In this section, we will have a closer look at a particular type of quadratic equations called **Rank-1 (quadratic) Constraints Systems**, which are a common standard in zero-knowledge proof systems. We will start with a general introduction to those constrain systems and then look at their relation to formal languages. Then we will look into a common way to compute solutions to those systems.

R1CS representation To understand what **Rank-1 (quadratic) Constraint Systems** [R1CS] are in detail, let \mathbb{F} be a field, n, m and $k \in \mathbb{N}$ three numbers and a_j^i, b_j^i and $c_j^i \in \mathbb{F}$ constants from \mathbb{F} for every index $0 \leq j \leq n + m$ and $1 \leq i \leq k$. Then a Rank-1 Constraint System is defined as the following set of k many equations:

$$\begin{aligned} (a_0^1 + \sum_{j=1}^n a_j^1 \cdot I_j + \sum_{j=1}^m a_{n+j}^1 \cdot W_j) \cdot (b_0^1 + \sum_{j=1}^n b_j^1 \cdot I_j + \sum_{j=1}^m b_{n+j}^1 \cdot W_j) &= c_0^1 + \sum_{j=1}^n c_j^1 \cdot I_j + \sum_{j=1}^m c_{n+j}^1 \cdot W_j \\ &\vdots \\ (a_0^k + \sum_{j=1}^n a_j^k \cdot I_j + \sum_{j=1}^m a_{n+j}^k \cdot W_j) \cdot (b_0^k + \sum_{j=1}^n b_j^k \cdot I_j + \sum_{j=1}^m b_{n+j}^k \cdot W_j) &= c_0^k + \sum_{j=1}^n c_j^k \cdot I_j + \sum_{j=1}^m c_{n+j}^k \cdot W_j \end{aligned}$$

If a Rank-1 Constraint System is given, the parameter k is called the **number of constraints** and each equation is called a **constraint**. If a pair of strings $\langle I_1, \dots, I_n \rangle; \langle W_1, \dots, W_m \rangle$ of field elements satisfies theses equations, $\langle I_1, \dots, I_n \rangle$ is called an **instance** and $\langle W_1, \dots, W_m \rangle$ is called a **witness** of the system.

Remark 5 (Matrix notation). The presentation of Rank-1 Constraint Systems can be simplified using the notation of vectors and matrices, which abstracts over the indices. In fact if $x = (1, I, W) \in \mathbb{F}^{1+n+m}$ is a $(n + m + 1)$ -dimensional vector, A, B, C are $(n + m + 1) \times k$ -dimensional matrices and \odot is the **Schur/Hadamard product**, then a R1CS can be written as

$$Ax \odot Bx = Cx$$

However, since we did not introduced vector spaces and matrix calculus in the book, we use XXX as the defining equation for rank-1 constraints systems. We only highlighted the matrix notation, because it is sometimes used in the literature.

It can be shown that every bounded computation is expressible as a Rank-1 Constraint System and R1CS is therefore a universal model for bounded computations. We will derive some

Schur/Hadamard product

add reference

insights into common approaches of how to compile bounded computation into Rank-1 Constraint Systems in chapter 7.

Generally speaking, the idea of a Rank-1 Constraint System is to keep track of all the values that any variable can hold during a computation and to bind the relationships among all those variables that are implied by the computation itself. Once relations between all steps of a computer program are constrained, program execution is then enforced to be computed in exactly in the expected way without any opportunity for deviations. In this sense, solutions to Rank-1 Constraint Systems are proofs of proper program execution.

Example 116 (R1CS for 3-Factorization). To provide a better intuition of Rank-1 Constraint Systems, consider the language $L_{3.fac_zk}$ from example 114 again. As we have seen, $L_{3.fac_zk}$ consists of words $\langle I_1 \rangle; \langle W_1, W_2, W_3 \rangle$ over the alphabet \mathbb{F}_{13} such that $I_1 = W_1 \cdot W_2 \cdot W_3$. We show how to rewrite the problem as a Rank-1 Constraint System.

Since R1CS are systems of quadratic equations, expressions like $W_1 \cdot W_2 \cdot W_3$ which contain products of more than two factors (which are therefore not quadratic) have to be rewritten in a process often called **flattening**. To flatten the defining equation $I_1 = W_1 \cdot W_2 \cdot W_3$ of $L_{3.fac_zk}$ we introduce a new variable W_4 , which captures two of the three multiplications in $W_1 \cdot W_2 \cdot W_3$. We get the following two constraints

$$\begin{array}{ll} W_1 \cdot W_2 = W_4 & \text{constraint 1} \\ W_4 \cdot W_3 = I_1 & \text{constraint 2} \end{array}$$

Given some instance I_1 , any solution (W_1, W_2, W_3, W_4) to this system of equations provides a solution to the original equation $I_1 = W_1 \cdot W_2 \cdot W_3$ and vice versa. Both equations are therefore equivalent in the sense that solutions are in a 1:1 correspondence.

Looking at both equations from this constraints system, we see how each constraint enforces a step in the computation. In fact, constraint 1 forces any computation to multiply the witness W_1 and W_2 first. Otherwise it would not be possible to compute the witness W_4 , which is needed to solve constraint 2. Witness W_4 therefore expresses the constraining of an intermediate computational state.

At this point, one might ask why equation 1 constrains the system to compute $W_1 \cdot W_2$ first. In order to compute $W_1 \cdot W_2 \cdot W_3$, calculating $W_2 \cdot W_3$, or $W_1 \cdot W_3$ in the beginning and then multiplying the result with the remaining factor gives the exact same result. The reason is purely a matter of choice. For example, the following R1CS would define the exact same language:

$$\begin{array}{ll} W_2 \cdot W_3 = W_4 & \text{constraint 1} \\ W_4 \cdot W_1 = I_1 & \text{constraint 2} \end{array}$$

It follows that R1CS are in general **not unique** descriptions of any given situation: many different R1CS are able to describe the same problem.

To see that the two quadratic equations qualify as a Rank-1 Constraint System, choose the parameter $n = 1$, $m = 4$ and $k = 2$ as well as

$$\begin{array}{llllll} a_0^1 = 0 & a_1^1 = 0 & a_2^1 = 1 & a_3^1 = 0 & a_4^1 = 0 & a_5^1 = 0 \\ a_0^2 = 0 & a_1^2 = 0 & a_2^2 = 0 & a_3^2 = 0 & a_4^2 = 0 & a_5^2 = 1 \\ \\ b_0^1 = 0 & b_1^1 = 0 & b_2^1 = 0 & b_3^1 = 1 & b_4^1 = 0 & b_5^1 = 0 \\ b_0^2 = 0 & b_1^2 = 0 & b_2^2 = 0 & b_3^2 = 0 & b_4^2 = 1 & b_5^2 = 0 \\ \\ c_0^1 = 0 & c_1^1 = 0 & c_2^1 = 0 & c_3^1 = 0 & c_4^1 = 0 & c_5^1 = 1 \\ c_0^2 = 0 & c_1^2 = 1 & c_2^2 = 0 & c_3^2 = 0 & c_4^2 = 0 & c_5^2 = 0 \end{array}$$

With this choice, the Rank-1 Constraint System of our 3-factorization problem can be written in its most general form as follows:

$$\begin{aligned} (a_0^1 + a_1^1 I_1 + a_2^1 W_1 + a_3^1 W_2 + a_4^1 W_3 + a_5^1 W_4) \cdot (b_0^1 + b_1^1 I_1 + b_2^1 W_1 + b_3^1 W_2 + b_4^1 W_3 + b_5^1 W_4) &= (c_0^1 + c_1^1 I_1 + c_2^1 W_1 + c_3^1 W_2 + c_4^1 W_3 + c_5^1 W_4) \\ (a_0^2 + a_1^2 I_1 + a_2^2 W_2 + a_3^2 W_2 + a_4^2 W_3 + a_5^2 W_4) \cdot (b_0^2 + b_1^2 I_1 + b_2^2 W_2 + b_3^2 W_2 + b_4^2 W_3 + b_5^2 W_4) &= (c_0^2 + c_1^2 I_1 + c_2^2 W_2 + c_3^2 W_2 + c_4^2 W_3 + c_5^2 W_4) \end{aligned}$$

4172 *Example 117* (R1CS for the Tiny-Jubjub curve points). Consider the languages $L_{\text{tiny.jj.1}}$ from
 4173 example 115, which consist of words $\langle I_1, I_2 \rangle$ over the alphabet \mathbb{F}_{13} such that $3 \cdot I_1^2 + I_2^2 =$
 4174 $1 + 8 \cdot I_1^2 \cdot I_2^2$.

We derive a Rank-1 Constraint System such that its solutions are in a 1:1 correspondence with words in $L_{\text{tiny.jj.1}}$. To achieve this, we first rewrite the defining equation:

$$\begin{aligned} 3 \cdot I_1^2 + I_2^2 &= 1 + 8 \cdot I_1^2 \cdot I_2^2 && \Leftrightarrow \\ 0 &= 1 + 8 \cdot I_1^2 \cdot I_2^2 - 3 \cdot I_1^2 - I_2^2 && \Leftrightarrow \\ 0 &= 1 + 8 \cdot I_1^2 \cdot I_2^2 + 10 \cdot I_1^2 + 12 \cdot I_2^2 \end{aligned}$$

Since R1CSs are systems of quadratic equations, we have to reformulate this expression into a system of quadratic equations. To do so, we have to introduce new variables that constrain intermediate steps in the computation and we have to decide if those variables should be instance or witness variable. We decide to declare all new variables as witness variables and get the following constraints

$$\begin{aligned} I_1 \cdot I_1 &= W_1 && \text{constraint 1} \\ I_2 \cdot I_2 &= W_2 && \text{constraint 2} \\ (8 \cdot W_1) \cdot W_2 &= W_3 && \text{constraint 3} \\ (12 \cdot W_2 + W_3 + 10 \cdot W_1 + 1) \cdot 1 &= 0 && \text{constraint 4} \end{aligned}$$

To see that these four quadratic equations qualify as a Rank-1 Constraint System according to equation ??, choose the parameter $n = 2$, $m = 3$ and $k = 4$:

$$\begin{array}{cccccc} a_0^1 = 0 & a_1^1 = 1 & a_2^1 = 0 & a_3^1 = 0 & a_4^1 = 0 & a_5^1 = 0 \\ a_0^2 = 0 & a_1^2 = 0 & a_2^2 = 1 & a_3^2 = 0 & a_4^2 = 0 & a_5^2 = 0 \\ a_0^3 = 0 & a_1^3 = 0 & a_2^3 = 0 & a_3^3 = 8 & a_4^3 = 0 & a_5^3 = 0 \\ a_0^4 = 1 & a_1^4 = 0 & a_2^4 = 0 & a_3^4 = 10 & a_4^4 = 12 & a_5^4 = 1 \\ \\ b_0^1 = 0 & b_1^1 = 1 & b_2^1 = 0 & b_3^1 = 0 & b_4^1 = 0 & b_5^1 = 0 \\ b_0^2 = 0 & b_1^2 = 0 & b_2^2 = 1 & b_3^2 = 0 & b_4^2 = 0 & b_5^2 = 0 \\ b_0^3 = 0 & b_1^3 = 0 & b_2^3 = 0 & b_3^3 = 0 & b_4^3 = 1 & b_5^3 = 0 \\ b_0^4 = 1 & b_1^4 = 0 & b_2^4 = 0 & b_3^4 = 0 & b_4^4 = 0 & b_5^4 = 0 \\ \\ c_0^1 = 0 & c_1^1 = 0 & c_2^1 = 0 & c_3^1 = 1 & c_4^1 = 0 & c_5^1 = 0 \\ c_0^2 = 0 & c_1^2 = 0 & c_2^2 = 0 & c_3^2 = 0 & c_4^2 = 1 & c_5^2 = 0 \\ c_0^3 = 0 & c_1^3 = 0 & c_2^3 = 0 & c_3^3 = 0 & c_4^3 = 0 & c_5^3 = 1 \\ c_0^4 = 0 & c_1^4 = 0 & c_2^4 = 0 & c_3^4 = 0 & c_4^4 = 0 & c_5^4 = 0 \end{array}$$

With this choice, the Rank-1 Constraint System of our tiny-jubjub curve point problem can be

written in its most general form as follows:

$$\begin{aligned} (a_0^1 + a_1^1 I_1 + a_2^1 I_2 + a_3^1 W_1 + a_4^1 W_2 + a_5^1 W_3) \cdot (b_0^1 + b_1^1 I_1 + b_2^1 I_2 + b_3^1 W_1 + b_4^1 W_2 + b_5^1 W_3) &= (c_0^1 + c_1^1 I_1 + c_2^1 I_2 + c_3^1 W_1 + c_4^1 W_2 + c_5^1 W_3) \\ (a_0^2 + a_1^2 I_1 + a_2^2 I_2 + a_3^2 W_1 + a_4^2 W_2 + a_5^2 W_3) \cdot (b_0^2 + b_1^2 I_1 + b_2^2 I_2 + b_3^2 W_1 + b_4^2 W_2 + b_5^2 W_3) &= (c_0^2 + c_1^2 I_1 + c_2^2 I_2 + c_3^2 W_1 + c_4^2 W_2 + c_5^2 W_3) \\ (a_0^3 + a_1^3 I_1 + a_2^3 I_2 + a_3^3 W_1 + a_4^3 W_2 + a_5^3 W_3) \cdot (b_0^3 + b_1^3 I_1 + b_2^3 I_2 + b_3^3 W_1 + b_4^3 W_2 + b_5^3 W_3) &= (c_0^3 + c_1^3 I_1 + c_2^3 I_2 + c_3^3 W_1 + c_4^3 W_2 + c_5^3 W_3) \\ (a_0^4 + a_1^4 I_1 + a_2^4 I_2 + a_3^4 W_1 + a_4^4 W_2 + a_5^4 W_3) \cdot (b_0^4 + b_1^4 I_1 + b_2^4 I_2 + b_3^4 W_1 + b_4^4 W_2 + b_5^4 W_3) &= (c_0^4 + c_1^4 I_1 + c_2^4 I_2 + c_3^4 W_1 + c_4^4 W_2 + c_5^4 W_3) \end{aligned}$$

4175 To see that solutions to this constraints system are in 1:1 correspondence with words in $L_{tiny.jj.1}$,
4176 let $\langle I_1, I_2 \rangle; \langle W_1, W_2, W_3 \rangle$ be a solution, then $\langle I_1, I_2 \rangle$ is a word in $L_{tiny.jj.1}$, since the
4177 defining R1CS implies that I_1 and I_2 satisfy the twisted Edwards equation of the tiny-jubjub
4178 curve. On the other hand, let $\langle I_1, I_2 \rangle$ be a word in $L_{tiny.jj.1}$. Then $\langle I_1, I_2 \rangle; \langle I_1^2, I_2^2, 8 \cdot I_1^2 \cdot$
4179 $I_2^2 \rangle$ is a solution to our R1CS.

4180 *Exercise 86.* Consider the language L_{add} from exercise 85. Define an R1CS, such that solutions
4181 to this R1CS are in 1:1 correspondence with words in L_{add} .

4182 **R1CS Satisfiability** To understand how Rank-1 Constraint Systems define formal languages,
4183 observe that every R1CS over a field \mathbb{F} defines a decision function over the alphabet $\Sigma_I \times \Sigma_W =$
4184 $\mathbb{F} \times \mathbb{F}$ in the following way:

$$R_{R1CS} : (\mathbb{F})^* \times (\mathbb{F})^* \rightarrow \{true, false\} ; (I; W) \mapsto \begin{cases} true & (I; W) \text{ satisfies R1CS} \\ false & \text{else} \end{cases} \quad (6.7)$$

4185 Every R1CS therefore defines a formal language. The grammar of this language is encoded
4186 in the constraints, words are solutions to the equations and a **statement** is a knowledge claim
4187 “Given instance I , there is a witness W such that $(I; W)$ is a solution to the Rank-1 Constraint
4188 System”. A constructive proof to this claim is therefore an assignment of a field element to
4189 every witness variable, which is verified whenever the set of all instance and witness variables
4190 solves the R1CS.

Remark 6 (R1CS satisfiability). It should be noted that in our definition, every R1CS defines its own language. However, in more theoretical approaches, another language usually called **R1CS satisfiability** is often considered, which is useful when it comes to more abstract problems like expressiveness or the computational complexity of the class of **all** R1CS. From our perspective, the R1CS satisfiability language is obtained by the union of all R1CS languages that are in our definition. To be more precise, let the alphabet $\Sigma = \mathbb{F}$ be a field. Then

$$L_{R1CS_SAT(\mathbb{F})} = \{(i; w) \in \Sigma^* \times \Sigma^* \mid \text{there is a R1CS } R \text{ such that } R(i; w) = true\}$$

4191 *Example 118* (3-Factorization). Consider the language $L_{3.fac_zk}$ from example 114 and the
4192 R1CS defined in example 116. As we have seen in 116, solutions to the R1CS are in 1:1 cor-
4193 respondence with solutions to the decision function of $L_{3.fac_zk}$. Both languages are therefore
4194 equivalent in the sense that there is a 1:1 correspondence between words in both languages.

To give an intuition of what constructive R1CS based proofs in $L_{3.fac_zk}$ look like, consider the instance $I_1 = 11$. To prove the statement “There exists a witness W such that $(I_1; W)$ is a word in $L_{3.fac_zk}$ ” constructively, a proof has to provide a solution to the R1CS from example 116, that is an assignments to all witness variables W_1, W_2, W_3 and W_4 . Since the alphabet is \mathbb{F}_{13} , an example assignment is given by $W = \langle 2, 3, 4, 6 \rangle$ since $(I_1; W)$ satisfies the R1CS

$$\begin{aligned} W_1 \cdot W_2 &= W_4 & \# 2 \cdot 3 &= 6 \\ W_4 \cdot W_3 &= I_1 & \# 6 \cdot 4 &= 11 \end{aligned}$$

4195 A proper constructive proof is therefore given by $\pi = \langle 2, 3, 4, 6 \rangle$. Of course, π is not the only
 4196 possible proof for this statement. Since factorization is not unique in a field in general, another
 4197 constructive proof is given by $\pi' = \langle 3, 5, 12, 2 \rangle$.

Example 119 (The tiny-jubjub curve). Consider the language $L_{\text{tiny.jj.1}}$ from example 115 and its associated R1CS from example 117. To see how constructive proofs in $L_{\text{tiny.jj.1}}$ using the R1CS from example 117 look like, consider the instance $\langle I_1, I_2 \rangle = \langle 11, 6 \rangle$. To prove the statement “There exists a witness W such that $(\langle I_1, I_2 \rangle; W)$ is a word in $L_{\text{tiny.jj.1}}$ ” constructively, a proof has to provide a solution to the R1CS 117, which is an assignments to all witness variables W_1 , W_2 and W_3 . Since the alphabet is \mathbb{F}_{13} , an example assignment is given by $W = \langle 4, 10, 8 \rangle$ since $(\langle I_1, I_2 \rangle; W)$ satisfies the R1CS

$$\begin{array}{ll} I_1 \cdot I_1 = W_1 & 11 \cdot 11 = 4 \\ I_2 \cdot I_2 = W_2 & 6 \cdot 6 = 10 \\ (8 \cdot W_1) \cdot W_2 = W_3 & (8 \cdot 4) \cdot 10 = 8 \\ (12 \cdot W_2 + W_3 + 10 \cdot W_1 + 1) \cdot 1 = 0 & 12 \cdot 10 + 8 + 10 \cdot 4 + 1 = 0 \end{array}$$

4198 A proper constructive proof is therefore given by $\pi = \langle 4, 10, 8 \rangle$, which shows that the instance
 4199 $\langle 11, 6 \rangle$ is a point on the tiny-jubjub curve.

4200 **Modularity** As we discussed in 6.1, it is often useful to construct complex statements and
 4201 their representing languages from simple ones. Rank-1 Constraint Systems are particularly
 4202 useful for this, as the intersection of two R1CS over the same alphabet results in a new R1CS
 4203 over that same alphabet.

4204 To be more precise, let S_1 and S_2 be two R1CS over \mathbb{F} , then a new R1CS S_3 is obtained
 4205 by the intersection $S_3 = S_1 \cap S_2$ of S_1 and S_2 . In this context, intersection means that both the
 4206 equations of S_1 **and** the equations of S_2 have to be satisfied in order to provide a solution for the
 4207 system S_3 .

4208 As a consequence, developers are able to construct complex R1CS from simple ones and
 4209 this modularity provides the theoretical foundation for many R1CS compilers, as we will see in
 4210 chapter 7.

4211 6.2.2 Algebraic Circuits

4212 As we have seen in the previous paragraphs, Rank-1 Constraint Systems are quadratic equations
 4213 such that solutions are knowledge proofs for the existence of words in associated languages.
 4214 From the perspective of a prover, it is therefore important to solve those equations efficiently.

4215 However, in contrast to systems of linear equations, no general methods are known that solve
 4216 systems of quadratic equations efficiently. Rank-1 Constraint Systems are therefore impractical
 4217 from a provers perspective and auxiliary information is needed that helps to compute solutions
 4218 efficiently.

4219 Methods which compute R1CS solutions are sometimes called **witness generator func-**
 4220 **tions**. To provide a common example, we introduce another class of decision functions called
 4221 **algebraic circuits**. As we will see, every algebraic circuit defines an associated R1CS and also
 4222 provides an efficient way to compute solutions for that R1CS.

4223 It can be shown that every space- and time-bounded computation is expressible as an alge-
 4224 braic circuit. Transforming high-level computer programs into those circuits is a process often
 4225 called **flattening**. We will look at those transformations in chapter 7.

In this section we will introduce our model for algebraic circuits and look at the concept of circuit execution and valid assignments. After that, we will show how to derive Rank-1 Constraint Systems from circuits and how circuits are useful to compute solutions to associated R1CS efficiently.

Algebraic circuit representation To see what algebraic circuits are, let \mathbb{F} be a field. An algebraic circuit is then a directed acyclic (multi)graph that computes a polynomial function over \mathbb{F} . Nodes with only outgoing edges (source nodes) represent the variables and constants of the function and nodes with only incoming edges (sink nodes) represent the outcome of the function. All other nodes have exactly two incoming edges and represent the field operations **addition** as well as **multiplication**. Graph edges are directed and represent the flow of the computation along the nodes.

To be more precise, in this book, we call a directed acyclic multi-graph $C(\mathbb{F})$ an **algebraic circuit** over \mathbb{F} if the following conditions hold:

- The set of edges has a total order.
- Every source node has a label that represents either a variable or a constant from the field \mathbb{F} .
- Every sink node has exactly one incoming edge and a label that represents either a variable or a constant from the field \mathbb{F} .
- Every node that is neither a source nor a sink has exactly two incoming edges and a label from the set $\{+, *\}$ that represents either addition or multiplication in \mathbb{F} .
- All outgoing edges from a node have the same label.
- Outgoing edges from a node with a label that represents a variable have a label.
- Outgoing edges from a node with a label that represents multiplication have a label, if there is at least one labeled edge in both input path.
- All incoming edges to sink nodes have a label.
- If an edge has two labels S_i and S_j it gets a new label $S_i = S_j$.
- No other edge has a label.
- Incoming edges to labeled sink nodes, where the label is a constant $c \in \mathbb{F}$ are labeled with the same constant. Every other edge label is taken from the set $\{W, I\}$ and indexed compatible with the order of the edge set.

It should be noted that the details in the definitions of algebraic circuits vary between different sources. We use this definition as it is conceptually straightforward and well-suited for pen-and-paper computations.

To get a better intuition of our definition, let $C(\mathbb{F})$ be an algebraic circuit. Source nodes are the inputs to the circuit and either represent variables or constants. In a similar way, sink nodes represent termination points of the circuit and are either output variables or constants. Constant sink nodes enforce computational outputs to take on certain values.

Nodes that are neither source nodes nor sink nodes are called **arithmetic gates**. Arithmetic gates that are decorated with the “+”-label are called **addition-gates** and arithmetic gates that

are decorated with the “.”-label are called **multiplication-gates**. Every arithmetic gate has exactly two inputs, represented by the two incoming edges.

Since the set of edges is ordered, we can write it as a string $\langle E_1, E_2, \dots, E_n \rangle$ for some $n \in \mathbb{N}$ and we use those indices to index the edge labels, too. Edge labels are therefore either constants or symbols like I_j , W_j , where j is an index compatible with the edge order. Labels I_j represent instance variables, labels W_j witness variables. Labels on the outgoing edges of input variables constrain the associated variable to that edge.

Notation and Symbols 14. In synthesizing algebraic circuits, assigning instance I_j or witness W_j labels to appropriate edges is often the final step. It is therefore convenient to not distinguish these two types of edges in previous steps. To account for that, we often simply write S_j for an edge label, indicating that the instance/witness property of the label is unspecified and it might represent both an instance or a witness label.

Example 120 (Generalized factorization SNARK). To give a simple example of an algebraic circuit, consider our 3-factorization problem from example 114 again. To express the problem in the algebraic circuit model, consider the following function

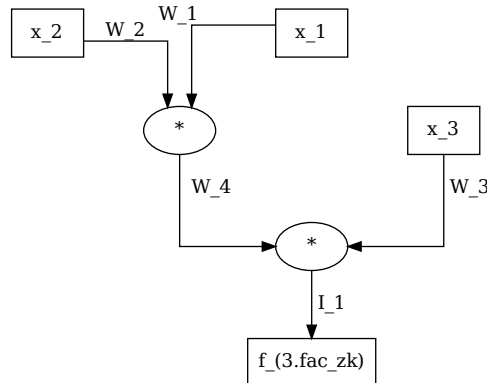
$$f_{3.fac} : \mathbb{F}_{13} \times \mathbb{F}_{13} \times \mathbb{F}_{13} \rightarrow \mathbb{F}_{13}; (x_1, x_2, x_3) \mapsto x_1 \cdot x_2 \cdot x_3$$

Using this function, we can describe the zero-knowledge 3-factorization problem from 114, in the following way: Given instance $I_1 \in \mathbb{F}_{13}$, a valid witness is a preimage of $f_{3.fac}$ at the point I_1 , i.e., a valid witness consists of three values W_1 , W_2 and W_3 from \mathbb{F}_{13} such that $f_{3.fac}(W_1, W_2, W_3) = I_1$.

To see how this function can be transformed into an algebraic circuit over \mathbb{F}_{13} , it is a common first step to introduce brackets into the function’s definition and then write the operations as binary operators, in order to highlight how exactly every field operation acts on its two inputs. Due to the associativity laws in a field, we have several choices. We choose

$$\begin{aligned} f_{3.fac}(x_1, x_2, x_3) &= x_1 \cdot x_2 \cdot x_3 && \# \text{ bracket choice} \\ &= (x_1 \cdot x_2) \cdot x_3 && \# \text{ operator notation} \\ &= MUL(MUL(x_1, x_2), x_3) \end{aligned}$$

Using this expression, we can write an associated algebraic circuit by first constraining the variables to edge labels $W_1 = x_1$, $W_2 = x_2$ and $W_3 = x_3$ as well as $I_1 = f_{3.fac}(x_1, x_2, x_3)$, taking the distinction between witness and instance inputs into account. We then rewrite the operator representation of $f_{3.fac}$ into circuit nodes and get the following:



4289 In this case, the directed acyclic multi-graph is a binary tree with three leaves (the source
 4290 nodes) labeled by x_1, x_2 and x_3 , one root (the single sink node) labeled by $f_{3, fac}(x_1, x_2, x_3)$ and
 4291 two internal nodes, which are labeled as multiplication gates.

4292 The order we use to label the edges is chosen to make the edge labeling consistent with
 4293 the choice of W_4 as defined in definition 6.2.2. This order can be obtained by a depth-first
 4294 right-to-left-first traversal algorithm.

Example 121. To give a more realistic example of an algebraic circuit, look at the defining equation of the tiny-jubjub curve 69 again. A pair of field elements $(x, y) \in \mathbb{F}_{13}^2$ is a curve point, precisely if the following equation holds:

$$3 \cdot x^2 + y^2 = 1 + 8 \cdot x^2 \cdot y^2$$

To understand how one might transform this identity into an algebraic circuit, we first rewrite this equation by shifting all terms to the right. We get the following:

$$\begin{aligned} 3 \cdot x^2 + y^2 &= 1 + 8 \cdot x^2 \cdot y^2 && \Leftrightarrow \\ 0 &= 1 + 8 \cdot x^2 \cdot y^2 - 3 \cdot x^2 - y^2 && \Leftrightarrow \\ 0 &= 1 + 8 \cdot x^2 \cdot y^2 + 10 \cdot x^2 + 12 \cdot y^2 \end{aligned}$$

Then we use this expression to define a function such that all points of the tiny-jubjub curve are characterized as the function preimages at 0.

