
Operational notes

Document updated on **December 1, 2021**.

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
- text that needs advice from the communications/marketing team: Aaron & Shane
- text that needs to be completed or otherwise edited (by Sylvia)

Todo list

zero-knowledge proofs	11
played with	11
finite field	11
elliptic curve	11
Update reference when content is finalized	11
mathematical	11
numerical	11
a list of additional exercises	12
think about them	12
add some more informal explanation of absolute value	13
We haven't really talked about what a ring is at this point	13
What's the significance of this distinction?	14
reverse	14
Turing machine	14
polynomial time	14
sub-exponentially, with $\mathcal{O}((1 + \epsilon)^n)$ and some $\epsilon > 0$	14
Add text	15
\mathbb{Q} of fractions	15
Division in the usual sense is not defined for integers	15
Add more explanation of how this works	16
pseudocode	17
modular arithmetics	17
actual division	17
multiplicative inverses	17
rational numbers	17
exponentiation function	19
See XXX	19
once they accept that this is a new kind of calculations, its actually not that hard	19
perform Euclidean division on them	19
This Sage snippet should be described in more detail.	20
prime fields	22
residue class rings	22
Algorithm sometimes floated to the next page, check this for final version	22
Add a number and title to the tables	24
(-1) should be $(-a)$?	25
we have	27
rephrase	31
subtrahend	32
minuend	32

what does this mean?	37
Def Subgroup, Fundamental theorem of cyclic groups.	39
add reference when available	40
add reference when available	40
add reference	41
check references to previous examples	42
RSA crypto system	42
size 2048-bits	42
rainder class group	42
check reference	42
add reference	42
check reference	43
polynomial time	43
exponential time	43
TODO: Fundamental theorem of finite cyclic groups	43
check reference	43
run-time complexity	44
add reference	44
S: what does "efficiently" mean here?	44
computational hardness assumptions	44
check reference	44
add reference	45
explain last sentence more	45
add reference	46
Legendre symbol	46
Euler's formular	46
These are only explained later in the text, “	46
TODO: theorem: every factor of order defines a subgroup...	47
Is there a term for this property?	48
Check Sage code wrt local setup	48
add reference	50
TODO: DOUBLE CHECK THIS REASONING.	50
Check Sage code wrt local setup	50
Mirco: We can do better than this	52
check reference	53
add reference	53
add reference	54
add reference	56
check reference	56
add reference	57
add more examples protocols of SNARK	57
add reference	57
gives	57
gives	57
add reference	57
Abelian groups	57
codomain	57
Add numbering to definitions	58

■ Check change of wording	58
■ add reference	58
■ add reference	59
■ Why are we repeating this example here again?	59
■ S: are we introducing elliptic curves in section 1 or 2?	60
■ add reference	61
■ write paragraph on exponentiation	61
■ add reference	61
■ To understand it	61
■ add reference	61
■ add reference	62
■ group pairings	62
■ add reference	63
■ add reference	65
■ a certain type of geometry	65
■ add reference	66

MoonMath manual

TechnoBob and the Least Scruples crew

December 1, 2021

Contents

1	Introduction	4
1.1	Target audience	4
1.2	The Zoo of Zero-Knowledge Proofs	5
	To Do List	7
	Points to cover while writing	7
2	Preliminaries	8
2.1	Preface and Acknowledgements	8
2.2	Purpose of the book	8
2.3	How to read this book	9
2.4	Cryptological Systems	9
2.5	SNARKS	9
2.6	complexity theory	9
	2.6.1 Runtime complexity	9
2.7	Software Used in This Book	10
	2.7.1 Sagemath	10
3	Arithmetics	11
3.1	Introduction	11
	3.1.1 Aims and target audience	11
	3.1.2 The structure of this chapter	12
3.2	Integer Arithmetics	12
	Euclidean Division	15
	The Extended Euclidean Algorithm	17
3.3	Modular arithmetic	18
	Congurency	19
	Modular Arithmetics	19
	The Chinese Remainder Theorem	22
	Modular Inverses	25
3.4	Polynomial Arithmetics	28
	Polynomial Arithmetics	32
	Euklidean Division	33
	Prime Factors	35
	Lange interpolation	37
4	Algebra	39
4.1	Groups	39
	Commutative Groups	40
	Finite groups	42

	Generators	42
	The discrete Logarithm problem	42
4.1.1	Cryptographic Groups	43
	The discrete logarithm assumption	44
	The decisional Diffie–Hellman assumption	46
	The computational Diffie–Hellman assumption	46
	Cofactor Clearing	47
4.1.2	Hashing to Groups	47
	Hash functions	47
	Hashing to cyclic groups	49
	Hashing to modular arithmetics	50
	Pedersen Hashes	53
	MimC Hashes	54
	Pseudo Random Functions in DDH-A groups	54
4.2	Commutative Rings	54
	Hashing to Commutative Rings	57
4.3	Fields	57
	Prime fields	59
	Square Roots	60
	Exponentiation	61
	Hashing into prime fields	61
	Extension Fields	62
	Hashing into extension fields	65
4.4	Projective Planes	65
5	Elliptic Curves	68
5.1	Elliptic Curve Arithmetics	68
5.1.1	Short Weierstraß Curves	68
	Affine short Weierstraß form	69
	Affine compressed representation	73
	Affine group law	73
	Scalar multiplication	77
	Projective short Weierstraß form	80
	Projective Group law	81
	Coordinate Transformations	82
5.1.2	Montgomery Curves	82
	Affine Montgomery Form	82
	Affine Montgomery coordinate transformation	85
	Montgomery group law	86
5.1.3	Twisted Edwards Curves	87
	Twisted Edwards Form	87
	Twisted Edwards group law	88
5.2	Elliptic Curves Pairings	90
	Embedding Degrees	90
	Elliptic Curves over extension fields	91
	Full Torsion groups	92
	Torsion-Subgroups	93
	The Weil Pairing	94

5.3	Hashing to Curves	97
	Try and increment hash functions	97
5.4	Constructing elliptic curves	99
	The Trace of Frobenious	100
	The j -invariant	101
	The Complex Multiplication Method	101
	The <i>BLS6_6</i> pen& paper curve	108
	Hashing to the pairing groups	113
6	Statements	115
6.1	Formal Languages	115
	Checking Relations	115
	Instance and Witness	117
	Modularity and Gadgets	119
6.2	Statement Representatuons	119
6.2.1	Circuit Satisfiability	120
6.3	Computational Models	122
6.3.1	Rank-1 Constraint Systems	122
	Gadgets	123
	Boolean Algebra	123
	Boolean Constraint	124
	AND-constraints	124
	NOT constraint	125
	Binary representations	125
	Conditional (ternary) operator	126
	Range Proofs	127
	UIntN	127
	Bit constraints	127
	Twisted Edwards curves	127
	Twisted Edwards curves constraints	128
	Twisted Edwards curves addition	128
	Twisted Edwards curves inversion	129
	Twisted Edwards curves scalar multiplication	130
	Curve Cycles	130
	The RAM Model	130
	Generalizations	130
6.3.2	Quadratic Arithmetic Programs	130
6.3.3	Quadratic span programs	133
6.4	proof system	133
6.4.1	Succinct NIZK	134
	Common Reference String Generation	135
	Groth16	135
7	Exercises and Solutions	143

Chapter 1

Introduction

This is a 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>
- Snarkl: <http://ace.cs.ohio.edu/~gstewart/papers/snaarkl.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 illus- trative 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 particu- larly 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 matu- rity. 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 grwat 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, for example, [1] or [2], 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 [3].

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

In 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 website 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

Arithmetics

3.1 Introduction

3.1.1 Aims and target audience

The goal of this chapter is to enable a reader who is starting out with nothing more than basic high school algebra to be able to solve basic tasks in elliptic curve cryptography without the need of a computer.

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 Groth [2016], some knowledge of mathematics is needed to be able to follow the discussion.

Without a solid grounding in mathematics, someone who is interested in learning the concepts of zero-knowledge proofs, but who has never seen or **played with**, say, a **finite field**, or an **elliptic curve**, may quickly become overwhelmed. This is not so much due to the complexity of the mathematics needed, 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 hard. 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 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 integer arithmetics. At the same time, we'll attempt to teach you to "think mathematically", and to show you that there are numbers and **methatical** 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.

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 the wealth of **numerical** examples. We believe that such an informal, example-driven approach to learning

zero-knowledge proofs

played with

finite field

elliptic curve

Update reference when content is finalized

methatical

numerical

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 you focus on what 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.

a list of
additional
exercises

3.1.2 The structure of this chapter

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

think
about
them

3.2 Integer Arithmetics

In a sense, integer arithmetics is at the heart of large parts of modern cryptography, because it provides the most basic tools for doing computations in those systems. Fortunately, most readers will probably remember integer arithmetics 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 arithmetics concepts to refresh your memory and fill any knowledge gaps.

In what follows, we apply standard mathematical notations, and use the symbol \mathbb{Z} for the set of all **integers**: S: I think it'd be useful to explain the difference between $:=$ and $=$ as well. We have a table on this in the ZKAPs whitepaper.

M: Yeah maybe we use the more suggestive leftarrows aks \leftarrow ? If a table of symbols is unavoidable then ok, I find I super ugly, though

S: The table below is similar to what we have in the ZKAPs whitepaper. I think it's easier to read than a wall of text explaining the same things. We can make it more visually different (e.g. typesetting it in "dark mode", and probably move it earlier in the chapter.

Notation used in this chapter

Symbol	Meaning of Symbol	Example	Explanation
=	equals	$a = r$	a and r have the same value
:=	defining a variable	$\mathbb{Z} := \{\dots, -2, -1, 0, 1, 2, \dots\}$	\mathbb{Z} is the set of integers
\in	from the set	$a \in \mathbb{Z}$	a is an integer

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

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 $|a|$ stands for the **absolute value** of a , that is, the non-negative value of a without regard to its sign:

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

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

add some more informal explanation of absolute value

In addition, we use the symbol \mathbb{N} for the set of all **counting numbers** (also called natural numbers). So whenever you see the symbol \mathbb{N} , think of the set of all non negative integers including the number 0:

$$\mathbb{N} := \{0, 1, 2, 3, \dots\} \quad (3.4)$$

Any number that is smaller than 0, that is, any number that has a minus sign, is not part of \mathbb{N} . All counting numbers are integers, but not the other way round. In other words, counting numbers are a subset of integers.

To make it easier to memorize new concepts and symbols, we might frequently link to definitions (See 3.1 for a definition of \mathbb{Z}) in the beginning, but as to 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.

Both sets \mathbb{N} and \mathbb{Z} 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 more difficult as these increase in complexity. We will frequently invoke the SageMath system (2.7.1) for more complicated computations. One way to invoke the integer type in Sage is: **We haven't really talked about what a ring is at this point**

```
sage: ZZ # A sage notation for the integer type
Integer Ring
sage: NN # A sage notation for the counting number type
Non negative integer semiring
sage: ZZ(5) # Get an element from the Ring of integers
5
sage: ZZ(5) + ZZ(3)
8
sage: ZZ(5) * NN(3)
15
sage: ZZ.random_element(10**50)
61902477905204399784317350280236793711210996981837
```

add some more informal explanation of absolute value

We haven't really talked about what a ring is at this point

```

sage: ZZ(27713).str(2) # Binary string representation      13
110110001000001                                           14
sage: NN(27713).str(2) # Binary string representation      15
110110001000001                                           16
sage: ZZ(27713).str(16) # Hexadecimal string representation 17
6c41                                                         18

```

One set of numbers that is of particular interest to us is **prime numbers**, which are counting 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** (since even numbers greater than 2 are all divisible by 2, they are not 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. \mathbb{P} is infinite and can be ordered according to size, so that we can write them as follows:

$$2, 3, 5, 7, 11, 13, 17, 19, 23, 29, 31, 37, 41, 43, 47, 53, 59, 61, 67, \dots \quad (3.5)$$

This is sequence A000040 in [OEIS](#), the On-Line Encyclopedia of Integer Sequences. In particular, we can talk about small and large prime numbers.

As the **fundamental theorem of arithmetics** 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 $n \in \mathbb{N}_{\geq 2}$ be any natural number. Then there are always prime numbers $p_1, p_2, \dots, p_k \in \mathbb{P}$, such that

$$n = p_1 \cdot p_2 \cdot \dots \cdot p_k. \quad (3.6)$$

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 $19214758032624000 \in \mathbb{N}$. To get its prime factors, we can successively divide it by all prime numbers in ascending order starting with 2:*

$$19214758032624000 = 2 \cdot 2 \cdot 2 \cdot 2 \cdot 2 \cdot 2 \cdot 2 \cdot 3 \cdot 3 \cdot 3 \cdot 5 \cdot 5 \cdot 5 \cdot 7 \cdot 11 \cdot 17 \cdot 17 \cdot 23 \cdot 43 \cdot 43 \cdot 47$$

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

```

sage: n = NN(19214758032624000)                             19
sage: factor(n)                                               20
2^7 * 3^3 * 5^3 * 7 * 11 * 17^2 * 23 * 43^2 * 47             21

```

This computation reveals an important observation: Computing the factorization of an integer is computationally expensive, while the reverse, that is, computing the product of a given set of prime numbers, is fast. **MIRCO**: inverse process? Its not reversing something actually, but my english doesn't resolve to this level very well

From this, an important question arises: How fast we can compute the prime factorization of a natural number? This is the famous **factorization problem** and, as far as we know, there is no method on a classical **Turing machine** that is able to compute this representation in **polynomial time**. The fastest algorithm known today run **sub-exponentially**, with $\mathcal{O}((1 + \varepsilon)^n)$ and some $\varepsilon > 0$.

It follows that number factorization \Leftrightarrow prime number multiplication is an example of a so-called **one-way function**: Something that is easy to compute in one direction, but hard to

What's the significance of this distinction?

reverse

Turing machine

polynomial time

sub-exponentially with $\mathcal{O}((1 + \varepsilon)^n)$ and

compute in the other direction. **The existence of one-way functions is a basic cryptographic assumptions that the security of many cryptographic systems is based on.**

It should be pointed out, however, that the American mathematician Peter Williston Shor developed an algorithm in 1994 which can calculate the prime factor representation of a natural number in polynomial time on a quantum computer. The consequence of this is that cryptosystems, which are based on the time complexity of the prime factor problem, are unsafe as soon as practically usable quantum computers become available. *Add text along the lines of "this is the best we got for now" Possibly something on when we can reasonably expect quantum computers to become accessible/usable enough*

Add text

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

Exercise 2. Compute the factorization of 6469693230 and double check your results using Sage.

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

1. The equation is defined over the type of natural numbers.
2. The equation is defined over the type of integers.

Exercise 4. Consider the following equation $2x^3 - x^2 - 2x = -1$. Compute the set of all solutions x under the following assumptions:

1. The equation is defined over the type of natural numbers.
2. The equation is defined over the type of integers.
3. The equation is defined over the type \mathbb{Q} of fractions.

 \mathbb{Q} of fractions

Euclidean Division *Division in the usual sense is not defined for integers*, as, for example, 7 divided by 3 will not be an integer again. However it is possible to divide any two integers with a remainder. So for example 7 divided by 3 is equal to 2 with a remainder of 1 , since $7 = 2 \cdot 3 + 1$.

Division in the usual sense is not defined for integers

Doing integer division like this is probably something many of us remember from school. It is usually called **Euclidean division**, or **division with a remainder**, and it is an essential technique to understand many concepts in this 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 counting number $r \in \mathbb{N}$, with $0 \leq r < |b|$ such that

$$a = m \cdot b + r \quad (3.7)$$

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**.

Notation and Symbols 1. Suppose that the numbers a, b, m and r satisfy equation (3.7). Then we often write

$$a \operatorname{div} b := m, \quad a \operatorname{mod} b := r \quad (3.8)$$

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 $b|a$.

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. It can be shown, that both the quotient and the remainder always exist and are unique, as long as the dividend is different from 0.

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 3.27 to the divisor -17 and the dividend 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 SageMath to do the computation for us. We get

```
sage: ZZ(-17) // ZZ(4) # Integer quotient      22
-5                                              23
sage: ZZ(-17) % ZZ(4) # remainder             24
3                                              25
sage: ZZ(4).divides(ZZ(-17)) # self divides other 26
False                                         27
sage: ZZ(4).divides(ZZ(12))                  28
True                                         29
```

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. (It should be noted, however, that there are faster methods like **Newton–Raphson division**.)

As long division is the standard method used for pen-&-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. [Add more explanation of how this works](#)

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 3.7, 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

Add more
explanation
of
how this
works

compute as follows

$$\begin{array}{r}
 8457 \\
 17 \overline{) 143785} \\
 \underline{136} \\
 77 \\
 \underline{68} \\
 98 \\
 \underline{85} \\
 135 \\
 \underline{119} \\
 16
 \end{array} \tag{3.9}$$

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)) # Euclidean Division      30
      (8457, 16)                                           31
sage: ZZ(143785) == ZZ(8457)*ZZ(17) + ZZ(16) # check      32
True                                                       33

```

Exercise 5 (Integer Long Division). Find an $m \in \mathbb{Z}$ as well as an $r \in \mathbb{N}$ 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 . In which cases are your solutions unique?

$$(a, b) = (0, 7)$$

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

The Extended Euclidean Algorithm One of the most critical parts in this book is modular arithmetics XXX and its application in the computations in so-called **finite fields**, as we explain in XXX. In modular arithmetics, it is sometimes possible to define actual division and multiplicative inverses of numbers, that is very different from inverses as we know them from other systems like factional numbers.

However, to actually compute those inverses, we have to get familiar with the so-called **Extended Euclidean Algorithm**. A few more terms are necessary to explain the concept: The **greatest common divisor** (GCD) of two nonzero integers a and b is the greatest non-zero counting 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. In addition, two counting numbers are called **relative primes** or **coprimes**, if their greatest common divisor is 1.

The Extended Euclidean Algorithm is a method to calculate the greatest common divisor of two counting numbers a and $b \in \mathbb{N}$, as well as two additional integers $s, t \in \mathbb{Z}$, such that the following equation holds:

$$\gcd(a, b) = s \cdot a + t \cdot b \tag{3.10}$$

The following pseudocode shows in detail how to calculate these numbers with the Extended Euclidean Algorithm:

The algorithm is simple enough to be done effectively in pen-&-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:

modular
arith-
meticsactual
divisionmultiplicative
inversesfactional
numbers

Algorithm 1 Extended Euclidean Algorithm**Require:** $a, b \in \mathbb{N}$ with $a \geq b$ **procedure** EXT-EUCLID(a, b) $r_0 \leftarrow a$ $r_1 \leftarrow b$ $s_0 \leftarrow 1$ $s_1 \leftarrow 0$ $k \leftarrow 1$ **while** $r_k \neq 0$ **do** $q_k \leftarrow r_{k-1} \text{ div } r_k$ $r_{k+1} \leftarrow r_{k-1} - q_k \cdot r_k$ $s_{k+1} \leftarrow s_{k-1} - q_k \cdot s_k$ $k \leftarrow k + 1$ **end while****return** $\gcd(a, b) \leftarrow r_{k-1}$, $s \leftarrow s_{k-1}$ and $t := (r_{k-1} - s_{k-1} \cdot a) \text{ div } b$ **end procedure****Ensure:** $\gcd(a, b) = s \cdot a + t \cdot b$

Example 4. To illustrate the algorithm, let's 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

k	r_k	s_k	$t_k = (r_k - s_k \cdot a) \text{ div } b$
0	12	1	0
1	5	0	1
2	2	1	-2
3	1	-2	5

From this we can see that 12 and 5 are relatively prime (coprime), since their greatest common divisor 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)
```

34

35

Exercise 7 (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 8 (Towards Prime fields). Let $n \in \mathbb{N}$ be a counting number and p a prime number, such that $n < p$. What is the greatest common divisor $\gcd(p, n)$?