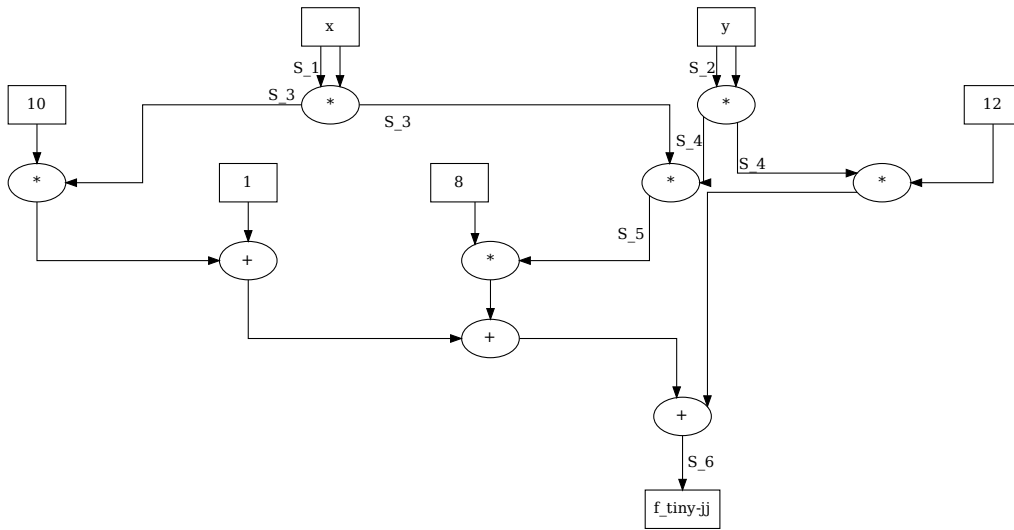
$$f_{tiny-jj} : \mathbb{F}_{13} \times \mathbb{F}_{13} \rightarrow \mathbb{F}_{13} ; (x, y) \mapsto 1 + 8 \cdot x^2 \cdot y^2 + 10 \cdot x^2 + 12 \cdot y^2$$

4295 Every pair of field elements $(x, y) \in \mathbb{F}_{13}^2$ with $f_{tiny-jj}(x, y) = 0$ is a point on the tiny-jubjub
 4296 curve, and there are no other curve points. The preimage $f_{tiny-jj}^{-1}(0)$ is therefore a complete
 4297 description of the tiny-jubjub curve.

We can transform this function into an algebraic circuit over \mathbb{F}_{13} . We first introduce brackets into potentially ambiguous expressions and then rewrite the function in terms of binary operators. We get the following:

$$\begin{aligned} f_{tiny-jj}(x, y) &= 1 + 8 \cdot x^2 \cdot y^2 + 10 \cdot x^2 + 12y^2 && \Leftrightarrow \\ &= ((8 \cdot ((x \cdot x) \cdot (y \cdot y))) + (1 + 10 \cdot (x \cdot x))) + (12 \cdot (y \cdot y)) && \Leftrightarrow \\ &= ADD(ADD(MUL(8, MUL(MUL(x, x), MUL(y, y))), ADD(1, MUL(10, MUL(x, x))), MUL(12, MUL(y, y)))) \end{aligned}$$

4298 Since we haven't decided which part of the computation should be instance and which part
 4299 should be witness, we use the unspecified symbol S to represent edge labels. Constraining all
 4300 variables to edge labels $S_1 = x$, $S_2 = y$ and $S_6 = f_{tiny-jj}$, we get the following circuit, representing the function $f_{tiny-jj}$, by inductively replacing binary operators with their associated
 4301 arithmetic gates:
 4302

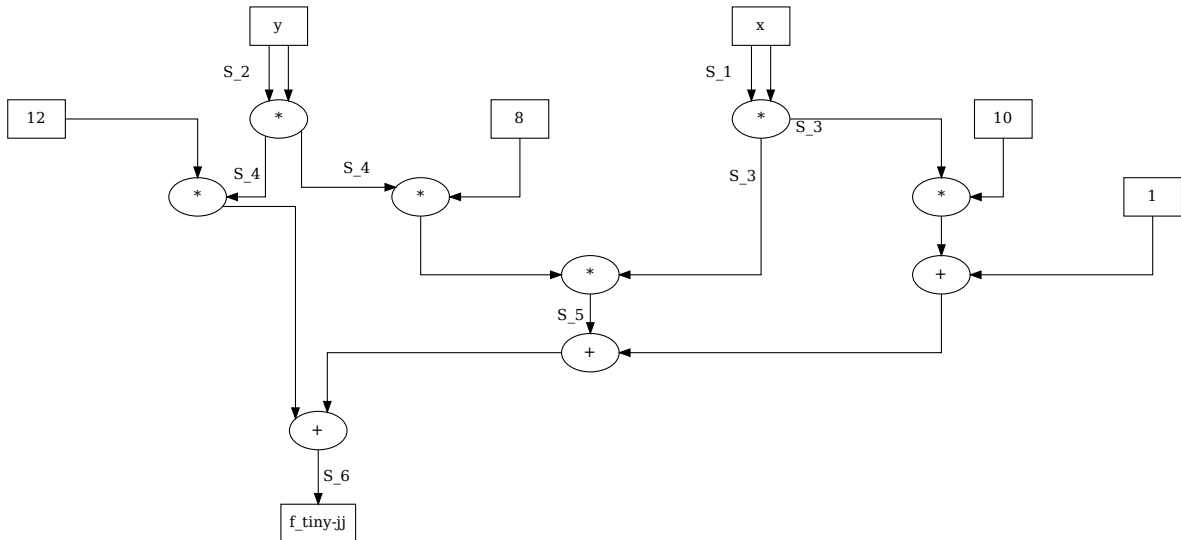


4303

4304 This circuit is not a graph, but a multigraph, since there is more than one edge between some of
 4305 the nodes.

4306 In the process of designing of circuits from functions, it should be noted that circuit rep-
 4307 resentations are not unique in general. In case of the function $f_{\text{tiny-jj}}$, the circuit shape is
 4308 dependent on our choice of bracketing in $??$. An alternative design is for example, given by the
 4309 following circuit, which occurs when the bracketed expression $8 \cdot ((x \cdot x) \cdot (y \cdot y))$ is replaced by
 4310 the expression $(x \cdot x) \cdot (8 \cdot (y \cdot y))$.

4311



4312

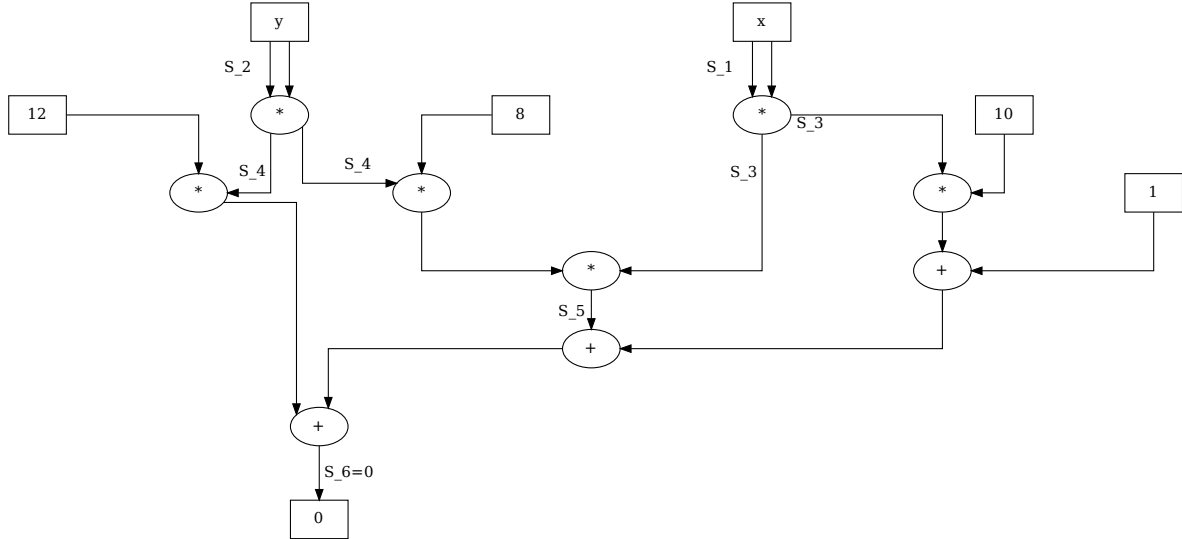
4313

4314 Of course, both circuits represent the same function, due to the associativity and commutativity
 4315 laws that hold true in any field.

4316 With a circuit that represents the function $f_{\text{tiny-jj}}$, we can now proceed to derive a circuit
 4317 that constrains arbitrary pairs (x, y) of field elements to be points on the tiny-jubjub curve. To do
 4318 so, we have to constrain the output to be zero, that is, we have to constrain $S_6 = 0$. To indicate

4319 this in the circuit, we replace the output variable by the constant 0 and constrain the related edge
 4320 label accordingly. We get the following:

4321

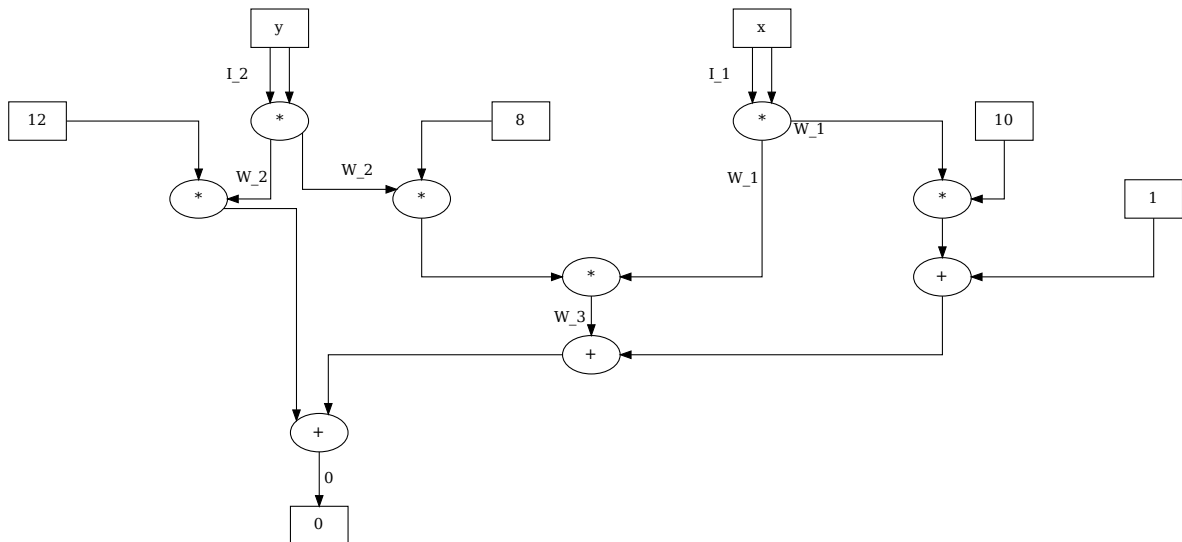


4322

4323

4324 The previous circuit enforces input values assigned to the labels S_1 and S_2 to be points on the
 4325 tiny-jubjub curve. However, it does not specify which labels are considered instance and which
 4326 are considered witness. The following circuit defines the inputs to be instances, while all other
 4327 labels represent witnesses:

4328



4329

4330

4331 It can be shown that every space- and time-bounded computation can be transformed into
 4332 an algebraic circuit. We call any process that transforms a bounded computation into a circuit
 4333 **flattening**.

Circuit Execution Algebraic circuits are directed, acyclic multi-graphs, where nodes represent variables, constants, or addition and multiplication gates. In particular, every algebraic circuit with n input nodes decorated with variable symbols and m output nodes decorated with variables can be seen as a function that transforms an input string (x_1, \dots, x_n) from \mathbb{F}^n into an output string (f_1, \dots, f_m) from \mathbb{F}^m . The transformation is done by sending values associated to nodes along their outgoing edges to other nodes. If those nodes are gates, then the values are transformed according to the gate label and the process is repeated along all edges until a sink node is reached. We call this computation **circuit execution**.

When executing a circuit, it is possible to not only compute the output values of the circuit but to derive field elements for all edges, and, in particular, for all edge labels in the circuit. The result is a string $\langle S_1, S_2, \dots, S_n \rangle$ of field elements associated to all labeled edges, which we call a **valid assignment** to the circuit. In contrast, any assignment $\langle S'_1, S'_2, \dots, S'_n \rangle$ of field elements to edge labels that can not arise from circuit execution is called an **invalid assignment**.

Valid assignments can be interpreted as **proofs for proper circuit execution** because they keep a record of the computational result as well as intermediate computational steps.

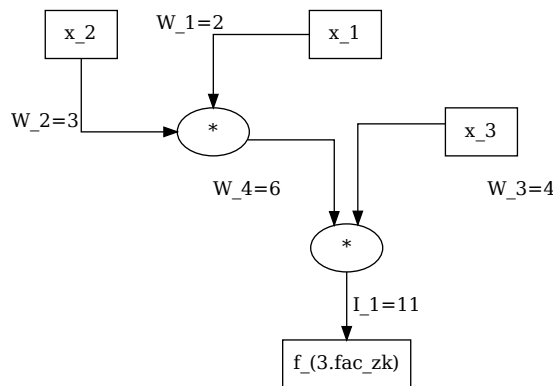
Example 122 (3-factorization). Consider the 3-factorization problem from example 114 and its representation as an algebraic circuit from example 120. We know that the string of edge labels is given by $S := \langle I_1; W_1, W_2, W_3, W_4 \rangle$.

To understand how this circuit is executed, consider the variables $x_1 = 2$, $x_2 = 3$ as well as $x_3 = 4$. Following all edges in the graph, we get the assignments $W_1 = 2$, $W_2 = 3$ and $W_3 = 4$. Then the assignments of W_1 and W_2 enter a multiplication gate and the output of the gate is $2 \cdot 3 = 6$, which we assign to W_4 , i.e. $W_4 = 6$. The values W_4 and W_3 then enter the second multiplication gate and the output of the gate is $6 \cdot 4 = 11$, which we assign to I_1 , i.e. $I_1 = 11$.

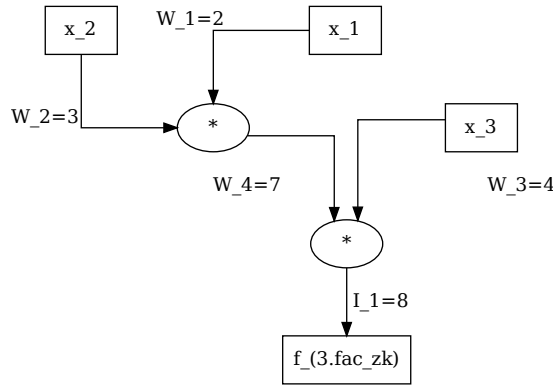
A valid assignment to the 3-factorization circuit $C_{3, \text{fac}}(\mathbb{F}_{13})$ is therefore given by the following string of field elements from \mathbb{F}_{13} :

$$S_{\text{valid}} := \langle 11; 2, 3, 4, 6 \rangle \quad (6.8)$$

We can visualise this assignment by assigning every computed value to its associated label in the circuit as follows:



To see what an invalid assignment looks like, consider the assignment $S_{\text{err}} := \langle 8; 2, 3, 4, 7 \rangle$. In this assignment, the input values are the same as in the previous case. The associated circuit is:

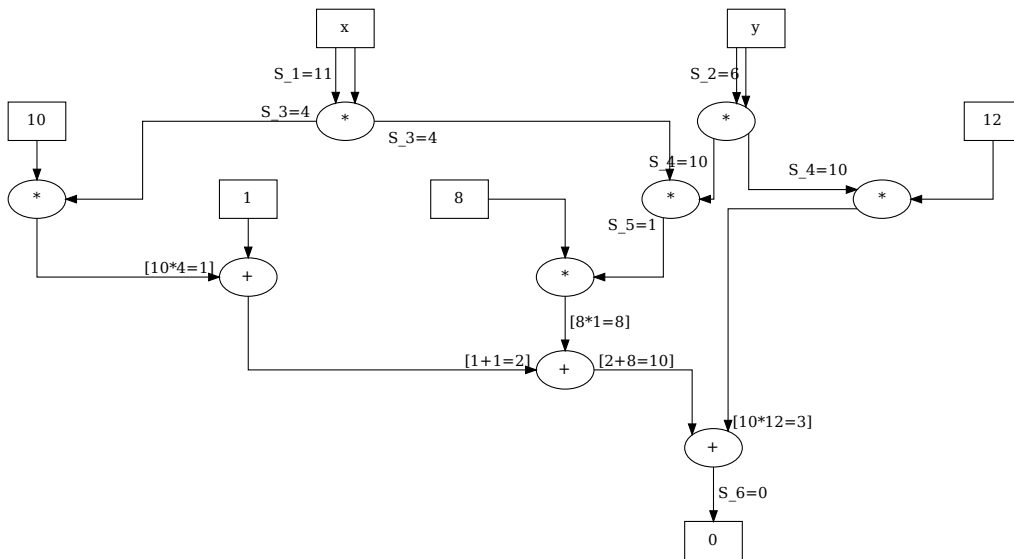


4365

4366 This assignment is invalid, as the assignments of I_1 and W_4 cannot be obtained by executing the
 4367 circuit.

4368 *Example 123.* To compute a more realistic algebraic circuit execution, consider the defining
 4369 circuit $C_{\text{tiny-jj}}(\mathbb{F}_{13})$ from example 121 again. We already know from the way this circuit is
 4370 constructed that any valid assignment with $S_1 = x$, $S_2 = y$ and $S_6 = 0$ will ensure that the pair
 4371 (x, y) is a point on the tiny-jubjub curve in its Edwards representation (equation 5.21).

4372 From example 5.21, we know that the pair $(11, 6)$ is a proper point on the tiny-jubjub curve
 4373 and we use this point as input to a circuit execution. We get the following:



4374

Executing the circuit, we indeed compute $S_6 = 0$ as expected, which proves that $(11, 6)$ is a point on the tiny-jubjub curve in its Edwards representation. A valid assignment of $C_{\text{tiny-jj}}(\mathbb{F}_{13})$ is therefore given by the following string:

$$S_{\text{tiny-jj}} = \langle S_1, S_2, S_3, S_4, S_5, S_6 \rangle = \langle 11, 6, 4, 10, 1, 0 \rangle$$

4375 **Circuit Satisfiability** To understand how algebraic circuits give rise to formal languages, ob-
 4376 serve that every algebraic circuit $C(\mathbb{F})$ over a fields \mathbb{F} defines a decision function over the al-

4377 phabet $\Sigma_I \times \Sigma_W = \mathbb{F} \times \mathbb{F}$ in the following way:

$$R_{C(\mathbb{F})} : \mathbb{F}^* \times \mathbb{F}^* \rightarrow \{true, false\} ; (I; W) \mapsto \begin{cases} true & (I; W) \text{ is valid assignment to } C(\mathbb{F}) \\ false & \text{else} \end{cases} \quad (6.9)$$

4378 Every algebraic circuit therefore defines a formal language. The grammar of this language is
 4379 encoded in the shape of the circuit, words are assignments to edge labels that are derived from
 4380 circuit execution, and **statements** are knowledge claims “Given instance I , there is a witness
 4381 W such that $(I; W)$ is a valid assignment to the circuit”. A constructive proof to this claim
 4382 is therefore an assignment of a field element to every witness variable, which is verified by
 4383 executing the circuit to see if the assignment of the execution meets the assignment of the
 4384 proof.

4385 In the context of zero-knowledge proof systems, executing circuits is also often called **wit-**
 4386 **ness generation**, since in applications the instance part is usually public, while its the task of a
 4387 prover to compute the witness part.

Remark 7 (Circuit satisfiability). Similar to 6, it should be noted that, in our definition, every circuit defines its own language. However, in more theoretical approaches another language usually called **circuit satisfiability** is often considered, which is useful when it comes to more abstract problems like expressiveness, or computational complexity of the class of **all** algebraic circuits over a given field. From our perspective the circuit satisfiability language is obtained by union of all circuit languages that are in our definition. To be more precise, let the alphabet $\Sigma = \mathbb{F}$ be a field. Then

$$L_{CIRCUIT_SAT(\mathbb{F})} = \{(i; w) \in \Sigma^* \times \Sigma^* \mid \text{there is a circuit } C(\mathbb{F}) \text{ such that } (i; w) \text{ is valid assignment}\}$$

4388 *Example 124 (3-Factorization).* Consider the circuit $C_{3.fac}$ from example 120 again. We call
 4389 the associated language $L_{3.fac_circ}$.

4390 To understand how a constructive proof of a statement in $L_{3.fac_circ}$ looks like, consider the
 4391 instance $I_1 = 11$. To provide a proof for the statement “There exist a witness W such that $(I_1; W)$
 4392 is a word in $L_{3.fac_circ}$ ” a proof therefore has to consists of proper values for the variables W_1 ,
 4393 W_2 , W_3 and W_4 . Any prover therefore has to find input values for W_1 , W_2 and W_3 and then
 4394 execute the circuit to compute W_4 under the assumption $I_1 = 11$.

4395 Example 122 implies that $\langle 2, 3, 4, 6 \rangle$ is a proper constructive proof and in order to verify
 4396 the proof a verifier needs to execute the circuit with instance $I_1 = 11$ and inputs $W_1 = 2$, $W_2 = 3$
 4397 and $W_3 = 4$ to decide whether the proof is a valid assignment or not.

4398 *Exercise 87.* Consider the circuit $C_{tiny-jj}(\mathbb{F}_{13})$ from example 121, with its associated language
 4399 $L_{tiny-jj}$. Construct a proof π for the instance $\langle 11, 6 \rangle$ and verify the proof.

4400 **Associated Constraint Systems** As we have seen in 6.2.1, Rank-1 Constraint Systems define
 4401 a way to represent statements in terms of a system of quadratic equations over finite fields,
 4402 suitable for pairing-based zero-knowledge proof systems. However, those equations provide no
 4403 practical way for a prover to actually compute a solution. On the other hand, algebraic circuits
 4404 can be executed in order to derive valid assignments efficiently.

4405 In this paragraph, we show how to transform any algebraic circuit into a Rank-1 Constraint
 4406 System such that valid circuit assignments are in 1:1 correspondence with solutions to the asso-
 4407 ciated RICS.

4408 To see this, let $C(\mathbb{F})$ be an algebraic circuit over a finite field \mathbb{F} , with a string of edge labels
 4409 $\langle S_1, S_2, \dots, S_n \rangle$. Then we start with an empty RICS and one of the following steps is executed
 4410 for every edge label S_j from that set:

- If the edge label S_j is an outgoing edge of a multiplication gate, the R1CS gets a new quadratic constraint

$$(\text{left input}) \cdot (\text{right input}) = S_j \quad (6.10)$$

In this expression (left input) is the output from the symbolic execution of the subgraph that consists of the left input edge of this gate and all edges and nodes that have this edge in their path, starting with constant inputs or labeled outgoing edges of other nodes.

In the same way (right input) is the output from the symbolic execution of the subgraph that consists of the right input edge of this gate and all edges and nodes that have this edge in their path, starting with constant inputs or labeled outgoing edges of other nodes.

- If the edge label S_j is an outgoing edge of an addition gate, the R1CS gets a new quadratic constraint

$$(\text{left input} + \text{right input}) \cdot 1 = S_j \quad (6.11)$$

In this expression (left input) is the output from the symbolic execution of the subgraph that consists of the left input edge of this gate and all edges and nodes that have this edge in their path, starting with constant inputs or labeled outgoing edges of other nodes.

In the same way (right input) is the output from the symbolic execution of the subgraph that consists of the right input edge of this gate and all edges and nodes that have this edge in their path, starting with constant inputs or labeled outgoing edges of other nodes.

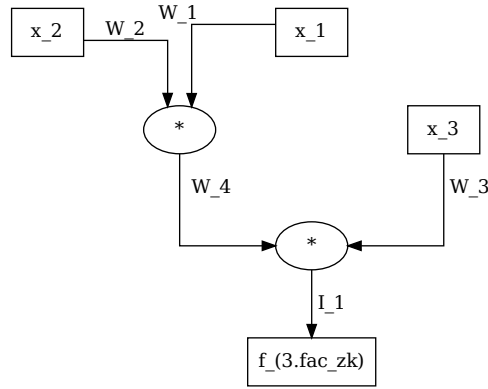
- No other edge label adds a constraint to the system.

If an algebraic circuit $C(\mathbb{F})$ is constructed according to the rules from 6.2.2, the result of this method is a Rank-1 Constraint System, and, in this sense, every algebraic circuit $C(\mathbb{F})$ generates a R1CS R , which we call the **associated R1CS** of the circuit. It can be shown that a string of field elements $\langle S_1, S_2, \dots, S_n \rangle$ is a valid assignment to a circuit if and only if the same string is a solution to the associated R1CS. Circuit executions therefore compute solutions to Rank-1 constraint Systems efficiently.

To understand the contribution of algebraic gates to the number of constraints, note that, according to construction 6.2.2, multiplication gates have labels on their outgoing edges if and only if there is at least one labeled edge in both input paths, or if the outgoing edge is an input to a sink node. This implies that multiplication with a constant is essentially free in the sense that it doesn't add a new constraint to the system, as long as that multiplication gate is not an input to an output node.

Moreover, addition gates have labels on their outgoing edges if and only if they are inputs to sink nodes. This implies that addition is essentially free in the sense that it doesn't add a new constraint to the system, as long as that addition gate is not an input to an output node.

Example 125 (3-factorization). Consider our 3-factorization problem from example 114 and the associated circuit $C_{3.fac}(\mathbb{F}_{13})$ from example 120. Our task is to transform this circuit into an equivalent Rank-1 Constraint System.



4446

4447 We start with an empty R1CS, and, in order to generate all constraints, we have to iterate over
 4448 the set of edge labels $\langle I_1; W_1, W_2, W_3, W_4 \rangle$.

Starting with the edge label I_1 , we see that it is an outgoing edge of a multiplication gate, and, since both input edges are labeled, we have to add the following constraint to the system:

$$\begin{aligned} (\text{left input}) \cdot (\text{right input}) &= I_1 && \Leftrightarrow \\ W_4 \cdot W_3 &= I_1 \end{aligned}$$

4449 Next, we consider the edge label W_1 and, since, it's not an outgoing edge of a multiplication or
 4450 addition gate, we don't add a constraint to the system. The same holds true for the labels W_2
 4451 and W_3 .

For edge label W_4 , we see that it is an outgoing edge of a multiplication gate, and, since both input edges are labeled, we have to add the following constraint to the system:

$$\begin{aligned} (\text{left input}) \cdot (\text{right input}) &= W_4 && \Leftrightarrow \\ W_2 \cdot W_1 &= W_4 \end{aligned}$$

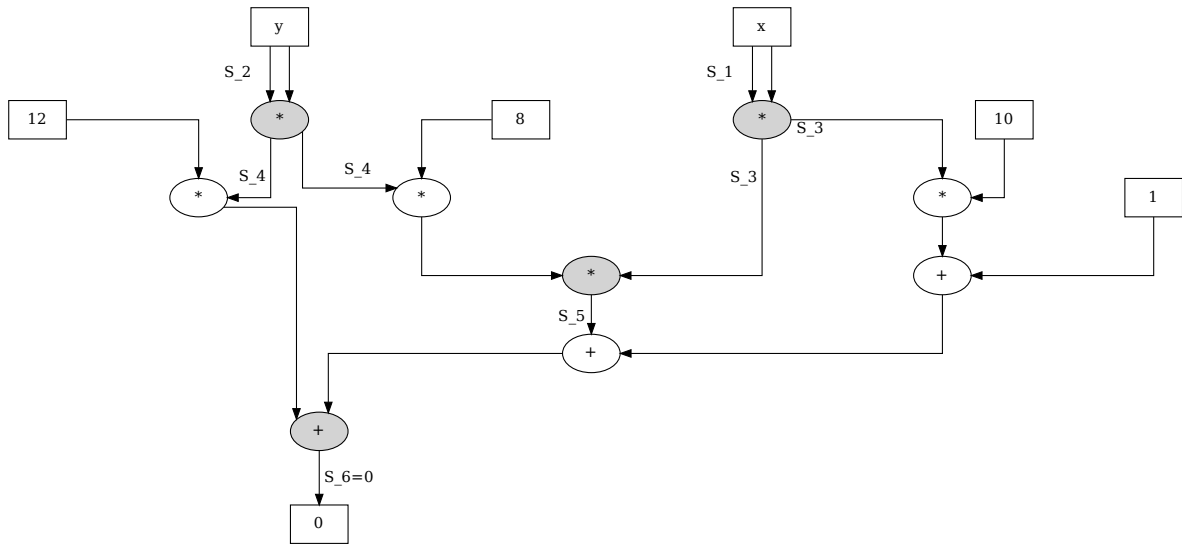
Since there are no more labeled edges, all constraints are generated, and we have to combine them to get the associated R1CS of $C_{3, \text{fac}}(\mathbb{F}_{13})$:

$$\begin{aligned} W_4 \cdot W_3 &= I_1 \\ W_2 \cdot W_1 &= W_4 \end{aligned}$$

4452 This system is equivalent to the R1CS we derived in example 116. The languages $L_{3, \text{fac_zk}}$ and
 4453 $L_{3, \text{fac_circ}}$ are therefore equivalent and both the circuit as well as the R1CS are just two different
 4454 ways of expressing the same language.