Exercise 9. Find all numbers $k \in \mathbb{N}$ with $0 \leq k \leq 100$ such that $\gcd(100, k) = 5$.

Exercise 10. Show that $\gcd(n, m) = \gcd(n + m, m)$ for all $n, m \in \mathbb{N}$.

3.3 Modular arithmetic

In mathematics, **modular arithmetic** is a system of arithmetic for integers, 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 arithmetics generalizes the clock example to arbitrary moduli and studies equations and phenomena that arise in this new kind of arithmetics. It is of central importance for understanding most modern crypto systems, in large parts because the **exponentiation function** has an inverse with respect to certain moduli that is hard to compute. In addition, we will see that it provides the foundation of what is called finite fields ().

exponentiation
function

See XXX

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 accept that this is a new kind of calculations, its actually not that hard.**

once they
accept
that this
is a new
kind of
calcula-
tions, its
actually
not that
hard

Congruency In what follows, let $n \in \mathbb{N}$ with $n \geq 2$ be a fixed counting number, that we will call the **modulus** of our modular arithmetics 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 5. 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 .

perform
Euclidean
division
on them

We can formalize this intuition of what congruency 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. Then a and b are said to be **congruent with respect to the modulus n** , if and only if the following equation holds

$$a \bmod n = b \bmod n \quad (3.11)$$

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

$$a \equiv b \pmod{n} \quad (3.12)$$

Exercise 11. Which of the following pairs of numbers are congruent with respect to the modulus 13: $(5, 19)$, $(13, 0)$, $(-4, 9)$, $(0, 0)$.

Exercise 12. Find all integers x , such that the congruency $x \equiv 4 \pmod{6}$ is satisfied.

Modular Arithmetics One particularly useful thing about congruencies is, that we can do calculations (arithmetics), much like we can with integer equations. That is, we can add or multiply numbers on both sides. The main difference is probably that the congruency $a \equiv b \pmod{n}$ is only equivalent to the congruency $k \cdot a \equiv k \cdot b \pmod{n}$ for some non zero integer $k \in \mathbb{Z}$, whenever k and the modulus n are coprime. The following list gives a set of useful rules:

Suppose that the congruencies $a_1 \equiv b_1 \pmod{n}$ as well as $a_2 \equiv b_2 \pmod{n}$ are satisfied for integers $a_1, a_2, b_1, b_2 \in \mathbb{Z}$ and that $k \in \mathbb{Z}$ is another integer. Then:

- $a_1 + k \equiv b_1 + k \pmod{n}$ (compatibility with translation)
- $k \cdot a_1 \equiv k \cdot b_1 \pmod{n}$ (compatibility with scaling)
- $a_1 + a_2 \equiv b_1 + b_2 \pmod{n}$ (compatibility with addition)
- $a_1 \cdot a_2 \equiv b_1 \cdot b_2 \pmod{n}$ (compatibility with multiplication)

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

Note that the previous rules are implications, not equivalences, which means that you can not necessarily reverse those rules. The following rules makes this precise:

- If $a_1 + k \equiv b_1 + k \pmod{n}$, then $a_1 \equiv b_1 \pmod{n}$
- If $k \cdot a_1 \equiv k \cdot b_1 \pmod{n}$ and k is coprime with n , then $a_1 \equiv b_1 \pmod{n}$
- If $k \cdot a_1 \equiv k \cdot b_1 \pmod{k \cdot n}$, then $a_1 \equiv b_1 \pmod{n}$

Another property of congruencies, not known in the traditional arithmetics of integers is the **Fermat's Little Theorem**. In simple words, it states that, in modular arithmetics, 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:

$$k^p \equiv k \pmod{p}, \quad (3.13)$$

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

$$k^{p-1} \equiv 1 \pmod{p} \quad (3.14)$$

We can use Sage to compute examples for both k being coprime and not coprime to p :

```
sage: ZZ(137).gcd(ZZ(64))
1
sage: ZZ(64)**ZZ(137) % ZZ(137) == ZZ(64) % ZZ(137)
True
sage: ZZ(64)**ZZ(137-1) % ZZ(137) == ZZ(1) % ZZ(137)
True
sage: ZZ(1918).gcd(ZZ(137))
137
sage: ZZ(1918)**ZZ(137) % ZZ(137) == ZZ(1918) % ZZ(137)
True
sage: ZZ(1918)**ZZ(137-1) % ZZ(137) == ZZ(1) % ZZ(137)
False
```

This Sage snippet should be described in more detail.

Now, since for the sake of readers who have never encountered modular arithmetics before, let's compute an example that contains most of the concepts described in this section:

Example 6. Assume that we choose the modulus 6 and that our task is to solve the following congruency 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 *why integers?* **MIRCO:** *I think this is emergent. Congruencies work on integers*, we can proceed in a similar way as we would if we had an equation to solve. Since both sides of a congruency contain ordinary integers, we can rewrite the left side as follows: $7 \cdot (2x + 21) + 11 = 14x + 147 = 14x + 158$. We can therefore rewrite the congruency 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 congruency 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 congruency 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 congruency, 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. 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 congruency. 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 congruency $7 \cdot (2x + 21) + 11 \equiv x - 102 \pmod{6}$. We double check for, say, $x = 4$ as well as $x = 14 + 12 \cdot 6 = 86$ using sage:

```
sage: (ZZ(7) * (ZZ(2) * ZZ(4) + ZZ(21)) + ZZ(11)) % ZZ(6) == (ZZ(4) - ZZ(102)) % ZZ(6)
True
sage: (ZZ(7) * (ZZ(2) * ZZ(76) + ZZ(21)) + ZZ(11)) % ZZ(6) == (ZZ(76) - ZZ(102)) % ZZ(6)
True
```

Readers who had not been familiar with modular arithmetics until now and who might be discouraged by how complicated modular arithmetics seems at this point, should keep two things in mind. First, computing congruencies in modular arithmetics is not really more complicated than computations in more familiar number systems (e.g. fractional numbers), it is just

a matter of getting used to it. Second, the theory of **prime fields** (and more general **residue class rings**) takes a different view on modular arithmetics with the attempt to simplify matters. In other words, once we understand prime field arithmetics, things become conceptually cleaner and more easy to compute.

prime
fieldsresidue
class rings

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

Exercise 14. Choose the modulus 23 and find all solutions $x \in \mathbb{Z}$ to the following congruency $69x \equiv 5 \pmod{23}$

Exercise 15. Choose the modulus 23 and find all solutions $x \in \mathbb{Z}$ to the following congruency $69x \equiv 46 \pmod{23}$

The Chinese Remainder Theorem We have seen how to solve congruencies in modular arithmetic. However, one question that remains is how to solve systems of congruencies with different moduli? The answer is given by the **Chinese remainder theorem**, which states that 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 so-called **simultaneous congruency**

$$\begin{aligned} x &\equiv a_1 \pmod{n_1} \\ x &\equiv a_2 \pmod{n_2} \\ &\dots \\ x &\equiv a_k \pmod{n_k} \end{aligned} \tag{3.15}$$

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: **Algorithm sometimes floated to the next page, check this for final version**

Algorithm 2 Chinese Remainder Theorem

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

procedure CONGRUENCY-SYSTEMS-SOLVER($k, a_0, \dots, a_{k-1}, n_0, \dots, n_{k-1}$)

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

while $j < k$ **do**

$N_j \leftarrow N / n_j$

$(_, s_j, t_j) \leftarrow \text{EXT-EUCLID}(N_j, n_j)$

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

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 3.15.

Algorithm
sometimes
floated
to the
next page,
check this
for final
version

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](#)

Example 7. *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

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

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 $\{\dots, -2222, -1067, 88, 1243, 2398, \dots\}$. In particular, there are infinitely many different solutions. 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
```

52

53

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 consider all integers that have the same remainder with respect to a given modulus n in Euclidean division to be equivalent. Then we can go a step further, and identify each set of numbers with equal remainder with that remainder and call it a **remainder class** or **residue class** in modulo n arithmetics.

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 equivalence class and some element of the second, then add or multiply them in the usual way and see which equivalence class the result is contained in. The following example makes this abstract description more concrete:

Example 8 (Arithmetics modulo 6). *Choosing the modulus $n = 6$, we have six equivalence 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 addition of those equivalence classes, say $2 + 5$, one chooses arbitrary elements from both sets, say 14 and -1 , adds those numbers in the usual way and then looks at the equivalence class of the result.

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

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

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

·	0	1	2	3	4	5
0	0	0	0	0	0	0
1	0	1	2	3	4	5
2	0	2	4	0	2	4
3	0	3	0	3	0	3
4	0	4	2	0	4	2
5	0	5	2	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. It is called **modular 6 arithmetics** and written as \mathbb{Z}_6 .

To see why such an identification of a congruency class with its remainder is useful and actually simplifies congruency computations a lot, let's go back to the congruency from example 6 again:

$$7 \cdot (2x + 21) + 11 \equiv x - 102 \pmod{6} \quad (3.16)$$

As shown in example 6, the arithmetics of congruencies can deviate from ordinary arithmetics: For example, division needs to check whether the modulus and the dividend are co-primes, and solutions are not unique in general.

We can rewrite this congruency 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

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

We can use the multiplication and addition table above to solve the equation on the right like we would solve normal integer equations: *Add a number and title to the tables*

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

Add a number and title to the tables

So we see that, 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 congruency, 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 arithmetics type. This is particularly useful to double-check our computations:

<code>sage: Z6 = Integers(6)</code>	54
<code>sage: Z6(2) + Z6(5)</code>	55
<code>1</code>	56
<code>sage: Z6(7) * (Z6(2) * Z6(4) + Z6(21)) + Z6(11) == Z6(4) - Z6(102)</code>	57
<code>True</code>	58

Jargon 1 (k -bit modulus). In cryptographic papers, we can 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 8 describes a 3-bit modulus arithmetics system.

Exercise 16. Let a, b, k be integers, such that $a \equiv b \pmod{n}$ holds. Show $a^k \equiv b^k \pmod{n}$.

Exercise 17. Let a, n be integers, such that a and n are not coprime. For which $b \in \mathbb{Z}$ does the congruency $a \cdot x \equiv b \pmod{n}$ have a solution x and how does the solution set look in that case?

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:

$$a \cdot a^{-1} = 1 \quad (3.17)$$

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:

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

Example 9. 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 10. 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 $a \neq 1$ has a multiplicative inverse, since the equation $a \cdot x = 1$ has no integer solutions for $a \neq 1$.

The definition of multiplicative inverse works verbatim for addition as well. In the case of integers, the neutral element with respect to addition is 0, since $a + 0 = 0$ for all integers $a \in \mathbb{Z}$. The additive inverse always exist and is given by the negative number $-a$, since $a + (-1) = 0$.

(-1)
should
be (-a)?

Example 11. Looking at the set \mathbb{Z}_6 of residual classes modulo 6 from example 8, 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 modulo 6, it makes sense to “divide” by 5 in \mathbb{Z}_6 . 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 arithmetics.

The remaining question is to understand which elements have multiplicative inverses in modular arithmetics. The answer is that, in modular n arithmetics, a residue class r has a multiplicative inverse, if and only if n and r are coprime. Since $\text{ggt}(n, r) = 1$ in that case, we know from the Extended Euclidean Algorithm that there are numbers s and t , such that

$$1 = s \cdot n + t \cdot r \quad (3.19)$$

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

Example 12 (Multiplicative inverses in \mathbb{Z}_6). In the previous example, we looked up multiplicative inverses in \mathbb{Z}_6 from the lookup-table in Example 8. In real world examples, it is usually impossible to write down those lookup tables, as the modulus is way too large, and the sets occasionally contain more elements than there are atoms in the observable universe.

Now, trying to determine that $2 \in \mathbb{Z}_6$ has no multiplicative inverse in \mathbb{Z}_6 without using the lookup table, we immediately observe that 2 and 6 are not coprime, since their greatest common divisor is 2. It follows that equation 3.19 has no solutions s and t , which means that 2 has no multiplicative inverse in \mathbb{Z}_6 .

The same reasoning works for 3 and 4, as neither of these are coprime with 6. The case of 5 is different, since $\text{ggt}(6, 5) = 1$. To compute the multiplicative inverse of 5, we use the Extended Euclidean Algorithm and compute the following:

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

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

```
sage: ZZ(6).xgcd(ZZ(5))
(1, 1, -1)
```

59
60

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 XXX that in these cases all remainder classes must have modular inverses, since $\text{ggt}(r, n) = 1$ for prime n and $r < n$. 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 have

we have

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

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

Example 13 (Modular 5 arithmetics). *To see the unique properties of modular arithmetics whenever the modulus is a prime number, we will replicate our findings from example 8, 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*

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

Addition and multiplication can be transferred to the equivalence classes, in a way exactly parallel to Example 8. This results in the following addition and multiplication tables:

+	0	1	2	3	4
0	0	1	2	3	4
1	1	2	3	4	0
2	2	3	4	0	1
3	3	4	0	1	2
4	4	0	1	2	3

·	0	1	2	3	4
0	0	0	0	0	0
1	0	1	2	3	4
2	0	2	4	1	3
3	0	3	1	4	2
4	0	4	3	2	1

Calling the set of remainder classes in modular 5 arithmetics with this addition and multiplication \mathbb{F}_5 (for reasons we explain in more detail in XXX), we see some subtle but important differences to the situation in \mathbb{Z}_6 . In particular, we see that in the multiplication table, every remainder $r \neq 0$ has the entry 1 in its row and therefore has a multiplicative inverse. In addition, there are no non-zero elements such that their product is zero.

To use Fermat's little theorem in \mathbb{F}_5 for computing multiplicative inverses (instead of using the multiplication table), let's consider $3 \in \mathbb{F}_3$. We know that the multiplicative inverse is given 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 $3 \cdot 2 = 1$ in \mathbb{F}_5 .

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

```
sage: Z5 = Integers(5) 61
sage: Z5(3) ** (5-2) 62
2 63
sage: Z5(3) ** (-1) 64
2 65
sage: Z5(3) ** (5-2) == Z5(3) ** (-1) 66
True 67
```


Example 14. To understand one of the principal differences between prime number modular arithmetics and non-prime number modular arithmetics, consider the linear equation $a \cdot x + b = 0$ defined over both types \mathbb{F}_5 and \mathbb{Z}_6 . Since in \mathbb{F}_5 every non zero element has a multiplicative inverse, we can always solve these types of equations in \mathbb{F}_5 , which is not true in \mathbb{Z}_6 . To see that, consider the equation $3x + 3 = 0$. In \mathbb{F}_5 we have the following:

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

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

$$\begin{array}{ll} 3x + 3 = 0 & \# \text{ add 3 and on both sides} \\ 3x + 3 + 3 = 3 & \# \text{ addition-table: } 3 + 3 = 0 \\ 3x = 3 & \# \text{ no multiplicative inverse of 3 exists} \end{array}$$

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 8), we find that there are three solutions $x \in \{1, 3, 5\}$, such that $3x + 3 = 0$ holds true for all of them.

Exercise 18. Consider the modulus $n = 24$. Which of the integers 7, 1, 0, 805, -4255 have multiplicative inverses in modular 24 arithmetics? Compute the inverses, in case they exist.

Exercise 19. Find the set of all solutions to the congruency $17(2x + 5) - 4 \equiv 2x + 4 \pmod{5}$. Then project the congruency into \mathbb{F}_5 and solve the resulting equation in \mathbb{F}_5 . Compare the results.

Exercise 20. Find the set of all solutions to the congruency $17(2x + 5) - 4 \equiv 2x + 4 \pmod{6}$. Then project the congruency into \mathbb{Z}_6 and try to solve the resulting equation in \mathbb{Z}_6 .

3.4 Polynomial Arithmetics

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

$$P(x) := \sum_{j=0}^m a_j x^j = a_m x^m + a_{m-1} x^{m-1} + \cdots + a_1 x + a_0, \quad (3.20)$$

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 **univariate 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 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.

If an univariate polynomial $P(x) = \sum_{j=0}^m a_j x^j$ is given, that is not the zero polynomial, we call

$$\deg(P) := m \quad (3.21)$$

the *degree* of P and define the degree of the zero polynomial to be $-\infty$, where $-\infty$ (negative infinity) is a symbol with the property that $-\infty + m = -\infty$ for all counting numbers $m \in \mathbb{N}$. In addition, we write

$$\text{Lc}(P) := a_m \quad (3.22)$$

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 .

Example 15 (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:*

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

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 polynomial of degree 3 and leading coefficient 1. The following expressions are not integer polynomial

$$\begin{aligned} Q_1(x) &= 2x^2 + 4 + 3x^{-2} \\ Q_2(x) &= 0.5x^4 - 2x \\ Q_3(x) &= 1/x \end{aligned}$$

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. Note, however, that Sage defines the degree of the zero polynomial to be -1 .

```

sage: Zx = ZZ['x'] # integer polynomials with indeterminate x 68
sage: Zt.<t> = ZZ[] # integer polynomials with indeterminate t 69
sage: Zx 70
Univariate Polynomial Ring in x over Integer Ring 71
sage: Zt 72
Univariate Polynomial Ring in t over Integer Ring 73
sage: p1 = Zx([17, -4, 2]) 74
sage: p1 75
2*x^2 - 4*x + 17 76
sage: p1.degree() 77
2 78

```

```

sage: p1.leading_coefficient() 79
2 80
sage: p2 = Zt(t^23) 81
sage: p2 82
t^23 83
sage: p6 = Zx([0]) 84
sage: p6.degree() 85
-1 86

```

Example 16 (Polynomials over \mathbb{Z}_6). Recall our definition of the residue classes \mathbb{Z}_6 and their arithmetics as defined in Example 8. 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 are:

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

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:

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

Again, we can use Sage to do computations with polynomials that have their coefficients in \mathbb{Z}_6 . To do so, we have to specify the symbol for the indeterminate and the type for the coefficients:

```

sage: Z6 = Integers(6) 87
sage: Z6x = Z6['x'] 88
sage: Z6x 89
Univariate Polynomial Ring in x over Ring of integers modulo 6 90
sage: p1 = Z6x([5, -4, 2]) 91
sage: p1 92
2*x^2 + 2*x + 5 93
sage: p1 = Z6x([17, -4, 2]) 94
sage: p1 95
2*x^2 + 2*x + 5 96
sage: Z6x(x-2)*Z6x(x+3)*Z6x(x-5) == Z6x(x^3 + 2*x^2 + x) 97
True 98

```

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

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 of type R and let $b \in R$ be an element of that type. Then the **evaluation** of P at b is given by

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

Example 17. Consider the integer polynomials from example XXX 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:

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

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

rephrase

sage: <code>Zx = ZZ['x']</code>	99
sage: <code>p1 = Zx([17, -4, 2])</code>	100
sage: <code>p7 = Zx(x-2)*Zx(x+3)*Zx(x-5)</code>	101
sage: <code>p1(ZZ(2))</code>	102
17	103
sage: <code>p7(ZZ(-6)) == ZZ(-264)</code>	104
True	105

Example 18. Consider the polynomials with coefficients in \mathbb{Z}_6 from example XXX 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:

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

sage: <code>Z6 = Integers(6)</code>	106
sage: <code>Z6x = Z6['x']</code>	107

```
sage: p1 = Z6x([5, -4, 2])
sage: p1(Z6(2)) == Z6(5)
True
```

108

109

110

Exercise 21. Compare both expansions of P_7 from $\mathbb{Z}[x]$ and from $\mathbb{Z}_6[x]$ in example XXX and example XXX, and consider the definition of \mathbb{Z}_6 as given in example XXX. Can you see how the definition of P_7 over \mathbb{Z} projects to the definition over \mathbb{Z}_6 if you consider the residue classes of \mathbb{Z}_6 ?

Polynomial Arithmetics 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**.

subtrahend

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 factors, since we defined $-\infty \cdot m = \infty$ for every integer $m \in \mathbb{Z}$. Using Sage's definition of degree, this would not hold, as the zero polynomials degree is -1 in Sage, which would violate this rule.

minuend

Example 19. To given an example of how polynomial arithmetics 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

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

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

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

```

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 20. Let us consider the polynomials of the previous example but interpreted in modular 6 arithmetics. 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

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

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

```

sage: Z6x = Integers(6)['x']
sage: P = Z6x([2, -4, 5])
sage: Q = Z6x([5, 0, -2, 1])
sage: P+Q == Z6x(x^3 +3*x^2 +2*x +1)
True
sage: P*Q == Z6x(5*x^5 +4*x^4 +4*x^3+3*x^2+4*x +4)
True

```

Exercise 22. Compare the sum $P+Q$ and the product $P \cdot Q$ from the previous two examples XXX and XXX and consider the definition of \mathbb{Z}_6 as given in example XXX. How can we derive the computations in $\mathbb{Z}_6[x]$ from the computations in $\mathbb{Z}[x]$?

Euklidean Division The ring of polynomials shares a lot of properties with integers. In particular, the concept of Euclidean division and the algorithm of long division is also defined for polynomials. Recalling the Euclidean division of integers XXX, we know that, given two integers a and $b \neq 0$, there is always another integer m and a counting number r with $r < |b|$ such that $a = m \cdot b + r$ holds.

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

$$A = M \cdot B + R \quad (3.26)$$

and $\deg(R) < \deg(B)$. Similarly to integer Euclidean division, both M and R are uniquely defined by these relations.

$$A \operatorname{div} B := M, \quad A \operatorname{mod} B := R \quad (3.27)$$

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**.

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

$$\begin{array}{l} M \leftarrow 0 \\ R \leftarrow A \\ d \leftarrow \deg(B) \\ c \leftarrow Lc(B) \\ \mathbf{while} \deg(R) \geq d \mathbf{do} \\ \quad S := Lc(R) \cdot c^{-1} \cdot x^{\deg(R)-d} \\ \quad M \leftarrow M + S \\ \quad R \leftarrow R - S \cdot B \end{array}$$
end procedure

Example 21 (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 3. Our goal is to find solutions to equation XXX, that is, we need to find the quotient polynomial $M \in \mathbb{Z}[x]$ and the remainder polynomial $R \in \mathbb{Z}[x]$ such that $x^5 + 2x^3 - 9 = M(x) \cdot (x^2 + 4x - 1) + R$. Using a notation that is mostly used in Commonwealth countries, we compute as follows:*

34

We therefore get $M(x) = x^3 - 4x^2 + 19x - 80$ as well as $R(x) = 339x - 89$ 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])
sage: M = Zx([-80, 19, -4, 1])
sage: R = Zx([-89, 339])
sage: A == M*B + R
True

```

125
126
127
128
129
130
131

Example 22. 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 XXX 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 23. Consider the polynomial expressions $P(x) := -3x^4 + 4x^3 + 2x^2 + 4$ and $Q(x) = x^2 - 4x + 2$. Compute the Euclidean division of P by Q in the following types:

1. $P, Q \in \mathbb{Z}[x]$
2. $P, Q \in \mathbb{Z}_6[x]$
3. $P, Q \in \mathbb{F}_5[x]$

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 24. Show that the polynomial $P(x) = 2x^4 - 3x + 4 \in \mathbb{F}_5[x]$ is a factor of the polynomial $Q(x) = x^7 + 4x^6 + 4x^5 + x^3 + 2x^2 + 2x + 3 \in \mathbb{F}_5[x]$, that is show $P|Q$. What is $Q \div P$?

Prime Factors Recall that the fundamental theorem of arithmetics XXX tells us that every number is the product of prime numbers. Something similar holds for polynomials, too.

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

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

This representation is unique, except for permutations in the factors and is called the **prime factorization** of P .

Example 23. 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 $a^2 = 3$.

```
sage: Zx = ZZ['x'] 132
sage: p = Zx(x^2-3) 133
sage: p.roots() 134
[] 135
sage: p.factor() 136
x^2 - 3 137
```

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

Finding prime factors of a polynomial is hard. As we have seen in example XXX, points where a polynomial evaluates to zero, i.e points $x_0 \in R$ with $P(x_0) = 0$ are of special interest, since it can be shown the polynomial $F(x) = (x - x_0)$ is always a factor of P . The converse, however, is not necessarily true, because a polynomial can have irreducible prime factors.

Points where a polynomial evaluates to zero are called the **roots** of the polynomial. To be more precise, let $P \in R[x]$ be a polynomial. Then the set of all roots of P is defined as

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

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. In fact, it is well known that, for polynomials of degree 5 or higher, there is, in general, no closed expression, from which the roots can be deduced.

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 24. Consider our integer polynomial $P_7(x) = x^3 - 4x^2 - 11x + 30$ from example XXX 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 XXX that the integer polynomial $x^2 - 3$ is irreducible. It follows that it has no roots, since every root defines a prime factor.

Example 25. 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 :

```
sage: Zx = ZZ['x'] 138
sage: p = Zx(x^7 + 3*x^6 + 3*x^5 + x^4 - x^3 - 3*x^2 - 3*x - 1) 139
sage: p.roots() 140
[(1, 1), (-1, 4)] 141
sage: p.factor() 142
(x - 1) * (x + 1)^4 * (x^2 + 1) 143
```

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 prime factorization

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

Lange interpolation One particularly useful property of polynomials is that a polynomial of degree m is completely determined on $m + 1$ evaluation points. Seeing this from a different angle, we can (sometimes) uniquely derive a polynomial of degree m from a set

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

This "few too many" property of polynomials is used in many places, like for example in erasure codes. It is also of importance in snarks and we therefore need to understand a method to actually compute a polynomial from a set of points.

what does this mean?

If the coefficients of the polynomial we want to find have a notion of multiplicative inverse, it is always possible to find such a polynomial. One method for this is called **Lagrange interpolation**. It works as follows: Given a set like 3.31, a polynomial P of degree $m + 1$ with $P(x_i) = y_i$ for all pairs (x_i, y_i) from S is given by the following algorithm:

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 26. 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 fractional number coefficients. Since \mathbb{Q} has multiplicative inverses, we can use the Lagrange interpolation algorithm from 4, to compute the polynomial.

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

And, indeed, evaluation of P on the x -values of S gives the correct points, since $P(0) = 4$, $P(-2) = 1$ and $P(2) = 3$.

Example 27. 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 $P \in \mathbb{F}_5[x]$ from this data. Since we know that multiplicative inverses exist in \mathbb{F}_5 , algorithm XXX applies and we can compute a unique polynomial of degree 2 in $\mathbb{F}_5[x]$ from S . We can use the lookup tables XXX for computation in \mathbb{F}_5 and get the following:

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

And, indeed, evaluation of P on the x -values of S gives the correct points, since $P(0) = 4$, $P(-2) = 1$ and $P(2) = 3$.

Exercise 25. Consider example XXX and example XXX again. Why is it not possible to apply algorithm XXX if we consider S as a set of integers, nor as a set in \mathbb{Z}_6 ?

Chapter 4

Algebra

In the previous chapter, we gave an introduction to the basic computational skills needed for a pen-and-paper approach to SNARKs. In this chapter, we get a bit more abstract and clarify a lot of mathematical terminology and jargon.

When you read papers about cryptography, or mathematical papers in general, you will frequently come across algebraic terms like **groups**, **fields**, **rings** and similar. To be able to follow these papers, it is necessary to get at least some understanding of such terms. In this chapter, we therefore provide a short introduction to these terms.

In a nutshell, algebraic types like groups or fields define sets that are analogous to numbers in various aspects, in the sense that you can add, subtract, multiply or divide on those sets.

We know many examples of sets that fall under those categories, such as natural numbers, integers, rational or the real numbers. In some sense, these are the most fundamental examples of such sets.

Def Sub-group, Fundamental theorem of cyclic groups.

4.1 Groups

Groups are abstractions that capture the essence of mathematical phenomena, like addition and subtraction, multiplication and division, permutations, or symmetries.

To understand groups, let us think back to when we learned about addition and subtraction of integers in school (putting integer multiplication aside for the moment). We learned that we can always add two integers, and that the result is guaranteed to be an integer again. We also learned that adding zero to any integer means that “nothing happens”, that it doesn’t matter in which order we add a given set of integers, that operations within brackets should be computed before operations outside brackets and that, for every integer, there is always another integer such that when we add both together we get zero (the negative).

These conditions are the defining properties of a group, and mathematicians have recognized that the exact same set of rules can be found in very different mathematical structures. It therefore makes sense to give a formal definition of what a group should be, detached from any concrete example. 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 definition of a group:

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

- **Existence of a neutral element:** There is a $e \in \mathbb{G}$ for all $g \in \mathbb{G}$, such that $e \cdot g = g$ as well as $g \cdot e = g$.
- **Existence of an inverse:** For every $g \in \mathbb{G}$ there is a $g^{-1} \in \mathbb{G}$, such that $g \cdot g^{-1} = e$ as well as $g^{-1} \cdot g = e$.
- **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.

Rephrasing the abstract definition in layman's terms, a group is something where we can do computations in a way that resembles the behaviour 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. Let (\mathbb{G}, \cdot) be a finite group. If there is no risk of ambiguity, we frequently drop the symbol \cdot and simply write \mathbb{G} as a notation for the group keeping the group law implicit.

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

add ref-
erence
when
available

Example 28 (Integer Addition and Subtraction). The set $(\mathbb{Z}, +)$ of integers together with integer addition is the archetypical example of a group, where the group law is traditionally written as $+$ (instead of \cdot). To compare integer addition against the abstract axioms of a group, we first see that 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 $a \in \mathbb{Z}$. In addition, we know that $(a + b) + c = a + (b + c)$, so integers with addition are indeed a group in the abstract sense.

Example 29 (The trivial group). The most basic example of a group is group with just one element $\{\bullet\}$ and the group law $\bullet \cdot \bullet = \bullet$.

Commutative Groups When we look at the general definition of a group, we see that it is somewhat different from what we know from integers. We know that the order in which we add two integers doesn't matter, as, for example, $4 + 2$ is the same as $2 + 4$. However we also know from example XXX that this is not always the case in groups.

To capture the special case of a group where the order in which the group law is executed doesn't matter, the concept of so-called a **commutative group** is introduced. To be more precise, a group is called commutative if $g_1 \cdot g_2 = g_2 \cdot g_1$ holds for all $g_1, g_2 \in \mathbb{G}$.

add ref-
erence
when
available

Notation and Symbols 4. In case (\mathbb{G}, \cdot) is a commutative group, we frequently use the so-called **additive notation** $(\mathbb{G}, +)$, that is, we write $+$ instead of \cdot for the group law and $-g := g^{-1}$ for the inverse of an element $g \in \mathbb{G}$.

Example 30. Consider the group of integers with integer addition again. Since $a + b = b + a$ for all integers, this group is the archetypical example of a commutative group. Since there are infinitely many integers, $(\mathbb{Z}, +)$ is not a finite group.

Example 31. Consider our definition of modulo 6 residue classes $(\mathbb{Z}_6, +)$ as defined in the addition table from example 8. As we can see, the residue class 0 is the neutral element in modulo 6 arithmetics, and the inverse of a residue class r is given by $6 - r$, since $r + (6 - r) = 6$, which is congruent to 0, since $6 \bmod 6 = 0$. Moreover $(r_1 + r_2) + r_3 = r_1 + (r_2 + r_3)$ is inherited from integer arithmetic.

We therefore see that $(\mathbb{Z}_6, +)$ is a group, and, since the addition table in example 8 is symmetrical, we see $r_1 + r_2 = r_2 + r_1$ which shows that $(\mathbb{Z}_6, +)$ is commutative.

The previous example of a commutative groups 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 $(\mathbb{Z}, +)$ 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 .

Of particular importance for pairing-based cryptography in general and SNARKs in particular are so-called **pairing maps** on commutative groups. To be more precise let \mathbb{G}_1 , \mathbb{G}_2 and \mathbb{G}_3 be three commutative groups. For historical reasons, we write the group law on \mathbb{G}_1 and \mathbb{G}_2 in additive notation and the group law on \mathbb{G}_3 in multiplicative notation. Then a **pairing map** is a function

$$e(\cdot, \cdot) : \mathbb{G}_1 \times \mathbb{G}_2 \rightarrow \mathbb{G}_3 \quad (4.1)$$

that takes pairs (g_1, g_2) (products) of elements from \mathbb{G}_1 and \mathbb{G}_2 and maps them somehow to elements from \mathbb{G}_3 , such that the *bilinearity* property holds: For all $g_1, g'_1 \in \mathbb{G}_1$ and $g_2 \in \mathbb{G}_2$ we have $e(g_1 + g'_1, g_2) = e(g_1, g_2) \cdot e(g'_1, g_2)$ and for all $g_1 \in \mathbb{G}_1$ and $g_2, g'_2 \in \mathbb{G}_2$ we have $e(g_1, g_2 + g'_2) = e(g_1, g_2) \cdot e(g_1, g'_2)$.

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

So, roughly speaking, bilinearity means that it doesn't matter if we first execute the group law on any side and then apply the bilinear map, or if we first apply the bilinear map and then apply the group law. Moreover, non-degeneracy means that the result of the pairing is zero if and only if at least one of the input values is zero.

Example 32. Maybe the most basic example of a non-degenerate pairing is obtained if we take \mathbb{G}_1 , \mathbb{G}_2 and \mathbb{G}_3 all to be the groups of integers with addition $(\mathbb{Z}, +)$. Then the following map defines a non-degenerate pairing:

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

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

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

Exercise 26. Consider example XXX again and let \mathbb{F}_5^* be the set of all remainder classes from \mathbb{F}_5 without the class 0. Then $\mathbb{F}_5^* = \{1, 2, 3, 4\}$. Show that (\mathbb{F}_5^*, \cdot) is a commutative group.

add reference

Exercise 27. Generalizing the previous exercise, consider general moduli n and let \mathbb{Z}_n^* be the set of all remainder classes from \mathbb{Z}_n without the class 0. Then $\mathbb{Z}_n^* = \{1, 2, \dots, n - 1\}$. Give 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 proof the commutative group axioms.

Exercise 28. Consider the remainder class groups $(\mathbb{Z}_n, +)$ for some modulus n . Show that the map

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

is bilinear. Why is it not a pairing in general and what condition must be imposed on n , such that the map is a pairing?

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 5. Let \mathbb{G} be a finite group. Then we frequently write $\text{ord}(\mathbb{G})$ or $|\mathbb{G}|$ for the order of \mathbb{G} .

Example 33. Consider the remainder class groups $(\mathbb{Z}_6, +)$ from example 8 and $(\mathbb{F}_5, +)$ from example 13, and the group (\mathbb{F}_5^*, \cdot) from exercise 26. We can easily see that the order of $(\mathbb{Z}_6, +)$ is 6, the order of $(\mathbb{F}_5, +)$ is 5 and the order of (\mathbb{F}_5^*, \cdot) is 4.

To be more general, considering arbitrary moduli n , we know from Euclidean division that the order of the remainder class group $(\mathbb{Z}_n, +)$ is n .

Exercise 29. The **RSA crypto system** is based on a modulus n that is typically the product of two prime numbers of **size 2048-bits**. What is the approximate order of the **rainder class group** $(\mathbb{Z}_n, +)$ in this case?

Generators These are sets of elements that can be used to generate the entire group by applying the group law repeatedly to these elements or their inverses only. Generators are of particular interest when working with groups.

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 the smallest possible set of generators for a given group. Of particular interest in this regard are groups that have a single generator, that is, there exists an 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 a single generator are called **cyclic groups**.

Example 34. The most basic example of a cyclic group is the group of integers $(\mathbb{Z}, +)$ with integer addition. 1 is a single 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 $-4 = -1 + (-1) + (-1) + (-1)$.

Example 35. Consider a modulus n and the remainder class groups $(\mathbb{Z}_n, +)$ from example 33. 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 .

Example 36. Let $p \in \mathbb{P}$ be prime number and (\mathbb{F}_p^*, \cdot) the finite group from exercise XXX. Then (\mathbb{F}_p^*, \cdot) is cyclic and every element $g \in \mathbb{F}_p^*$ is a generator.

The discrete Logarithm problem In cryptography in general, and in SNARK development in particular, we often do computations "in the exponent" of a generator. To see what this means, 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 a map, called the **exponential map** with respect to the generator g

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

where g^x means "multiply g x -times by itself and $g^0 = e_{\mathbb{G}}$. This 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} .

check references to previous examples

RSA crypto system

size 2048-bits

rainder class group

check reference

add reference

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 laws.

Since 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. This is what is usually meant by saying we do our computations "in the exponent".

Example 37. Consider the multiplicative group (\mathbb{F}_5^*, \cdot) from example 26. We know that \mathbb{F}_5^* is a cyclic group of order 4 and that every element is a generator. Choose $3 \in \mathbb{F}_5^*$, we then know that the map

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

respects the group law of addition in \mathbb{Z}_4 and the group law of multiplication in \mathbb{F}_5^* . And indeed doing a computation like

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

in the exponent gives the same result as doing the same computation in \mathbb{F}_5^* , that is

$$\begin{aligned} 3^{2+3-2} &= 3^2 \cdot 3^3 \cdot 3^{-2} \\ &= 4 \cdot 2 \cdot (-3)^2 \\ &= 3 \cdot 2^2 \\ &= 3 \cdot 4 \\ &= 2 \end{aligned}$$

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

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

Discrete logarithms are highly important in cryptography as there are groups such that the exponential map and its inverse, the discrete logarithm, are believed to be one-way functions, that is, while it is possible to compute the exponential map in **polynomial time**, computing the discrete log takes (sub)-**exponential time**. We have discussed this briefly following example 3.5 in the previous chapter, and will look at this and similar problems in more detail in the next section.

4.1.1 Cryptographic Groups

In this section, we will look at families of groups, which are believed to satisfy certain so-called **computational hardness assumptions**, that is, the hypothesis that a particular problem cannot be solved efficiently (where efficiently typically means "in polynomial time of a given security parameter") in the groups under consideration.

Example 38. To highlight the concept of the computational hardness assumption, consider the group of integers \mathbb{Z} from example 3.5. One of the best known and most researched examples of computational hardness is the assumption that the factorization of integers into prime numbers cannot be solved by any algorithm in polynomial time with respect to the bit-length of the integer.

To be more precise, the computational hardness assumption of integer factorization assumes that, given any integer $z \in \mathbb{Z}$ with bit-length b , there is no integer k and no algorithm with the

check
reference

polynomial
time

exponential
time

TODO:
Funda-
mental
theorem
of finite
cyclic
groups

check
reference

run-time complexity of $\mathcal{O}(b^k)$ that is able to find the prime numbers $p_1, p_2, \dots, p_j \in \mathbb{P}$, such that $z = p_1 \cdot p_2 \cdot \dots \cdot p_j$.

This hardness assumption was proven to be false, since Shor's algorithm shows that integer factorization is at least efficiently possible on a quantum computer, since the running time complexity of this algorithm is $\mathcal{O}(b^3)$. However, no such algorithm is known on a classical computer.

In the realm of classical computers, however, we still have to call the non-existence of such an algorithm an "assumption" because, to date, there is no proof that it is actually impossible to find one. The problem is that it is hard to reason about algorithms that we don't know.

So, despite the fact that there is currently no known algorithm that can factor integers efficiently on a classical computer, we cannot exclude that such an algorithm might exist in principle, and that someone eventually will discover it in the future.

However, what still makes the assumption plausible, despite the absence of any actual proof, is the fact that, after decades of extensive search, still no such algorithm has been found.

In what follows, we will describe a few *computational hardness assumptions* that arise in the context of groups in cryptography, because we will refer to them throughout the book.

The discrete logarithm assumption The so-called discrete logarithm problem 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 4.2 that there is a so-called exponential map $g^{(\cdot)} : \mathbb{Z}_r \rightarrow \mathbb{G} : x \mapsto g^x$, which maps the residue classes from module r arithmetic onto the group in a 1 : 1 correspondence. The **discrete logarithm problem** is then the task of finding inverses to this map, that is, to find a solution $x \in \mathbb{Z}_r$ to the following equation for some given $h \in \mathbb{G}$:

$$h = g^x \quad (4.4)$$

In other words, the **discrete logarithm assumption (DL-A)** is the assumption that there exists no algorithm with running time polynomial in the "security parameter $\log_2(r)$ ", that is able to compute some x if only h , g and g^x are given in \mathbb{G} . If this is the case for \mathbb{G} , we call \mathbb{G} a **DL-A group**.

Rephrasing the previous definition into simple words, DL-A groups are believed to have the property 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 size of the group r is large enough.

Example 39 (Public key cryptography). One the most basic examples of an application for DL-A groups is in public key cryptography, where some pair (\mathbb{G}, g) is publicly agreed on, such that \mathbb{G} is a finite cyclic group of sufficiently large order r , where it is believed that the discrete logarithm assumption holds, and g is a generator of \mathbb{G} .

In this setting, a secret key is nothing but 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 hard to find solutions x to the equation

$$pk = g^x$$

As the previous example shows, identifying DL-A 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.

run-time complexity

S: what does "efficiently" mean here?

computational hardness assumptions

check reference

Example 40 (Modular arithmetics for Fermat's primes). *It is widely believed that the discrete logarithm problem is hard in multiplicative groups \mathbb{Z}_p^* of prime number modular arithmetics. However, this is not true in general. To see that, consider any so-called Fermat's prime, which is a prime number $p \in \mathbb{P}$, such that $p = 2^n + 1$ for some number n .*

We know from XXX that in this case $\mathbb{Z}_p^ = \{1, 2, \dots, p-1\}$ is a group with respect to integer multiplication in modular p arithmetics and since $p = 2^n + 1$, the order of \mathbb{Z}_p^* is 2^n , which implies that the associated security parameter is given by $\log_2(2^n) = n$.*

We show that, in this case, \mathbb{Z}_p^ is not a DL-A group, by constructing an algorithm, which is able compute some $x \in \mathbb{Z}_{2^n}$ for any given generator g and arbitrary element h of \mathbb{F}_p^* , such that*

$$h = g^x$$

holds and the running time complexity of the constructed algorithm is $\mathcal{O}(n^2)$, which is quadratic in the security parameter $n = \log_2(2^n)$.

To define such an algorithm, let us assume that the generator g is a public constant and that a group element h is given. Our task is to compute x efficiently.

The first thing to note is that, since x is a number in modular 2^n arithmetic, we can write the binary representation of x as

$$x = c_0 \cdot 2^0 + c_1 \cdot 2^1 + \dots + c_n \cdot 2^n$$

with binary coefficients $c_j \in \{0, 1\}$. In particular, x is an n -bit number if interpreted as an integer.

We then use this representation to construct an algorithm that computes the bits c_j one after another, starting at c_0 . To see how this can be achieved, observe that we can determine c_0 by raising the input h to the power of 2^{n-1} in \mathbb{F}_p^ . We use the exponential laws and compute*

$$\begin{aligned} h^{2^{n-1}} &= (g^x)^{2^{n-1}} \\ &= \left(g^{c_0 \cdot 2^0 + c_1 \cdot 2^1 + \dots + c_n \cdot 2^n} \right)^{2^{n-1}} \\ &= g^{c_0 \cdot 2^{n-1}} \cdot g^{c_1 \cdot 2^1 \cdot 2^{n-1}} \cdot g^{c_2 \cdot 2^2 \cdot 2^{n-1}} \dots g^{c_n \cdot 2^n \cdot 2^{n-1}} \\ &= g^{c_0 \cdot 2^{n-1}} \cdot g^{c_1 \cdot 2^0 \cdot 2^n} \cdot g^{c_2 \cdot 2^1 \cdot 2^n} \dots g^{c_n \cdot 2^{n-1} \cdot 2^n} \end{aligned}$$

Now, since g is a generator and \mathbb{F}_p^ is cyclic of order 2^n , we know $g^{2^n} = 1$ and therefore $g^{k \cdot 2^n} = 1^k = 1$. From this, it follows that all but the first factor in the last expression are equal to 1 and we can simplify the expression into*

$$h^{2^{n-1}} = g^{c_0 \cdot 2^{n-1}}$$

Now, in case $c_0 = 0$, we get $h^{2^{n-1}} = g^0 = 1$ and in case $c_0 = 1$, we get $h^{2^{n-1}} = g^{2^{n-1}} \neq 1$ (To see that $g^{2^{n-1}} \neq 1$, recall that g is a generator of \mathbb{F}_p^ and hence is cyclic of order 2^n , which implies $g^y \neq 1$ for all $y < 2^n$).*

So raising h to the power of 2^{n-1} determines c_0 , and we can apply the same reasoning to the coefficient c_1 by raising $h \cdot g^{-c_0 \cdot 2^0}$ to the power of 2^{n-2} . This approach can then be repeated until all the coefficients c_j of x are found.

Assuming that exponentiation in \mathbb{F}_p^ can be done in logarithmic running time complexity $\log(p)$, it follows that our algorithm has a running time complexity of $\mathcal{O}(\log^2(p)) = \mathcal{O}(n^2)$, since we have to execute n exponentiations to determine the n binary coefficients of x .*

From this, it follows that whenever p is a Fermat's prime, the discrete logarithm assumption does not hold in \mathbb{F}_p^ .*

add reference

explain last sentence more

The decisional Diffie–Hellman assumption To describe the decisional Diffie–Hellman assumption, let \mathbb{G} be a finite cyclic group of order r and let g be a generator of \mathbb{G} . The DDH assumption then assumes that there is no algorithm that has a polynomial running time complexity in the security parameter $s = \log(r)$ that is able to distinguish the so-called DDH-triple (g^a, g^b, g^{ab}) from any triple (g^a, g^b, g^c) for randomly and independently chosen parameters $a, b, c \in \mathbb{Z}_r$. If this is the case for \mathbb{G} , we call \mathbb{G} a **DDH-A group**.

It is easy to see that DDH-A is a stronger assumption than DL-A, in the sense that the discrete logarithm assumption is necessary for the decisional Diffie–Hellman assumption to hold, but not the other way around.

To see why, 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 residue class $x \in \mathbb{Z}_p$ 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 $z = g^{ab}$ 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 hold:

Example 41 (Efficiently computable pairings). *Let \mathbb{G} be a finite, cyclic group of order r with generator g , such that the discrete logarithm assumption holds and such that there is a pairing map $e(\cdot, \cdot) : \mathbb{G} \times \mathbb{G} \rightarrow \mathbb{G}_T$ for some target group \mathbb{G}_T that is computable in polynomial time of the parameter $\log(r)$.*

In a setting like this, it is easy to show that DDH-A cannot hold, since given some triple (g^a, g^b, z) , it is possible to decide in polynomial time w.r.t $\log(r)$ whether $z = g^{ab}$ or not. To see that check

$$e(g^a, g^b) = e(g, z)$$

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 degeneracy property, the equality decides $z = g^{ab}$.

It follows that DDH-A is indeed weaker than DL-A and groups with efficient pairings cannot be DDH-A groups. The following example shows another important class of groups where DDH-A does not hold: multiplicative groups of prime number residue classes.

Example 42. *Let p be a prime number and $\mathbb{Z}_p^* = \{1, 2, \dots, p-1\}$ the multiplicative group of modular p arithmetics as in example XXX. As we have seen in XXX, this group is finite and cyclic of order $p-1$ and every element $g \neq 1$ is a generator.*

To see that \mathbb{F}_p^ cannot be a DDH-A group, recall from XXX that the **Legendre symbol** $\left(\frac{x}{p}\right)$ of any $x \in \mathbb{F}_p^*$ is efficiently computable by **Euler's formular**. But the Legendre symbol of g^a reveals if a is even or odd. Given g^a , g^b and g^{ab} , one can thus efficiently compute and compare the least significant bit of a , b and ab , respectively, which provides a probabilistic method to distinguish g^{ab} from a random group element g^c .*

The computational Diffie–Hellman assumption To describe the computational Diffie–Hellman assumption, let \mathbb{G} be a finite cyclic group of order r and let g be a generator of \mathbb{G} . The computational Diffie–Hellman assumption assumes that, given randomly and independently chosen residue classes $a, b \in \mathbb{Z}_r$, 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-A group.

In general, it is not known if CDH-A is a stronger assumption than DL-A, or if both assumptions are equivalent. It is known that DL-A is necessary for CDH-A but the other direction is

add reference

Legendre symbol

Euler's formular

These are only explained later in the text, “

currently not well understood. In particular, there are no groups known where DL-A holds but CDH-A does not hold [Fifield, 2012].

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 residue class $x \in \mathbb{Z}_p$ 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, which means that there are groups where CDH-A holds and DDH-A does not hold, while there cannot be groups such that DDH-A holds but CDH-A 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 if $z = g^{ab}$ or not.

Several variations and special cases of the CDH-A 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 $g^{x^{-1}}$.

Cofactor Clearing

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 general way to represent arbitrary data, we can understand a general **hash function** as a map

$$H : \{0, 1\}^* \rightarrow \{0, 1\}^k \quad (4.5)$$

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. So, in our definition, a hash function maps binary strings of arbitrary size onto binary strings of size exactly k . We call the images of H , that is, the values returned by the hash function **hash values**, **digests**, or simply **hashes**.

A hash function must be deterministic, that is, when we insert the same input x into H , the image $H(x)$ must always be the same. In addition, a hash function should be as uniform as possible, 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.

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 $s.\text{len}() > k$ to a string of size k and by filling any string s' of size $s'.\text{len}() < k$ with zeros. To make this hash function deterministic, we define that both truncation and filling should happen “on the left”.*

For example if $k = 3$, $x_1 = (0000101011101010011101010101)$ and $x_2 = 1$ then $H(x_1) = (101)$ and $H(x_2) = (001)$. It is easy to see that this hash function is deterministic and uniform.

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 practically infeasible to find a string $x \in \{0, 1\}^*$ such that $H(x) = y$ holds. This property is usually called **preimage-resistance**.

TODO:
theorem:
every
factor
of order
defines
a sub-
group...

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.

As cryptographically secure hash functions map tiny changes in input values onto large change in the output, implementation errors that change the outcome are usually easy to spot by comparing them to expected output values. The definitions of cryptographically secure 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.

Is there a term for this property?

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

$$H_k('') = (000 \dots 000)$$

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.

In addition, it is easy to construct collusions as all strings of size $> k$ that share the same k -bits "on the right" are mapped to the same hash value.

Also, this hash function is not very chaotic, 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 **PyCrypto** 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 PyCrypto 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*

$$\text{SHA256} : \{0, 1\}^* \rightarrow \{0, 1\}^{256}$$

that maps binary strings of arbitrary length onto binary strings of length 256. To evaluate a proper implementation of the SHA256 hash function, the digest of the empty string is supposed to be

$$\text{SHA256}('') = \text{e3b0c44298fc1c149afb4c8996fb92427ae41e4649b934ca495991b7852b855}$$

For better human readability, it is common practise to represent the digest of a string in a hexadecimal representation rather than in its binary form. We can use Sage to compute SHA256 and freely transit between binary, hexadecimal and decimal representations. To do so, we have to import PyCrypto and then load SHA_256: [Check Sage code wrt local setup](#)

Check Sage code wrt local setup