4455 *Example 126.* To consider a more general transformation, we consider the tiny-jubjub circuit
 4456 from example 123 again. A proper circuit is given by the following graph, where we highlighted
 4457 all nodes that contribute a constraint to the R1CS:

4458



4459

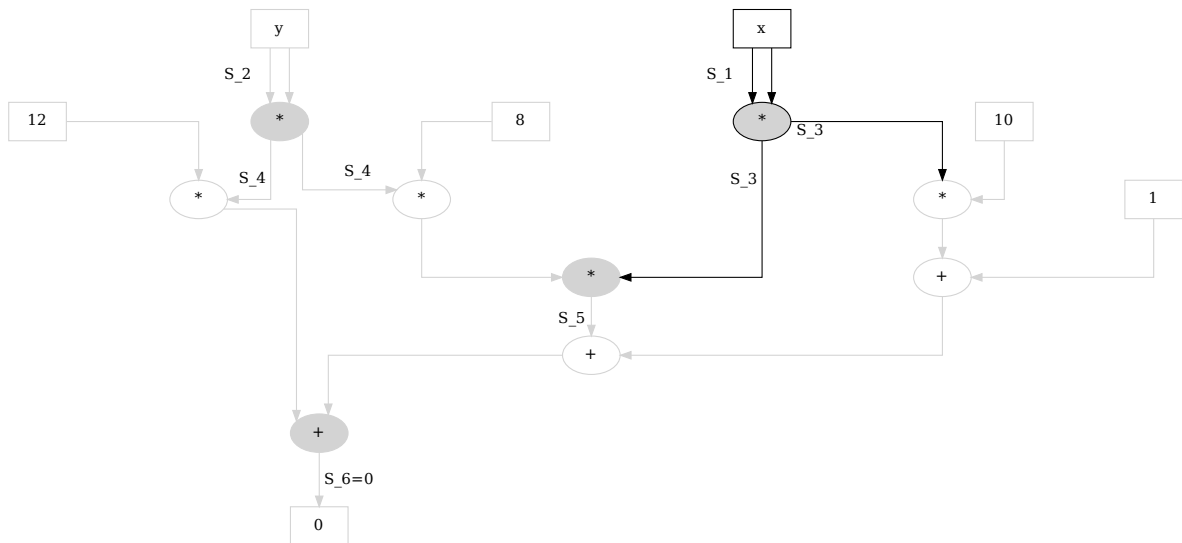
4460

4461 To compute the number of constraints, observe that we have 3 multiplication gates that have
 4462 labels on their outgoing edges and 1 addition gate that has a label on its outgoing edge. We
 4463 therefore have to compute 4 quadratic constraints.

4464 In order to derive the associated R1CS, we have start with an empty R1CS and then iterate
 4465 over the set $\langle S_1, S_2, S_3, S_4, S_5, S_6 = 0 \rangle$ of all edge labels, in order to generate the constraints.

4466 Considering edge label S_1 , we see that the associated edges are not outgoing edges of any
 4467 algebraic gate, and we therefore have to add no new constraint to the system. The same holds
 4468 true for edge label S_2 . Looking at edge label S_3 , we see that the associated edges are outgoing
 4469 edges of a multiplication gate and that the associated subgraph is given by:

4470



4471

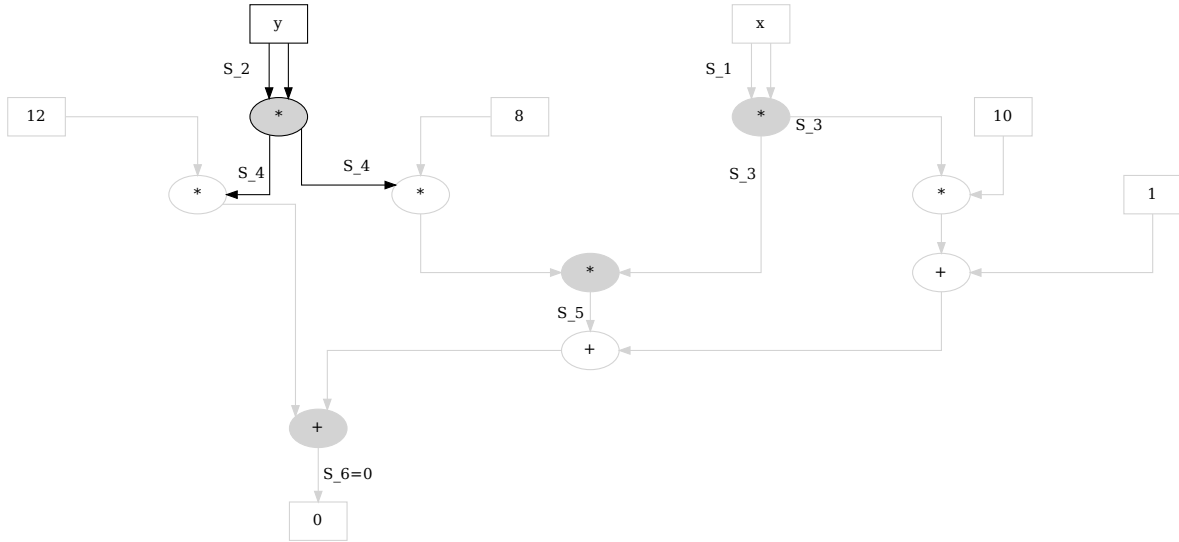
4472

Both the left and the right input to this multiplication gate are labeled by S_1 . We therefore have

to add the following constraint to the system:

$$S_1 \cdot S_1 = S_3$$

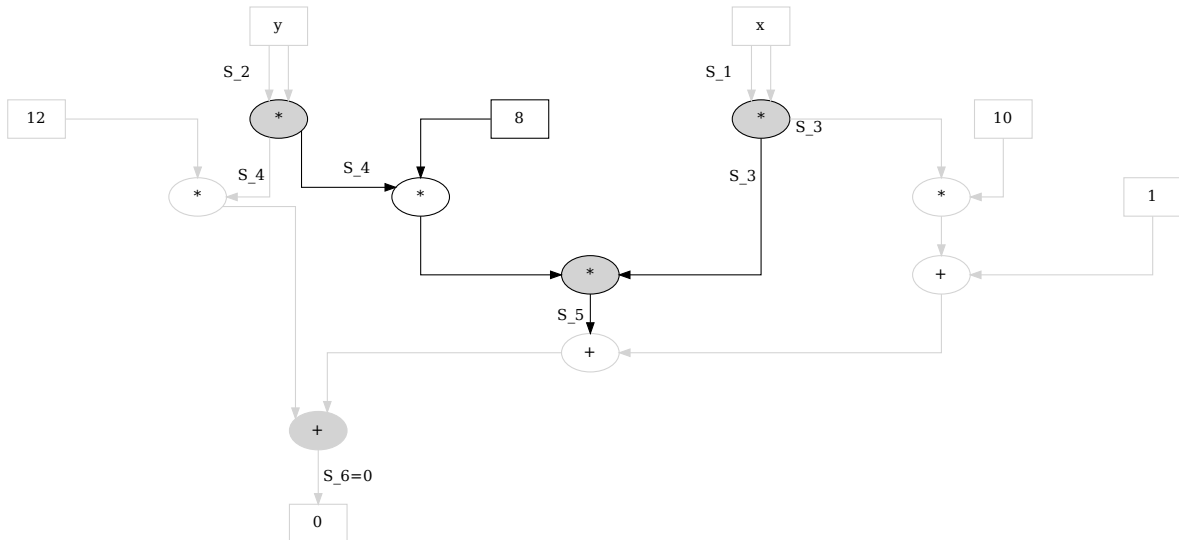
Looking at edge label S_4 , we see that the associated edges are outgoing edges of a multiplication gate and that the associated subgraph is given by:



Both the left and the right input to this multiplication gate are labeled by S_2 and we therefore have to add the following constraint to the system:

$$S_2 \cdot S_2 = S_4$$

Edge label S_5 is more interesting. To see how it implies a constraint, we have to construct the associated subgraph first, which consists of all edges, nodes, and paths, starting either at a constant input or a labeled edge. We get

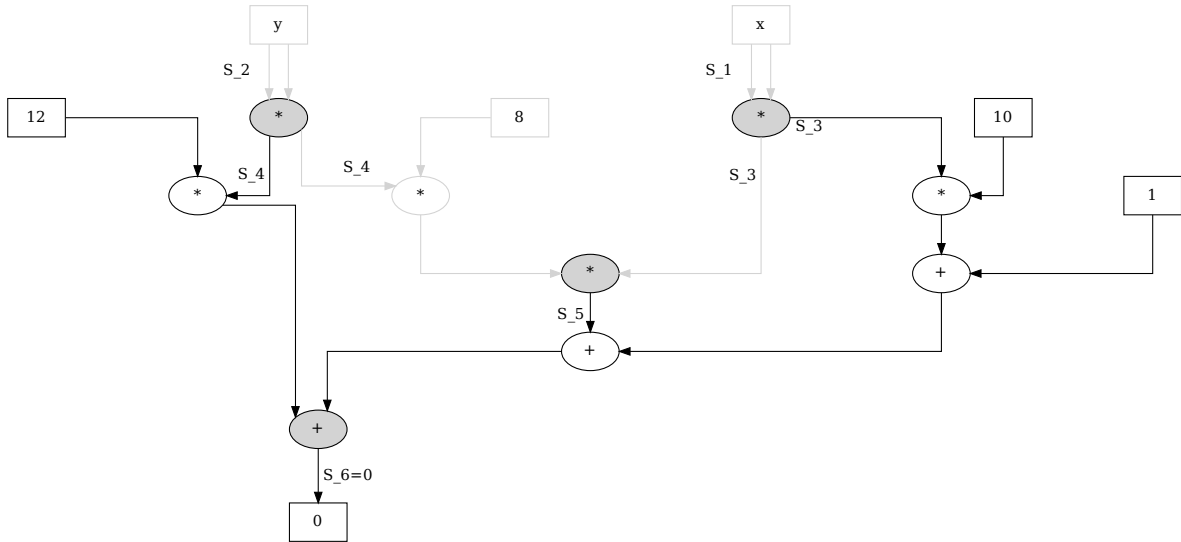


The right input to the associated multiplication gate is given by the labeled edge S_3 . However, the left input is not a labeled edge, but has a labeled edge in one of its path. To compute the left factor of that constraint, we have to compute the output of the subgraph associated to the left edge, which is $S_4 \cdot 8$. This gives the constraint

$$(S_4 \cdot 8) \cdot S_3 = S_5$$

4484 The last edge label is the constant $S_6 = 0$. To see how it implies a constraint, we have to
 4485 construct the associated subgraph, which consists of all edges, nodes, and paths, starting either
 4486 at a constant input or a labeled edge. We get

4487



4488

4489

Both the left and the right input are unlabeled, but have a labeled edges in their path. Since the gate is an addition gate, the right factor in the quadratic constraint is always 1 and the left factor is computed by symbolically executing all inputs to all gates in the sub-circuit. We get

$$(12 \cdot S_4 + S_5 + 10 \cdot S_3 + 1) \cdot 1 = 0$$

Since there are no more labeled outgoing edges, we are done deriving the constraints. Combining all constraints together, we get the following R1CS:

$$S_1 \cdot S_1 = S_3$$

$$S_2 \cdot S_2 = S_4$$

$$(S_4 \cdot 8) \cdot S_3 = S_5$$

$$(12 \cdot S_4 + S_5 + 10 \cdot S_3 + 1) \cdot 1 = 0$$

4490 which is equivalent to the R1CS we derived in example 117 both the circuit as well as the R1CS
 4491 are just two different ways to express the same language.

4492 6.2.3 Quadratic Arithmetic Programs

4493 We have introduced algebraic circuits and their associated Rank-1 Constraint Systems as two
 4494 particular models able to represent bounded computation. Both models define formal languages,

and associated membership as well as knowledge claims can be proofed in a constructive way by executing the circuit in order to compute solutions to its associated R1CS.

One reason why those systems are useful in the context of succinct zero-knowledge proof systems is because any R1CS can be transformed into another computational model called a **Quadratic Arithmetic Program** [QAP], which serves as the basis for some of the most efficient succinct non-interactive zero-knowledge proof generators that currently exist.

As we will see, proving statements for languages that have decision functions defined by Quadratic Arithmetic Programs can be achieved by providing certain polynomials, and those proofs can be verified by checking a particular divisibility property of those polynomials.

QAP representation To understand what Quadratic Arithmetic Programs are in detail, let \mathbb{F} be a field and R a Rank-1 Constraint System over \mathbb{F} such that the number of non-zero elements in \mathbb{F} is strictly larger than the number k of constraints in R . Moreover, let a_j^i, b_j^i and $c_j^i \in \mathbb{F}$ for every index $0 \leq j \leq n+m$ and $1 \leq i \leq k$, be the defining constants of the R1CS and m_1, \dots, m_k be arbitrary, invertible and distinct elements from \mathbb{F} .

Then a **Quadratic Arithmetic Program** associated to the R1CS R is the following set of polynomials over \mathbb{F} :

$$QAP(R) = \left\{ T \in \mathbb{F}[x], \{A_j, B_j, C_j \in \mathbb{F}[x]\}_{h=0}^{n+m} \right\} \quad (6.12)$$

Here $T(x) := \prod_{l=1}^k (x - m_l)$ is a polynomial of degree k , called the **target polynomial** of the QAP and A_j, B_j as well as C_j are the unique degree $k-1$ polynomials defined by the following equation:

$$A_j(m_i) = a_j^i, \quad B_j(m_i) = b_j^i, \quad C_j(m_i) = c_j^i \quad \text{for all } j = 1, \dots, n+m+1, i = 1, \dots, k \quad (6.13)$$

Given some Rank-1 Constraint System, an associated Quadratic Arithmetic Program is therefore nothing but a set of polynomials, computed from the constants in the R1CS. To see that the polynomials A_j, B_j and C_j are uniquely defined by the equations 6.13, recall that a polynomial of degree $k-1$ is completely determined by k evaluation points and it can be computed for example by Lagrange interpolation 4.

Computing a QAP from any given R1CS can be achieved in the following three steps. If the R1CS consists of k constraints, first choose k different, invertible element from the field \mathbb{F} . Every choice defines a different QAP for the same R1CS. Then compute the target polynomial T according to its definition 6.12. After that use Lagrange's method 4 to compute the polynomials A_j for every $1 \leq j \leq k$ from the set

$$S_{A_j} = \{(m_1, a_j^1), \dots, (m_k, a_j^k)\} \quad (6.14)$$

After that is done, execute the analog computation for the polynomials B_j and C_j for every $1 \leq j \leq k$.

Example 127 (Generalized factorization SNARK). To provide a better intuition of Quadratic Arithmetic Programs and how they are computed from their associated Rank-1 Constraint Systems, consider the language $L_{3.fac_zk}$ from example 114 and its associated R1CS from example 116:

$$\begin{array}{ll} W_1 \cdot W_2 = W_4 & \text{constraint 1} \\ W_4 \cdot W_3 = I_1 & \text{constraint 2} \end{array}$$

In this example we want to transform this R1CS into an associated QAP. According to example 116 the defining constants a_j^i , b_j^i and c_j^i of the R1CS are given as follows:

$$\begin{array}{llllll} a_0^1 = 0 & a_1^1 = 0 & a_2^1 = 1 & a_3^1 = 0 & a_4^1 = 0 & a_5^1 = 0 \\ a_0^2 = 0 & a_1^2 = 0 & a_2^2 = 0 & a_3^2 = 0 & a_4^2 = 0 & a_5^2 = 1 \\ \\ b_0^1 = 0 & b_1^1 = 0 & b_2^1 = 0 & b_3^1 = 1 & b_4^1 = 0 & b_5^1 = 0 \\ b_0^2 = 0 & b_1^2 = 0 & b_2^2 = 0 & b_3^2 = 0 & b_4^2 = 1 & b_5^2 = 0 \\ \\ c_0^1 = 0 & c_1^1 = 0 & c_2^1 = 0 & c_3^1 = 0 & c_4^1 = 0 & c_5^1 = 1 \\ c_0^2 = 0 & c_1^2 = 1 & c_2^2 = 0 & c_3^2 = 0 & c_4^2 = 0 & c_5^2 = 0 \end{array}$$

Since the R1CS is defined over the field \mathbb{F}_{13} and since it has two constraints, we need to choose two arbitrary but invertible and distinct elements m_1 and m_2 from \mathbb{F}_{13} . We choose $m_1 = 5$, and $m_2 = 7$ and with this choice we get the target polynomial

$$\begin{array}{ll} T(x) = (x - m_1)(x - m_2) & \# \text{ Definition of } T \\ = (x - 5)(x - 7) & \# \text{ Insert our choice} \\ = (x + 8)(x + 6) & \# \text{ Negatives in } \mathbb{F}_{13} \\ = x^2 + x + 9 & \# \text{ expand} \end{array}$$

4526 Then we have to compute the polynomials A_j , B_j and C_j by their defining equation from the
4527 R1CS coefficients. Since the R1CS has two constraining equations, those polynomials are of
4528 degree 1 and they are defined by their evaluation at the point $m_1 = 5$ and the point $m_2 = 7$.

At point m_1 , each polynomial A_j is defined to be a_j^1 and at point m_2 , each polynomial A_j is defined to be a_j^2 . The same holds true for the polynomials B_j as well as C_j . Writing all these equations down, we get:

$$\begin{array}{llllll} A_0(5) = 0, & A_1(5) = 0, & A_2(5) = 1, & A_3(5) = 0, & A_4(5) = 0, & A_5(5) = 0 \\ A_0(7) = 0, & A_1(7) = 0, & A_2(7) = 0, & A_3(7) = 0, & A_4(7) = 0, & A_5(7) = 1 \\ \\ B_0(5) = 0, & B_1(5) = 0, & B_2(5) = 0, & B_3(5) = 1, & B_4(5) = 0, & B_5(5) = 0 \\ B_0(7) = 0, & B_1(7) = 0, & B_2(7) = 0, & B_3(7) = 0, & B_4(7) = 1, & B_5(7) = 0 \\ \\ C_0(5) = 0, & C_1(5) = 0, & C_2(5) = 0, & C_3(5) = 0, & C_4(5) = 0, & C_5(5) = 1 \\ C_0(7) = 0, & C_1(7) = 1, & C_2(7) = 0, & C_3(7) = 0, & C_4(7) = 0, & C_5(7) = 0 \end{array}$$

4529 Lagrange's interpolation implies that a polynomial of degree k , that is zero on $k + 1$ points has
4530 to be the zero polynomial. Since our polynomials are of degree 1 and determined on 2 points,
4531 we therefore know that the only non-zero polynomials in our QAP are A_2 , A_5 , B_3 , B_4 , C_1 and
4532 C_5 , and that we can use Lagrange's interpolation to compute them.

To compute A_2 we note that the set S_{A_2} in our version of Lagrange's interpolation is given by $S_{A_2} = \{(m_1, a_2^1), (m_2, a_2^2)\} = \{(5, 1), (7, 0)\}$. Using this set we get:

$$\begin{array}{ll} A_2(x) = a_2^1 \cdot \left(\frac{x - m_2}{m_1 - m_2}\right) + a_2^2 \cdot \left(\frac{x - m_1}{m_2 - m_1}\right) = 1 \cdot \left(\frac{x - 7}{5 - 7}\right) + 0 \cdot \left(\frac{x - 5}{7 - 5}\right) \\ = \frac{x - 7}{-2} = \frac{x - 7}{11} & \# 11^{-1} = 6 \\ = 6(x - 7) = 6x + 10 & \# -7 = 6 \text{ and } 6 \cdot 6 = 10 \end{array}$$

To compute A_5 , we note that the set S_{A_5} in our version of Lagrange's method is given by $S_{A_5} = \{(m_1, a_5^1), (m_2, a_5^2)\} = \{(5, 0), (7, 1)\}$. Using this set we get:

$$\begin{aligned} A_5(x) &= a_5^1 \cdot \left(\frac{x - m_2}{m_1 - m_2} \right) + a_5^2 \cdot \left(\frac{x - m_1}{m_2 - m_1} \right) = 0 \cdot \left(\frac{x - 7}{5 - 7} \right) + 1 \cdot \left(\frac{x - 5}{7 - 5} \right) \\ &= \frac{x - 5}{2} \quad \# 2^{-1} = 7 \\ &= 7(x - 5) = 7x + 4 \quad \# -5 = 8 \text{ and } 7 \cdot 8 = 4 \end{aligned}$$

4533 Using Lagrange's interpolation, we can deduce that $A_2 = B_3 = C_5$ as well as $A_5 = B_4 = C_1$,
4534 since they are polynomials of degree 1 that evaluate to same values on 2 points. Using this, we
4535 get the following set of polynomials

$A_0(x) = 0$	$B_0(x) = 0$	$C_0(x) = 0$
$A_1(x) = 0$	$B_1(x) = 0$	$C_1(x) = 7x + 4$
$A_2(x) = 6x + 10$	$B_2(x) = 0$	$C_2(x) = 0$
$A_3(x) = 0$	$B_3(x) = 6x + 10$	$C_3(x) = 0$
$A_4(x) = 0$	$B_4(x) = 7x + 4$	$C_4(x) = 0$
$A_5(x) = 7x + 4$	$B_5(x) = 0$	$C_5(x) = 6x + 10$

4537 We can invoke Sage to verify our computation. In sage every polynomial ring has a function
4538 `lagrange_polynomial` that takes the defining points as inputs and the associated Lagrange
4539 polynomial as output.

```

4540 sage: F13 = GF(13)                                     643
4541 sage: F13t.<t> = F13[]                                   644
4542 sage: T = F13t((t-5)*(t-7))                             645
4543 sage: A2 = F13t.lagrange_polynomial([(5,1),(7,0)])       646
4544 sage: A5 = F13t.lagrange_polynomial([(5,0),(7,1)])       647
4545 sage: T == F13t(t^2 + t + 9)                             648
4546 True                                                    649
4547 sage: A2 == F13t(6*t + 10)                               650
4548 True                                                    651
4549 sage: A5 == F13t(7*t + 4)                                652
4550 True                                                    653

```

4551 Combining this computation with the target polynomial we derived earlier, a Quadratic
4552 Arithmetic Program associated to the Rank-1 Constraint System $R_{3.fac_zk}$ is given as follows:

$$\begin{aligned} QAP(R_{3.fac_zk}) &= \{x^2 + x + 9, \\ &\quad \{0, 0, 6x + 10, 0, 0, 7x + 4\}, \{0, 0, 0, 6x + 10, 7x + 4, 0\}, \{0, 7x + 4, 0, 0, 0, 6x + 10\}\} \end{aligned}$$

4553 *Exercise 88.* Consider the Rank-1 Constraint System for points on the tiny-jubjub curve from
4554 example 117. Compute an associated QAP for this R1CS and double check your computation
4555 using sage.

4556 **QAP Satisfiability** One of the major points of Quadratic Arithmetic Programs in proving sys-
4557 tems is that solutions of their associated Rank-1 Constraint Systems are in 1:1 correspondence
4558 with certain polynomials P divisible by the target polynomial T of the QAP. Verifying solutions

to the R1CS and hence, checking proper circuit execution is then achievable by polynomial division of P by T .

To be more specific, let R be some Rank-1 Constraint System with associated variables $(\langle I_1, \dots, I_n \rangle; \langle W_1, \dots, W_m \rangle)$ and let $QAP(R)$ be a Quadratic Arithmetic Program of R . Then the string $(\langle I_1, \dots, I_n \rangle; \langle W_1, \dots, W_m \rangle)$ is a solution to the R1CS if and only if the following polynomial is divisible by the target polynomial T :

$$P_{(I;W)} = (A_0 + \sum_j^n I_j \cdot A_j + \sum_j^m W_j \cdot A_{n+j}) \cdot (B_0 + \sum_j^n I_j \cdot B_j + \sum_j^m W_j \cdot B_{n+j}) - (C_0 + \sum_j^n I_j \cdot C_j + \sum_j^m W_j \cdot C_{n+j}) \quad (6.15)$$

To understand how Quadratic Arithmetic Programs define formal languages, observe that every QAP over a field \mathbb{F} defines a decision function over the alphabet $\Sigma_I \times \Sigma_W = \mathbb{F} \times \mathbb{F}$ in the following way:

$$R_{QAP} : (\mathbb{F})^* \times (\mathbb{F})^* \rightarrow \{true, false\} ; (I;W) \mapsto \begin{cases} true & P_{(I;W)} \text{ is divisible by } T \\ false & \text{else} \end{cases} \quad (6.16)$$

This means that every QAP defines a formal language L_{QAP} , and, if the QAP is associated to an R1CS, the language generated by the QAP and the language generated by the R1CS are equivalent. In the context of languages generated by Quadratic Arithmetic Programs, a **statement** is then a membership claim “There is a word $(I;W)$ in L_{QAP} ”. A proof to this claim is therefore given by a polynomial $P_{(I;W)}$, which is verified by dividing $P_{(I;W)}$ by T .

Note the structural similarities and differences in the definition of an R1CS and its associated language in ??, of circuits and their associated languages in 6.2.2 and of QAPs and their associated languages as explained in this part. For circuits and their associated Rank-1 Constraint Systems, a constructive proof consists of a valid assignment of field elements to the edges of the circuit, or the variables in the R1CS. However, in the case of QAPs, a valid proof consists of a polynomial $P_{(I;W)}$.

To compute a constructive proof for a statement in L_{QAP} given some instance I , a prover first needs to compute a constructive proof W of the associated R1CS, e.g. by executing the circuit of the R1CS. With $(I;W)$ at hand, the prover can then compute the polynomial $P_{(I;W)}$ and publish the polynomial as proof.

Verifying a constructive proof in the case of a circuit is achieved by executing the circuit and then by comparing the result against the given proof. Verifying the same proof in the R1CS picture means checking if the elements of the proof satisfy the R1CS equations. In contrast, verifying a proof in the QAP picture is done by polynomial division of the proof P by the target polynomial T . The proof is verified if and only if P is divisible by T .

Example 128. Consider the Quadratic Arithmetic Program $QAP(R_{3, fac_zk})$ from example 127 and its associated R1CS from equation 116. To give an intuition of how proofs in the language $L_{QAP(R_{3, fac_zk})}$ look like, let's consider the instance $I_1 = 11$. As we know from example 122, $(W_1, W_2, W_3, W_5) = (2, 3, 4, 6)$ is a proper witness, since $(\langle I_1 \rangle; \langle W_1, W_2, W_3, W_5 \rangle) = (\langle 11 \rangle; \langle 2, 3, 4, 6 \rangle)$ is a valid circuit assignment and hence, a solution to R_{3, fac_zk} and a constructive proof for language $L_{R_{3, fac_zk}}$.

In order to transform this constructive proof into a knowledge proof in language $L_{QAP(R_{3, fac_zk})}$, a prover has to use the elements of the constructive proof, to compute the polynomial $P_{(I;W)}$.