```

sage: QQ                                     144
Rational Field                               145
sage: QQ(1/5) # Get an element from the field of rational 146
         numbers
1/5                                           147
sage: QQ(1/5) / QQ(3) # Division             148
1/15                                         149

```

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 length k for some parameter k . 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 are usually 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

$$H : \{0, 1\}^* \rightarrow \mathbb{G} \quad (4.6)$$

Common properties of hash functions, like uniformity, are desirable but not always realized in actual real world instantiations of hash-to-group functions, so we skip those requirements for now and keep the definition very general.

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. If the task is to implement a hash-to- \mathbb{G} 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 $0 \leq z < 2^k$.*

To be more precise, choose an ordinary hash function $H : \{0, 1\}^ \rightarrow \{0, 1\}^k$ for some parameter k and a generator g of \mathbb{G} . Then the expression*

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

is a positive integer, where $H(s)_j$ means the bit at the j -th position of $H(s)$. A hash-to-group function for the group \mathbb{G} can then be defined as a concatenation of the exponential map $g^{(\cdot)}$ of g with the interpretation of $H(s)$ as an integer:

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

Constructing a hash-to-group function like this is easy to implement for cyclic groups and might be good enough in certain applications. It is however, almost never adequate in cryptographic applications, as discrete log relations might be constructible between two given hash value $H_g(s)$ and $H_g(t)$.

To see that, assume that \mathbb{G} is of order r and that $z_{H(s)}$ has a multiplicative inverse in modular r arithmetics. In that case, we can compute $x = z_{H(t)} \cdot z_{H(s)}^{-1}$ in \mathbb{Z}_r and have found a discrete log

relation between the group hash values, that is, we have found some x with $H_g(t) = (H_g(s))^x$ since

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

Applications where discrete log relations between hash values are undesirable therefore need different approaches, and many of those approaches start with a way to hash into the sets \mathbb{Z}_r of modular r arithmetics.

Hashing to modular arithmetics One of the most widely used applications of hash-into-group functions are hash functions that map into the set \mathbb{Z}_r of modular r arithmetics for some modulus r . 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 arbitrary hash functions can be interpreted as binary representations of integers as explained in example XXX.

It follows from this interpretation that one simple method of hashing into \mathbb{Z}_r is constructed by observing that if r is a modulus with a bit-length of $k = r.\text{nbits}()$, then every binary string $(b_0, b_1, \dots, b_{k-2})$ of length $k - 1$ defines an integer z in the range $0 \leq z < 2^{k-1} \leq r$, by defining

$$z = b_0 \cdot 2^0 + b_1 \cdot 2^1 + \dots + b_{k-2} \cdot 2^{k-2} \quad (4.7)$$

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

$$H_{r.\text{nbits}()-1} : \{0, 1\}^* \rightarrow \mathbb{Z}_r : s \mapsto H(s)_0 \cdot 2^0 + H(s)_1 \cdot 2^1 + \dots + H(s)_{k-2} \cdot 2^{k-2} \quad (4.8)$$

where $H(s)_j$ means the j -th bit of the image binary string $H(s)$ of the original binary hash function.

A drawback of this hash function is that the distribution of the hash values in \mathbb{Z}_r is not necessarily uniform. In fact, if $r - 2^{k-1} \neq 0$, then by design $H_{r.\text{nbits}()-1}$ will never hash onto values $z \geq 2^{k-1}$. Good moduli r are therefore as close to 2^{k-1} as possible, while less good moduli are closer to 2^k . In the worst case, that is, $r = 2^k - 1$, it misses $2^{k-1} - 1$, that is almost half of all elements, from \mathbb{Z}_r .

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

Example 47. To give an implementation of the $H_{r.\text{nbits}()-1}$ hash function, we use a 5-bit truncation of the SHA256 hash from example 45 and define a hash into \mathbb{Z}_{16} by

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

Since $k = 16.\text{nbits}() = 5$ and $16 - 2^{k-1} = 0$, this hash maps uniformly onto \mathbb{Z}_{16} . We can invoke Sage to implement it e.g. like this: *Check Sage code wrt local setup*

```
sage: F2 = GF(2)
sage: F2(1) # Get an element from GF(2)
1
sage: F2(1) + F2(1) # Addition
```

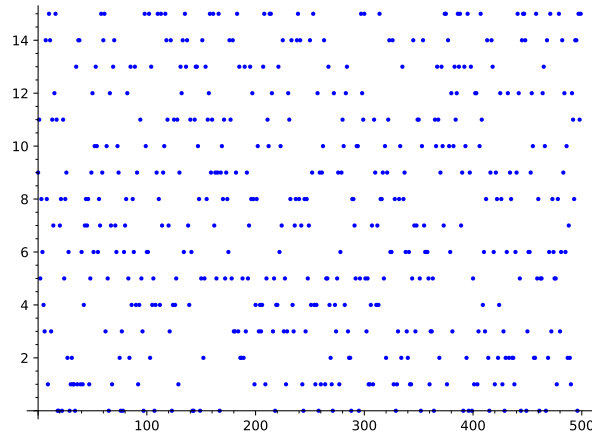
add reference

TODO:
DOUBLE
CHECK
THIS
REA-
SONING.

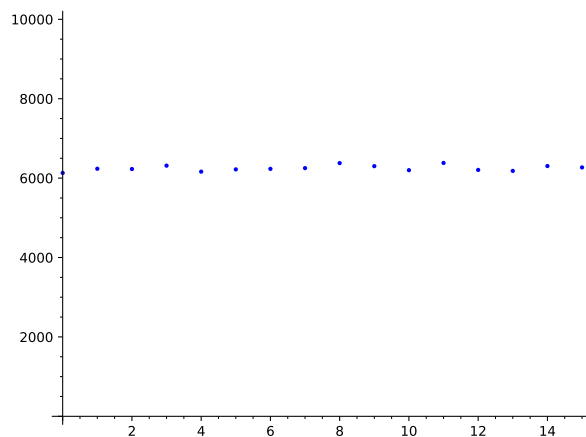
Check
Sage code
wrt local
setup

0	154
<code>sage: F2(1) / F2(1) # Division</code>	155
1	156

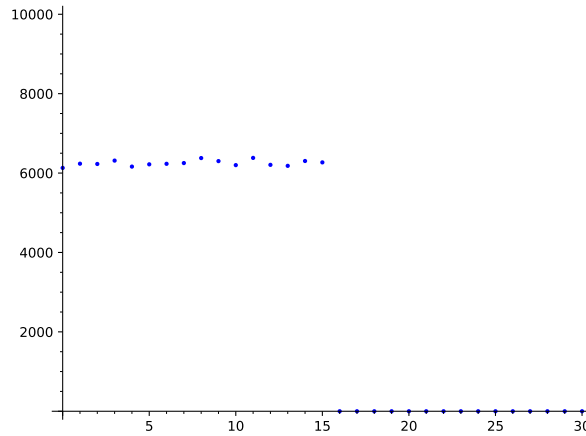
We can then use sage to apply this function to a large set of input values in order to plot a visualization of the distribution over the set $\{0, \dots, 15\}$. Executing over 500 input values gives:



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



The uniformity of the distribution problem becomes apparent if we want to construct a similar hash function for \mathbb{Z}_r for any r in the range $17 \leq r \leq 31$. In this case, the definition of the hash function is exactly the same as for \mathbb{Z}_{16} and hence the images will not exceed the value 16. So, for example, in the case of hashing to \mathbb{Z}_{31} , the hash function never maps to any value larger than 16, leaving almost half of all numbers out of the image range.



The second widely used method of hashing into \mathbb{Z}_r is constructed by observing that if r is a modulus with a bit-length of $r.bits() = k_1$ and $H : \{0, 1\}^* \rightarrow \{0, 1\}^{k_2}$ is a hash function that produces digests of size k_2 , with $k_2 \geq k_1$, then a hash-to-group function can be constructed by interpreting the image of H as a binary representation of an integer and then taking the modulus by r to map into \mathbb{Z}_r . To be more precise

$$H'_{mod_r} : \{0, 1\}^* \rightarrow \mathbb{Z}_r : s \mapsto \left(H(s)_0 \cdot 2^0 + H(s)_1 \cdot 2^1 + \dots + H(s)_{k_2} \cdot 2^{k_2} \right) \bmod n \quad (4.9)$$

where $H(s)_j$ means the j 'th bit of the image binary string $H(s)$ of the original binary hash function.

A drawback of this hash function is that computing the modulus requires some computational effort. In addition, the distribution of the hash values in \mathbb{Z}_r might not be even, depending on the difference $2^{k_2+1} - r$. An advantage is that potential properties like preimage resistance or collision resistance of the original hash function $H(\cdot)$ are preserved and the distribution can be made almost uniform, with only negligible bias, depending on what modulus r and images size k_2 are chosen.

Example 48. To give an implementation of the H_{mod_r} 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 e.g. like this:

```
sage: Z3 = GF(3) # prime field 157
sage: Z3t.<t> = Z3[] # polynomials over Z3 158
sage: P = Z3t(t^2+1) 159
sage: P.is_irreducible() 160
True 161
sage: F3_2.<t> = GF(3^2, name='t', modulus=P) 162
sage: F3_2 163
Finite Field in t of size 3^2 164
sage: F3_2(t+2)*F3_2(2*t+2) == F3_2(2) 165
True 166
```

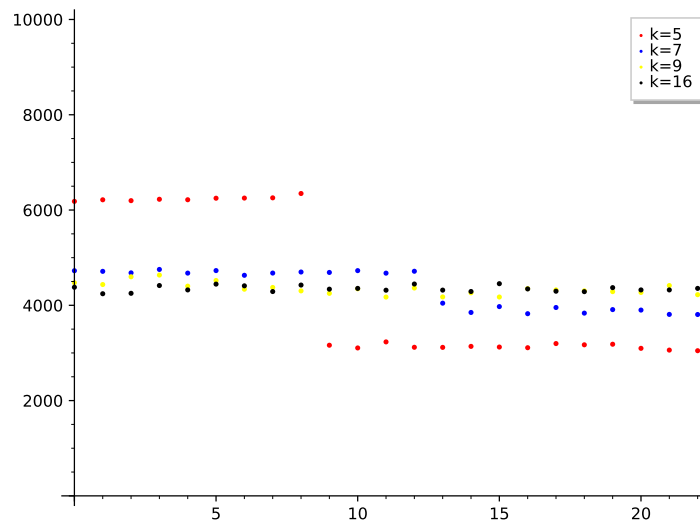
Mirco:
We can
do better
than this