In the case of $(\langle I_1 \rangle; \langle W_1, W_2, W_3, W_5 \rangle) = (\langle 11 \rangle; \langle 2, 3, 4, 6 \rangle)$, the associated proof

is computed as follows:

$$\begin{aligned}
P_{(I;W)} &= (A_0 + \sum_j^n I_j \cdot A_j + \sum_j^m W_j \cdot A_{n+j}) \cdot (B_0 + \sum_j^n I_j \cdot B_j + \sum_j^m W_j \cdot B_{n+j}) - (C_0 + \sum_j^n I_j \cdot C_j + \sum_j^m W_j \cdot C_{n+j}) \\
&= (2(6x + 10) + 6(7x + 4)) \cdot (3(6x + 10) + 4(7x + 4)) - (11(7x + 4) + 6(6x + 10)) \\
&= ((12x + 7) + (3x + 11)) \cdot ((5x + 4) + (2x + 3)) - ((12x + 5) + (10x + 8)) \\
&= (2x + 5) \cdot (7x + 7) - (9x) \\
&= (x^2 + 2 \cdot 7x + 5 \cdot 7x + 5 \cdot 7) - (9x) \\
&= (x^2 + x + 9x + 9) - (9x) \\
&= x^2 + x + 9
\end{aligned}$$

4596 Given instance $I_1 = 11$ a prover therefore provides the polynomial $x^2 + x + 9$ as proof. To verify
4597 this proof, any verifier can then look up the target polynomial T from the QAP and divide $P_{(I;W)}$
4598 by T . In this particular example, $P_{(I;W)}$ is equal to the target polynomial T , and hence, it is
4599 divisible by T with $P/T = 1$. The verifier therefore verifies the proof.

```

4600 sage: F13 = GF(13) 654
4601 sage: F13t.<t> = F13[] 655
4602 sage: T = F13t(t^2 + t + 9) 656
4603 sage: P = F13t((2*(6*t+10)+6*(7*t+4))*(3*(6*t+10)+4*(7*t+4)) 657
4604             - (11*(7*t+4)+6*(6*t+10)))
4605 sage: P == T 658
4606 True 659
4607 sage: P % T # remainder 660
4608 0 661

```

To give an example of a false proof, consider the string $(\langle I_1 \rangle; \langle W_1, W_2, W_3, W_4 \rangle) = (\langle 11 \rangle, \langle 2, 3, 4, 8 \rangle)$. Executing the circuit, we can see that this is not a valid assignment and not a solution to the R1CS, and hence, not a constructive knowledge proof in $L_{3, \text{fac_zk}}$. However, a prover might use these values to construct a false proof $P'_{(I;W)}$:

$$\begin{aligned}
P'_{(I;W)} &= (A_0 + \sum_j^n I_j \cdot A_j + \sum_j^m W_j \cdot A_{n+j}) \cdot (B_0 + \sum_j^n I_j \cdot B_j + \sum_j^m W_j \cdot B_{n+j}) - (C_0 + \sum_j^n I_j \cdot C_j + \sum_j^m W_j \cdot C_{n+j}) \\
&= (2(6x + 10) + 8(7x + 4)) \cdot (3(6x + 10) + 4(7x + 4)) - (8(6x + 10) + 11(7x + 4)) \\
&= 8x^2 + 6
\end{aligned}$$

Given instance $I_1 = 11$, a prover therefore provides the polynomial $8x^2 + 6$ as proof. To verify this proof, any verifier can look up the target polynomial T from the QAP and divide $P'_{(I;W)}$ by T . However, polynomial division has the following remainder:

$$(8x^2 + 6)/(x^2 + x + 9) = 8 + \frac{5x + 12}{x^2 + x + 9}$$

4609 This implies that $P'_{(I;W)}$ is not divisible by T , and hence, the verifier does not verify the proof.
4610 Any verifier can therefore show that the proof is false.

```

4611 sage: F13 = GF(13) 662
4612 sage: F13t.<t> = F13[] 663
4613 sage: T = F13t(t^2 + t + 9) 664
4614 sage: P = F13t((2*(6*t+10)+8*(7*t+4))*(3*(6*t+10)+4*(7*t+4)) - ( 665
4615             8*(6*t+10)+11*(7*t+4)))

```


4616	<code>sage: P == F13t(8*t^2 + 6)</code>	666
4617	<code>True</code>	667
4618	<code>sage: P % T # remainder</code>	668
4619	<code>5*t + 12</code>	669

Chapter 7

Circuit Compilers

As we have seen in the previous chapter, statements can be formalized as membership or knowledge claims in formal languages, and algebraic circuits as well as Rank-1 Constraint Systems are two practically important ways to define those languages.

However, both algebraic circuits and Rank-1 Constraint Systems are not ideal from a developers point of view, because they deviate substantially from common programming paradigms. Writing real-world applications as circuits and the associated verification in terms of Rank-1 Constraint Systems is at least as troublesome as writing any other low-level language like assembler code. To allow for complex statement design, it is therefore necessary to have some kind of compiler framework, capable of transforming high-level languages into arithmetic circuits and associated Rank-1 Constraint Systems.

As we have seen in chapter 6 and in 6.2.1 as well as 6.2.2, both arithmetic circuits and Rank-1 Constraint Systems have a modularity property 6.2.1 by which it is possible to synthesize complex circuits from simple ones. A basic approach taken by many circuit/R1CS compilers is therefore to provide a library of atomic and simple circuits and then define a way to combine those basic building blocks into arbitrary complex systems.

In this chapter, we provide an introduction to basic concepts of so-called **circuit compilers** and derive a toy language which we can “compile” in a pen-and-paper approach into graphical representations of algebraic circuits and their associated Rank-1 Constraint Systems.

We start with a general introduction to our toy programming language, and then introduce atomic types like booleans and unsigned integers. Then we define the fundamental control flow primitives like the if-then-else conditional and the bounded loop. We will look at basic functionality primitives like elliptic curve cryptography. Primitives like these are often called **gadgets** in the literature.

7.1 A Pen-and-Paper Language

To explain basic concepts of circuit compilers and their associated high-level languages, we derive an informal toy language and associated “brain-compiler” which we name **PAPER (Pen-And-Paper Execution Rules)**. **PAPER** allows programmers to define statements in Rust-like pseudo-code. The language is inspired by `zokrates` and `circom`.

7.1.1 The Grammar

In **PAPER**, any statement is defined as an ordered list of functions, where any function has to be declared in the list before it is called in another function of that list. The last entry in a statement

add references to these languages?

has to be a special function, called `main`. Functions take a list of typed parameters as inputs and compute a tuple of typed variables as output, where `type_functions` are special functions that define how to transform one type into another type, ultimately transforming any type into elements of the base field where the circuit is defined over.

Any statement is parameterized over the field that the circuit will be defined on, and has additional optional parameters of unsigned type, needed to define the size of arrays or the counter of bounded loops. The following definition makes the grammar of a statement precise using a command line language like description:

```
statement <Name> {F:<Field> [ , <N_1: unsigned>, ... ] } {
  [fn <Name> ([[pub]<Arg>:<Type>, ...]) -> (<Type>, ...)] {
    [let [pub] <Var>:<Type> ; ... ]
    [let const <Const>:<Type>=<Value> ; ... ]
    Var<==>(fn ([<Arg>|<Const>|<Var>, ...]) | (<Arg>|<Const>|<Var>)) ;
    return (<Var>, ...) ;
  } ; ... ]
  fn main ([[pub]<Arg>:<Type>, ...]) -> (<Type>, ...) {
    [let [pub] <Var>:<Type> ; ... ]
    [let const <Const>:<Type>=<Value> ; ... ]
    Var<==>(fn ([<Arg>|<Const>|<Var>, ...]) | (<Arg>|<Const>|<Var>)) ;
    return (<Var>, ...) ;
  } ;
}
```

Function arguments and variables are witness variables by default, but can be declared as instance by the `pub` specifier. Declaring arguments and variables as instances always overwrites any previous or conflicting witness declarations. Every argument, constant or variable has a type, and every type is defined as a function that transforms that type into another type. In order for a PAPER program to compile successfully, all type transformations must be composed in such a way that the final type is the base field where the circuit is defined over:

```
type_function <TYPE>( t1 : <TYPE_1>) -> TYPE_2{
  let t2: TYPE_2 <==> fn(TYPE_1)
  return t2
}
```

Many real-world circuit languages are based on a similar, but of course more sophisticated approach than PAPER. The purpose of PAPER is to show basic principles of circuit compilers and their associated high-level languages.

Example 129. To get a better understanding of the grammar of PAPER, the following constitutes proper high-level code that follows the grammar of the PAPER language, assuming that all types in that code have been defined elsewhere.

```
statement MOCK_CODE {F: F_43, N_1 = 1024, N_2 = 8} {
  fn foo(in_1 : F, pub in_2 : TYPE_2) -> F {
    let const c_1 : F = 0 ;
    let const c_2 : TYPE_2 = SOME_VALUE ;
    let pub out_1 : F ;
    out_1<==> c_1 ;
    return out_1 ;
  } ;
  fn bar(pub in_1 : F) -> F {
```

```

4701     let out_1 : F ;
4702     out_1<==foo(in_1);
4703     return out_1 ;
4704 } ;
4705
4706 fn main(in_1 : TYPE_1)->(F, TYPE_2){
4707     let const c_1 : TYPE_1  = SOME_VALUE ;
4708     let const c_2 : F = 2;
4709     let const c_3 : TYPE_2  = SOME_VALUE  ;
4710     let pub out_1 : F ;
4711     let out_2 : TYPE_2 ;
4712     c_1 <== in_1 ;
4713     out_1 <== foo(c_2) ;
4714     out_2 <== TYPE_2 ;
4715     return (out_1,out_2) ;
4716 } ;
4717 }

```

7.1.2 The Execution Phases

In contrast to normal executable programs, programs for circuit compilers have two modes of execution. The first mode, usually called the **setup phase**, is executed in order to generate the circuit and its associated Rank-1 Constraint System, the latter of which is then usually used as input to some zero-knowledge proof system as explained in 8.

The second mode of execution is usually called the **prover phase**. In this phase, some assignment to all instance variables of the circuit is usually given as input and the task of a prover is to compute a valid assignment to all witness variables of the circuit. Depending on the use case, this valid assignment is then either directly used as constructive proof for proper circuit execution or is transferred as input to the proof generation algorithm of some zero-knowledge proof system, where the full-sized, non hiding constructive proof is processed into a succinct proof with various levels of zero knowledge.

Modern circuit languages and their associated compilers abstract over those two phases and provide a unified **interphase** to the developer, who then writes a single program that can be used in both phases.

To give the reader a clear, conceptual distinction between the two phases, PAPER keeps them separated. PAPER-code can be “brain-compiled” during the **setup-phase** in a pen-and-paper approach into a graphical circuit representation. Once a circuit is derived, it can be executed in a **prover phase** to generate a valid assignment. The valid assignment is then interpreted as a constructive proof for a knowledge claim in the associated language.

The Setup Phase In PAPER, the task of the setup phase is to compile code in the PAPER language into a visual representation of an algebraic circuit. Deriving the circuit from the code in a pen-and-paper style is what we call **brain-compiling**.

Given some statement description that adheres to the correct grammar, we start the graphical circuit compilation process with an empty circuit, compile the main function first and then inductively compile all other functions as they are called during the process.

For every function that we currently compile, we draw a box-node for every input argument, every variable and every constant of that function. If the node represents a variable, we label it with that variable’s name, and if it represents a constant, we label it with that constant’s value.

We group arguments into a subgraph labeled “inputs” and return values into a subgraph labeled “outputs”. We then group everything into a subgraph and label that subgraph with the function’s name.

After this is done, we have to do a consistency and type check for every occurrence of the assignment operator `<==`. We have to ensure that the expression on the right side of the operator is well defined and that the types of both side match.

Then we compile the right side of every occurrence of the assignment operator `<==`. If the right side is a constant or variable defined in this function, we draw a dotted line from the box-node that represents the left side of `<==` to the box node that represents the right side of the same operator. If the right side represents an argument of that function we draw a line from the box-node that represents the left side of `<==` to the box node that represents the right side of the same operator.

If the right side of the `<==` operator is a function, we look into our database, find its associated circuit and draw it. If no circuit is associated to that function yet, we repeat the compilation process for that function, drawing edges from the function’s argument to its input nodes and from the functions output nodes to the nodes on the right side of `<==`.

During that process, edge labels are drawn according to the defining rules of algebraic circuits from 6.2.2. If the associated variable represents a witness variable, we use the *W* label to indicate a witness, and if it represents a instance variable, we use the *I* label to indicate an instance. Variables are witnesses by default and the *pub* specifier indicates that the variable is an instance.

Once this is done, we compile all occurring types of all variables in a function, by compiling the `type_function` of each type. We do this inductively until we reach the type of the base field. Circuits have no notion of types, only of field elements; hence, every type needs to be compiled to the field type in a sequence of compilation steps.

The compilation stops once we have inductively replaced all functions by their circuits. The result is a circuit that contains many unnecessary box nodes. In a final **optimization step**, all box nodes that are directly linked to each other are collapsed into a single node, and all box nodes that represent the same constants are collapsed into a single node.

Of course, PAPER’s brain-compiler is not properly defined in any formal manner. Its purpose is to highlight important steps that real-world compilers undergo in their setup phases.

Example 130 (A trivial Circuit). To give an intuition of how to write and compile circuits in the PAPER language, consider the following statement description:

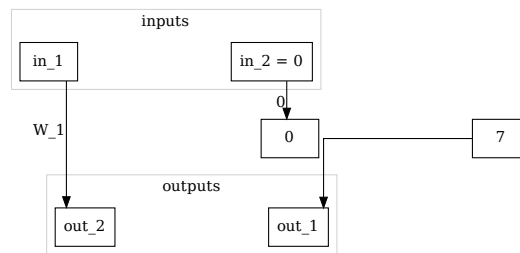
```
statement trivial_circuit {F:F_13} {
  fn main{F}{in1 : F, pub in2 : F} -> (F,F){
    let const outc1 : F = 0 ;
    let const incl : F = 7 ;
    let out1 : F ;
    let out2 : F ;
    out1 <== incl;
    out2 <== in1;
    outc1 <== in2;
    return (out1, out2) ;
  }
}
```

To brain-compile this statement into an algebraic circuit with PAPER, we start with an empty circuit and evaluate function `main`, which is the only function in this statement.

We draw box-nodes for every argument, every constant and every variable of the function

and label them with their names or values, respectively. Then we do a consistency and type check for every \leq operator in the function. Since the circuit only wires inputs to outputs and all elements have the same type, the check is valid.

Then we evaluate the right side of the assignment operators. Since, in our case, the right side of each operator is not a function, we draw edges from the box-nodes on the right side to the associated box node on the left side. To label those edges, we use the general rules of algebraic circuits as defined in 6.2.2. According to those rules, every incoming edge of a sink node has a label and every outgoing edge of a source node has a label, if the node is labeled with a variable. Since nodes that represent constants are implicitly assumed to be private, and since the public specifier determines if an edge is labeled with W or I , we get the following circuit:



The Prover Phase In PAPER, a so-called **prover phase** can be executed once the setup phase has generated a graphic circuit representation from its associated high-level code. This is done by executing the circuit while assigning proper values to all input nodes of the circuit. However, in contrast to most real-world compilers, PAPER does not tell the prover how to find proper input values to a given circuit. Real-world programming languages usually provide this data by computations that are done outside of the circuit.

Example 131. Consider the circuit from example 123. Valid assignments to this circuit are constructive proofs that the pair of inputs $\langle I_1, I_2 \rangle$ is a point on the tiny-jubjub curve. However, the circuit does not provide a way to actually compute proper values for I_1 and I_2 . Any real-world system therefore needs an auxiliary computation that provides those values.

7.2 Common Programing concepts

In this section, we cover concepts that appear in almost every programming language, and see how they can be implemented in circuit compilers.

7.2.1 Primitive Types

Primitive data types like booleans, (unsigned) integers, or strings are the most basic building blocks one can expect to find in every general high-level programming language. In order to write statements as computer programs that compile into circuits, it is therefore necessary to implement primitive types as constraint systems, and define their associated operations as circuits.

In this section, we look at some common ways to achieve this. After a recapitulation of the atomic type for the base field where the circuit is defined on, we start with an implementation of the boolean type and its associated boolean algebra as circuits. After that, we define unsigned integers based on the boolean type, and leave the implementation of signed integers as an exercise to the reader.

The base-field type

Since both algebraic circuits and their associated Rank-1 Constraint Systems are defined over a finite field, elements from that field are the atomic informational units in those models. In this sense, field elements $x \in \mathbb{F}$ are for algebraic circuits what bits are for computers.

In PAPER, we write \mathbb{F} for this type and specify the actual instance of the field type in curly brackets after the name of a given statement. Two functions are associated to this type, which are induced by the **addition** and **multiplication** law in the field \mathbb{F} . We write

$$\text{MUL} : \mathbb{F} \times \mathbb{F} \rightarrow \mathbb{F} ; (x, y) \mapsto \text{MUL}(x, y) \quad (7.1)$$

$$\text{ADD} : \mathbb{F} \times \mathbb{F} \rightarrow \mathbb{F} ; (x, y) \mapsto \text{ADD}(x, y) \quad (7.2)$$

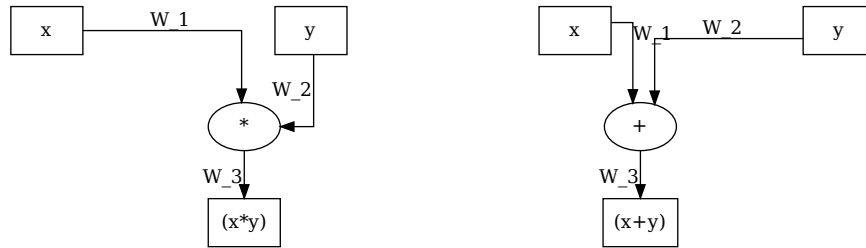
Circuit compilers have to compile these functions into arithmetic gates, as explained in 6.2.2. Every other function has to be expressed in terms of these two atomic functions.

To represent addition and multiplication in the PAPER language, we define the following two functions:

```
fn MUL(x : F, y : F) -> F{}
```

```
fn ADD(x : F, y : F) -> F{}
```

The compiler then compiles every occurrence of the MUL or the ADD function into the following graphical circuit representations:



Example 132 (Basic gates). To give an intuition of how a real-world compiler might transform addition and multiplication in algebraic expressions into a circuit, consider the following PAPER statement:

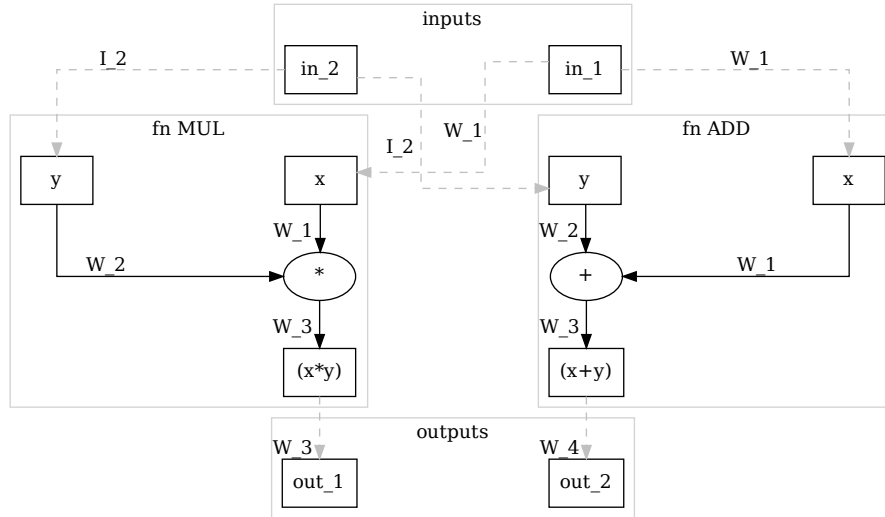
```
statement basic_ops {F:F_13} {
  fn main(in_1 : F, pub in_2 : F) -> (F, F){
    let out_1 : F ;
    let out_2 : F ;
    out_1 <== MUL(in_1, in_2) ;
    out_2 <== ADD(in_1, in_2) ;
    return (out_1, out_2) ;
  }
}
```

To compile this into an algebraic circuit, we start with an empty circuit and evaluate the function `main`, which is the only function in this statement. We draw an inputs subgraph containing box-nodes for every argument of the function, and an outputs subgraph containing box-nodes for every factor in the return value. Since all of these nodes represent variables of the `field` type, we don't have to add any type constraints to the circuit.

We check the validity of every expression on the right side of every \leq operator including a type check. In our case, every variable is of the `field` type and hence the types match the types of the `MUL` as well as the `ADD` function and the type of the left sides of \leq operators.

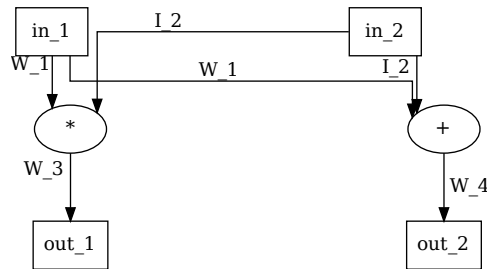
We evaluate the expressions on the right side of every \leq operator inductively, replacing every occurrence of a function with a subgraph that represents its associated circuit.

According to `PAPER`, every occurrence of the instance specifier `pub` overwrites the associate witness default value. Using the appropriate edge labels we get:



Any real-world compiler might process its associated high-level language in a similar way, replacing functions, or gadgets by predefined associated circuits. This process is often followed by various optimization steps that try to reduce the number of constraints as much as possible.

In `PAPER`, we optimize this circuit by collapsing all box nodes that are directly connected to other box nodes, adhering to the rule that a variable's `pub` specifier overwrites any witness specifier. Reindexing edge labels, we get the following circuit as our pen and paper compiler output:



Example 133 (3-factorization). Consider our 3-factorization problem from example 111 and the associated circuit $C_{3, \text{fac_zk}}(\mathbb{F}_{13})$ we provided in example 121. To understand the process of replacing high-level functions by their associated circuits inductively, we want define a `PAPER` statement that we brain-compile into an algebraic circuit equivalent to $C_{3, \text{fac_zk}}(\mathbb{F}_{13})$:


```

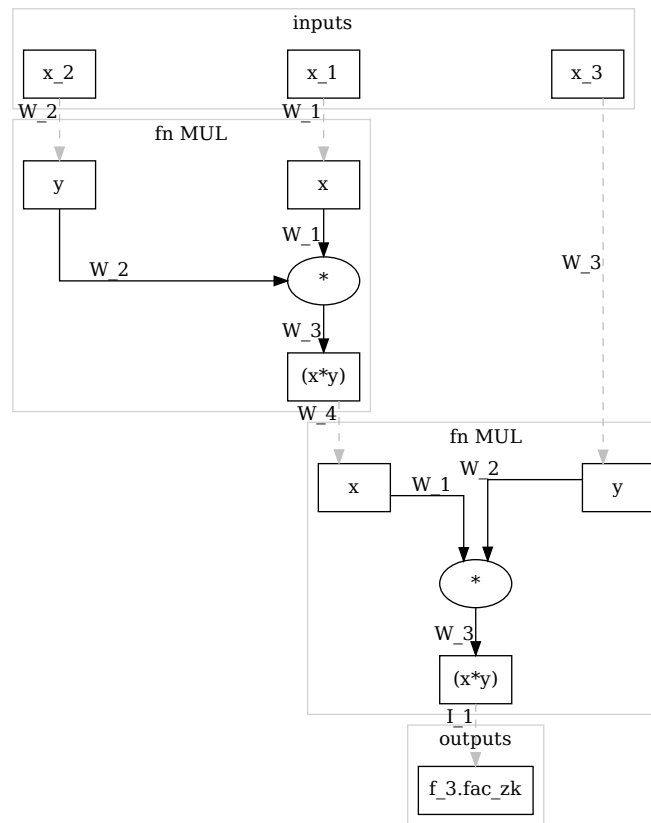
4883 statement 3_fac_zk {F:F_13} {
4884   fn main(x_1 : F, x_2 : F, x_3 : F) -> F{
4885     let pub 3_fac_zk : F ;
4886     f_3.fac_zk <== MUL( MUL( x_1 , x_2 ) , x_3 ) ;
4887     return 3_fac_zk ;
4888   }
4889 }

```

Using PAPER, we start with an empty circuit and then add 3 input nodes to the input subgraph as well as 1 output node to the output subgraph. All these nodes are decorated with the associated variable names. Since all of these nodes represent variables of the `field` type, we don't have to add any type constraints to the circuit.

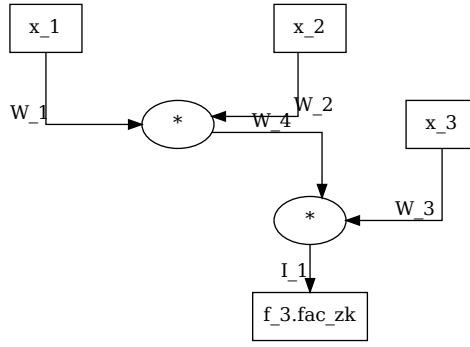
We check the validity of every expression on the right side of the single `<==` operator including a type check.

We evaluate the expressions on the right side of every `<==` operator inductively. We have two nested multiplication functions and we replace them by the associated multiplication circuits, starting with the most outer function. We get:



4899

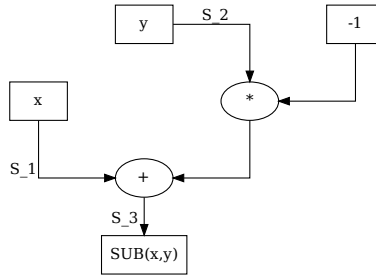
In a final optimization step, we collapse all box nodes directly connected to other box nodes, adhering to the rule that a variable's `public` specifier overwrites any `private` specifier. Reindexing edge labels we get the following circuit:



4903

4904 **The Subtraction Constraint System** By definition, algebraic circuits only contain addition
 4905 and multiplication gates, and it follows that there is no single gate for field subtraction, despite
 4906 the fact that subtraction is a native operation in every field.

4907 High-level languages and their associated circuit compilers, therefore, need another way to
 4908 deal with subtraction. To see how this can be achieved, recall that subtraction is defined by addi-
 4909 tion with the additive inverse, and that the inverse can be computed efficiently by multiplication
 4910 with -1 . A circuit for field subtraction is therefore given by



4911

4912 Using the general method from 6.2.2, the circuits associated Rank-1 Constraint System is given
 4913 by:

$$(S_1 + (-1) \cdot S_2) \cdot 1 = S_3 \quad (7.3)$$

4914 Any valid assignment $\langle S_1, S_2, S_3 \rangle$ to this circuit therefore enforces the value S_3 to be the
 4915 difference $S_1 - S_2$.

4916 Real-world compilers usually provide a gadget or a function to abstract over this circuit such
 4917 that programmers can use subtraction as if it were native to circuits. In PAPER, we define the
 4918 following subtraction function that compiles to the previous circuit:

```

4919 fn SUB(x : F, y : F) -> F{
4920   let rslt : F ;
4921   constant c : F = -1 ;
4922   rslt <== ADD(x , MUL( y , c) );
4923   return rslt ;
4924 }
```

4925 In the setup phase of a statement, we compile every occurrence of the SUB function into an
 4926 instance of its associated subtraction circuit, and edge labels are generated according to the
 4927 rules from 6.2.2.

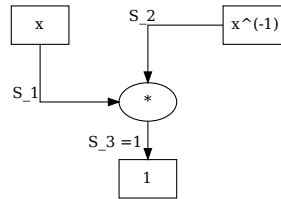
The Inversion Constraint System By definition, algebraic circuits only contain addition and multiplication gates, and it follows that there is no single gate for field inversion, despite the fact that inversion is a native operation in every field.

If the underlying field is a prime field, one approach would be to use Fermat’s little theorem 3.3 to compute the multiplicative inverse inside the circuit. To see how this works, let \mathbb{F}_p be the prime field. The multiplicative inverse x^{-1} of a field element $x \in \mathbb{F}$ with $x \neq 0$ is then given by $x^{-1} = x^{p-2}$, and computing x^{p-2} in the circuit therefore computes the multiplicative inverse.

Unfortunately, real-world primes p are large and computing x^{p-2} by repeated multiplication of x with itself is infeasible. A “square and multiply” approach is faster, as it computes the power in roughly $\log_2(p)$ steps, but still adds a lot of constraints to the circuit.

Computing inverses in the circuit makes no use of the fact that inversion is a native operation in any field. A more constraints friendly approach is therefore to compute the multiplicative inverse outside of the circuit and then only enforce correctness of the computation in the circuit.