```

sage: F3_2(2*t+2)^(-1) # multiplicative inverse      167
2*t + 1                                             168
sage: # verify our solution to (t+1)(x^2 + (2t+2)) = 2  169
sage: F3_2(t+1)*(F3_2(t)**2 + F3_2(2*t+2)) == F3_2(2) 170
True                                              171
sage: F3_2(t+1)*(F3_2(2*t)**2 + F3_2(2*t+2)) == F3_2(2) 172
True                                              173

```

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



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}_r is then achievable by first computing z , and then trying to see if $z \in \mathbb{Z}_r$. 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 number z 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 5.

Depending on the parameters, this method can be very efficient. In fact, if k is sufficiently large and r is close to 2^{k+1} , the probability for $z < r$ 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.

Once some hash function into modular arithmetics is found, it can often be combined with additional techniques to hash into more general finite cyclic groups. The following paragraphs describes a few of those methods widely adopted in SNARK development.

Pedersen Hashes The so-called **Pedersen hash function** [Pedersen, 1992] provides a way to map binary inputs of fixed size k onto elements of finite cyclic groups that avoids discrete log relations between the images as they occur in the naive approach XXX. Combining it with a classical hash function provides a hash function that maps strings of arbitrary length onto group elements.

check
reference

add refer-
ence

Algorithm 5 Hash-to- \mathbb{Z}_n **Require:** $r \in \mathbb{Z}$ with $r.\text{nbits}() = k$ and $s \in \{0, 1\}^*$ **procedure** TRY-AND-INCREMENT(r, 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** $z < r$ **return** x **end procedure****Ensure:** $z \in \mathbb{Z}_r$

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

$$H_{\text{Ped}} : (\mathbb{Z}_r)^j \rightarrow \mathbb{G} : (x_1, \dots, x_j) \mapsto \prod_{i=1}^j g_i^{x_i} \quad (4.10)$$

It can be shown that Pedersen's hash function is collision-resistant under the assumption that \mathbb{G} is a DL-A group. However, it is important to note that Pedersen hashes cannot be assumed to be **pseudorandom** and should therefore not be used where a hash function serves as an approximation of a random **oracle**.

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

To see how Pedersen hashes can be used to define an actual hash-to-group function according to our definition, we can use any of the hash-to- \mathbb{Z}_r functions as we have derived them in XXX.

add reference

MimC Hashes [Albrecht et al., 2016]

Pseudo Random Functions in DDH-A groups As noted in XXX, Pederson's hash function does not have the properties a random function and should therefore not be instantiated as such. To look at a construction that serves as a random oracle function in groups where the decisional Diffie–Hellman construction is assumed to hold true, let \mathbb{G} be a DDH-A group of order r with generator g and $\{a_0, a_1, \dots, a_k\} \subset \mathbb{Z}_r^*$ a uniform randomly generated set of numbers invertible in modular r arithmetics. Then a pseudo-random function is given by

$$F_{\text{rand}} : \{0, 1\}^{k+1} \rightarrow \mathbb{G} : (b_0, \dots, b_k) \mapsto g^{b_0 \cdot \prod_{i=1}^k a_i^{b_i}} \quad (4.11)$$

Of course, if $H : \{0, 1\}^* \rightarrow \{0, 1\}^{k+1}$ is a random oracle, then the concatenation of F_{rand} and H , defines a random oracle

$$H_{\text{rand}, \mathbb{G}} : \{0, 1\}^* \rightarrow \mathbb{G} : s \mapsto F_{\text{rand}}(H(s)) \quad (4.12)$$

4.2 Commutative Rings

Thinking of back to operations on integers, we know that there are two of these: addition and multiplication. As we have seen, addition defines a group structure on the set of integers.

However, multiplication does not define a group structure, given that integers in general don't have multiplicative inverses.

Configurations like this constitute a so-called **commutative ring with unit**. To be more precise, a commutative ring with unit $(R, +, \cdot, 1)$ is a set R provided with two maps $+: R \cdot R \rightarrow R$ and $\cdot: R \cdot R \rightarrow R$, called **addition** and **multiplication**, 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 $r_1, r_2 \in R$.
- **Existence of a unit:** There is an element $1 \in R$, such that $1 \cdot g$ holds 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 laws $g_1 \cdot (g_2 + g_3) = g_1 \cdot g_2 + g_1 \cdot g_3$ holds.

Example 49 (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.*

Example 50 (Underlying commutative group of a ring). *Every commutative ring with unit $(R, +, \cdot, 1)$ gives rise to a group, if we disregard multiplication.*

The following example is more interesting. The motivated reader is encouraged to think through this example, not so much because we need this in what follows, but more so as it helps to detach the reader from familiar styles of computation.

Example 51. *Let $S := \{\bullet, \star, \odot, \otimes\}$ be a set that contains four elements and let addition and multiplication on S be defined as follows:*

\cup	\bullet	\star	\odot	\otimes
\bullet	\bullet	\star	\odot	\otimes
\star	\star	\odot	\otimes	\bullet
\odot	\odot	\otimes	\bullet	\star
\otimes	\otimes	\bullet	\star	\odot

\circ	\bullet	\star	\odot	\otimes
\bullet	\bullet	\bullet	\bullet	\bullet
\star	\bullet	\star	\odot	\otimes
\odot	\bullet	\odot	\bullet	\odot
\otimes	\bullet	\otimes	\odot	\star

Then (S, \cup, \circ) 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 number when it comes to bracketing and computation rules. The only differences are the symbols and the actual way to add and multiply. With this in mind, we

solve the equation for x in the “usual way”:

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

So even though this equation looked really alien at first glance, we could solve it basically exactly the way we solve “normal” equations, like we do for fractional numbers, for example.

Note, however, that in a ring, things can be very different than most of us are used to whenever a multiplicative inverse would be needed to solve an equation in the usual way. For example the equation

$$\odot \circ x = \otimes$$

cannot be solved for x in the usual way, since there is no multiplicative inverse for \odot in our ring. We can confirm this by looking at the multiplication table to see that no such x exists.

As another example, the equation

$$\odot \circ x = \odot$$

does not have a single solution but two: $x \in \{\star, \otimes\}$. Having no solution or two solutions is certainly not something to expect from types like \mathbb{Q} .

Example 52. Considering polynomials again, we note from their definition that what we have called the type R of the coefficients must in fact be a commutative ring with a unit, since we need addition, multiplication, commutativity and the existence of a unit for $R[x]$ to have the properties we expect.

Considering R to be a ring with addition and multiplication of polynomials as defined in XXX actually makes $R[x]$ into a commutative ring with a unit, too, where the polynomial 1 is the multiplicative unit.

add reference

Example 53. Let n be a modulus and $(\mathbb{Z}_n, +, \cdot)$ the set of all remainder classes of integers modulo n , with the projection of integer addition and multiplication as defined in XXX. It can be shown that $(\mathbb{Z}_n, +, \cdot)$ is a commutative ring with unit 1.

Considering the exponential map from page 42 again, let \mathbb{G} be a finite cyclic group of order n with generator $g \in \mathbb{G}$. Then the ring structure of $(\mathbb{Z}_n, +, \cdot)$ is mapped onto the group structure of \mathbb{G} in the following way:

check reference

$$\begin{aligned}
 g^{x+y} &= g^x \cdot g^y & \text{for all } x, y \in \mathbb{Z}_n \\
 g^{x \cdot y} &= (g^x)^y & \text{for all } x, y \in \mathbb{Z}_n
 \end{aligned}$$

This of particular interest in cryptography and SNARKs, as it allows for the evaluation of polynomials with coefficients in \mathbb{Z}_n to be evaluated “in the exponent”. To be more precise, let

$p \in \mathbb{Z}_n[x]$ be a polynomial with $p(x) = a_m \cdot x^m + a_{m-1}x^{m-1} + \dots + a_1x + a_0$. Then the previously defined exponential laws XXX imply that

$$\begin{aligned} g^{p(x)} &= g^{a_m \cdot x^m + a_{m-1}x^{m-1} + \dots + a_1x + a_0} \\ &= \left(g^{x^m}\right)^{a_m} \cdot \left(g^{x^{m-1}}\right)^{a_{m-1}} \cdot \dots \cdot (g^x)^{a_1} \cdot g^{a_0} \end{aligned}$$

add reference

and hence to evaluate p at some point s in the exponent, we can insert s into the right hand side of the last equation and evaluate the product.

As we will see, this is a key insight to understand many SNARK protocols like e.g. Groth16 [Groth, 2016] or XXX.

Example 54. To give an example of the evaluation of a polynomial in the exponent of a finite cyclic group, consider the exponential map from example XXX:

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

add more examples protocols of SNARK

add reference

Choosing the polynomial $p(x) = 2x^2 + 3x + 1$ from $\mathbb{Z}_4[x]$, we can evaluate the polynomial at say $x = 2$ in the exponent of 3 in two different ways. On the one hand, we can evaluate p at 2 and then write the result into the exponent, which gives the following:

gives

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

On the other hand, we can use the right hand side of the equation to evaluate p at 2 in the exponent of 3, which gives the following:

gives

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

Hashing to Commutative Rings As we have seen in XXX, various constructions for hashing-to-groups are known and used in applications. As commutative rings are Abelian groups, when we disregard the multiplicative structure, hash-to-group constructions can be applied for hashing into commutative rings, too. This is possible in general, as the codomain of a general hash function $\{0, 1\}^*$ is just the set of binary strings of arbitrary but finite length, which has no algebraic structure that the hash function must respect.

add reference

Abelian groups

codomain

4.3 Fields

We started this chapter with the definition of a group (section 4.1), which we then expanded into the definition of a commutative ring with a unit (section 4.2). Such rings generalize the behaviour of integers. In this section, we will look at the special case 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} , which are in a sense an extension of the ring of integers, that is, constructed by including newly defined multiplicative inverses (fractions) to the integers.

Now, considering the definition of a ring XXX again, we define a **field** $(\mathbb{F}, +, \cdot)$ to be a set \mathbb{F} , together with two maps $+: \mathbb{F} \cdot \mathbb{F} \rightarrow \mathbb{F}$ and $\cdot: \mathbb{F} \cdot \mathbb{F} \rightarrow \mathbb{F}$, called *addition* and *multiplication*, such that the following conditions hold:

Add numbering to definitions

- $(\mathbb{F}, +)$ 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) For all $g_1, g_2, g_3 \in \mathbb{F}$ the distributive law $g_1 \cdot (g_2 + g_3) = g_1 \cdot g_2 + g_1 \cdot g_3$ holds.

If a field is given and the definition of its addition and multiplication is not ambiguous, we will often simply write \mathbb{F} instead of $(\mathbb{F}, +, \cdot)$ to denote the field. We moreover write \mathbb{F}^* to describe the multiplicative group of the field, that is, the set of elements with the multiplication as group law excluding the neutral element of addition.

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 1 equals zero, i.e. for which $\sum_{i=1}^n 1 = 0$. If such a $n > 0$ exists, the field is also-called 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 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?

Check change of wording

Example 55 (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 counting number $n \in \mathbb{N}$, such that $\sum_{j=0}^n 1 = 0$ in the set of rational numbers, the characteristic $\text{char}(\mathbb{Q})$ of the field \mathbb{Q} is zero. In Sage rational numbers are called as follows: ??*

Example 56 (Field with two elements). *It can be shown that in any field, the neutral element 0 of addition must be different from the neutral element 1 of multiplication, 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:

+	0	1
0	0	1
1	1	0

·	0	1
0	0	0
1	0	1

Since $1 + 1 = 0$ in the field \mathbb{F}_2 , we know that the characteristic of \mathbb{F}_2 is there, that is, we have $\text{char}(\mathbb{F}_2) = 0$.

For reasons we will understand better in XXX, Sage defines this field as a so-called Galois field with 2 elements. You can call it in Sage as follows: ??

add reference

Example 57. Both the real numbers \mathbb{R} as well as the complex numbers \mathbb{C} are well known examples of fields.

Exercise 30. Consider our remainder class ring $(\mathbb{F}_5, +, \cdot)$ and show that it is a field. What is the characteristic of \mathbb{F}_5 ?

Prime fields As we have seen in the various examples of the previous sections, modular arithmetics behaves similarly to 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.

However, we have also seen in XXX 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 of 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 .

add reference

To distinguish this important case from arbitrary remainder class rings, we write $(\mathbb{F}_p, +, \cdot)$ for the field of all remainder classes for a prime number modulus $p \in \mathbb{P}$ 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 many desirable properties. One of them is that, since these sets are finite and a prime field of characteristic, p can be represented on a computer in roughly $\log_2(p)$ amount of space without precision problems that are unavoidable for computer representations of infinite sets, e.g. rational numbers or integers.

Since prime fields are special cases of remainder class rings, all computations remain the same. Addition and multiplication can be computed by first doing normal integer addition and multiplication, and then taking the remainder modulus p . Subtraction and division can be computed by adding or multiplying with the additive or the multiplicative inverse, respectively. The additive inverse $-x$ of a field element $x \in \mathbb{F}_p$ is given by $p - x$, and the multiplicative inverse of $x \neq 0$ is given by x^{p-2} , or can be computed using the Extended Euclidean Algorithm.

Note that these computations might not be the fastest to implement on a computer. They are, however, useful in this book, as they are easy to compute for small prime numbers.

Example 58. The smallest field is the field \mathbb{F}_2 of characteristic 2 as we have seen in example 56. It is the prime field of the prime number 2.

Example 59. To summarize the basic aspects of computation in prime fields, let us consider the prime field \mathbb{F}_5 and simplify the following expression

Why are we repeating this example here again?

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

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 were 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 3.10 on page 17). To refresh our memories, the task is to compute $x^{-1} \cdot 3 + t \cdot 5 = 1$, but t is actually irrelevant. We get

k	r_k	x_k^{-1}	$t_k = (r_k - s_k \cdot a) \text{ div } b$
0	3	1	.
1	5	0	.
2	3	1	.
3	2	-1	.
4	1	2	.

So the multiplicative inverse of 3 in \mathbb{Z}_5 is 2 and indeed if compute $3 \cdot 2$ we get 1 in \mathbb{F}_5 .

Square Roots In this part, we deal with square numbers, also called **quadratic residues** and **square roots** in prime fields. This is of particular importance in our studies on elliptic curves, as only square numbers can actually be points on an elliptic curve.

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

$$x^2 = y \quad (4.13)$$

In this case, y is called a **quadratic residue**. On the other hand, if y is given and the quadratic equation has no solution x , we call y a **quadratic non-residue**. For any $y \in \mathbb{F}_p$, we write

$$\sqrt{y} := \{x \in \mathbb{F}_p \mid x^2 = y\} \quad (4.14)$$

for the set of all square roots of y in the prime field \mathbb{F}_p . (If y is a quadratic non-residue, then $\sqrt{y} = \emptyset$ (an empty set), and if $y = 0$, then $\sqrt{y} = \{0\}$)

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

It can be shown that in any prime field every non zero element has either no square root or two of them. We adopt the convention to call the smaller one (when interpreted as an integer) as the **positive** square root and the larger one as the **negative**. This makes sense, as the larger one can always be computed as the modulus minus the smaller one, which is the definition of the negative in prime fields.

Example 60 (Quadratic (Non)-Residues and roots in \mathbb{F}_5). Let us consider our example prime field \mathbb{F}_5 again. All square numbers can be found on the main diagonal of the multiplication table XXX. As you can see, in \mathbb{Z}_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, why we will recapitulate it here:

S: are we introducing elliptic curves in section 1 or 2?

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

$$\left(\frac{y}{p}\right) := \begin{cases} 1 & \text{if } y \text{ has square roots} \\ -1 & \text{if } y \text{ has no square roots} \\ 0 & \text{if } y = 0 \end{cases} \quad (4.15)$$

Example 61. Look at the quadratic residues and non residues in \mathbb{F}_5 from example XXX again, we can deduce the following Legendre symbols, from example XXX.

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

The Legendre symbol gives 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 theoretic use, as the following so-called **Euler criterion** gives 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

$$\left(\frac{y}{p}\right) = y^{\frac{p-1}{2}}. \quad (4.16)$$

Example 62. Looking at the quadratic residues and non residues in \mathbb{F}_5 from example XXX again, we can compute the following Legendre symbols using the Euler criterium:

add reference

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

Exercise 31. Consider the prime field \mathbb{F}_{13} . Find the set of all pairs $(x, y) \in \mathbb{F}_{13} \times \mathbb{F}_{13}$ that satisfy the equation

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

Exponentiation TO APPEAR...

write paragraph on exponentiation

Hashing into prime fields An important problem in SNARK development is the ability to hash to (various subsets) of elliptic curves. As we will see in XXX, those curves are often defined over prime fields, and hashing to a curve then might start with hashing to the prime field. It is therefore important to understand how to hash into prime fields.

add reference

To understand it, note that in XXX we have looked at a few constructions of how to hash into the residue class rings \mathbb{Z}_n for arbitrary $n > 1$. As prime fields are just special instances of those rings, all hashing into \mathbb{Z}_n functions can be used for hashing into prime fields, too.

To understand it

add reference

Extension Fields We defined prime fields in the previous section. They are the basic building blocks for cryptography in general and SNARKs in particular.

However, as we will see in, XX so-called **pairing based SNARK** systems are crucially dependent on **group pairings** XXX defined over the group of rational points of elliptic curves. For those pairings to be non-trivial, the elliptic curve must not only be defined over a prime field, but over a so-called **extension field** of a given prime field.

group pairings

We therefore have to understand field extensions. To understand them, first observe that the field \mathbb{F}' is called an **extension** of a field \mathbb{F} if \mathbb{F} is a subfield of \mathbb{F}' , that is, \mathbb{F} is a subset of \mathbb{F}' and restricting the addition and multiplication laws of \mathbb{F}' to the subset \mathbb{F} recovers the appropriate laws of \mathbb{F} .

Now it can be shown that whenever $p \in \mathbb{P}$ is a prime and $m \in \mathbb{N}$ a natural number, then there is a field \mathbb{F}_{p^m} with characteristic p and p^m elements such that \mathbb{F}_{p^m} is an extension field of the prime field \mathbb{F}_p .

Similarly 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.

To be more precise, let $P \in \mathbb{F}_p[x]$ be an irreducible polynomial of degree m with coefficients from the given prime field \mathbb{F}_p . Then the underlying set \mathbb{F}_{p^m} of the extension field is given by the set of all polynomials with a degree less than m :

$$\mathbb{F}_{p^m} := \{a_{m-1}x^{m-1} + a_{m-2}x^{m-2} + \dots + a_1x + a_0 \mid a_i \in \mathbb{F}_p\} \quad (4.17)$$

which can be shown to be the set of all remainders when dividing any polynomial $Q \in \mathbb{F}_p[x]$ by P . So elements of the extension field are polynomials of degree less than m . This is analogous to how \mathbb{F}_p is the set of all remainders when dividing integers by p .

Addition is then inherited from $\mathbb{F}_p[x]$, which means that addition on \mathbb{F}_{p^m} is defined as normal addition of polynomials. To be more precise, we have

$$+ : \mathbb{F}_{p^m} \times \mathbb{F}_{p^m} \rightarrow \mathbb{F}_{p^m}, \left(\sum_{j=0}^m a_j x^j, \sum_{j=0}^m b_j x^j \right) \mapsto \sum_{j=0}^m (a_j + b_j) x^j \quad (4.18)$$

and we can see that the neutral element is (the polynomial) 0, and that the additive inverse is given by the polynomial with all negative coefficients.

Multiplication is inherited from $\mathbb{F}_p[x]$, too, but we have to divide the result by our modulus polynomial P , whenever the degree of the resulting polynomial is equal or greater to m . To be more precise, we have

$$\cdot : \mathbb{F}_{p^m} \times \mathbb{F}_{p^m} \rightarrow \mathbb{F}_{p^m}, \left(\sum_{j=0}^m a_j x^j, \sum_{j=0}^m b_j x^j \right) \mapsto \left(\sum_{n=0}^{2m} \sum_{i=0}^n a_i b_{n-i} x^n \right) \bmod P \quad (4.19)$$

and we can see that the neutral element is (the polynomial) 1. It is, however, not obvious from this definition how the multiplicative inverse looks.

We can easily 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 a p number of 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 product by P 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, which means that, from an abstract point of view, they are the same thing. From an implementations point of view, however, some choices are preferable, because they allow for faster computations.

To summarize, we have seen that when a prime field \mathbb{F}_p is given, then 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 fields

$$\mathbb{F}_p \subset \mathbb{F}_{p^{m_1}} \subset \cdots \subset \mathbb{F}_{p^{m_k}} \quad (4.20)$$

whenever the power m_j divides the power m_{j+1} , such that $\mathbb{F}_{p^{m_j}}$ is a subfield of $\mathbb{F}_{p^{m_{j+1}}}$.

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 63 (The Extension field \mathbb{F}_{3^2}). *In (XXX) we have constructed the prime field \mathbb{F}_3 . In this example, we apply the definition (XXX) of a field extension to construct \mathbb{F}_{3^2} . We start by choosing an irreducible polynomial of degree 2 with coefficients in \mathbb{F}_3 . We try $P(t) = t^2 + 1$. Maybe 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 never zero. We compute*

add reference

$$P(0) = 0^2 + 1 = 1$$

$$P(1) = 1^2 + 1 = 2$$

$$P(2) = 2^2 + 1 = 1 + 1 = 2$$

This implies that P is irreducible. The set \mathbb{F}_{3^2} then contains all polynomials of degrees lower than two, with coefficients in \mathbb{F}_3 , which is precisely

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

So our extension field contains 9 elements as expected. 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.

As it was the case in previous examples, we can use the table to deduce the negative of any element from \mathbb{F}_{32} . For example, in \mathbb{F}_{32} 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 divide it by P and keep the remainder. To see how this works, compute the product of $t+2$ and $2t+2$ in \mathbb{F}_{32}

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

So the product of $t+2$ and $2t+2$ in \mathbb{F}_{32} is 2. Doing this computation for all elements gives the following multiplication table:

\cdot	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	$2t$

As it was the case in previous examples, we can use the table to deduce the multiplicative inverse of any non-zero element from \mathbb{F}_{32} . For example in \mathbb{F}_{32} we have $(2t+1)^{-1} = 2t+2$, since $(2t+1) \cdot (2t+2) = 1$.

From the multiplication table, we can also see that the only quadratic residues in \mathbb{F}_{32} are 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 $\sqrt{2t} = \{t+1, 2t+2\}$.

Since \mathbb{F}_{32} is a field, we can solve equations as we would for other fields, like the rational numbers. To see that lets find all $x \in \mathbb{F}_{32}$ that solve the quadratic equation $(t+1)(x^2 + (2t+2)) = 2$. So we compute:

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

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

Exercise 32. Consider the extension field \mathbb{F}_{32} from the previous example and find all pairs of elements $(x, y) \in \mathbb{F}_{32}$, such that

$$y^2 = x^3 + 4$$

Exercise 33. Show that the polynomial $P = x^3 + x + 1$ from $\mathbb{F}_5[x]$ is irreducible. Then consider the extension field \mathbb{F}_{5^3} defined relative to P . Compute the multiplicative inverse of $(2t^2 + 4) \in \mathbb{F}_{5^3}$ using the extended Euklidean algorithm. Then find all $x \in \mathbb{F}_{5^3}$ that solve the equation

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

Hashing into extension fields In XXX we have seen how to hash into prime fields. As elements of extension fields can be seen as polynomials over prime fields, hashing into extension fields is therefore possible, if every coefficient of the polynomial is hashed independently.

add reference

4.4 Projective Planes

Projective planes are a certain type of geometry defined over a given field. In a sense, projective planes extend the concept of the ordinary Euclidean plane by including “points at infinity.”

a certain type of geometry

Such an inclusion of infinity points makes them particularly useful in the description of elliptic curves, as the description of such a curve in an ordinary plane needs an additional symbol “the point at infinity” to give the set of points on the curve the structure of a group. Translating the curve into projective geometry, then includes this “point at infinity” more naturally into the set of all points on a projective plane.

To understand the idea for the construction of projective planes, note that in an ordinary Euclidean plane, two lines either intersect in a single point, or are parallel. In the latter case both lines are either the same, that is, they intersect in all points, or do not intersect at all. A projective plane can then be thought of as an ordinary plane, but equipped with additional “points at infinity” such that two different lines always intersect in a single point. Parallel lines intersect “at infinity”.

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 three tuples over \mathbb{F} and $x \in \mathbb{F}^3$ with $x = (X, Y, Z)$. Then there is exactly one line in \mathbb{F}^3 that intersects both $(0, 0, 0)$ and x . This line is given by

$$[X : Y : Z] := \{(k \cdot X, k \cdot Y, k \cdot Z) \mid k \in \mathbb{F}\} \quad (4.21)$$

A point in the projective plane over \mathbb{F} is then defined as such a line and the projective plane is the set of all such points, that is

$$\mathbb{FP}^2 := \{[X : Y : Z] \mid (X, Y, Z) \in \mathbb{F}^3 \text{ with } (X, Y, Z) \neq (0, 0, 0)\} \quad (4.22)$$

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

To understand why $[X : Y : Z]$ is called a line, consider the situation where the underlying field \mathbb{F} are the real numbers \mathbb{R} . Then \mathbb{R}^3 can be seen as the three dimensional space and $[X : Y : Z]$ is then an ordinary line in this 3-dimensional space that intersects zero and the point with coordinates X, Y and Z .

The key observation here is that points in the projective plane are lines in the 3-dimensional space \mathbb{F}^3 , also for finite fields, the terms space and line share very little visual similarity with their counterparts over the real 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 rather, where two different coordinates (X_1, Y_1, Z_1) and (X_2, Y_2, Z_2) , with describe the same point, if and only if there is some field element k , such that $(X_1, Y_1, Z_1) = (k \cdot X_2, k \cdot Y_2, k \cdot Z_2)$. Point $[X : Y : Z]$ are called **projective coordinates**.

Notation and Symbols 6 (Projective coordinates). *Projective coordinates of the form $[X : Y : 1]$ are descriptions of so-called **affine points** and 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 64. Consider the field \mathbb{F}_3 from example XXX. 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 contain 13 elements.

add reference

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 $(0,0,0)$. Since those lines are parameterized by tuples (x_1, x_2, x_3) . We compute:

$$\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}$$

Those lines define the 13 points in the projective plane $\mathbb{F}_3\mathbb{P}$ as follows

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

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

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

Exercise 34. *Construct the so-called Fano plane, that is, the projective plane over the finite field \mathbb{F}_2 .*

Chapter 5

Elliptic Curves

TODO: Elliptic Curve asymmetric cryptography examples. Private key, generator, public key. Generally speaking, elliptic curves are "curves" defined in geometric planes like the Euklidean or the projective plane over some given field. One of the key features of elliptic curves over finite fields from the point of view of cryptography is their set of points has a group law, such that the resulting group is finite and cyclic and it is believed that the discrete logarithm problem on these groups is hard.

A special class of elliptic curves are so called *pairing friendly curve*, which have a notation of a group pairing as defined in XXX. This pairing has cryptographicall nice prperties. Those curve are useful in the development of SNAKS, since they allow to compute so called R1CS-satisfiability "in the exponent" (THIS HAS TO BE REWRITTEN WITH WAY MORE DETAIL)

In this chapter we introduce epileptic curves as they are used in pairing based approaches to the construction of snarks. The eliptic curves we consider are all defined over prime fields or prime field extensions and the reader should be familiar with the contend of the previous section on those fields.

In its most generality elliptic curves are defined as a smooth projective curve of genus 1 defined over some field \mathbb{F} with a distinguished \mathbb{F} -rational point, but this definition is not very useful for the introductory character of this book. We will therefore look at 3 more practical definitions in the following sections, by introducing Weierstraß, Montgomery and Edwards curves. All of them are useful in cryptography and nesessary to understand for the contnuation of the book.

5.1 Elliptic Curve Arithmetics

5.1.1 Short Weierstraß Curves

In this section we introduce the so called short Weierstraß curves, which are the most general types of curves over finite fields of characteristic greater then 3.

We start with their reprrsentation in affine space. This reprresentation has the advantage that affine points are just pairs of numbers which is more convinient to work with for the beginner. However it has the disadvantage that a special "point at infinity" that is not a point on the curve, is necessary to describe the group structure. We introduce the elliptic curve group law and describe elliptic curve scalar multiplication, which is nothing but an instatation of the exponential map from general cyclic groups.

Then we look at the projective representation of short Weierstrass curves. It has the advantage that no special symbol is necessary to represent the point at infinity but comes with the drawback that projective points are classes of numbers, which might be a bit unusual for a beginner.

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

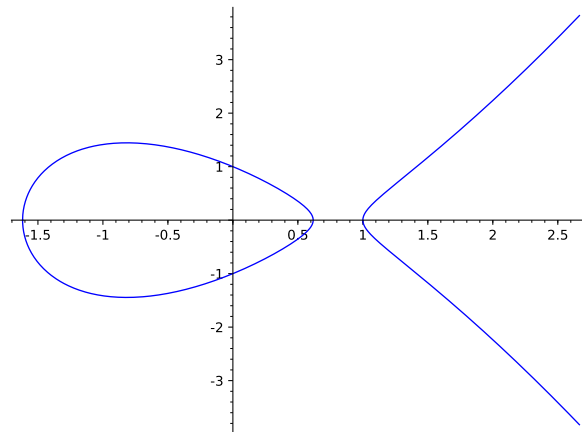
Affine short Weierstrass form Probably the least abstract and most straightforward way to introduce elliptic curves for non-mathematicians and beginners is the so-called affine representation of a short Weierstrass curve. To see what this is, let \mathbb{F} be a finite field of order q and $a, b \in \mathbb{F}$ two field elements such that $4a^3 + 27b^2 \bmod q \neq 0$. Then a **short Weierstrass elliptic curve** $E(\mathbb{F})$ over \mathbb{F} in its affine representation is the set

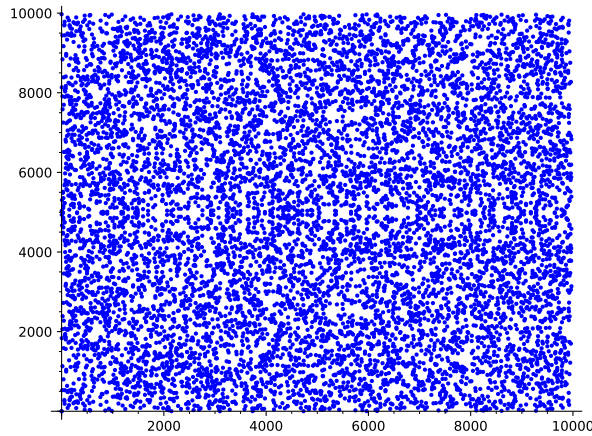
$$E(\mathbb{F}) = \{(x, y) \in \mathbb{F} \times \mathbb{F} \mid y^2 = x^3 + a \cdot x + b\} \cup \{\mathcal{O}\} \quad (5.1)$$

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**.

Notation and Symbols 7. *In the literature, the set $E(\mathbb{F})$, which includes the symbol \mathcal{O} is often called the set of rational points of the elliptic curve, in which case the curve itself is usually written as E/\mathbb{F} . However in what follows we will frequently identify an elliptic curve with its set of rational points and therefore use the symbol $E(\mathbb{F})$ instead. This is possible in our case, since we only really care about the group structure of the curve in consideration.*

The term "curve" appears, because in the ordinary 2-dimensional plane \mathbb{R}^2 , the set of all points (x, y) 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 in the real affine plane \mathbb{R}^2 , that is the pair (x, y) contains real numbers, while the second one is defined in the affine plane \mathbb{F}_{9973}^2 , which means that both x and y are from the prime field \mathbb{F}_{9973} . Every blue dot represents a pair (x, y) that is a solution to $y^2 = x^3 - 2x + 1$ and as we can see the second curve hardly looks like a geometric structure one would naturally call a curve. So the geometric intuitions from \mathbb{R}^2 is kind of obfuscated in curves over finite fields.

The identity $6 \cdot (4a^3 + 27b^2) \bmod q \neq 0$ ensures that the curve is non-singular, which basically means that the curve has no cusps or self-intersections.

When dealing with elliptic curves computations can quickly become cumbersome and tedious. So on the one hand side the reader is advised to do as many computations in a pen and paper style as possible. This helps a lot to get a deeper understanding for the details. On the other hand side however, computations are sometimes simply too large to be done by hand and one might get lost in the details. Fortunately sage is very helpful in dealing with elliptic curves. It is there a goal of this book to introduce the reader to the great elliptic curve capabilities of sage. One way to define elliptic curves and work with them goes like this: ?? The following three examples will give a more practical understanding of what an elliptic curve is and how we can compute them. The reader is advised to read them carefully and ideally to parallel the computation themselves. We will repeatedly build on these examples in this chapter and use the second example at various places in this book.

Example 65. *To provide the reader with a small example of an elliptic curve, where all computation can be done in a pen and paper style, consider the prime field \mathbb{F}_5 from example (XXX). The reader who had worked through the examples and exercises in the previous section knows this prime field well.*

To define an elliptic curve over \mathbb{F}_5 , we have to choose two numbers a and b from that field. Assuming we choose $a = 1$ and $b = 1$ then $4a^3 + 27b^2 \equiv 1 \pmod{5}$ from which follows that the corresponding elliptic curve $E_1(\mathbb{F}_5)$ is given by the set of all pairs (x, y) from \mathbb{F}_5 that satisfy the equation $y^2 = x^3 + x + 1$, together with the special symbol \mathcal{O} , which represents the "point at infinity".

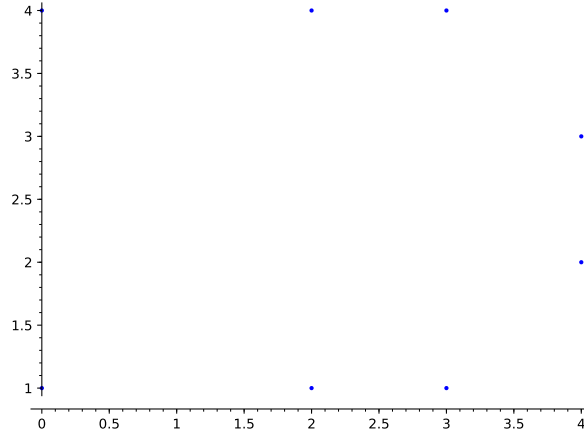
To get a better understanding of that curve, observe that if we choose arbitrarily the pair $(x, y) = (1, 1)$, we see that $1^2 \neq 1^3 + 1 + 1$ and hence $(1, 1)$ is not an element of the curve $E_1(\mathbb{F}_5)$. On the other hand choosing for example $(x, y) = (2, 1)$ gives $1^2 = 2^3 + 2 + 1$ and hence the pair $(2, 1)$ is an element of $E_1(\mathbb{F}_5)$ (Remember that all computations are done in modulo 5 arithmetic).

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:

$$E_1(\mathbb{F}_5) = \{\mathcal{O}, (0, 1), (2, 1), (3, 1), (4, 2), (4, 3), (0, 4), (2, 4), (3, 4)\}$$

So our elliptic curve is a set of 9 elements. 8 of which are pairs of numbers and one special symbol \mathcal{O} . Visualizing E_1 gives:



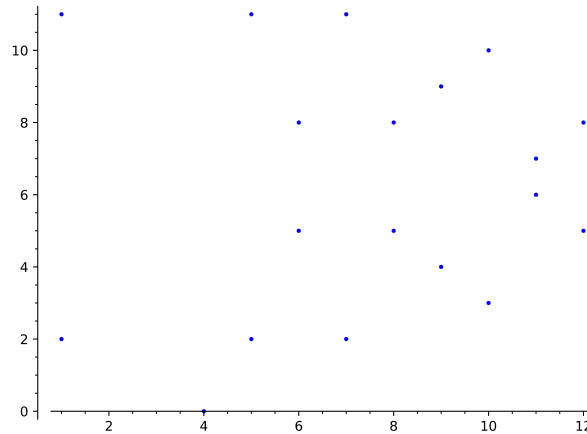
In the development of SNARKS it is sometimes necessary to do elliptic curve cryptograph "in a circuit", which basically means that the elliptic curves needs to be implemented in a certain SNARK-friendly way. We will look at what this means in XXX. To be able to do this efficiently it is desirable to have curves with special properties. The following example is a pen and paper version of such a curve, that parallels the definition of a cryptographically secure curve called *Baby-JubJub* which is extensively used in real world snarks. The interested reader is advised to read this example carefully as we will use it and build on it in various places throughout the book.

Example 66 (Pen-JubJub). Consider the prime field \mathbb{F}_{13} from exercise XXX. 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 write PJJ_13 for this curve and call it the *Pen-JubJub* curve.

Now 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

$$PJJ_13 = \{\mathcal{O}, (1, 2), (1, 11), (4, 0), (5, 2), (5, 11), (6, 5), (6, 8), (7, 2), (7, 11), (8, 5), (8, 8), (9, 4), (9, 9), (10, 3), (10, 10), (11, 6), (11, 7), (12, 5), (12, 8)\}$$

As we can see the curve consist of 20 points. 19 points from the affine plane and the point at infinity. To get a visual impression of the PJJ_13 curve, we might plot all of its points (except the point at infinity) in the $\mathbb{F}_{13} \times \mathbb{F}_{13}$ affine plane. We get:



As we will see in what follows this curve is kind of special as it is possible to represent it in two alternative forms, called the Montgomery and the twisted Edwards form (See xxx and XXX).

Now that we have seen two pen and paper friendly elliptic curves, let's 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. The only difference is that the prime number modulus of the prime field is much larger. Typical examples use prime numbers, which have binary representations in the size of more than double the size of the desired security level. So if for example a security of 128 bit is desired, a prime modulus of binary size ≥ 256 is chosen. The following example provides such a curve.

Example 67 (Bitcoin's Secp256k1 curve). To give an example of a real world, cryptographically secure curve, let's 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 prime number

$$p = 115792089237316195423570985008687907853269984665640564039457584007908834671663$$

which has a binary representation that needs 256 bits. This implies that the \mathbb{F}_p approximately contains 2^{256} many elements. So the underlying field is large. To get an image 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.

Curve Secp256k1 is then defined by the parameters $a, b \in \mathbb{F}_p$ with $a = 0$ and $b = 7$. Since $4 \cdot 0^3 + 27 \cdot 7^2 \mod p = 1323$, those parameters indeed define an elliptic curve given by

$$\text{Secp256k1} = \{(x, y) \in \mathbb{F}_p \times \mathbb{F}_p \mid y^2 = x^3 + 7\}$$

Clearly Secp256k1 is a curve, too large to do computations by hand, since it can be shown that Secp256k1 contains

$$r = 115792089237316195423570985008687907852837564279074904382605163141518161494337$$

many elements, where r is a prime number that also has a binary representation of 256 bits. Cryptographically secure elliptic curves are therefore not useful in pen and paper computations. Fortunately Sage handles large curves efficiently: ??

Exercise 35. Look-up the definition of curve BLS12-381, implement it in Sage and compute its order.

Affine compressed representation As we have seen in example XXX, cryptographically secure elliptic curves are defined over large prime fields, where elements of those fields typically need more than 255 bits storage on a computer. Since elliptic curve points consists of pairs of those field element, they need double that amount of storage.

To reduce the amount of space needed to represent a curve point note however, that up to a sign the y -coordinate of a curve point can be computed from the x -coordinate, by simply inserting x into the Weierstraß equation and then computing the roots of the result. This gives two results and it follows that we can represent a curve point in **compressed form** by simply storing the x -coordinate together with a single sign bit only, the latter of which deterministically decides which of the two roots to choose. In case that the y -coordinate is zero, both sign bit give the same result.

For example 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.

Example 68 (Pen-JubJub). *To understand the concept of compressed curve points a bit better consider the PJJ_13 curve from example XXX 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 PJJ_13 -point need 8-bits of storage in uncompressed form, while it would need only 5 bits in compressed form. To see how this works, recall that in uncompressed form we have*

$$PJJ_13 = \{\mathcal{O}, (1,2), (1,11), (4,0), (5,2), (5,11), (6,5), (6,8), (7,2), (7,11), \\ (8,5), (8,8), (9,4), (9,9), (10,3), (10,10), (11,6), (11,7), (12,5), (12,8)\}$$

Using the technique of point compression, we can replace the y -coordinate in each (x,y) pair by a sign bit, indicating, wheather or not y is closer to 0 or to 13. So y values in the range $[0, \dots, 6]$ having sign bit 0 and y -values in the range $[7, \dots, 12]$ having sign bit 1. Applying this to the points in PJJ_13 gives the compressed representation:

$$PJJ_13 = \{\mathcal{O}, (1,0), (1,1), (4,0), (5,0), (5,1), (6,0), (6,1), (7,0), (7,1), \\ (8,0), (8,1), (9,0), (9,1), (10,0), (10,1), (11,0), (11,1), (12,0), (12,1)\}$$

Note that the numbers $7, \dots, 12$ are the negatives (additive inverses) of the numbers $1, \dots, 6$ in modular 13 arithmetics and that $-0 = 0$. Calling the compression bit a "sign bit" therefore makes sense.

To recover the uncompressed point of say $(5,1)$, we insert the x -ccordinate 5 into the Weierstraß equation and get $y^2 = 5^3 + 8 \cdot 5 + 8 = 4$. As expected 4 is a quadratic residue in \mathbb{F}_{13} with roots $\sqrt{4} = \{2, 11\}$. Now since the sign bit of the point is 1, we have to choose the root closer to the modulus 13 which is 11. The uncompressed point is therefore $(5, 11)$.

Looking at the previous examples, compression rate looks not very impressive. The followin example therefore looks at the Secp256k1 curve to show that compression is actually useful.

Example 69. *Consider the Secp256k1 curve from example XXX again. The following code involves sage to generate a random affine curve point, we then apply our compression method ??*

Affine group law One of the key properties of an elliptic curve is that it is possible to define a group law on the set of its rational points, such that the point at infinity serves as the neutral element and inverses are reflections on the x -axis.

The origin of this law can be understood in a geometric picture and is known as the *chord-and-tangent rule*. In the affine representation of a short Weierstraß curve, the rule can be described in the following way:

- (Point addition) Let $P, Q \in E(\mathbb{F}) \setminus \{\mathcal{O}\}$ with $P \neq Q$ be two distinct points on an elliptic curve, that are both not the point at infinity. Then the sum of P and Q is defined as follows: Consider the line l which intersects the curve in P and Q . If l intersects the elliptic curve 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. If it does not intersect the curve at a third point define the sum to be the point at infinity \mathcal{O} . It can be shown, that no such chord-line will intersect the curve in more than three points, so addition is not ambiguous.
- (Point doubling) Let $P \in E(\mathbb{F}) \setminus \{\mathcal{O}\}$ be a point on an elliptic curve, that is not the point at infinity. Then the sum of P with itself (the doubling) is defined as follows: Consider the line which is tangent to the elliptic curve at P , if this line intersects the elliptic curve at a second point R' . The sum $2P = P + P$ is then the reflection of R' at the x -axis. If it does not intersect the curve at a third point define the sum to be the point at infinity \mathcal{O} . It can be shown, that no such tangent-line will intersect the curve in more than two points, so addition is not ambiguous.
- (Point at infinity) We define the point at infinity \mathcal{O} as the neutral element of addition, that is we define $P + \mathcal{O} = P$ for all points $P \in E(\mathbb{F})$.

It can be shown that the points of an elliptic curve form a commutative group with respect to the tangent and chord rule, such that \mathcal{O} acts the neutral element and the inverse of any element $P \in E(\mathbb{F})$ is the reflection of P on the x -axis.

To translate the geometric description into algebraic equations, first observe that for any two given curve points $(x_1, y_1), (x_2, y_2) \in E(\mathbb{F})$, it can be shown that the identity $x_1 = x_2$ implies $y_2 = \pm y_1$, which shows that the following rules are a complete description of the affine addition law.

- (Neutral element) Point at infinity \mathcal{O} is the neutral element.
- (Additive inverse) The additive inverse of \mathcal{O} is \mathcal{O} and for any other curve point $(x, y) \in E(\mathbb{F}) \setminus \{\mathcal{O}\}$, the additive inverse is given by $(x, -y)$.
- (Addition rule) For any two curve points $P, Q \in E(\mathbb{F})$ addition is defined by one of the following three cases:
 1. (Adding the neutral element) If $Q = \mathcal{O}$, then the sum is defined as $P \oplus Q = P$.
 2. (Adding inverse elements) If $P = (x, y)$ and $Q = (x, -y)$, the sum is defined as $P \oplus Q = \mathcal{O}$.
 3. (Adding non self-inverse equal points) If $P = (x, y)$ and $Q = (x, y)$ with $y \neq 0$, the sum $2P = (x', y')$ is defined by

$$x' = \left(\frac{3x^2 + a}{2y} \right)^2 - 2x \quad , \quad y' = \left(\frac{3x^2 + a}{2y} \right)^2 (x - x') - y$$

4. (Adding non inverse different points) If $P = (x_1, y_1)$ and $Q = (x_2, y_2)$ such that $x_1 \neq x_2$, the sum $R = P + Q$ with $R = (x_3, y_3)$ is defined by

$$x_3 = \left(\frac{y_2 - y_1}{x_2 - x_1} \right)^2 - x_1 - x_2 \quad , \quad y_3 = \left(\frac{y_2 - y_1}{x_2 - x_1} \right) (x_1 - x_3) - y_1$$

Note that short Weierstraß curve points P with $P = (x, 0)$ are inverse to themselves, which implies $2P = \mathcal{O}$ in this case.

Notation and Symbols 8. Let \mathbb{F} be a field and $E(\mathbb{F})$ be an elliptic curve over \mathbb{F} . We write \oplus for the group law on $E(\mathbb{F})$ and $(E(\mathbb{F}), \oplus)$ for the group of rational points.

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 the next paragraph this can be 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 70. Consider the elliptic curve $E_1(\mathbb{F}_5)$ from example XXX again. As we have seen, the set of rational points contains 9 elements and is given by

$$E_1(\mathbb{F}_5) = \{\mathcal{O}, (0, 1), (2, 1), (3, 1), (4, 2), (4, 3), (0, 4), (2, 4), (3, 4)\}$$

We know that this set defines a group, so we can add any two elements from $E_1(\mathbb{F}_5)$ 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, that is rule number 4 from XXX to compute the sum $(0, 1) \oplus (4, 2)$. We get

$$\begin{aligned} x_3 &= \left(\frac{y_2 - y_1}{x_2 - x_1} \right)^2 - x_1 - x_2 && \# \text{ insert points} \\ &= \left(\frac{2 - 1}{4 - 0} \right)^2 - 0 - 4 && \# \text{ simplify in } \mathbb{F}_5 \\ &= \left(\frac{1}{4} \right)^2 + 1 = 4^2 + 1 = 1 + 1 = 2 \end{aligned}$$

$$\begin{aligned} y_3 &= \left(\frac{y_2 - y_1}{x_2 - x_1} \right) (x_1 - x_3) - y_1 && \# \text{ insert points} \\ &= \left(\frac{2 - 1}{4 - 0} \right) (0 - 2) - 1 && \# \text{ simplify in } \mathbb{F}_5 \\ &= \left(\frac{1}{4} \right) \cdot 3 + 4 = 4 \cdot 3 + 4 = 2 + 4 = 1 \end{aligned}$$