To understand how this can be achieved, observe that a field element $y \in \mathbb{F}$ is the multiplicative inverse of a field element $x \in \mathbb{F}$ if and only if $x \cdot y = 1$ in \mathbb{F} . We can use this, and define a circuit that has two inputs, x and y , and enforces $x \cdot y = 1$. It is then guaranteed that y is the multiplicative inverse of x . The price we pay is that we can not compute y by circuit execution, but auxiliary data is needed to tell any prover which value of y is needed for a valid circuit assignment. The following circuit defines the constraint



Using the general method from 6.2.2, the circuit is transformed into the following Rank-1 Constraint System:

$$S_1 \cdot S_2 = 1 \quad (7.4)$$

Any valid assignment $\langle S_1, S_2 \rangle$ to this circuit enforces that S_2 is the multiplicative inverse of S_1 , and, since there is no field element S_2 such that $0 \cdot S_2 = 1$, it also handles the fact that the multiplicative inverse of 0 is not defined in any field.

Real-world compilers usually provide a gadget or a function to abstract over this circuit, and those functions compute the inverse x^{-1} as part of their witness generation process. Programmers then don’t have to care about providing the inverse as auxiliary data to the circuit. In PAPER, we define the following inversion function that compiles to the previous circuit:

```

fn INV(x : F, y : F) -> F {
  let x_inv : F ;
  constant c : F = 1 ;
  c <== MUL( x , y ) ;
  x_inv <== y ;
  return x_inv ;
}

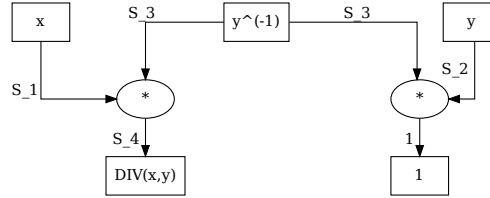
```

As we see, this functions takes two inputs, the field value and its inverse. It therefore does not handle the computation of the inverse by itself. This is to keep PAPER as simple as possible.

In the setup phase, we compile every occurrence of the INV function into an instance of the inversion circuit 7.2.1, and edge labels are generated according to the rules from 6.2.2.

The Division Constraint System By definition, algebraic circuits only contain addition and multiplication gates, and it follows that there is no single gate for field division, despite the fact that division is a native operation in every field.

Implementing division as a circuit, we use the fact that division is multiplication with the multiplicative inverse. We therefore define division as a circuit using the inversion circuit and constraint system from the previous paragraph. Expensive inversion is computed outside of the circuit and then provided as circuit input. We get



Using the method from 6.2.2, we transform this circuit into the following Rank-1 Constraint System:

$$\begin{aligned} S_2 \cdot S_3 &= 1 \\ S_1 \cdot S_3 &= S_4 \end{aligned}$$

Any valid assignment $\langle S_1, S_2, S_3, S_4 \rangle$ to this circuit enforces S_4 to be the field division of S_1 by S_2 . It handles the fact that division by 0 is not defined, since there is no valid assignment in case $S_2 = 0$.

In PAPER, we define the following division function that compiles to the previous circuit:

```
fn DIV(x : F, y : F, y_inv : F) -> F {
  let DIV : F ;
  DIV <== MUL( x , INV( y, y_inv ) ) ;
  return DIV
}
```

In the setup phase, we compile every occurrence of the binary DIV operator into an instance of the inversion circuit.

Exercise 89. Let F be the field \mathbb{F}_5 of modular 5 arithmetics from example 14. Brain-compile the following PAPER statement into an algebraic circuit:

```
statement STUPID_CIRC {F: F_5} {
  fn foo(in_1 : F, in_2 : F)->(out_1 : F, out_2 : F){
    constant c_1 : F = 3 ;
    out_1<== ADD( MUL( c_1 , in_1 ) , in_1 ) ;
    out_2<== INV( c_1 , in_2 ) ;
  } ;

  fn main(in_1 : F, in_2 : F)->(out_1 : F, out_2 : TYPE_2){
    constant (c_1,c_2) : (F,F) = (3,2) ;
    (out_1,out_2) <== foo(in_1, in_2) ;
  } ;
}
```

Exercise 90. Consider the tiny-jubjub curve from example 69 and its associated circuit 120. Write a statement in PAPER that brain-compiles the statement into a circuit equivalent to the one derived in 120, assuming that curve point is the instance and every other assignment is a witness.

Exercise 91. Let $F = \mathbb{F}_{13}$ be the modular 13 prime field and $x \in F$ some field element. Define a statement in PAPER such that given instance x a field element $y \in F$ is a witness for the statement if and only if y is the square root of x .

Brain-compile the statement into a circuit and derive its associated Rank-1 Constraint System. Consider the instance $x = 9$ and compute a constructive proof for the statement.

The boolean Type

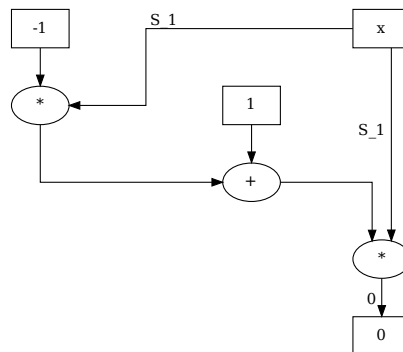
Booleans are a classical primitive type, implemented by virtually every higher programming language. It is therefore important to implement booleans in circuits. One of the most common ways to do this is by interpreting the additive and multiplicative neutral element $\{0, 1\} \subset \mathbb{F}$ as the two boolean values such that 0 represents *false* and 1 represents *true*. Boolean operators like *and*, *or*, or *xor* are then expressible as algebraic circuits over \mathbb{F} .

Representing booleans this way is convenient, because the elements 0 and 1 are defined in any field. The representation is therefore independent of the actual field in consideration.

To fix boolean algebra notation, we write 0 to represent *false* and 1 to represent *true*, and we write \wedge to represent the boolean AND as well as \vee to represent the boolean OR operator. The boolean NOT operator is written as \neg .

The boolean Constraint System To represent booleans by the additive and multiplicative neutral elements of a field, a constraint is required to actually enforce variables of boolean type to be either 1 or 0. In fact, many of the following circuits that represent boolean functions are only correct under the assumption that their input variables are constrained to be either 0 or 1. Not constraining boolean variables is a common problem in circuit design.

In order to constrain an arbitrary field element $x \in \mathbb{F}$ to be 1 or 0, the key observation is that the equation $x \cdot (1 - x) = 0$ has only the two solutions 0 and 1 in any field. Implementing this equation as a circuit therefore generates the correct constraint:



Using the method from 6.2.2, we transform this circuit into the following Rank-1 Constraint System:

$$S_1 \cdot (1 - S_1) = 0$$

Any valid assignment $\langle S_1 \rangle$ to label of this circuit therefore enforces S_1 to be either the field element 0 or 1.

Some real-world circuit compilers (like ZOKRATES or BELLMAN) are typed, while others (like circom) are not. However, all of them have their way of dealing with the binary constraint. In PAPER, we define the boolean type by its type_function that compiles to the previous circuit:

```

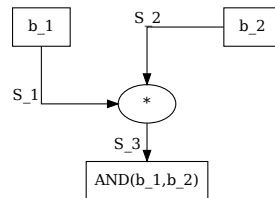
type_function BOOL(b : BOOL) -> F {
  let x : F ;
  let const c1 : F = 0 ;
  let const c2 : F = 1 ;
  let const c3 : F = -1 ;
  c1 <== MUL( b , ADD( c2 , MUL( b , c3 ) ) ) ;
  x <== b ;
  return x ;
}

```

In the setup phase of a statement, we compile every occurrence of a variable of boolean type into an instance of its associated boolean circuit.

The AND operator constraint system Given two field elements b_1 and b_2 from \mathbb{F} that are constrained to represent boolean variables, we want to find a circuit that computes the logical **and** operator $AND(b_1, b_2)$ as well as its associated R1CS that enforces $b_1, b_2, AND(b_1, b_2)$ to satisfy the constraint system if and only if $b_1 \wedge b_2 = AND(b_1, b_2)$ holds true.

The key insight here is that, given three boolean constraint variables b_1, b_2 and b_3 , the equation $b_1 \cdot b_2 = b_3$ is satisfied in \mathbb{F} if and only if the equation $b_1 \wedge b_2 = b_3$ is satisfied in boolean algebra. The logical operator \wedge is therefore implementable in \mathbb{F} by field multiplication of its arguments and the following circuit computes the \wedge operator in \mathbb{F} , assuming all inputs are restricted to be 0 or 1:



The associated Rank-1 Constraint System can be deduced from the general process 6.2.2 and consists of the following constraint:

$$S_1 \cdot S_2 = S_3 \quad (7.5)$$

Common circuit languages typically provide a gadget or a function to abstract over this circuit such that programers can use the \wedge operator without caring about the associated circuit. In PAPER, we define the following function that compiles to the \wedge -operator's circuit:

```

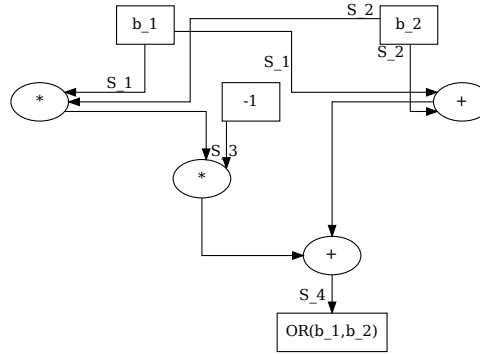
fn AND(b_1 : BOOL, b_2 : BOOL) -> BOOL{
  let AND : BOOL ;
  AND <== MUL( b_1 , b_2 ) ;
  return AND ;
}

```

In the setup phase of a statement, we compile every occurrence of the AND function into an instance of its associated \wedge -operator's circuit.

The OR operator constraint system Given two field elements b_1 and b_2 from \mathbb{F} that are constrained to represent boolean variables, we want to find a circuit that computes the logical **or** operator $OR(b_1, b_2)$ as well as its associated R1CS that enforces $b_1, b_2, OR(b_1, b_2)$ to satisfy the constraint system if and only if $b_1 \vee b_2 = OR(b_1, b_2)$ holds true.

Assuming that three variables b_1, b_2 and b_3 are boolean constraint, the equation $b_1 + b_2 - b_1 \cdot b_2 = b_3$ is satisfied in \mathbb{F} if and only if the equation $b_1 \vee b_2 = b_3$ is satisfied in boolean algebra. The logical operator \vee is therefore implementable in \mathbb{F} by the following circuit, assuming all inputs are restricted to be 0 or 1:



The associated Rank-1 Constraint System can be deduced from the general process 6.2.2 and consists of the following constraints:

$$\begin{aligned} S_1 \cdot S_2 &= S_3 \\ (S_1 + S_2 - S_3) \cdot 1 &= S_4 \end{aligned}$$

Common circuit languages typically provide a gadget or a function to abstract over this circuit such that programers can use the \vee operator without caring about the associated circuit. In PAPER, we define the following function that compiles to the \vee -operator's circuit:

```

5081 fn OR(b_1 : BOOL, b_2 : BOOL) -> BOOL {
5082   let OR : BOOL ;
5083   let const c1 : F = -1 ;
5084   OR <== ADD (ADD (b_1, b_2) , MUL (c1, MUL (b_1, b_2) ) ) ;
5085   return OR ;
5086 }
```

In the setup phase of a statement, we compile every occurrence of the OR function into an instance of its associated \vee -operator's circuit.

Exercise 92. Let \mathbb{F} be a finite field and let b_1 as well as b_2 two boolean constrained variables from \mathbb{F} . Show that the equation $OR(b_1, b_2) = 1 - (1 - b_1) \cdot (1 - b_2)$ holds true.

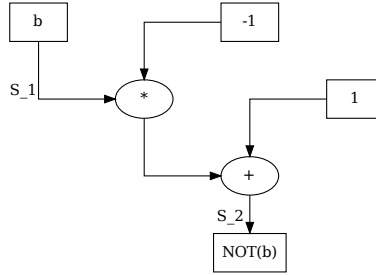
Use this equation to derive an algebraic circuit with ingoing variables b_1 and b_2 and outgoing variable $OR(b_1, b_2)$ such that b_1 and b_2 are boolean constrained and the circuit has a valid assignment, if and only if $OR(b_1, b_2) = b_1 \vee b_2$.

Use the technique from 6.2.2 to transform this circuit into a Rank-1 Constraint System and find its full solution set. Define a PAPER function that brain-compiles into the circuit.

The NOT operator constraint system Given a field element b from \mathbb{F} that is constrained to represent a boolean variable, we want to find a circuit that computes the logical **NOT** operator

5098 $NOT(b)$ as well as its associated R1CS that enforces $b, NOT(b)$ to satisfy the constraint system
 5099 if and only if $\neg b = NOT(b)$ holds true.

5100 Assuming that two variables b_1 and b_2 are boolean constrained, the equation $(1 - b_1) = b_2$
 5101 is satisfied in \mathbb{F} if and only if the equation $\neg b_1 = b_2$ is satisfied in boolean algebra. The logical
 5102 operator \neg is therefore implementable in \mathbb{F} by the following circuit, assuming all inputs are
 5103 restricted to be 0 or 1:



5104

The associated Rank-1 Constraint System can be deduced from the general process 6.2.2 and consists of the following constraints

$$(1 - S_1) \cdot 1 = S_2$$

5105 Common circuit languages typically provide a gadget or a function to abstract over this circuit
 5106 such that programers can use the \neg operator without caring about the associated circuit. In
 5107 PAPER, we define the following function that compiles to the \neg -operator's circuit:

```

5108 fn NOT(b : BOOL -> BOOL{
5109   let NOT : BOOL ;
5110   let const c1 = 1 ;
5111   let const c2 = -1 ;
5112   NOT <== ADD( c1 , MUL( c2 , b) ) ;
5113   return NOT ;
5114 }
```

5115 In the setup phase of a statement, we compile every occurrence of the NOT function into an
 5116 instance of its associated \neg -operator's circuit.

5117 *Exercise 93.* Let \mathbb{F} be a finite field. Derive algebraic circuits and associated Rank-1 Constraint
 5118 Systems for the following operators: NOR, XOR, NAND, EQU.

5119 **Modularity** As we have seen in chapter 6, both algebraic circuits and R1CS have a modularity
 5120 property, and as we have seen in this section, all basic boolean functions are expressible in
 5121 circuits. Combining those two properties shows that it is possible to express arbitrary boolean
 5122 functions as algebraic circuits.

5123 The expressiveness of algebraic circuits and therefore Rank-1 Constraint Systems is as gener-
 5124 al as the expressiveness of boolean circuits. An important implication is that the languages
 5125 $L_{R1CS-SAT}$ and $L_{Circuit-SAT}$ as defined in 6 and 6.2.2, are as general as the famous language
 5126 L_{3-SAT} , which is known to be \mathcal{NP} -complete.

5127 *Example 134.* To give an example of how a compiler might construct complex boolean ex-
 5128 pressions in algebraic circuits from simple ones and how we derive their associated Rank-1
 5129 Constraint Systems, let's look at the following PAPER statement:


```

5130 statement BOOLEAN_STAT {F: F_p} {
5131     fn main(b_1:BOOL,b_2:BOOL,b_3:BOOL,b_4:BOOL )-> BOOL {
5132         let pub b_5 : BOOL ;
5133         b_5 <== AND( OR( b_1 , b_2) , AND( b_3 , NOT( b_4) ) ) ;
5134         return b_5 ;
5135     } ;
5136 }

```

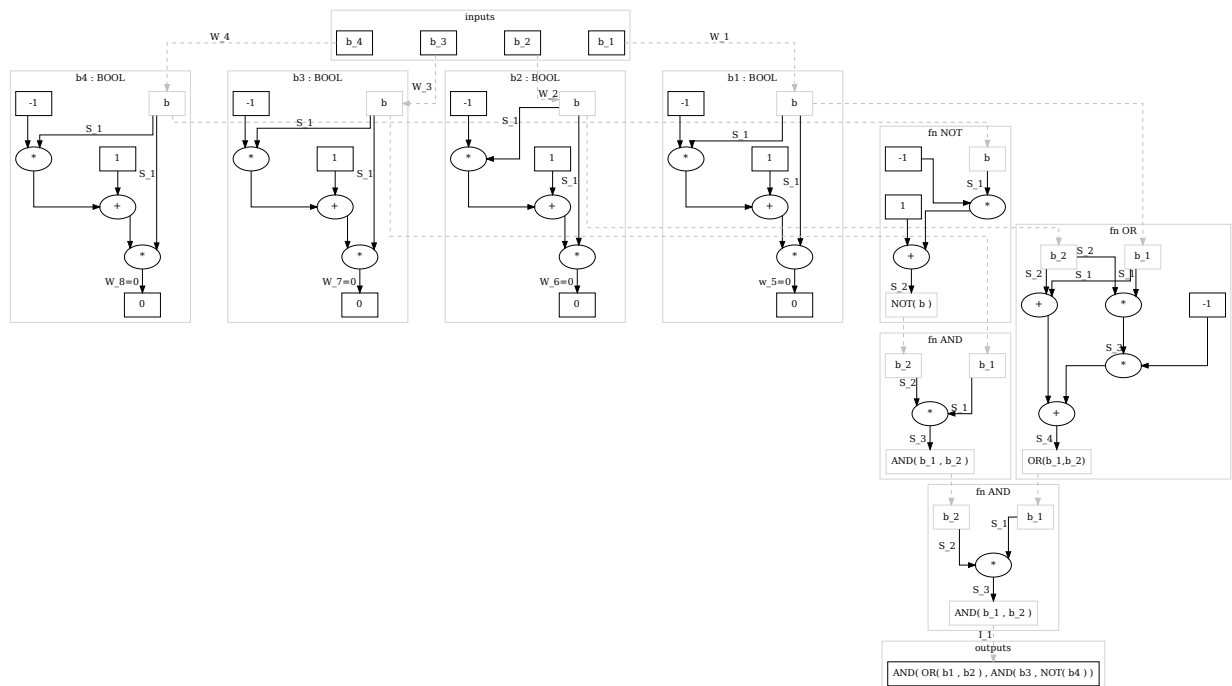
The code describes a circuit that takes four witness input variables b_1, b_2, b_3 and b_4 of boolean type and computes an instance variable output b_5 such that the following boolean expression holds true:

$$(b_1 \vee b_2) \wedge (b_3 \wedge \neg b_4) = b_5$$

During a setup-phase, a circuit compiler transforms this high-level language statement into a circuit and associated Rank-1 Constraint Systems and hence defines a language $L_{BOOLEAN\ STAT}$.

To see how this might be achieved, we use PAPER as an example to execute the setup-phase and compile `BOOLEAN_STAT` into a circuit. Taking the definition of the boolean constraint 7.2.1 as well as the definitions of the appropriate boolean operators into account, we get the following circuit:

5143



5144

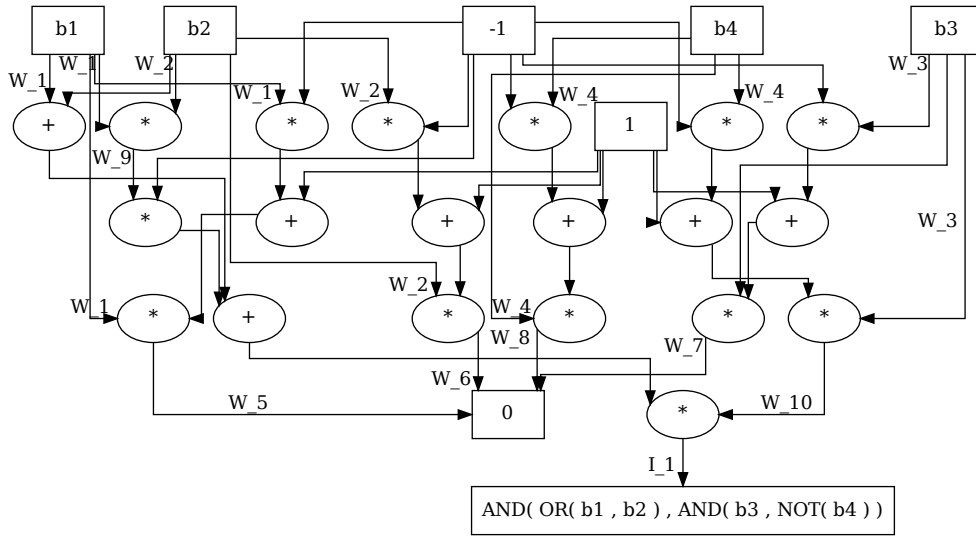
5145

5146

Simple optimization then collapses all box-nodes that are directly linked and all box nodes that represent the same constants. After relabeling the edges, the following circuit represents the circuit associated to the `BOOLEAN_STAT` statement:

5149

can we
rotate this
by 90° ?
Good
question.
IDK



5150

5151 Given some instance variable I_1 from \mathbb{F}_{13} , a valid assignment to this circuit consists of witness
 5152 variables W_1, W_2, W_3, W_4 from \mathbb{F}_{13} such that the equation $I_1 = (W_1 \vee W_2) \wedge (W_3 \wedge \neg W_4)$ holds
 5153 true. In addition, a valid assignment also has to contain witness variables W_5, W_6, W_7, W_8, W_9
 5154 and W_{10} , which can be derived from circuit execution. The variables W_5, \dots, W_8 ensure that the
 5155 first four witnesses are constrained to be either 0 or 1 but not any other field element, and the
 5156 others enforce the boolean operations in the expression.

To compute the associated R1CS, we can use the general method from 6.2.2 and look at every labeled outgoing edge not coming from a source node in the optimized circuit. We declare the edge going to the single output node as instance, and every other edge as witness. In this case we get:

$$\begin{aligned}
 W_5 : W_1 \cdot (1 - W_1) &= 0 && \text{boolean constraints} \\
 W_6 : W_2 \cdot (1 - W_2) &= 0 \\
 W_7 : W_3 \cdot (1 - W_3) &= 0 \\
 W_8 : W_4 \cdot (1 - W_4) &= 0 \\
 W_9 : W_1 \cdot W_2 &= W_9 && \text{first OR-operator constraint} \\
 W_{10} : W_3 \cdot (1 - W_4) &= W_{10} && \text{AND(.,NOT(.))-operator constraints} \\
 I_1 : (W_1 + W_2 - W_9) \cdot W_{10} &= I_1 && \text{AND-operator constraints}
 \end{aligned}$$

5157 The reason why this R1CS only contains a single constraint for the multiplication gate in the
 5158 OR-circuit, while the general definition 7.2.1 requires two constraints, is that the second con-
 5159 straint in ?? only appears because the final addition gate is connected to an output node. In this
 5160 case, however, the final addition gate from the OR-circuit is enforced in the left factor of the I_1
 5161 constraint. Something similar holds true for the negation circuit.

During a prover-phase, some public instance I_5 must be given. To compute a constructive proof for the statement of the associated languages with respect to instance I_5 , a prover has to find four boolean values W_1, W_2, W_3 and W_4 such that

$$(W_1 \vee W_2) \wedge (W_3 \wedge \neg W_4) = I_5$$

holds true. In our case neither the circuit nor the PAPER statement specifies how to find those values, and it is a problem that any prover has to solve outside of the circuit. This might or might not be true for other problems, too. In any case, once the prover found those values, they can execute the circuit to find a valid assignment.

To give a concrete example, let $I_1 = 1$ and assume $W_1 = 1$, $W_2 = 0$, $W_3 = 1$ and $W_4 = 0$. Since $(1 \vee 0) \wedge (1 \wedge \neg 0) = 1$, those values satisfy the problem and we can use them to execute the circuit. We get

$$\begin{aligned} W_5 &= W_1 \cdot (1 - W_1) = 0 \\ W_6 &= W_2 \cdot (1 - W_2) = 0 \\ W_7 &= W_3 \cdot (1 - W_3) = 0 \\ W_8 &= W_4 \cdot (1 - W_4) = 0 \\ W_9 &= W_1 \cdot W_2 = 0 \\ W_{10} &= W_3 \cdot (1 - W_4) = 1 \\ I_1 &= (W_1 + W_2 - W_9) \cdot W_{10} = 1 \end{aligned}$$

A constructive proof of knowledge of a witness, for instance, $I_1 = 1$, is therefore given by the string $\pi = \langle W_5, W_6, W_7, W_8, W_9, W_{10} \rangle = \langle 0, 0, 0, 0, 0, 1 \rangle$.

Arrays

The array type represents a fixed-size collection of elements of equal type, each selectable by one or more indices that can be computed at run time during program execution.

Arrays are a classical type, implemented by many higher programing languages that compile to circuits or Rank-1 Constraint Systems. However, most high-level circuit languages support **static** arrays, i.e., arrays whose length is known at compile time only.

The most common way to compile arrays to circuits is to transform any array of a given type τ and size N into N circuit variables of type τ . Arrays are therefore **syntactic sugar**, with the purpose to make code easier for humans to read, and write. In PAPER, we define the following array type_function:

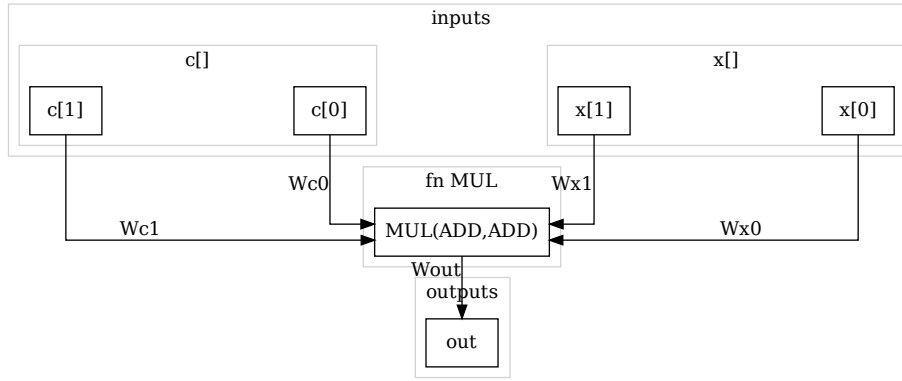
```
type_function <Name>: <Type>[N : unsigned] -> (Type, ...) {
  return (<Name>[0], ...)
}
```

In the setup phase of a statement, we compile every occurrence of an array of size N that contains elements of type Type into N variables of type Type .

Example 135. To give an intuition of how a real-world compiler might transform arrays into circuit variables, consider the following PAPER statement:

```
statement ARRAY_TYPE {F: F_5} {
  fn main(x: F[2]) -> F {
    let constant c: F[2] = [2, 4] ;
    let out : F <== MUL(ADD(x[1], c[0]), ADD(x[0], c[1])) ;
    return out ;
  } ;
}
```

During a setup phase, a circuit compiler might then replace any occurrence of the array type by a tuple of variables of the underlying type, and then use those variables in the circuit synthesis process instead. To see how this can be achieved, we use PAPER as an example. Abstracting over the sub-circuit of the computation, we get the following circuit:



5196

5197 The Unsigned Integer Type

5198 Unsigned integers of size N , where N is usually a power of two, represent non-negative integers
 5199 in the range $0 \dots 2^N - 1$. They have a notion of addition, subtraction and multiplication, defined
 5200 by modular 2^N arithmetics. If some N is given, we write uN for the associated type.

5201 **The uN Constraint System** Many high-level circuit languages define the various uN types as
 5202 arrays of size N , where each element is of boolean type. This parallels their representation on
 5203 common computer hardware and allows for efficient and straightforward definition of common
 5204 operators, like the various shift operators, or the logical operators.

5205 Assuming that some unsigned integer N is known at compile time in PAPER, we define
 5206 the following uN type_function, which casts a an unsigned integer into an array of boolean
 5207 variables:

```
5208 type_function uN -> BOOL[N] {
5209   let base2 : BOOL[N] ;
5210   base2[0] <== uN[0] ;
5211   base2[1] <== uN[1] ;
5212   ...
5213   base2[N] <== uN[N] ;
5214   return base2 ;
5215 }
```

To enforce an N -tuple of field elements $\langle b_0, \dots, b_{N-1} \rangle$ to represent an element of type uN we therefore need N boolean constraints

$$\begin{aligned}
 S_0 \cdot (1 - S_0) &= 0 \\
 S_1 \cdot (1 - S_1) &= 0 \\
 &\dots \\
 S_{N-1} \cdot (1 - S_{N-1}) &= 0
 \end{aligned}$$

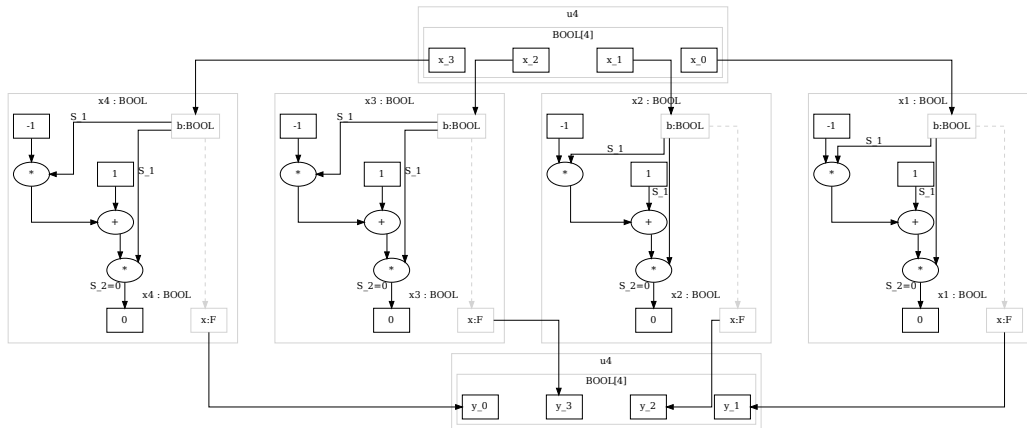
5216 *Remark 8.* Representing the uN type as boolean arrays is conceptually clean and works over
 5217 generic base fields. However, representing unsigned integers in this way requires a lot of space
 5218 as every bit is represented as a field element and if the base field is large, those field elements
 5219 require considerable space in hardware.

It should be noted that, in some cases, there is another, more space- and Constraint System efficient approach for representing unsigned integers that can be used whenever the underlying base field is sufficiently large. To understand this, recall that addition and multiplication in a prime field \mathbb{F}_p is equal to addition and multiplication of integers, as long as the sum or the product does exceed neither the modulus p of the base field nor the modulus 2^N of the unsigned integer type. Under those limitations it is possible to represent the uN type inside the base-field type whenever N is small enough. This however is not safe and care has to be taken to never overflow any of those moduli, or underflow 0.

Example 136. To give an intuition of how a real-world compiler might transform unsigned integers into circuit variables, consider the following PAPER statement, which implement the classical ring-shift operator on the u4 type as a circuit:

```
statement RING_SHIFT{F: F_p, N=4} {
  fn main(x: uN)-> uN {
    let y : uN ;
    y <== [x[1],x[2],x[3],x[0]] ;
    return y ;
  } ;
}
```

During the setup-phase, a circuit compiler might then replace any occurrence of the uN type by N variables of `boolean` type. Using the definition of booleans, each of these variables is then transformed into the `field` type and a boolean constraint system. To see how this can be achieved, we use PAPER as an example and get the following circuit:



During the prover phase, the function `main` is called with an actual input of u4 type, say $x=14$. The Prover then has to transform the decimal value 14 into its 4-bit binary representation $\text{Bits}(14)_2 = \langle 0, 1, 1, 1 \rangle$ outside of the circuit. Then the array of field values $x[4] = [0, 1, 1, 1]$ is used as an input to the circuit. Since all 4 field elements are either 0 or 1, the four boolean constraints are satisfied and the output is a ring shift of the input array of the four field elements given by $[1, 1, 1, 0]$, which represents the u4 element 7.

The Unsigned Integer Operators Since elements of uN type are represented as boolean arrays, shift operators are implemented in circuits simply by rewiring the boolean input variables to the output variables accordingly.

Logical operators, like AND, OR, or NOT are defined on the uN type by invoking the appropriate boolean operators bitwise to every bit in the boolean array that represents the uN element.

Addition and multiplication can be represented similarly to how machines represent those operations. Addition can be implemented by first defining the **full adder** circuit and then combining N of these circuits into a circuit that adds two elements from the uN type.

Exercise 94. Let $F = \mathbb{F}_{13}$ and $N=4$ be fixed and let x be of uN type. Define circuits and associated R1CS for the left and right bit-shift operators $x \ll 2$ as well as $x \gg 2$. Execute the associated circuit for $x : u4 = 11$ and generate a constructive proof for R1CS satisfyability.

Exercise 95. Let $F = \mathbb{F}_{13}$ and $N=2$ be fixed. Define a circuit and associated R1CS for the addition operator $ADD : uN \times uN \rightarrow uN$. Execute the associated circuit to compute $ADD(2, 7)$ for $2, 7 \in uN$.

Exercise 96. Execute the setup phase for the following PAPER code (That is brain compile the code into a circuit and derive the associated R1CS).

```
statement MASK_MERGE {F:F_5, N=4} {
  fn main(pub a : uN, pub b : uN) -> uN {
    let constant mask : uN = 10 ;
    let r : uN ;
    r <== XOR(a, AND(XOR(a, b), mask)) ;
    return r ;
  }
}
```

Let L_{mask_merge} be the language defined by the circuit. Provide a constructive knowledge proof in L_{mask_merge} for the instance $I = (I_a, I_b) = (14, 7)$.

7.2.2 Control Flow

Most programming languages of the imperative or functional style have some notion of basic control structures to direct the order in which instructions are evaluated. Contemporary circuit compilers usually provide a single thread of execution and provide basic flow constructs that implement control flow in circuits. In this part we look at some basic control flow constructions and their implementation in circuits.

The Conditional Assignment

Writing high-level code that compiles to circuits, it is often necessary to have a way for conditional assignment of values or computational output to variables. One way to realize this in many programming languages is in terms of the conditional ternary assignment operator $?:$ that branches the control flow of a program according to some condition and then assigns the output of the computed branch to some variable:

```
variable = condition ? value_if_true : value_if_false
```

In this description, *condition* is a boolean expression and *value_if_true* as well as *value_if_false* are expressions that evaluate to the same type as *variable*.

In programming languages like Rust, another way to write the conditional assignment operator that is more familiar to many programmers is given by

```
variable = if condition then {
  value_if_true
```

```

5294 } else {
5295     value_if_false
5296 }

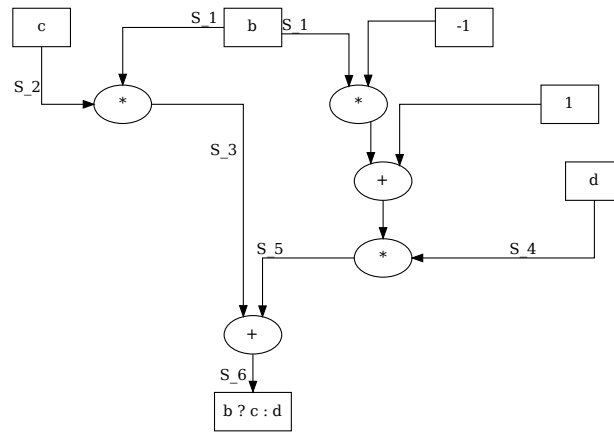
```

In most programming languages, it is a key property of the ternary assignment operator that the expression `value_if_true` is only evaluated if `condition` evaluates to true and the expression `value_if_false` is only evaluated if `condition` evaluates to false. In fact, computer programs would turn out to be very inefficient if the ternary operator would evaluate both expressions regardless of the value of `condition`.

A simple way to implement conditional assignment operator as a circuit can be achieved if the requirement that only one branch of the conditional operator is executed is dropped. To see that, let b , c and d be field elements such that b is boolean constrained. In this case, the following equation enforces a field element x to be the result of the conditional assignment operator:

$$x = b \cdot c + (1 - b) \cdot d \quad (7.6)$$

Expressing this equation in terms of the addition and multiplication operators from 7.2.1, we can flatten 7.6 into the following algebraic circuit:



5309

Note that, in order to compute a valid assignment to this circuit, both S_2 as well as S_4 are necessary. If the inputs to the nodes c and d are circuits themselves, both circuits need valid assignments and therefore have to be executed. As a consequence, this implementation of the conditional assignment operator has to execute all branches of all circuits, which is very different from the execution of common computer programs and contributes to the increased computational effort any prover has to invest, in contrast to the execution in other programming models.

We can use the general technique from 6.2.2 to derive the associated Rank-1 Constraint System of the conditional assignment operator. We get the following:

$$\begin{aligned}
 S_1 \cdot S_2 &= S_3 \\
 (1 - S_1) \cdot S_4 &= S_5 \\
 (S_3 + S_5) \cdot 1 &= S_6
 \end{aligned}$$

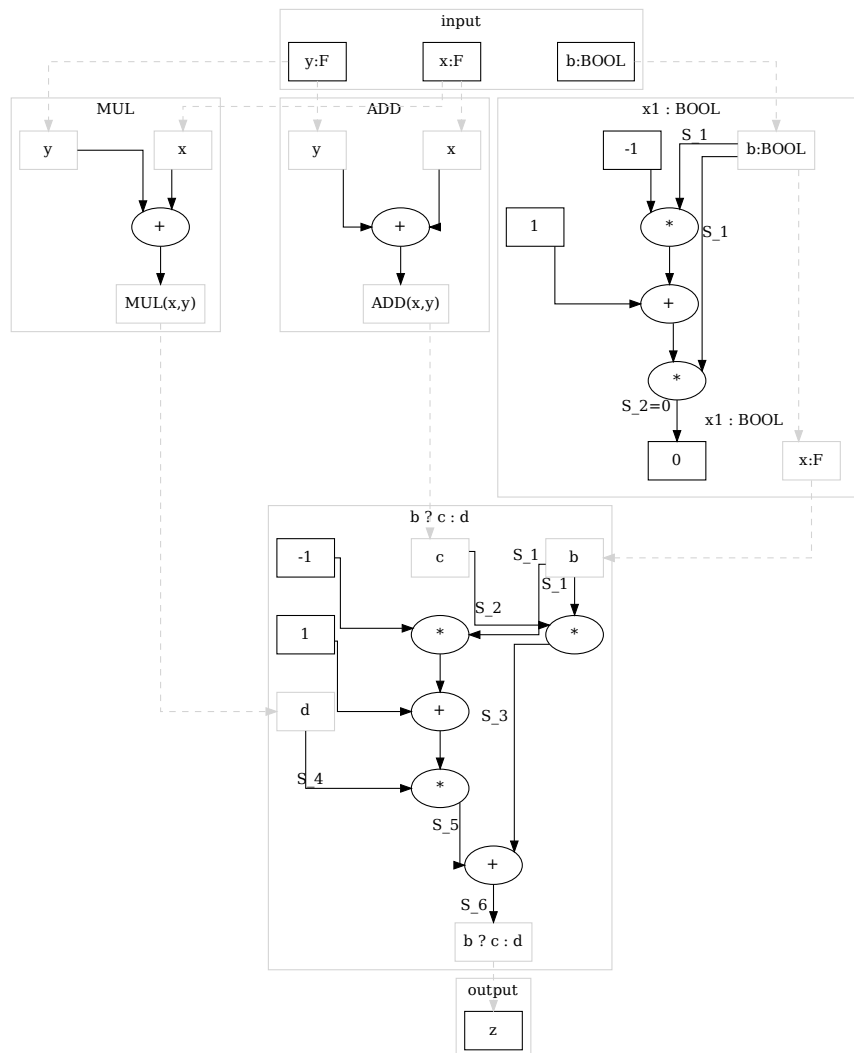
Example 137. To give an intuition of how a real-world circuit compiler might transform any high-level description of the conditional assignment operator into a circuit, consider the following PAPER code:

```

5320 statement CONDITIONAL_OP {F:F_p} {
5321     fn main(x : F, y : F, b : BOOL) -> F {
5322         let z : F
5323         z <== if b then {
5324             ADD(x,y)
5325         } else {
5326             MUL(x,y)
5327         } ;
5328         return z ;
5329     }
5330 }

```

Brain-compiling this code into a circuit, we first draw box nodes for all input and output variables, and then transform the boolean type into the field type together with its associated constraint. Then we evaluate the assignments to the output variables. Since the conditional assignment operator is the top level function, we draw its circuit and then draw the circuits for both conditional expressions. We get the following:



5336

Loops

In many programming languages, various loop control structures are defined that allow developers to execute expressions with a specified number of repetitions. In particular, it is often possible to implement unbounded loops like the loop structure give below:

```
while true do { }
```

In addition it is often possible to implement loop structures, where the number of execution steps in the loop depends on execution inputs or intermediate computational steps and is therefore unknown at compile time:

```
x = 0.5
while x != 0 do {
  x = 4*x*(1-x)
}
```

In contrast to this, algebraic circuits and Rank-1 Constraint Systems are not general enough to express arbitrary computation, but bounded computation only. As a consequence, it is not possible to implement unbounded loops, or loops with bounds that are unknown at compile time in those models. This can be easily seen since circuits are acyclic by definition, and implementing an unbounded loop as an acyclic graph requires a circuits of unbounded size. However, circuits are general enough to express bounded loops, where the upper bound on its execution is known at compile time. Those loop can be implemented in circuits by enrolling the loop.

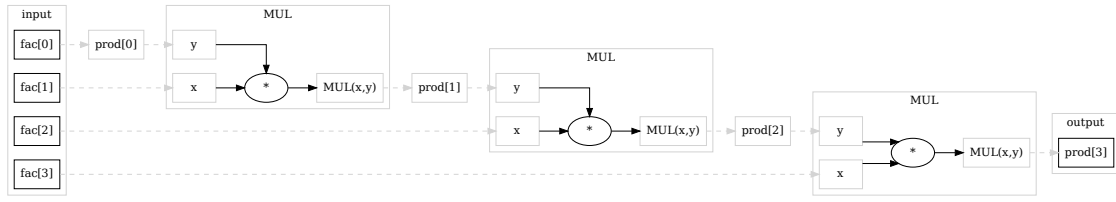
As a consequence, any programing language that compiles to algebraic circuits can only provide loop structures where the bound is a constant known at compile time. This implies that loops cannot depend on execution inputs, but on compile time parameters only.

Example 138. To give an intuition of how a real-world circuit compiler might transform any high-level description of a bounded `for` loop into a circuit, consider the following PAPER code:

```
statement FOR_LOOP {F:F_p, N: unsigned = 4} {
  fn main(fac : F[N]) -> F {
    let prod[N] : F ;
    prod[0] <== fac[0] ;
    for unsigned i in 1..N do [{
      prod[i] <== MUL(fac[i], prod[i-1]) ;
    }]
    return prod[N] ;
  }
}
```

Note that, in a program like this, the loop counter `i` has no expression in the derived circuit. It is a high level parameter that tells the compiler how to unroll the loop.

Brain-compiling this code into a circuit, we first draw box nodes for all input and output variables, noting that the loop counter is not represented in the circuit. Since all variables are of `field` type, we don't have to compile any type constraints. Then we evaluate the assignments to the output variables by unrolling the loop into 3 individual assignment operators. We get:



5379

7.2.3 Binary Field Representations

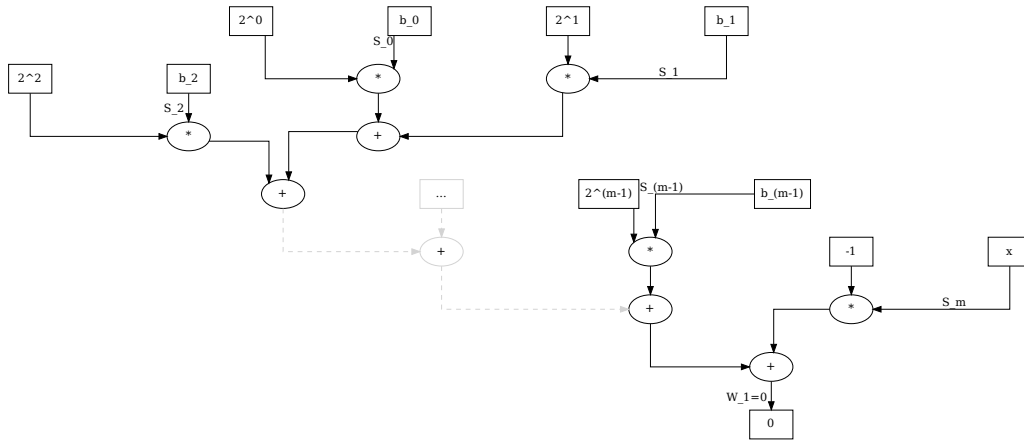
5380

5381 In applications, it is often necessary to enforce a binary representation of elements from the
 5382 field type. To derive an appropriate circuit over a prime field \mathbb{F}_p , let $m = |p|_2$ be the smallest
 5383 number of bits necessary to represent the prime modulus p . Then a bitstring $\langle b_0, \dots, b_{m-1} \rangle \in$
 5384 $\{0, 1\}^m$ is a binary representation of a field element $x \in \mathbb{F}_p$, if and only if

$$x = b_0 \cdot 2^0 + b_1 \cdot 2^1 + \dots + b_{m-1} \cdot 2^{m-1} \quad (7.7)$$

5385 In this expression, addition and exponentiation is considered to be executed in \mathbb{F}_p , which is well
 5386 defined since all terms 2^j for $0 \leq j < m$ are elements of \mathbb{F}_p . Note, however, that in contrast to
 5387 the binary representation of unsigned integers $n \in \mathbb{N}$, this representation is not unique in general,
 5388 since the modular p equivalence class might contain more than one binary representative.

5389 Considering that the underlying prime field is fixed and the most significant bit of the prime
 5390 modulus is m , the following circuit flattens equation 7.7, assuming all inputs b_1, \dots, b_m are of
 5391 boolean type.



5392

Applying the general transformation rule 6.2.2 to compute the associated Rank-1 Constraint Systems, we see that we actually only need a single constraint to enforce some binary representation of any field element. We get

$$(S_0 \cdot 2^0 + S_1 \cdot 2^1 + \dots + S_{m-1} \cdot 2^{m-1} - S_m) \cdot 1 = 0$$

5393 Given an array `BOOL[N]` of N boolean constrained field elements and another field element x ,
 5394 the circuit enforces `BOOL[N]` to be one of the binary representations of x . If `BOOL[N]` is not
 5395 a binary representation of x , no valid assignment and hence no solution to the associated R1CS
 5396 can exists.

Example 139. Consider the prime field \mathbb{F}_{13} . To compute binary representations of elements from that field, we start with the binary representation of the prime modulus 13, which is $\text{Bits}(13) = \langle 1, 0, 1, 1 \rangle$ since $13 = 1 \cdot 2^0 + 0 \cdot 2^1 + 1 \cdot 2^2 + 1 \cdot 2^3$. So $m = 4$ and we need up to 4 bits to represent any element $x \in \mathbb{F}_{13}$.

To see that binary representations are not unique in general, consider the element $2 \in \mathbb{F}_{13}$. It has the following two 4-bit, binary representations $\text{Bits}(2) = \langle 0, 1, 0, 0 \rangle$ and $\text{Bits}(2) = \langle 1, 1, 1, 1 \rangle$, since in \mathbb{F}_{13} we have

$$2 = \begin{cases} 0 \cdot 2^0 + 1 \cdot 2^1 + 0 \cdot 2^2 + 0 \cdot 2^3 \\ 1 \cdot 2^0 + 1 \cdot 2^1 + 1 \cdot 2^2 + 1 \cdot 2^3 \end{cases}$$

This is because the unsigned integers 2 and 15 are both in the modular 13 remainder class of 2 and hence are both representatives of 2 in \mathbb{F}_{13} .

To see how circuit the associated circuit works, we want to enforce the binary representation of $7 \in \mathbb{F}_{13}$. Since $m = 4$ we have to enforce a 4-bit representation for 7, which is $\langle 1, 1, 1, 0 \rangle$, since $7 = 1 \cdot 2^0 + 1 \cdot 2^1 + 1 \cdot 2^2 + 0 \cdot 2^3$. A valid circuit assignment is therefore given by $\langle S_0, S_1, S_2, S_3, S_4 \rangle = \langle 1, 1, 1, 0, 7 \rangle$ and, indeed, the assignment satisfies the required 5 constraints including the 4 boolean constraints for S_0, \dots, S_3 :

$$\begin{aligned} 1 \cdot (1 - 1) &= 0 & // \text{ boolean constraints} \\ 1 \cdot (1 - 1) &= 0 \\ 1 \cdot (1 - 1) &= 0 \\ 0 \cdot (1 - 0) &= 0 \\ (1 + 2 + 4 + 0 - 7) \cdot 1 &= 0 & // \text{ binary rep. constraint} \end{aligned}$$

7.2.4 Cryptographic Primitives

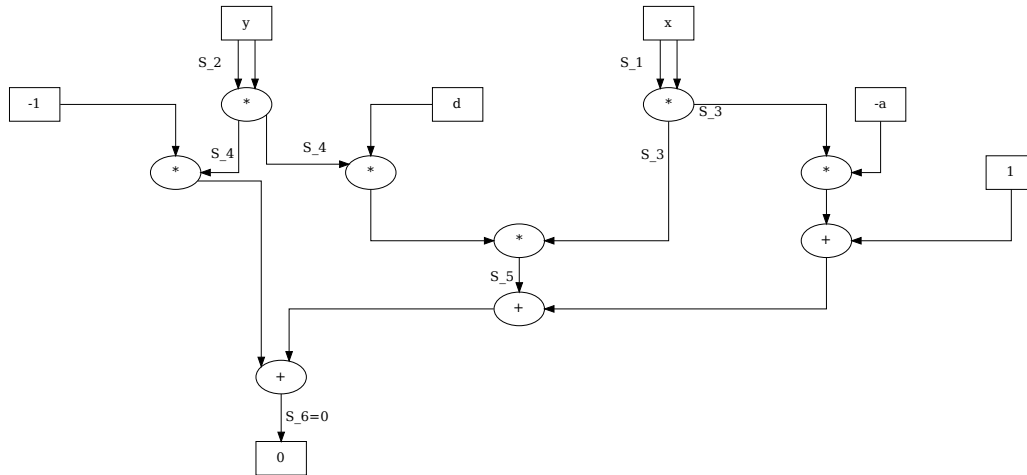
In applications, it is often required to do cryptography in a circuit. To do this, basic cryptographic primitives like hash functions or elliptic curve cryptography needs to be implemented as circuits. In this section, we give a few basic examples of how to implement such primitives.

Twisted Edwards curves

Implementing elliptic curve cryptography in circuits means to implement the defining curve equations as well as the algebraic operations, like the group law or the scalar multiplication as circuits. To do this efficiently, the curve must be defined over the same base field as the field that is used in the circuit.

For efficiency reasons, it is advantageous to choose an elliptic curve such that that all required constraints and operations can be implement with as few gates as possible. Twisted Edwards curves are particularly useful for that matter, since their group law is particularly simple and the same calculation can be used for all curve points including the point at infinity. This simplifies the circuit a lot.

Twisted Edwards curve constraints As we have seen in 5.3, a twisted Edwards curve over a finite field F is defined as the set of all pairs of points $(x, y) \in \mathbb{F} \times \mathbb{F}$ such that x and y satisfy the equation $a \cdot x^2 + y^2 = 1 + d \cdot x^2 y^2$ and as we have seen in example 121, we can transform this equation into the following circuit:



5421

The circuit enforces the two inputs of `field` type to satisfy the twisted Edwards curve equation and, as we know from example 126, the associated Rank-1 Constraint System is given by:

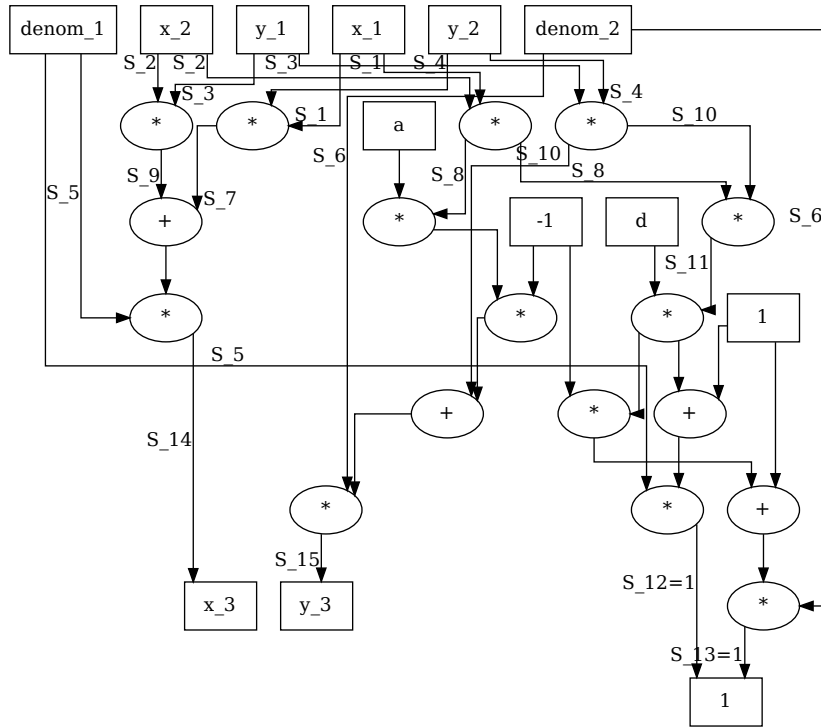
$$\begin{aligned}
 S_1 \cdot S_1 &= S_3 \\
 S_2 \cdot S_2 &= S_4 \\
 (S_4 \cdot d) \cdot S_3 &= S_5 \\
 (-1 \cdot S_4 + S_5 - a \cdot S_3 + 1) \cdot 1 &= 0
 \end{aligned}$$

5422 *Exercise 97.* Write the circuit and associated Rank-1 Constraint System for a Weierstrass curve
 5423 of a given field \mathbb{F} .

Twisted Edwards curve addition As we have seen in ??, a major advantage of twisted Edwards curves is the existence of an addition law that contains no branching and is valid for all curve points. Moreover, the neutral element is not given by any auxiliary symbol but the curve point $(0, 1)$. In fact, given two points (x_1, y_1) and (x_2, y_2) on a twisted Edwards curve, their sum is defined as

$$(x_3, y_3) = \left(\frac{x_1 y_2 + y_1 x_2}{1 + d \cdot x_1 x_2 y_1 y_2}, \frac{y_1 y_2 - a \cdot x_1 x_2}{1 - d \cdot x_1 x_2 y_1 y_2} \right)$$

5424 We can use the division circuit from ?? to flatten this equation into an algebraic circuit. In-
 5425 puts to the circuit are then not only the two curve points (x_1, y_1) and (x_2, y_2) , but also the
 5426 multiplicative inverses of the two denominators $inv_1 = (1 + d \cdot x_1 x_2 y_1 y_2)^{-1}$ as well as $inv_2 =$
 5427 $(1 - d \cdot x_1 x_2 y_1 y_2)^{-1}$, which any prover needs to compute outside of the circuit. We get



5428

Using the general technique from 6.2.2 to derive the associated Rank-1 Constraint System, we get the following result:

$$\begin{aligned}
 S_1 \cdot S_4 &= S_7 \\
 S_1 \cdot S_2 &= S_8 \\
 S_2 \cdot S_3 &= S_9 \\
 S_3 \cdot S_4 &= S_{10} \\
 S_8 \cdot S_{10} &= S_{11} \\
 S_5 \cdot (1 + d \cdot S_{11}) &= 1 \\
 S_6 \cdot (1 - d \cdot S_{11}) &= 1 \\
 S_5 \cdot (S_9 + S_7) &= S_{14} \\
 S_6 \cdot (S_{10} - a \cdot S_8) &= S_{15}
 \end{aligned}$$

5429 *Exercise 98.* Let \mathbb{F} be a field. Define a circuit that enforces field inversion for a point of a
 5430 twisted Edwards curve over \mathbb{F} .

5431 *Exercise 99.* Write the circuit and associated Rank-1 Constraint System for a Weierstrass addi-
 5432 tion law of a given field \mathbb{F} .

Chapter 8

Zero Knowledge Protocols

A so-called **zero-knowledge protocol** is a set of mathematical rules by which one party (usually called **the prover**) can convince another party (usually called **the verifier**) that a given statement is true, while not revealing any additional information apart from the truth of the statement.

As we have seen in chapter 6, given some language L and instance I , the knowledge claim “there is a witness W such that $(I; W)$ is a word in L ” is constructively provable by providing W to the verifier. However, the challenge for a zero-knowledge protocol is to prove knowledge of a witness without revealing any information beyond its bare existence.

add reference

In this chapter, we look at various systems that exist to solve this task. We start with an introduction to the basic concepts and terminology in zero-knowledge proving systems and then introduce the so-called Groth_16 protocol as one of the most efficient systems. We plan to update this chapter with new inventions in future versions of this book.

8.1 Proof Systems

From an abstract point of view, a proof system is a set of rules which models the generation and exchange of messages between two parties: a prover and a verifier. Its task is to ascertain whether a given string belongs to a formal language or not.

Proof systems are often classified by certain trust assumptions and the computational capabilities of both parties. In its most general form, the prover usually possesses unlimited computational resources but cannot be trusted, while the verifier has bounded computation power but is assumed to be honest.

Proving the membership statement for some string is executed by the generation of certain messages that are sent between prover and verifier, until the verifier is convinced that the string is an element of the language in consideration.

To be more specific, let Σ be an alphabet, and let L be a formal language defined over Σ . Then a **proof system** for language L is a pair of probabilistic interactive algorithms (P, V) , where P is called the **prover** and V is called the **verifier**.

Both algorithms are able to send messages to one another, and each algorithm has its own state, some shared initial state and access to the messages. The verifier is bounded to a number of steps which is polynomial in the size of the shared initial state, after which it stops and outputs either `accept` or `reject` indicating that it accepts or rejects a given string to be in L . In contrast, there are bounds on the computational power of the prover.

When the execution of the verifier algorithm stops the following conditions are required to hold:

- (Completeness) If the tuple $x \in \Sigma^*$ is a word in language L and both prover and verifier follow the protocol, the verifier outputs `accept`.
- (Soundness) If the tuple $x \in \Sigma^*$ is not a word in language L and the verifier follows the protocol, the verifier outputs `reject`, except with some small probability.

In addition, a proof system is called **zero-knowledge** if the verifier learns nothing about x other than $x \in L$.

The previous definition of proof systems is very general, and many subclasses of proving systems are known in the field. The type of languages that a proof system can support crucially depends on the abilities of the verifier (for example, whether it can make random choices) or on the nature and number of the messages that can be exchanged. If the system only requires to send a single message from the prover to the verifier, the proof system is called **non-interactive**, because no interaction other than sending the actual proof is required. In contrast, any other proof system is called **interactive**.

A proof system is usually called **succinct** if the size of the proof is shorter than the witness necessary to generate the proof. Moreover, a proof system is called **computationally sound** if soundness only holds under the assumption that the computational capabilities of the prover are polynomially bound. To distinguish general proofs from computationally sound proofs, the latter are often called **arguments**. Zero-knowledge, succinct, non-interactive arguments of knowledge claims are often abbreviated **zk-SNARKs**.

Example 140 (Constructive Proofs for Algebraic Circuits). To formalize our previous notion of constructive proofs for algebraic circuits, let \mathbb{F} be a finite field, and let $C(\mathbb{F})$ be an algebraic circuit over \mathbb{F} with associated language $L_{C(\mathbb{F})}$. A non-interactive proof system for $L_{C(\mathbb{F})}$ is given by the following two algorithms:

Given some instance I , the prover algorithm P uses its unlimited computational power to compute a witness W such that the pair $(I; W)$ is a valid assignment to $C(\mathbb{F})$ whenever the circuit is satisfiable for I . The prover then sends the constructive proof $(I; W)$ to the verifier.

On receiving a message $(I; W)$, the verifier algorithm V assigns the constructive proof $(I; W)$ to circuit $C(\mathbb{F})$, and decides whether the assignment is valid by executing all gates in the circuit. The runtime is polynomial in the number of gates. If the assignment is valid, the verifier returns `accepts`, if not, it returns `reject`.

To see that this proof system has the completeness and soundness properties, let $C(\mathbb{F})$ be a circuit of the field \mathbb{F} , and let I be an instance. The circuit may or may not have a witness W such that $(I; W)$ is a valid assignment to $C(\mathbb{F})$.

If no W exists, I is not part of any word in $L_{C(\mathbb{F})}$, and there is no way for P to generate a valid assignment. It follows that the verifier will not accept any claimed proof sent by P , which implies that the system has **soundness**.

If, on the other hand, W exists and P is honest, P can use its unlimited computational power to compute W and send $(I; W)$ to V , which V will accept in polynomial time. This implies that the system has **completeness**.

The system is non-interactive because the prover only sends a single message to the verifier, which contains the proof itself. Because in this simple system the witness itself is the proof, the proof system is **not** succinct.

8.2 The “Groth16” Protocol

In chapter 6, we have introduced algebraic [circuits, their associated rank-1 constraint systems](#) and their induced quadratic arithmetic programs. These models define formal languages, and

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associated memberships and knowledge claims can be constructively proofed by executing the circuit to compute a solution to its associated R1CS. The solution can then be transformed into a polynomial such that the polynomial is divisible by another polynomial if and only if the solution is correct.

In [\[1\]](#), Jens Groth provides a method that can transform those proofs into zero-knowledge succinct non-interactive arguments of knowledge. Assuming that the pairing groups $(\mathbb{G}_1, \mathbb{G}_2, \mathbb{G}_T, b)$ are given, the arguments are of constant size and consist of 2 elements from \mathbb{G}_1 and a single element from \mathbb{G}_2 , regardless of the size of the witness. They are zero-knowledge in the sense that the verifier learns nothing about the witness beside the fact that the instance-witness pair is a proper word in the language of the problem.

Verification is non-interactive and needs to compute a number of exponentiations proportional to the size of the instance, together with 3 group pairings in order to check a single equation.

The generated argument is perfectly zero-knowledge has perfect completeness and soundness in the generic bilinear group model, assuming the existence of a trusted third party that executes a preprocessing phase to generate a common reference string and a simulation trapdoor. This party must be trusted to delete the simulation trapdoor, since everyone in possession of it can simulate proofs.

To be more precise, let R be a rank-1 constraint system defined over some finite field \mathbb{F}_r . Then **Groth_16 parameters** for R are given by the following set:

$$\text{Groth_16} - \text{Param}(R) = (r, \mathbb{G}_1, \mathbb{G}_2, e(\cdot, \cdot), g_1, g_2) \quad (8.1)$$

In the equation above, \mathbb{G}_1 and \mathbb{G}_2 are finite cyclic groups of order r , g_1 is a generator of \mathbb{G}_1 , g_2 is a generator of \mathbb{G}_2 and $e : \mathbb{G}_1 \times \mathbb{G}_2 \rightarrow \mathbb{G}_T$ is a non-degenerate, bilinear pairing for some target group \mathbb{G}_T . In real-world applications, the parameter set is usually agreed on in advance.

Given some Groth_16 parameters, a **Groth_16 protocol** is then a quadruple of probabilistic polynomial algorithms (SETUP, PROVE, VFY, SIM) such that the following conditions hold:

- (Setup-Phase): $(CRS, \tau) \leftarrow \text{Setup}(R)$: Algorithm Setup takes the R1CS R as input and computes a common reference string CRS and a simulation trapdoor τ .
- (Prover-Phase): $\pi \leftarrow \text{Prove}(R, CRS, I, W)$: Given a constructive proof (I, W) for R , algorithm Prove takes the R1CS R , the common reference string CRS and the constructive proof (I, W) as input and computes an zk-SNARK π .
- Verify: $\{\text{accept}, \text{reject}\} \leftarrow \text{Vfy}(R, CRS, I, \pi)$: Algorithm Vfy takes the R1CS R , the common reference string CRS , the instance I and the zk-SNARK π as input and returns reject or accept.
- $\pi \leftarrow \text{Sim}(R, \tau, CRS, I)$: Algorithm Sim takes the R1CS R , the common reference string CRS , the simulation trapdoor τ and the instance I as input and returns a zk-SNARK π .

We will explain these algorithms together with detailed examples in the remainder of this section.

Assuming a trusted third party for the setup, the protocol is able to compute a zk-SNARK from a constructive proof for R , provided that r is sufficiently large, and, in particular, larger than the number of constraints in the associated R1CS.

Example 141 (The 3-Factorization Problem). Consider the 3-factorization problem from 111 and its associated algebraic circuit and rank-1 constraint system from 6.8. In this example,

we want to agree on a parameter set $(R, r, \mathbb{G}_1, \mathbb{G}_2, e(\cdot, \cdot), g_1, g_2)$ in order to use the Groth_16 protocol for our 3-factorization problem.

To find proper parameters, first observe that the circuit XXX, as well as its associated R1CS $R_{3, \text{fac_zk}}$ ex:3-factorization-r1cs and the derived QAP ??, are defined over the field \mathbb{F}_{13} . We therefore have $r = 13$ and need pairing groups \mathbb{G}_1 and \mathbb{G}_2 of order 13.

We know from 5.6.1 that the moon-math curve BLS6_6 has two subgroups $\mathbb{G}_1[13]$ and $\mathbb{G}_2[13]$, which are both of order 13. The associated Weil pairing b (5.50) is a proper bilinear map. We therefore choose those groups and the Weil pairing together with the generators $g_1 = (13, 15)$ and $g_2 = (7v^2, 16v^3)$ of $\mathbb{G}_1[13]$ and $\mathbb{G}_2[13]$, as a parameter:

$$\text{Groth_16} - \text{Param}(R_{3, \text{fac_zk}}) = (r, \mathbb{G}_1[13], \mathbb{G}_2[13], e(\cdot, \cdot), (13, 15), (7v^2, 16v^3))$$

It should be noted that our choice is not unique. Every pair of finite cyclic groups of order 13 that has a proper bilinear pairing qualifies as a Groth_16 parameter set. The situation is similar to real-world applications, where SNARKs with equivalent behavior are defined over different curves, used in different applications.

The Setup Phase To generate zk-SNARKs from constructive knowledge proofs in the Groth16 protocol, a preprocessing phase is required. This has to be executed a single time for every rank-1 constraint system and any associated quadratic arithmetic program. The outcome of this phase is a common reference string that prover and verifier need in order to generate and verify the zk-SNARK. In addition, a simulation trapdoor is produced that can be used to simulate proofs.

To be more precise, let L be a language defined by some rank-1 constraint system R such that a constructive proof of knowledge for an instance (I_1, \dots, I_n) in L consists of a witness (W_1, \dots, W_m) . Let $QAP(R) = \{T \in \mathbb{F}[x], \{A_j, B_j, C_j \in \mathbb{F}[x]\}_{j=0}^{n+m}\}$ be a quadratic arithmetic program associated to R , and let $\{\mathbb{G}_1, \mathbb{G}_2, e(\cdot, \cdot), g_1, g_2, \mathbb{F}_r\}$ be the set of Groth_16 parameters.

The setup phase then samples 5 random, **inverible** elements $\alpha, \beta, \gamma, \delta$ and s from the scalar field \mathbb{F}_r of the protocol and outputs the **simulation trapdoor** τ :

$$\tau = (\alpha, \beta, \gamma, \delta, s) \quad (8.2)$$

In addition, the setup phase uses those 5 random elements together with the two generators g_1 and g_2 and the quadratic arithmetic program to generate a **common reference string** $CRS_{QAP} = (CRS_{\mathbb{G}_1}, CRS_{\mathbb{G}_2})$ of language L :

$$CRS_{\mathbb{G}_1} = \left\{ g_1^\alpha, g_1^\beta, g_1^\delta, \left(g_1^{s^j}, \dots \right)_{j=0}^{\deg(T)-1}, \left(g_1^{\frac{\beta \cdot A_j(s) + \alpha \cdot B_j(s) + C_j(s)}{\gamma}}, \dots \right)_{j=0}^n \right\}$$

$$CRS_{\mathbb{G}_2} = \left\{ g_2^\beta, g_2^\gamma, g_2^\delta, \left(g_2^{s^j}, \dots \right)_{j=0}^{\deg(T)-1} \right\}$$

Common reference strings depend on the simulation trapdoor, and are therefore not unique to the problem. Any language can have more than one common reference string. The size of a common reference string is linear in the size of the instance and the size of the witness.

If a simulation trapdoor $\tau = (\alpha, \beta, \gamma, \delta, s)$ is given, we call the element s a **secret evaluation point** of the protocol, because if \mathbb{F}_r is the scalar field of the finite cyclic groups \mathbb{G}_1 and \mathbb{G}_2 , then

5579 a key feature of any common reference string is that it provides data to compute the evaluation
 5580 of any polynomial $P \in \mathbb{F}_r[x]$ of degree $\deg(P) < \deg(T)$ at the point s in the exponent of the
 5581 generator g_1 or g_2 , without knowing s .

To be more precise, let s be the secret evaluation point and let $P(x) = a_0 \cdot x^0 + a_1 \cdot x^1 + \dots + a_k \cdot x^k$ be a polynomial of degree $k < \deg(T)$ with coefficients in \mathbb{F}_r . Then we can compute $g_1^{P(s)}$ without knowing what the actual value of s is:

$$\begin{aligned} g_1^{P(s)} &= g_1^{a_0 \cdot s^0 + a_1 \cdot s^1 + \dots + a_k \cdot s^k} \\ &= g_1^{a_0 \cdot s^0} \cdot g_1^{a_1 \cdot s^1} \cdot \dots \cdot g_1^{a_k \cdot s^k} \\ &= \left(g_1^{s^0}\right)^{a_0} \cdot \left(g_1^{s^1}\right)^{a_1} \cdot \dots \cdot \left(g_1^{s^k}\right)^{a_k} \end{aligned}$$

5582 In this expression, all group points $g_1^{s^j}$ are part of the common reference string, hence, they can
 5583 be used to compute the result. The same holds true for the evaluation of $g_2^{P(s)}$, since the \mathbb{G}_2 part
 5584 of the common reference string contains the points $g_2^{s^j}$.

5585 In real-world applications, the simulation trapdoor is often called the **toxic waste** of the
 5586 setup-phase, while a common reference string is also-called the pair of **prover and verifier**
 5587 **key**.

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why

5588 In order to make the protocol secure, the setup needs to be executed in a way that guarantees
 5589 that the simulation trapdoor is deleted. Anyone in possession of it can generate arguments
 5590 without knowledge of a constructive proof. The most simple approach to achieving deletion of
 5591 the toxic waste is by a so-called **trusted third party**, where the trust assumption is that that
 5592 the party generates the common reference string precisely as defined and deletes the simulation
 5593 backdoor afterwards.

5594 However, as trusted third parties are not easy to find, more sophisticated protocols exist
 5595 in real-world applications. They execute the setup phase as a multi party computation, where
 5596 the proper execution can be publicly verified and the simulation trapdoor is deleted if at least
 5597 one participant deletes their individual contribution to the randomness. Each participant only
 5598 possesses a fraction of the simulation trapdoor, so it can only be recovered if all participants
 5599 collude and share their fraction.

Example 142 (The 3-factorization Problem). To see how the setup phase of a Groth_16 zk-SNARK can be computed, consider the 3-factorization problem from 111 and the parameters from page 195. As we have seen in ??, an associated quadratic arithmetic program is given as follows:

$$\begin{aligned} QAP(R_{3, fac_zk}) &= \{x^2 + x + 9, \\ &\quad \{0, 0, 6x + 10, 0, 0, 7x + 4\}, \{0, 0, 0, 6x + 10, 7x + 4, 0\}, \{0, 7x + 4, 0, 0, 0, 6x + 10\}\} \end{aligned}$$

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To transform this QAP into a common reference string, we choose the field elements $\alpha = 6$, $\beta = 5$, $\gamma = 4$, $\delta = 3$, $s = 2$ from \mathbb{F}_{13} . In real-world applications, it is important to sample those values randomly from the scalar field, but in our approach, we choose those non-random values to make them more memorizable, which helps in pen-and-paper computations. Our simulation trapdoor is then given as follows:

$$\tau = (6, 5, 4, 3, 2)$$

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5600 We keep this secret in order to simulate proofs later on, but we are careful though to hide τ
 5601 from anyone who hasn't read this book. Then we instantiate the common reference string XXX

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ence

5602 from those values. Since our groups are subgroups of the BLS_{6_6} elliptic curve, we use scalar
 5603 product notation instead of exponentiation.

To compute the \mathbb{G}_1 part of the common reference string, we use the logarithmic order of the group \mathbb{G}_1 XXX, the generator $g_1 = (13, 15)$, as well as the values from the simulation backdoor. Since $\deg(T) = 2$, we get the following:

add reference

$$\begin{aligned} [\alpha]_{g_1} &= [6](13, 15) = (27, 34) \\ [\beta]_{g_1} &= [5](13, 15) = (26, 34) \\ [\delta]_{g_1} &= [3](13, 15) = (38, 15) \end{aligned}$$

To compute the rest of the \mathbb{G}_1 part of the common reference string, we expand the indexed tuples and insert the secret random elements from the simulation backdoor. We get the following:

$$\begin{aligned} \left([s^j]_{g_1}, \dots \right)_{j=0}^1 &= \left([2^0](13, 15), [2^1](13, 15) \right) \\ &= \left((13, 15), (33, 34) \right) \\ \left(\left[\frac{\beta A_j(s) + \alpha B_j(s) + C_j(s)}{\gamma} \right]_{g_1}, \dots \right)_{j=0}^1 &= \left(\left[\frac{5A_0(2) + 6B_0(2) + C_0(2)}{4} \right](13, 15), \right. \\ &\quad \left. \left[\frac{5A_1(2) + 6B_1(2) + C_1(2)}{4} \right](13, 15) \right) \\ \left(\left[\frac{\beta A_{j+n}(s) + \alpha B_{j+n}(s) + C_{j+n}(s)}{\delta} \right]_{g_1}, \dots \right)_{j=1}^4 &= \left(\left[\frac{5A_2(2) + 6B_2(2) + C_2(2)}{3} \right](13, 15), \right. \\ &\quad \left[\frac{5A_3(2) + 6B_3(2) + C_3(2)}{3} \right](13, 15), \\ &\quad \left[\frac{5A_4(2) + 6B_4(2) + C_4(2)}{3} \right](13, 15), \\ &\quad \left. \left[\frac{5A_5(2) + 6B_5(2) + C_6(2)}{3} \right](13, 15) \right) \\ \left(\left[\frac{s^j \cdot T(s)}{\delta} \right]_{g_1} \right)_{j=0}^0 &= \left(\left[\frac{2^0 \cdot T(2)}{3} \right](13, 15) \right) \end{aligned}$$

To compute the curve points on the right side of these expressions, we need the polynomials from the associated quadratic arithmetic program and evaluate them on the secret point $s = 2$.

Since $4^{-1} = 10$ and $3^{-1} = 9$ in \mathbb{F}_{13} , we get the following:

$$\left[\frac{5A_0(2) + 6B_0(2) + C_0(2)}{4} \right](13, 15) = [(5 \cdot 0 + 6 \cdot 0 + 0) \cdot 10](13, 15) = [0](13, 15) =$$

\mathcal{O}

$$\left[\frac{5A_1(2) + 6B_1(2) + C_1(2)}{4} \right](13, 15) = [(5 \cdot 0 + 6 \cdot 0 + (7 \cdot 2 + 4)) \cdot 10](13, 15) = [11](13, 15) =$$

$(33, 9)$

$$\left[\frac{5A_2(2) + 6B_2(2) + C_2(2)}{3} \right](13, 15) = [(5 \cdot (6 \cdot 2 + 10) + 6 \cdot 0 + 0) \cdot 9](13, 15) = [2](13, 15) =$$

$(33, 34)$

$$\left[\frac{5A_3(2) + 6B_3(2) + C_3(2)}{3} \right](13, 15) = [(5 \cdot 0 + 6 \cdot (6 \cdot 2 + 10) + 0) \cdot 9](13, 15) = [5](13, 15) =$$

$(26, 34)$

$$\left[\frac{5A_4(2) + 6B_4(2) + C_4(2)}{3} \right](13, 15) = [(5 \cdot 0 + 6 \cdot (7 \cdot 2 + 4) + 0) \cdot 9](13, 15) = [10](13, 15) =$$

$(38, 28)$

$$\left[\frac{5A_5(2) + 6B_5(2) + C_5(2)}{3} \right](13, 15) = [(5 \cdot (7 \cdot 2 + 4) + 6 \cdot 0 + 0) \cdot 9](13, 15) = [4](13, 15) =$$

$(35, 28)$

$$\left[\frac{2^0 \cdot T(2)}{3} \right](13, 15) = [1 \cdot (2^2 + 2 + 9) \cdot 9](13, 15) = [5](13, 15) =$$

$(26, 34)$

Putting all those values together, we see that the \mathbb{G}_1 part of the common reference string is given by the following set of 12 points from the BLS_{6_6} 13-torsion group \mathbb{G}_1 :

$$CRS_{\mathbb{G}_1} = \left\{ \begin{array}{l} (27, 34), (26, 34), (38, 15), \left((13, 15), (33, 34) \right), \left(\mathcal{O}, (33, 9) \right) \\ \left((33, 34), (26, 34), (38, 28), (35, 28) \right), \left((26, 34) \right) \end{array} \right\}$$

To compute the \mathbb{G}_2 part of the common reference string, we use the logarithmic order of the group \mathbb{G}_2 XXX, the generator $g_2 = (7v^2, 16v^3)$, as well as the values from the simulation backdoor. Since $\deg(T) = 2$, we get the following:

$$[\beta]g_2 = [5](7v^2, 16v^3) = (16v^2, 28v^3)$$

$$[\gamma]g_2 = [4](7v^2, 16v^3) = (37v^2, 27v^3)$$

$$[\delta]g_2 = [3](7v^2, 16v^3) = (42v^2, 16v^3)$$

To compute the rest of the \mathbb{G}_2 part of the common reference string, we expand the indexed tuple and insert the secret random elements from the simulation backdoor. We get the following:

$$\begin{aligned} \left([s^j]g_2, \dots \right)_{j=0}^1 &= ([2^0](7v^2, 16v^3), [2^1](7v^2, 16v^3)) \\ &= ((7v^2, 16v^3), (10v^2, 28v^3)) \end{aligned}$$

Putting all these values together, we see that the \mathbb{G}_2 part of the common reference string is given by the following set of 5 points from the BLS_{6_6} 13-torsion group \mathbb{G}_2 :

$$CRS_{\mathbb{G}_2} = \left\{ (16v^2, 28v^3), (37v^2, 27v^3), (42v^2, 16v^3), (7v^2, 16v^3), (10v^2, 28v^3) \right\}$$

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Given the simulation trapdoor τ and the quadratic arithmetic program ??, the associated common reference string of the 3-factorization problem is as follows:

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$$\begin{aligned} CRS_{\mathbb{G}_1} &= \left\{ (27, 34), (26, 34), (38, 15), \left((13, 15), (33, 34) \right), \left(\mathcal{O}, (33, 9) \right) \right\} \\ &\quad \left\{ \left((33, 34), (26, 34), (38, 28), (35, 28) \right), \left((26, 34) \right) \right\} \\ CRS_{\mathbb{G}_2} &= \left\{ (16v^2, 28v^3), (37v^2, 27v^3), (42v^2, 16v^3), \left(7v^2, 16v^3 \right), (10v^2, 28v^3) \right\} \end{aligned}$$

We then publish this data to everyone who wants to participate in the generation of a zk-SNARK or its verification in the 3-factorization problem.

To understand how this common reference string can be used to evaluate polynomials at the secret evaluation point in the exponent of a generator, let's assume that we have deleted the simulation trapdoor. In that case, we have no way to know the secret evaluation point anymore, hence, we cannot evaluate polynomials at that point. However, we can evaluate polynomials of smaller degree than the degree of the target polynomial in the exponent of both generators at that point.

To see that, consider e.g. the polynomials $A_2(x) = 6x + 10$ and $A_5(x) = 7x + 4$ from the QAP of this problem. To evaluate these polynomials in the exponent of g_1 and g_2 at the secret point s without knowing the value of s (which is 2), we can use the common reference string and equation XXX. Using the scalar product notation instead of exponentiation, we get the following:

add refer-
ence

$$\begin{aligned} [A_2(s)]g_1 &= [6 \cdot s^1 + 10 \cdot s^0]g_1 \\ &= [6](33, 34) + [10](13, 15) & \# [s^0]g_1 = (13, 15), [s^1]g_1 = (33, 34) \\ &= [6 \cdot 2](13, 15) + [10](13, 15) = [9](13, 15) & \# \text{logarithmic order on } \mathbb{G}_1 \\ &= (35, 15) \\ [A_5(s)]g_1 &= [7 \cdot s^1 + 4 \cdot s^0]g_1 \\ &= [7](33, 34) + [4](13, 15) \\ &= [7 \cdot 2](13, 15) + [4](13, 15) = [5](13, 15) \\ &= (26, 34) \end{aligned}$$

Indeed, we are able to evaluate the polynomials in the exponent at a secret evaluation point, because that point is encrypted in the curve point $(33, 34)$ and its secrecy is protected by the discrete logarithm assumption. Of course, in our computation, we recovered the secret point $s = 2$, but that was only possible because we have a group of logarithmic order in order to simplify our pen-and-paper computations. Such an order is infeasible for computing in cryptographically secure curves. We can do the same computation on \mathbb{G}_2 and get the following:

$$\begin{aligned} [A_2(s)]g_2 &= [6 \cdot s^1 + 10 \cdot s^0]g_2 \\ &= [6](10v^2, 28v^3) + [10](7v^2, 16v^3) \\ &= [6 \cdot 2](7v^2, 16v^3) + [10](7v^2, 16v^3) = [9](7v^2, 16v^3) \\ &= (37v^2, 16v^3) \\ [A_5(s)]g_2 &= [7 \cdot s^1 + 4 \cdot s^0]g_2 \\ &= [7](10v^2, 28v^3) + [4](7v^2, 16v^3) \\ &= [7 \cdot 2](7v^2, 16v^3) + [4](7v^2, 16v^3) = [5](7v^2, 16v^3) \\ &= (16v^2, 28v^3) \end{aligned}$$

Apart from the target polynomial T , all other polynomials of the quadratic arithmetic program can be evaluated in the exponent this way.

The Prover Phase Given some rank-1 constraint system R and instance $I = (I_1, \dots, I_n)$, the task of the prover phase is to convince any verifier that a prover knows a witness W to instance I such that $(I; W)$ is a word in the language L_R of the system, without revealing anything about W .

To achieve this in the Groth_16 protocol, we assume that any prover has access to the rank-1 constraint system of the problem, in addition to some algorithm that tells the prover how to compute constructive proofs for the R1CS. In addition, the prover has access to a common reference string and its associated quadratic arithmetic program.

In order to generate a zk-SNARK for this instance, the prover first computes a valid constructive proof as explained in XXX, that is, the prover generates a proper witness $W = (W_1, \dots, W_m)$ such that $(I_1, \dots, I_n; W_1, \dots, W_m)$ is a solution to the rank-1 constraint system R .

The prover then uses the quadratic arithmetic program and computes the polynomial $P_{(I;W)}$, as explained in 6.15. They then divide $P_{(I;W)}$ by the target polynomial T of the quadratic arithmetic program. Since $P_{(I;W)}$ is constructed from a valid solution to the R1CS, we know from 6.15 that it is divisible by T . This implies that polynomial division of P by T generates another polynomial $H := P/T$, with $\deg(H) < \deg(T)$.

The prover then evaluates the polynomial $(H \cdot T)\delta^{-1}$ in the exponent of the generator g_1 at the secret point s , as explained in XXX. To see how this can be achieved, let $H(x)$ be the quotient polynomial P/T :

$$H(x) = H_0 \cdot x^0 + H_1 \cdot x^1 + \dots + H_k \cdot x^k \quad (8.3)$$

To evaluate $H \cdot T$ at s in the exponent of g_1 , the prover uses the common reference string and computes as follows:

$$g_1^{\frac{H(s) \cdot T(s)}{\delta}} = \left(g_1^{\frac{s^0 \cdot T(s)}{\delta}}\right)^{H_0} \cdot \left(g_1^{\frac{s^1 \cdot T(s)}{\delta}}\right)^{H_1} \dots \left(g_1^{\frac{s^k \cdot T(s)}{\delta}}\right)^{H_k}$$

After this has been done, the prover samples two random field elements $r, t \in \mathbb{F}_r$, and uses the common reference string, the instance variables I_1, \dots, I_n and the witness variables W_1, \dots, W_m to compute the following curve points:

$$\begin{aligned} g_1^W &= \left(g_1^{\frac{\beta \cdot A_{1+n}(s) + \alpha \cdot B_{1+n}(s) + C_{1+n}(s)}{\delta}}\right)^{W_1} \dots \left(g_1^{\frac{\beta \cdot A_{m+n}(s) + \alpha \cdot B_{m+n}(s) + C_{m+n}(s)}{\delta}}\right)^{W_m} \\ g_1^A &= g_1^\alpha \cdot g_1^{A_0(s)} \cdot \left(g_1^{A_1(s)}\right)^{I_1} \dots \left(g_1^{A_n(s)}\right)^{I_n} \cdot \left(g_1^{A_{n+1}(s)}\right)^{W_1} \dots \left(g_1^{A_{n+m}(s)}\right)^{W_m} \cdot \left(g_1^\delta\right)^r \\ g_1^B &= g_1^\beta \cdot g_1^{B_0(s)} \cdot \left(g_1^{B_1(s)}\right)^{I_1} \dots \left(g_1^{B_n(s)}\right)^{I_n} \cdot \left(g_1^{B_{n+1}(s)}\right)^{W_1} \dots \left(g_1^{B_{n+m}(s)}\right)^{W_m} \cdot \left(g_1^\delta\right)^t \\ g_2^B &= g_2^\beta \cdot g_2^{B_0(s)} \cdot \left(g_2^{B_1(s)}\right)^{I_1} \dots \left(g_2^{B_n(s)}\right)^{I_n} \cdot \left(g_2^{B_{n+1}(s)}\right)^{W_1} \dots \left(g_2^{B_{n+m}(s)}\right)^{W_m} \cdot \left(g_2^\delta\right)^t \\ g_1^C &= g_1^W \cdot g_1^{\frac{H(s) \cdot T(s)}{\delta}} \cdot \left(g_1^A\right)^t \cdot \left(g_1^B\right)^r \cdot \left(g_1^\delta\right)^{-r \cdot t} \end{aligned}$$

In this computation, the group elements $g_1^{A_j(s)}$, $g_1^{B_j(s)}$ and $g_2^{B_j(s)}$ can be derived from the common reference string and the quadratic arithmetic program of the problem, as we have seen in XXX. In fact, those points only have to be computed once, and can be published and reused

for multiple proof generations because they are the same for all instances and witnesses. All other group elements are part of the common reference string.

After all these computations have been done, a valid zero-knowledge succinct non-interactive argument of knowledge π in the Groth_16 protocol is given by the following three curve points:

$$\pi = (g_1^A, g_1^C, g_2^B) \quad (8.4)$$

As we can see, a Groth_16 zk-SNARK consists of 3 curve points, two points from \mathbb{G}_1 and 1 point from \mathbb{G}_2 . The argument is specifically designed this way because, in typical applications, \mathbb{G}_1 is a torsion group of an elliptic curve over some prime field, while \mathbb{G}_2 is a subgroup of a torsion group over an extension field. Elements from \mathbb{G}_1 therefore need less space to be stored, and computations in \mathbb{G}_1 are typically faster than in \mathbb{G}_2 .

Since the witness is encoded in the exponent of a generator of a cryptographically secure elliptic curve, it is hidden from anyone but the prover. Moreover, since any proof is randomized by the occurrence of the random field elements r and t , proofs are not unique to any given witness. This is an important feature because, if all proofs for the same witness would be the same, knowledge of a witness would destroy the zero-knowledge property of those proofs.

Example 143 (The 3-factorization Problem). To see how a prover might compute a zk-SNARK, consider the 3-factorization problem from 111, our protocol parameters from XXX as well as the common reference string from XXX.

Our task is to compute a zk-SNARK for the instance $I_1 = 11$ and its constructive proof $(W_1, W_2, W_3, W_4) = (2, 3, 4, 6)$ as computed in XXX. As we know from 6.15, the associated polynomial $P_{(I;W)}$ of the quadratic arithmetic program from XXX is given by the following equation:

$$P_{(I;W)} = x^2 + x + 9$$

Since $P_{(I;W)}$ is identical to the target polynomial $T(x) = x^2 + x + 9$ in this example, we know from XXX that the quotient polynomial $H = P/T$ is the constant degree 0 polynomial:

$$H(x) = H_0 \cdot x^0 = 1 \cdot x^0$$

We therefore use $[\frac{s^0 \cdot T(s)}{\delta}]_{g_1} = (26, 34)$ from our common reference string XXX of the 3-factorization problem and compute as follows:

$$\begin{aligned} [\frac{H(s) \cdot T(s)}{\delta}]_{g_1} &= [H_0](26, 34) = [1](26, 34) \\ &= (26, 34) \end{aligned}$$

In the next step, we have to compute all group elements required for a proper Groth16 zk-SNARK. We start with g_1^W . Using scalar products instead of the exponential notation, and \oplus for the group law on the BLS6_6 curve, we have to compute the point $[W]g_1$:

$$\begin{aligned} [W]g_1 &= [W_1]g_1 \oplus [W_2]g_1 \oplus [W_3]g_1 \oplus [W_4]g_1 \\ &= [\frac{\beta \cdot A_2(s) + \alpha \cdot B_2(s) + C_2(s)}{\delta}]_{g_1} \oplus [\frac{\beta \cdot A_3(s) + \alpha \cdot B_3(s) + C_3(s)}{\delta}]_{g_1} \oplus [\frac{\beta \cdot A_4(s) + \alpha \cdot B_4(s) + C_4(s)}{\delta}]_{g_1} \\ &\quad \oplus [\frac{\beta \cdot A_5(s) + \alpha \cdot B_5(s) + C_5(s)}{\delta}]_{g_1} \end{aligned}$$

To compute this point, we have to remember that a prover should not be in possession of the simulation trapdoor, hence, they do not know what α , β , δ and s are. In order to compute this group element, the prover therefore needs the common reference string. Using the logarithmic order from XXX and the witness, we get the following:

$$\begin{aligned}
[W]g_1 &= [2](33, 34) \oplus [3](26, 34) \oplus [4](38, 28) \oplus [6](35, 28) \\
&= [2 \cdot 2](13, 15) \oplus [3 \cdot 5](13, 15) \oplus [4 \cdot 10](13, 15) \oplus [6 \cdot 4](13, 15) \\
&= [2 \cdot 2 + 3 \cdot 5 + 4 \cdot 10 + 6 \cdot 4](13, 15) = [5](13, 15) \\
&= (26, 34)
\end{aligned}$$

5657 In a next step, we compute g_1^A . We sample the random point $r = 11$ from \mathbb{F}_{13} , using scalar
 5658 products instead of the exponential notation, and \oplus for the group law on the BLS6_6 curve.
 5659 We then have to compute the following expression:

$$\begin{aligned}
[A]g_1 &= [\alpha]g_1 \oplus [A_0(s)]g_1 \oplus [I_1][A_1(s)]g_1 \oplus [W_1][A_2(s)]g_1 \oplus [W_2][A_3(s)]g_1 \\
&\quad \oplus [W_3][A_4(s)]g_1 \oplus [W_4][A_5(s)]g_1 \oplus [r][\delta]g_1
\end{aligned}$$

Since we don't know what α , δ and s are, we look up $[\alpha]g_1$ and $[\delta]g_1$ from the common reference string. Recall from XXX that we can evaluate $[A_j(s)]g_1$ without knowing the secret evaluation point s . According to XXX, we have $[A_2(s)]g_1 = (35, 15)$, $[A_5(s)]g_1 = (26, 34)$ and $[A_j(s)]g_1 = \mathcal{O}$ for all other indices $0 \leq j \leq 5$. Since \mathcal{O} is the neutral element on \mathbb{G}_1 , we get the following:

$$\begin{aligned}
[A]g_1 &= (27, 34) \oplus \mathcal{O} \oplus [11]\mathcal{O} \oplus [2](35, 15) \oplus [3]\mathcal{O} \oplus [4]\mathcal{O} \oplus [6](26, 34) \oplus [11](38, 15) \\
&= (27, 34) \oplus [2](35, 15) \oplus [6](26, 34) \oplus [11](38, 15) \\
&= [6](13, 15) \oplus [2 \cdot 9](13, 15) \oplus [6 \cdot 5](13, 15) \oplus [11 \cdot 3](13, 15) \\
&= [6 + 2 \cdot 9 + 6 \cdot 5 + 11 \cdot 3](13, 15) = [9](13, 15) \\
&= (35, 15)
\end{aligned}$$

5660 In order to compute the two curve points $[B]g_1$ and $[B]g_2$, we sample another random element
 5661 $t = 4$ from \mathbb{F}_{13} . Using the scalar product instead of the exponential notation, and \oplus for the group
 5662 law on the BLS6_6 curve, we have to compute the following expressions:

$$\begin{aligned}
[B]g_1 &= [\beta]g_1 \oplus [B_0(s)]g_1 \oplus [I_1][B_1(s)]g_1 \oplus [W_1][B_2(s)]g_1 \oplus [W_2][B_3(s)]g_1 \\
&\quad \oplus [W_3][B_4(s)]g_1 \oplus [W_4][B_5(s)]g_1 \oplus [t][\delta]g_1 \\
[B]g_2 &= [\beta]g_2 \oplus [B_0(s)]g_2 \oplus [I_1][B_1(s)]g_2 \oplus [W_1][B_2(s)]g_2 \oplus [W_2][B_3(s)]g_2 \\
&\quad \oplus [W_3][B_4(s)]g_2 \oplus [W_4][B_5(s)]g_2 \oplus [t][\delta]g_2
\end{aligned}$$

Since we don't know what β , δ and s are, we look up the associated group elements from the common reference string. Recall from XXX that we can evaluate $[B_j(s)]g_1$ without knowing the secret evaluation point s . Since $B_3 = A_2$ and $B_4 = A_5$, we have $[B_3(s)]g_1 = (35, 15)$, $[B_4(s)]g_1 = (26, 34)$ according to XXX, and $[B_j(s)]g_1 = \mathcal{O}$ for all other indices $0 \leq j \leq 5$. Since \mathcal{O} is the neutral element on \mathbb{G}_1 , we get the following:

$$\begin{aligned}
[B]g_1 &= (26, 34) \oplus \mathcal{O} \oplus [11]\mathcal{O} \oplus [2]\mathcal{O} \oplus [3](35, 15) \oplus [4](26, 34) \oplus [6]\mathcal{O} \oplus [4](38, 15) \\
&= (26, 34) \oplus [3](35, 15) \oplus [4](26, 34) \oplus [4](38, 15) \\
&= [5](13, 15) \oplus [3 \cdot 9](13, 15) \oplus [4 \cdot 5](13, 15) \oplus [4 \cdot 3](13, 15) \\
&= [5 + 3 \cdot 9 + 4 \cdot 5 + 4 \cdot 3](13, 15) = [12](13, 15) \\
&= (13, 28)
\end{aligned}$$

$$\begin{aligned}
 [B]g_2 &= (16v^2, 28v^3) \oplus \mathcal{O} \oplus [11]\mathcal{O} \oplus [2]\mathcal{O} \oplus [3](37v^2, 16v^3) \oplus [4](16v^2, 28v^3) \oplus [6]\mathcal{O} \oplus [4](42v^2, 16v^3) \\
 &= (16v^2, 28v^3) \oplus [3](37v^2, 16v^3) \oplus [4](16v^2, 28v^3) \oplus [4](42v^2, 16v^3) \\
 &= [5](7v^2, 16v^3) \oplus [3 \cdot 9](7v^2, 16v^3) \oplus [4 \cdot 5](7v^2, 16v^3) \oplus [4 \cdot 3](7v^2, 16v^3) \\
 &= [5 + 3 \cdot 9 + 4 \cdot 5 + 4 \cdot 3](7v^2, 16v^3) = [12](7v^2 + 16v^3) \\
 &= (7v^2, 27v^3)
 \end{aligned}$$

In a last step, we combine the previous computations to compute the point $[C]g_1$ in the group \mathbb{G}_1 as follows:

$$\begin{aligned}
 [C]g_1 &= [W]g_1 \oplus \left[\frac{H(s) \cdot T(s)}{\delta} \right]g_1 \oplus [t][A]g_1 \oplus [r][B]g_1 \oplus [-r \cdot t][\delta]g_1 \\
 &= (26, 34) \oplus (26, 34) \oplus [4](35, 15) \oplus [11](13, 28) \oplus [-11 \cdot 4](38, 15) \\
 &= [5](13, 15) \oplus [5](13, 15) \oplus [4 \cdot 9](13, 15) \oplus [11 \cdot 12](13, 15) \oplus [-11 \cdot 4 \cdot 3](13, 15) \\
 &= [5 + 5 + 4 \cdot 9 + 11 \cdot 12 - 11 \cdot 4 \cdot 3](13, 15) = [7](13, 15) \\
 &= (27, 9)
 \end{aligned}$$

Given the instance $I_1 = 11$, we can now combine these computations and see that the following 3 curve points are a zk-SNARK for the witness $(W_1, W_2, W_3, W_4) = (2, 3, 4, 6)$:

$$\pi = ((35, 15), (27, 9), (7v^2, 27v^3))$$

We can now publish this zk-SNARK, or send it to a designated verifier. Note that, if we had sampled different values for r and t , we would have computed a different SNARK for the same witness. The SNARK, therefore, hides the witness perfectly, which means that it is impossible to reconstruct the witness from the SNARK.

The Verification Phase Given some rank-1 constraint system R , instance $I = (I_1, \dots, I_n)$ and zk-SNARK π , the task of the verification phase is to check that π is indeed an argument for a constructive proof. Assuming that the simulation trapdoor does not exist anymore and the verification checks the proof, the verifier can be convinced that someone knows a witness $W = (W_1, \dots, W_m)$ such that $(I; W)$ is a word in the language of R .

To achieve this in the Groth16 protocol, we assume that any verifier is able to compute the pairing map $e(\cdot, \cdot)$ efficiently, and has access to the common reference string used to produce the SNARK π . In order to verify the SNARK with respect to the instance (I_1, \dots, I_n) , the verifier computes the following curve point:

$$g_1^I = \left(g_1^{\frac{\beta \cdot A_0(s) + \alpha \cdot B_0(s) + C_0(s)}{\gamma}} \right) \cdot \left(g_1^{\frac{\beta \cdot A_1(s) + \alpha \cdot B_1(s) + C_1(s)}{\gamma}} \right)^{I_1} \cdots \left(g_1^{\frac{\beta \cdot A_n(s) + \alpha \cdot B_n(s) + C_n(s)}{\gamma}} \right)^{I_n}$$

With this group element, the verifier is able to verify the SNARK $\pi = (g_1^A, g_1^C, g_2^B)$ by checking the following equation using the pairing map:

$$e(g_1^A, g_2^B) = e(g_1^\alpha, g_2^\beta) \cdot e(g_1^I, g_2^\gamma) \cdot e(g_1^C, g_2^\delta) \quad (8.5)$$

If the equation holds true, the SNARK is accepted. If the equation does not hold, the SNARK is rejected.

Remark 9. We know from chapter 5 that computing pairings in cryptographically secure pairing groups is computationally expensive. As we can see, in the Groth16 protocol, 3 pairings are required to verify the SNARK, because the pairing $e(g_1^\alpha, g_2^\beta)$ is independent of the proof, meaning that can be computed once and then stored as an amendment to the verifier key.

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In [?], the author showed that 2 is the minimal amount of pairings that any protocol with similar properties has to use. This protocol is therefore close to the theoretical minimum. In the same paper, the author outlined an adaptation that only uses 2 pairings. However, that reduction comes with the price of much more overhead computation. Having 3 pairings is therefore a compromise that gives the overall best performance. To date, the Groth16 protocol is the most efficient in its class.

Example 144 (The 3-factorization Problem). To see how a verifier might check a zk-SNARK for some given instance I , consider the 3-factorization problem from 111, our protocol parameters from XXX, the common reference string from XXX as well as the zk-SNARK $\pi = ((35, 15), (27, 9), (7v^2, 27v^3))$, which claims to be an argument of knowledge for a witness for the instance $I_1 = 11$.

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In order to verify the zk-SNARK for that instance, we first compute the curve point g_1^I . Using scalar products instead of the exponential notation, and \oplus for the group law on the BLS6_6 curve, we have to compute the point $[I]g_1$ as follows:

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$$[I]g_1 = \left[\frac{\beta \cdot A_0(s) + \alpha \cdot B_0(s) + C_0(s)}{\gamma} \right]_{g_1} \oplus [I_1] \left[\frac{\beta \cdot A_1(s) + \alpha \cdot B_1(s) + C_1(s)}{\gamma} \right]_{g_1}$$

To compute this point, we have to remember that a verifier should not be in possession of the simulation trapdoor, which means that they do not know what α , β , γ and s are. In order to compute this group element, the verifier therefore needs the common reference string. Using the logarithmic order from XXX and instance I_1 , we get the following:

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$$\begin{aligned} [I]g_1 &= \left[\frac{\beta \cdot A_0(s) + \alpha \cdot B_0(s) + C_0(s)}{\gamma} \right]_{g_1} \oplus [I_1] \left[\frac{\beta \cdot A_1(s) + \alpha \cdot B_1(s) + C_1(s)}{\gamma} \right]_{g_1} \\ &= \mathcal{O} \oplus [11](33, 9) \\ &= [11 \cdot 11](13, 15) = [4](13, 15) \\ &= (35, 28) \end{aligned}$$

In the next step, we have to compute all the pairings involved in equation XXX. Using the logarithmic order on \mathbb{G}_1 and \mathbb{G}_2 as well as the bilinearity property of the pairing map we get the following:

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$$\begin{aligned}
e([A]_{g_1}, [B]_{g_2}) &= e((35, 15), (7v^2, 27v^3)) = e([9](13, 15), [12](7v^2, 16v^3)) \\
&= e((13, 15), (7v^2, 16v^3))^{9 \cdot 12} \\
&= e((13, 15), (7v^2, 16v^3))^{108} \\
e([\alpha]_{g_1}, [\beta]_{g_2}) &= e((27, 34), (16v^2, 28v^3)) = e([6](13, 15), [5](7v^2, 16v^3)) \\
&= e((13, 15), (7v^2, 16v^3))^{6 \cdot 5} \\
&= e((13, 15), (7v^2, 16v^3))^{30} \\
e([I]_{g_1}, [\gamma]_{g_2}) &= e((35, 28), (37v^2, 27v^3)) = e([4](13, 15), [4](7v^2, 16v^3)) \\
&= e((13, 15), (7v^2, 16v^3))^{4 \cdot 4} \\
&= e((13, 15), (7v^2, 16v^3))^{16} \\
e([C]_{g_1}, [\delta]_{g_2}) &= e((27, 9), (42v^2, 16v^3)) = e([7](13, 15), [3](7v^2, 16v^3)) \\
&= e((13, 15), (7v^2, 16v^3))^{7 \cdot 3} \\
&= e((13, 15), (7v^2, 16v^3))^{21}
\end{aligned}$$

5701 In order to check equation XXX, observe that the target group \mathbb{G}_T of the Weil pairing is
5702 a finite cyclic group of order 13. Exponentiation is therefore done in modular 13 arithmetics.
5703 Accordingly, since $108 \bmod 13 = 4$, we evaluate the left side of equation XXX as follows:

$$e([A]_{g_1}, [B]_{g_2}) = e((13, 15), (7v^2, 16v^3))^{108} = e((13, 15), (7v^2, 16v^3))^4$$

5704 Similarly, we evaluate the right side of equation XXX using modular 13 arithmetics and the
5705 exponential law $a^x \cdot a^y = a^{x+y}$:

$$\begin{aligned}
&e([\alpha]_{g_1}, [\beta]_{g_2}) \cdot e([I]_{g_1}, [\gamma]_{g_2}) \cdot e([C]_{g_1}, [\delta]_{g_2}) = \\
&e((13, 15), (7v^2, 16v^3))^{30} \cdot e((13, 15), (7v^2, 16v^3))^{16} \cdot e((13, 15), (7v^2, 16v^3))^{21} = \\
&e((13, 15), (7v^2, 16v^3))^4 \cdot e((13, 15), (7v^2, 16v^3))^3 \cdot e((13, 15), (7v^2, 16v^3))^8 = \\
&e((13, 15), (7v^2, 16v^3))^{4+3+8} = \\
&e((13, 15), (7v^2, 16v^3))^2
\end{aligned}$$

5706 As we can see, both the left and the right side of equation XXX are identical, which implies
5707 that the verification process accepts the simulated proof.

5708 **NOTE: UNFORTUNATELY NOT! :-((HENCE THERE IS AN ERROR SOMEWHERE ...**
5709 **NEED TO FIX IT AFTER VACATION**

5710 **Proof Simulation** During the execution of a setup phase, a common reference string is gen-
5711 erated, along with a simulation trapdoor, the latter of which must be deleted at the end of the
5712 setup-phase. As an alternative, a more complicated multi-party protocol like [XXX] can be
5713 used to split the knowledge of the simulation trapdoor among many different parties.

5714 In this paragraph, we will show why knowledge of the simulation trapdoor is problematic,
5715 and how it can be used to generate zk-SNARKs for a given instance without any knowledge or
5716 the existence of associated witness.

5717 To be more precise, let I be an instance for some R1CS language L_R . We call a zk-SNARK
5718 for L_R **forged** or **simulated** if it passes a verification but its generation does not require the
5719 existence of a witness W such that $(I; W)$ is a word in L_R .

To see how simulated zk-SNARKs can be computed, assume that a forger has knowledge of proper Groth_16 parameters, a quadratic arithmetic program of the problem, a common reference string and its associated simulation trapdoor τ :

$$\tau = (\alpha, \beta, \gamma, \delta, s) \quad (8.6)$$

Given some instance I , the forger’s task is to generate a zk-SNARK for this instance that passes the verification process, without having access to any other zk-SNARKs for this instance and without knowledge of a valid witness W .

To achieve this in the Groth_16 protocol, the forger can use the simulation trapdoor in combination with the QAP and two arbitrary field elements A and B from the scalar field \mathbb{F}_r of the pairing groups to g_1^C compute for the instance (I_1, \dots, I_n) as follows:

$$g_1^C = g_1^{\frac{A \cdot B}{\delta}} \cdot g_1^{-\frac{\alpha \cdot \beta}{\delta}} \cdot g_1^{-\frac{\beta A_0(s) + \alpha B_0(s) + C_0(s)}{\delta}} \cdot \left(g_1^{-\frac{\beta A_1(s) + \alpha B_1(s) + C_1(s)}{\delta}} \right)^{I_1} \cdots \left(g_1^{-\frac{\beta A_n(s) + \alpha B_n(s) + C_n(s)}{\delta}} \right)^{I_n}$$

The forger then publishes the zk-SNARK $\pi_{\text{forged}} = (g_1^A, g_1^C, g_2^B)$, which will pass the verification process and is computable without the existence of a witness (W_1, \dots, W_m) .

To see that the simulation trapdoor is necessary and sufficient to compute the simulated proof π_{forged} , first observe that both generators g_1 and g_2 are known to the forger, as they are part of the common reference string, encoded as $g_1^{s^0}$ and $g_2^{s^0}$. The forger is therefore able to compute $g_1^{A \cdot B}$. Moreover, since the forger knows α, β, δ and s from the trapdoor, they are able to compute all factors in the computation of g_1^C .

If, on the other hand, the simulation trapdoor is unknown, it is not possible to compute g_1^C , since, for example, the computational Diffie-Hellman assumption makes the derivation of $g_1^{\alpha \cdot \beta}$ from g_1^α and g_1^β infeasible.

Example 145 (The 3-factorization Problem). To see how a forger might simulate a zk-SNARK for some given instance I , consider the 3-factorization problem from 111, our protocol parameters from XXX, the common reference string from XXX and the simulation trapdoor $\tau = (6, 5, 4, 3, 2)$ of that CRS.

In order to forge a zk-SNARK for instance $I_1 = 11$, we don’t need a constructive proof for the associated rank-1 constraint system, which implies that we don’t have to execute the circuit $C_{3.\text{fac}}(\mathbb{F}_{13})$. Instead, we have to choose 2 arbitrary elements A and B from \mathbb{F}_{13} , and compute g_1^A, g_2^B and g_1^C as defined in XXX. We choose $A = 9$ and $B = 3$, and, since $\delta^{-1} = 3$, we compute as follows:

$$\begin{aligned} [A]g_1 &= [9](13, 15) = (35, 15) \\ [B]g_2 &= [3](7v^2, 16v^3) = (42v^2, 16v^3) \\ [C]g_1 &= \left[\frac{A \cdot B}{\delta} \right] g_1 \oplus \left[-\frac{\alpha \cdot \beta}{\delta} \right] g_1 \oplus \left[-\frac{\beta A_0(s) + \alpha B_0(s) + C_0(s)}{\delta} \right] g_1 \oplus \\ &\quad [I_1] \left[-\frac{\beta A_1(s) + \alpha B_1(s) + C_1(s)}{\delta} \right] g_1 \\ &= [(9 \cdot 3) \cdot 9](13, 15) \oplus [-(6 \cdot 5) \cdot 9](13, 15) \oplus [0](13, 15) \oplus [11][-(7 \cdot 2 + 4) \cdot 9](13, 15) \\ &= [9](13, 15) \oplus [3](13, 15) \oplus [12](13, 15) = [11](13, 15) \\ &= (33, 9) \end{aligned}$$

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This is all we need to generate our forged proof for the 3-factorization problem. We publish the simulated zk-SNARK:

$$\pi_{fake} = ((35, 15), (33, 9), (42v^2, 16v^3))$$

5748 Despite the fact that this zk-SNARK was generated without knowledge of a proper witness,
5749 it is indistinguishable from a zk-SNARK that proves knowledge of a proper witness.

5750 To see that, we show that our forged SNARK passes the verification process. In order to
5751 verify π_{fake} , we proceed as in XXX, and compute the curve point g_1^I for the instance $I_1 = 11$.
5752 Since the instance is the same as in example XXX, we can parallel the computation from XXX:

$$\begin{aligned} [I]g_1 &= \left[\frac{\beta \cdot A_0(s) + \alpha \cdot B_0(s) + C_0(s)}{\gamma} \right]g_1 \oplus [I_1] \left[\frac{\beta \cdot A_1(s) + \alpha \cdot B_1(s) + C_1(s)}{\gamma} \right]g_1 \\ &= (35, 28) \end{aligned}$$

In a next step we have to compute all the pairings involved in equation XXX. Using the logarithmic order on \mathbb{G}_1 and \mathbb{G}_2 as well as the bilinearity property of the pairing map we get

$$\begin{aligned} e([A]g_1, [B]g_2) &= e((35, 15), (42v^2, 16v^3)) = e([9](13, 15), [3](7v^2, 16v^3)) \\ &= e((13, 15), (7v^2, 16v^3))^{9 \cdot 3} \\ &= e((13, 15), (7v^2, 16v^3))^{27} \\ e([\alpha]g_1, [\beta]g_2) &= e((27, 34), (16v^2, 28v^3)) = e([6](13, 15), [5](7v^2, 16v^3)) \\ &= e((13, 15), (7v^2, 16v^3))^{6 \cdot 5} \\ &= e((13, 15), (7v^2, 16v^3))^{30} \\ e([I]g_1, [\gamma]g_2) &= e((35, 28), (37v^2, 27v^3)) = e([4](13, 15), [4](7v^2, 16v^3)) \\ &= e((13, 15), (7v^2, 16v^3))^{4 \cdot 4} \\ &= e((13, 15), (7v^2, 16v^3))^{16} \\ e([C]g_1, [\delta]g_2) &= e((33, 9), (42v^2, 16v^3)) = e([11](13, 15), [3](7v^2, 16v^3)) \\ &= e((13, 15), (7v^2, 16v^3))^{11 \cdot 3} \\ &= e((13, 15), (7v^2, 16v^3))^{33} \end{aligned}$$

In order to check equation XXX, observe that the target group \mathbb{G}_T of the Weil pairing is a finite cyclic group of order 13. Exponentiation is therefore done in modular 13 arithmetics. Using this, we evaluate the left side of equation XXX as follows:

$$e([A]g_1, [B]g_2) = e((13, 15), (7v^2, 16v^3))^{27} = e((13, 15), (7v^2, 16v^3))^1$$

since $27 \bmod 13 = 1$. Similarly, we evaluate the right side of equation XXX using modular 13 arithmetics and the exponential law $a^x \cdot a^y = a^{x+y}$. We get

$$\begin{aligned} e([\alpha]g_1, [\beta]g_2) \cdot e([I]g_1, [\gamma]g_2) \cdot e([C]g_1, [\delta]g_2) &= \\ e((13, 15), (7v^2, 16v^3))^{30} \cdot e((13, 15), (7v^2, 16v^3))^{16} \cdot e((13, 15), (7v^2, 16v^3))^{33} &= \\ e((13, 15), (7v^2, 16v^3))^4 \cdot e((13, 15), (7v^2, 16v^3))^3 \cdot e((13, 15), (7v^2, 16v^3))^7 &= \\ e((13, 15), (7v^2, 16v^3))^{4+3+7} &= \\ e((13, 15), (7v^2, 16v^3))^1 & \end{aligned}$$

5753 As we can see, both the left and the right side of equation XXX are identical, which implies
5754 that the verification process accepts the simulated proof. π_{fake} therefore convinces the veri-
5755 fier that a witness to the 3-factorization problem exists. However, no such witness was really
5756 necessary to generate the proof.

[add reference](#)

5757 **Chapter 9**

5758 **Exercises and Solutions**

5759 TODO: All exercises we provided should have a solution, which we give here in all detail.