So in our elliptic curve $E_1(\mathbb{F}_5)$ we get $(0, 1) \oplus (4, 2) = (2, 1)$ and indeed the pair $(2, 1)$ is an element of $E_1(\mathbb{F}_5)$ as expected. On the other hand we have $(0, 1) \oplus (0, 4) = \mathcal{O}$, since both points have equal x -coordinates and inverse y -coordinates rendering them as inverse to each other.

Adding the point $(4, 2)$ to itself, we have to use the tangent rule, that is rule 3 from XXX. We get

$$\begin{aligned}
 x' &= \left(\frac{3x^2 + a}{2y} \right)^2 - 2x && \# \text{ insert points} \\
 &= \left(\frac{3 \cdot 4^2 + 1}{2 \cdot 2} \right)^2 - 2 \cdot 4 && \# \text{ simplify in } \mathbb{F}_5 \\
 &= \left(\frac{3 \cdot 1 + 1}{4} \right)^2 + 3 \cdot 4 = \left(\frac{4}{4} \right)^2 + 2 = 1 + 2 = 3 \\
 \\
 y' &= \left(\frac{3x^2 + a}{2y} \right)^2 (x - x') - y && \# \text{ insert points} \\
 &= \left(\frac{3 \cdot 4^2 + 1}{2 \cdot 2} \right)^2 (4 - 3) - 2 && \# \text{ simplify in } \mathbb{F}_5 \\
 &= 1 \cdot 1 + 3 = 4
 \end{aligned}$$

So in our elliptic curve $E_1(\mathbb{F}_5)$ we get the doubling $2 \cdot (4, 2)$, that is $(4, 2) \oplus (4, 2) = (3, 4)$ and indeed the pair $(3, 4)$ is an element of $E_1(\mathbb{F}_5)$ as expected. The group $E_1(\mathbb{F}_5)$ has no self inverse points other than the neutral element \mathcal{O} , since no point has 0 as its y-coordinate. We can invoke sage to double check the computations. ??

Example 71 (Pen-JubJub). Consider the PJJ_13-curve from example XXX again and recall that its group of rational points is given by

$$\begin{aligned}
 PJJ_13 = \{ &\mathcal{O}, (1, 2), (1, 11), (4, 0), (5, 2), (5, 11), (6, 5), (6, 8), (7, 2), (7, 11), \\
 &(8, 5), (8, 8), (9, 4), (9, 9), (10, 3), (10, 10), (11, 6), (11, 7), (12, 5), (12, 8) \}
 \end{aligned}$$

In contrast to the group from the previous example, this group contains a self inverse point, which is different from the neutral element, given by $(4, 0)$. To see what this means, observe that we can not add $(4, 0)$ to itself using the tangent rule 3 from XXX, as the y-coordinate is zero. Instead we have to use rule 2, since $0 = -0$. We therefore get $(4, 0) \oplus (4, 0) = \mathcal{O}$ in PJJ_13. The point $(4, 0)$ is therefore inverse to itself, as adding it to itself gives the neutral element. ??

Example 72. Consider the Secp256k1 curve from example XXX again. The following code involves sage to generate a random affine curve point, we then apply our compression method ??

Exercise 36. Consider the PJJ_13-curve from example XXX.

1. Compute the inverse of $(10, 10)$, \mathcal{O} , $(4, 0)$ and $(1, 2)$.
2. Compute the expression $3 * (1, 11) - (9, 9)$.
3. Solve the equation $x + 2(9, 4) = (5, 2)$ for some $x \in PJJ_13$
4. Solve the equation $x \cdot (7, 11) = (8, 5)$ for $x \in \mathbb{Z}$

Scalar multiplication As we have seen in the previous section, elliptic curves $E(\mathbb{F})$ have the structure of a commutative group associated to them. It can moreover be shown, that this group is finite and cyclic, whenever the field is finite.

To understand the elliptic curve scalar multiplication, recall from XXX that every finite cyclic group of order q has a generator g and an associated exponential map $g^{(\cdot)} : \mathbb{Z}_q \rightarrow \mathbb{G}$, where g^n is the n -fold product of g with itself.

Now, elliptic curve scalar multiplication is then nothing but 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 r and P a generator of $E(\mathbb{F})$. Then the **elliptic curve scalar multiplication** with base P is given by

$$[\cdot]P : \mathbb{Z}_r \rightarrow E(\mathbb{F}); m \mapsto [m]P$$

where $[0]P = \mathcal{O}$ and $[m]P = P + P + \dots + P$ is the m -fold sum of P with itself. Elliptic curve scalar multiplication is therefore nothing but an instantiation of the general exponential map, when using additive instead of multiplicative notation. This map is a homomorphism of groups, which means that $[n + m]P = [n]P \oplus [m]P$.

As with all finite, cyclic groups the inverse of the exponential map exist and is usually called the *elliptic curve discrete logarithm map*. However elliptic curve are believed to be XXX-groups, which means that we don't know of any efficient way to actually compute this map.

Scalar multiplication and its inverse, the elliptic curve discrete logarithm, define the elliptic curve discrete logarithm *problem*, which consists of finding solutions $m \in \mathbb{Z}_r$, such that

$$P = [m]Q \tag{5.2}$$

holds. Any solution m is usually called a *discrete logarithm* relation between P and Q . If Q is a generator of the curve, then there is a discrete logarithm relation between Q and any other point, since Q generates the group by repeatedly adding Q to itself. So for generator Q and point P , we know some discrete logarithm relation exist. However since elliptic curves are believed to be XXX-groups, finding actual relations m is computationally hard, with runtimes approximately in the size of the order of the group. In practice we often need the assumption that a discrete logarithm relation exists, but that at the same time no one knows this relation.

One useful property of the exponential map in regard to the examples in this book, is that it can be used to greatly simplify pen and paper computations. As we have seen in example XXX, computing the elliptic curve addition law takes quite a bit of effort, when done without a computer. However when g is a generator of small pen and paper elliptic curve group of order r , we can use the exponential map to write the group as

$$\mathbb{G} = \{[1]g \rightarrow [2]g \rightarrow [3]g \rightarrow \dots \rightarrow [r-1]g \rightarrow \mathcal{O}\} \tag{5.3}$$

using cofactor clearing, which implies that $[r]g = \mathcal{O}$. "Logarithmic ordering" like this greatly simplifies complicated elliptic curve addition to the much simpler case of modular r addition. So in order to add two curve points P and Q , we only have to look up their discrete log relations with the generator, say $P = [n]g$ and $Q = [m]g$ and compute the sum as $P \oplus Q = [n + m]g$. This is, of course, only possible for small groups which we can organize as in XXX.

In the following example we will look at some implications of the fact that elliptic curves are finite cyclic groups. We will apply the fundamental theorem of finite cyclic groups and look how it reflects on the curves in consideration.

Example 73. Consider the elliptic curve group $E_1(\mathbb{F}_5)$ from example XXX. Since it is a finite cyclic group of order 9 and the prime factorization of 9 is $3 \cdot 3$, we can use the fundamental

theorem of finite cyclic groups to reason about all its subgroups. In fact since the only prime factor of 9 is 3, we know that $E_1(\mathbb{F}_5)$ has the following subgroups:

- $\mathbb{G}_1 = E_1(\mathbb{F}_5)$ is a subgroup of order 9. By definition any group is a subgroup of itself.
- $\mathbb{G}_2 = \{(2,1), (2,4), \mathcal{O}\}$ is a subgroup of order 3. This is the subgroup associated to the prime factor 3.
- $\mathbb{G}_3 = \{\mathcal{O}\}$ is a subgroup of order 1. This is the trivial subgroup.

Moreover since $E_1(\mathbb{F}_5)$ and all its subgroups are cyclic, we know from XXX, that they must have generators. For example the curve point $(2,1)$ is a generator of the order 3-subgroup \mathbb{G}_2 , since every element of \mathbb{G}_2 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 XXX, that it gives rise to an exponential map from the finite field \mathbb{F}_3 onto \mathbb{G}_2 defined by scalar multiplication

$$[\cdot](2,1) : \mathbb{F}_3 \rightarrow \mathbb{G}_2 : x \mapsto [x](2,1)$$

To give an example of a generator that generates the entire group $E_1(\mathbb{F}_5)$ consider the point $(0,1)$. Applying the tangent rule repeatedly we compute with some effort:

$$\begin{array}{ll} [0](0,1) = \mathcal{O} & [1](0,1) = (0,1) \\ [2](0,1) = (4,2) & [3](0,1) = (2,1) \\ [4](0,1) = (3,4) & [5](0,1) = (3,1) \\ [6](0,1) = (2,4) & [7](0,1) = (4,3) \\ [8](0,1) = (0,4) & [9](0,1) = \mathcal{O} \end{array}$$

Again, since $(2,1)$ is a generator we know from XXX, that it gives rise to an exponential map. However since the group order is not a prime number, the exponential maps, does not map a from any field but from the residue class ring \mathbb{Z}_9 only:

$$[\cdot](0,1) : \mathbb{Z}_9 \rightarrow \mathbb{G}_1 : x \mapsto [x](0,1)$$

Using the generator $(0,1)$ and its associated exponential map, we can write $E(\mathbb{F}_1)$ i logarithmic order with respect to $(0,1)$ as explained in XXX. We get

$$E_1(\mathbb{F}_5) = \{(0,1) \rightarrow (4,2) \rightarrow (2,1) \rightarrow (3,4) \rightarrow (3,1) \rightarrow (2,4) \rightarrow (4,3) \rightarrow (0,4) \rightarrow \mathcal{O}\}$$

indicating that the first element is a generator and the n -th element is the scalar product of n and the generator. To how this logarithmic orders like this simplify the computations in small elliptic curve groups, consider example XXX again. In that example we use the chord and tangent rule to compute $(0,1) \oplus (4,2)$. Now in the logarithmic order of $E_1(\mathbb{F})$ we can compute that sum much easier, since we can directly see that $(0,1) = [1](0,1)$ and $(4,2) = [2](0,1)$. We can then deduce $(0,1) \oplus (4,2) = (2,1)$ immediately, since $[1](0,1) \oplus [2](0,1) = [3](0,1) = (2,1)$.

To give another example, we can immediately see that $(3,4) \oplus (4,3) = (4,2)$, without doing any expensive elliptic curve addition, since we know $(3,4) = [4](0,1)$ as well as $(4,3) = [7](0,1)$

from the logarithmic representation of $E_1(\mathbb{F}_5)$ and since $4 + 7 = 2$ in \mathbb{Z}_9 , the result must be $[2](0, 1) = (4, 2)$.

Finally we can use $E_1(\mathbb{F}_5)$ as an example to understand the concept of cofactor clearing from XXX. Since the order of $E_1(\mathbb{F}_5)$ is 9 we only have a single factor, which happen to be the cofactor as well. Cofactor clearing then implies that we can map any element from $E_1(\mathbb{F}_5)$ onto its prime factor group \mathbb{G}_2 by scalar multiplication with 3. For example taking the element $(3, 4)$ which is not in \mathbb{G}_2 and multiplying it with 3, we get $[3](3, 4) = (2, 1)$, which is an element of \mathbb{G}_2 as expected.

In the following example we will look at the subgroups of our pen-jubjub curve, define generators and compute the logarithmic order for pen and paper computations. Then we have another look at the principle of cofactor clearing.

Example 74. Consider the pen-jubjub curve PJJ_13 from example XXX again. Since the order of PJJ_13 is 20 and the prime factorization of 20 is $2^2 \cdot 5$, we know that the PJJ_13 contains a "large" prime order subgroup of size 5 and a small prime order subgroup of size 2.

To compute those groups we can apply the technique of cofactor clearing in a try and repeat loop. We start the loop by arbitrarily choose an element $P \in PJJ_13$. Then we multiply that element with the cofactor of the group, we want to compute. If the result is \mathcal{O} , we try a different element and repeat the process until the result is different from the point at infinity.

To compute a generator for the small prime order subgroup $(PJJ_13)_2$, first observe that the cofactor is 10, since $20 = 2 \cdot 10$. We then arbitrarily choose the curve point $(5, 11) \in PJJ_13$ 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 $(PJJ_13)_2$. Logarithmic order of then gives

$$(PJJ_13)_2 = \{(4, 0) \rightarrow \mathcal{O}\}$$

as expected, since we know from example XXX that $(4, 0)$ is self inverse, with $(4, 0) \oplus (4, 0) = \mathcal{O}$. Double checking the computations using sage: **??** We can apply the same reasoning to the "large" prime order subgroup $(PJJ_13)_5$, which contains 5 elements. To compute a generator for this group, first observe that the associated cofactor is 4, since $20 = 5 \cdot 4$. We choose the curve point $(9, 4) \in PJJ_13$ again and compute $[4](9, 4) = (7, 11)$ and we can deduce that $(7, 11)$ is a generator of $(PJJ_13)_5$. Using the generator $(7, 11)$, we compute the exponential map $[\cdot](7, 11) : \mathbb{F}_5 \rightarrow PJJ_13$ and get

$$\begin{aligned} [0](7, 11) &= \mathcal{O} \\ [1](7, 11) &= (7, 11) \\ [2](7, 11) &= (8, 5) \\ [3](7, 11) &= (8, 8) \\ [4](7, 11) &= (7, 2) \end{aligned}$$

We can use this computation to write the large order prime group $(PJJ_13)_5$ of the pen-jubjub curve in logarithmic order, which we will use quite frequently in what follows. We get:

$$(PJJ_13)_5 = \{(7, 11) \rightarrow (8, 5) \rightarrow (8, 8) \rightarrow (7, 2) \rightarrow \mathcal{O}\}$$

From this, we can immediately see that for example $(8, 8) \oplus (7, 2) = (8, 5)$, 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 arefact of small groups where it is possible to write the entire group in a logarithmic order. The following example gives some understanding, why this is not possible in cryptographically secure groups

Example 75. *SEKTP BICOIN. DISCRET LOG HARDNESS PROHIBITS ADDITION IN THE FIELD...*

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 XXX we know, that points at infinity are handled as ordinary points in projective geometry. It make therefore 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 , $a, b \in \mathbb{F}$ two field elements such that $4a^3 + 27b^2 \bmod q \neq 0$ and \mathbb{FP}^2 the projective plane over \mathbb{F} . Then a **short Weierstrass elliptic curve** over \mathbb{F} in its projective representation is the set

$$E(\mathbb{FP}^2) = \{[X : Y : Z] \in \mathbb{FP}^2 \mid Y^2 \cdot Z = X^3 + a \cdot X \cdot Z^2 + b \cdot Z^3\} \quad (5.4)$$

of all points $[X : Y : Z] \in \mathbb{FP}^2$ from the projective plane, that satisfy the *homogenous* cubic equation $Y^2 \cdot Z = X^3 + a \cdot X \cdot Z^2 + b \cdot Z^3$.

To understand how the point at infinity is unified in this definition, recall from XXX that, in projective geometry points at infinity are given by homogeneous coordinates $[X : Y : 0]$. Inserting representatives $(x_1, y_1, 0) \in [X : Y : 0]$ from those classes into the defining homogenous cubic equations gives

$$\begin{aligned} y_1^2 \cdot 0 &= x_1^3 + a \cdot x_1 \cdot 0^2 + b \cdot 0^3 \\ 0 &= x_1^3 \end{aligned} \quad \Leftrightarrow$$

which shows that the only point at infinity that is also a point on a projective short Weierstraß curve is the class

$$[0, 1, 0] = \{(0, y, 0) \mid y \in \mathbb{F}\}$$

This point is the projective representation of \mathcal{O} . The projective representation of a short Weierstraß curve therefore has the advantage to not need a special symbol to represent the point at infinity \mathcal{O} from the affine definition.

Example 76. *To get an intuition of how an elliptic curve in projective geometry looks, consider curve $E_1(\mathbb{F}_5)$ from example (XXX). We know that in its affine representation, the set of rational points is given by*

$$E_1(\mathbb{F}_5) = \{\mathcal{O}, (0, 1), (2, 1), (3, 1), (4, 2), (4, 3), (0, 4), (2, 4), (3, 4)\}$$

which 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 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 homogenous cubic equation

$$y_1^2 z_1 = x_1^3 + 1 \cdot x_1 z_1^2 + 1 \cdot z_1^3$$

for any representative $(x_1, y_1, z_1) \in [X : Y : Z]$. We know from XXX, 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 XXX and see if both sides match.

For example, consider the projective point $[0 : 4 : 1]$. We know from XXX, that this point in the projective plane represents the line

$$[0 : 4 : 1] = \{(0, 0, 0), (0, 4, 1), (0, 3, 2), (0, 2, 3), (0, 1, 4)\}$$

in the three dimensional space \mathbb{F}^3 . To check whether or not $[0 : 4 : 1]$ satisfies XXX, we can insert any representative, that is we can insert any element from XXX. Each element satisfies the equation if and only if any other satisfies the equation. So we insert $(0, 4, 1)$ and get

$$1^2 \cdot 1 = 0^3 + 1 \cdot 0 \cdot 1^2 + 1 \cdot 1^3$$

which tells us that the affine point $[0 : 4 : 1]$ is indeed a solution. And as we can see, would just as well insert any other representative. For example inserting $(0, 3, 2)$ also satisfies XXX, since

$$3^2 \cdot 2 = 0^3 + 1 \cdot 0 \cdot 2^2 + 1 \cdot 2^3$$

To find the projective representation of E_1 , 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 can not satisfy XXX for any parameter a and b . So we can exclude it from our consideration.

Moreover a point at infinity $[X : Y : 0]$ can only satisfy equation XXX 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 from the finite field. So we can exclude all points at infinity except the point $[0 : 1 : 0]$.

So all points that remain are the affine points $[X : Y : 1]$. Inserting all of them into XXX we get the set of all projective curve points as

$$E_1(\mathbb{F}_5\mathbb{P}^2) = \{[0 : 1 : 0], [0 : 1 : 1], [2 : 1 : 1], [3 : 1 : 1], [4 : 2 : 1], [4 : 3 : 1], [0 : 4 : 1], [2 : 4 : 1], [3 : 4 : 1]\}$$

If we compare this with the affine representation we see that there is a 1:1 correspondence between the points in the affine representation XXX and the affine points in projective geometry and that the point $[0 : 1 : 0]$ represents the additional point \mathcal{O} in the projective representation.

Exercise 37. Compute the projective representation of the pen-jubjub curve and the logarithmic order of its large prime order subgroup with respect to the generator $(7, 11)$.

Projective Group law As we have seen in XXX, 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 rational points, described geometrically by the chord and tangent rule. 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 now, that in projective space it is guaranteed that any chord will always intersect the curve in three points and any tangent will intersect in two points including the tangent point. So the geometric picture simplifies as we don't need to consider external symbols and associated cases.

Again, 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 then usually described by the following algorithm, that minimizes the number of needed additions and multiplications in the base field.

Exercise 38. Compare that 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 have seen in example XXX, there was a close relation between the affine and the projective representation of a short Weierstrass curve. This was no accident. 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 given parameters a and b .

To specify the isomorphism, let $E(\mathbb{F})$ and $E(\mathbb{FP}^2)$ be an affine and a projective short Weierstraß curve defined for the same parameters a and b . Then the map

$$\Phi : E(\mathbb{F}) \rightarrow E(\mathbb{FP}^2) : \begin{array}{ll} (x, y) & \mapsto [x : y : 1] \\ \mathcal{O} & \mapsto [0 : 1 : 0] \end{array} \quad (5.5)$$

maps points from the affine representation to points from the projective representation of a short Weierstraß curve, that is if the pair of points (x, y) satisfies the affine equation $y^2 = x^3 + ax + b$, then all homogeneous coordinates $(x_1, y_1, z_1) \in [x : y : 1]$ satisfy the projective equation $y_1^2 \cdot z_1 = x_1^3 + ay_1 \cdot z_1^2 + b \cdot z_1^3$. The inverse is given by the map

$$\Phi^{-1} : E(\mathbb{FP}^2) \rightarrow E(\mathbb{F}) : [X : Y : Z] \mapsto \begin{cases} (\frac{X}{Z}, \frac{Y}{Z}) & \text{if } Z \neq 0 \\ \mathcal{O} & \text{if } Z = 0 \end{cases} \quad (5.6)$$

Note the only projective point $[X : Y : Z]$ with $Z \neq 0$ that satisfies XXX is given by the class $[0 : 1 : 0]$.

One key feature of Φ and its inverse is, that it respects the group structure, which means that $\Phi((x_1, y_1) \oplus (x_2, y_2))$ is equal to $\Phi(x_1, y_1) \oplus \Phi(x_2, y_2)$. The same holds true for the inverse map Φ^{-1} .

Maps with these properties are called *group isomorphisms* and from a mathematical point of view the existence of Φ implies, that both definitions are equivalent and implementations can choose freely between both representations.

5.1.2 Montgomery Curves

History and use of them (optimized scalar multiplication)

Affine Montgomery Form To see what a Montgomery curve in affine coordinates is, let \mathbb{F} be a finite field of characteristic > 2 and $A, B \in \mathbb{F}$ two field elements such that $B \neq 0$ and $A^2 \neq 4$. Then a **Montgomery elliptic curve** $M(\mathbb{F})$ over \mathbb{F} in its affine representation is the set

$$M(\mathbb{F}) = \{(x, y) \in \mathbb{F} \times \mathbb{F} \mid B \cdot y^2 = x^3 + A \cdot x^2 + x\} \cup \{\mathcal{O}\} \quad (5.7)$$

Algorithm 6 Projective 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: $[X_3 : Y_3 : Z_3] == [X_1 : Y_1 : Z_1] \oplus [X_2 : Y_2 : Z_2]$

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 distinguishid symbol \mathcal{O} , called the **point at infinity**.

Despite the fact that Montgomery curves look different then short Weierstrass curve, they are in fact 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 Weierstrass form. To see that assume that a curve in Montgomery form $By^2 = x^3 + Ax^2 + x$ is given. The associated Weierstrass form is then

$$y^2 = x^3 + \frac{3 - A^2}{3B^2} \cdot x + \frac{2A^3 - 9A}{27B^3}$$

On the other hand, an elliptic curve $E(\mathbb{F})$ over base field \mathbb{F} in Weierstrass form $y^2 = x^3 + ax + b$ can be converted to Montgomery form if and only if the following conditions hold:

- The number of points on $E(F)$ is divisible by 4
- The polynomial $z^3 + az + b \in \mathbb{F}[z]$ has at least one root $z_0 \in \mathbb{F}$
- $3z_0^2 + a$ is a quadratic residue in \mathbb{F} .

When these conditions are satisfied, then for $s = (\sqrt{3z_0^2 + a})^{-1}$ the equivalent Montgomery curve is defined by the equation

$$sy^2 = x^3 + (3z_0s)x^2 + x$$

If those properties are meet it is therefore possible to transform certain Weierstrass curve into Montgomery form. In the following example we will look at our pen-jubjub curve again and show that it is actually a Montgomery curve.

Example 77. Consider the prime field \mathbb{F}_{13} and the pen-jubjub curve PJJ_13 from example XXX. To see that it is a Montgomery curve, we have to check the properties from XXX:

Since the order of PJJ_13 is 20, which is divisible by 4, the first requirement is meet. Next, since $a = 8$ and $b = 8$, we have check if the polynomial $P(z) = z^3 + 8z + 8$ has a root in \mathbb{F}_{13} . We simply evaluate P at all numbers $z \in \mathbb{F}_{13}$ a find that $P(4) = 0$, so a root is given by $z_0 = 4$. In a last step we have to check, that $3 \cdot z_0^2 + a$ has a root in \mathbb{F}_{13} . We compute

$$\begin{aligned} 3z_0^2 + a &= 3 \cdot 4^2 + 8 \\ &= 3 \cdot 3 + 8 \\ &= 9 + 8 \\ &= 4 \end{aligned}$$

To see if 4 is a quadratic residue, we can use Eulers criterium XXX to compute the Legendre symbol of 4. We get:

$$\left(\frac{4}{13} \right) = 4^{\frac{13-1}{2}} = 4^6 = 1$$

so 4 indeed has a root in \mathbb{F}_{13} . In fact computing a root of 4 in \mathbb{F}_{13} is easy, since the integer root 2 of 4 is also one of its roots in \mathbb{F}_{13} . The other root is given by $13 - 4 = 9$.

Now since all requirements are met, we have shown that *PJJ_13* is indeed a Montgomery curve and we can use *XXX* to compute its associated Montgomery form. We compute

$$\begin{aligned}
 s &= \left(\sqrt{3 \cdot z_0^2 + 8} \right)^{-1} \\
 &= 2^{-1} && \# \text{ Fermat's little theorem} \\
 &= 2^{13-2} && \# 2048 \bmod 13 = 7 \\
 &= 7
 \end{aligned}$$

The defining equation for the Montgomery form of our pen-jubjub curve is then given by the following equation

$$\begin{aligned}
 sy^2 &= x^3 + (3z_0s)x^2 + x && \Rightarrow \\
 7 \cdot y^2 &= x^3 + (3 \cdot 4 \cdot 7)x^2 + x && \Leftrightarrow \\
 7 \cdot y^2 &= x^3 + 6x^2 + x
 \end{aligned}$$

So we get the defining parameters as $B = 7$ and $A = 6$ and we can write the pen-jubjub curve in its affine Montgomery representation as

$$PJJ_13 = \{(x, y) \in \mathbb{F}_{13} \times \mathbb{F}_{13} \mid 7 \cdot y^2 = x^3 + 6x^2 + x\} \cup \{\mathcal{O}\}$$

Now that we have the abstract definition of our pen-jubjub curve in Montgomery form, we can compute the set of points, by inserting all pairs $(x, y) \in \mathbb{F}_{13} \times \mathbb{F}_{13}$ similar to how we computed the curve points in its Weierstraß representation. We get

$$\begin{aligned}
 PJJ_13 = \{ &\mathcal{O}, (0, 0), (1, 4), (1, 9), (2, 4), (2, 9), (3, 5), (3, 8), (4, 4), (4, 9), \\
 &(5, 1), (5, 12), (7, 1), (7, 12), (8, 1), (8, 12), (9, 2), (9, 11), (10, 3), (10, 10) \}
 \end{aligned}$$

??

Affine Montgomery coordinate transformation Comparing the Montgomery representation of the previous example with the Weierstraß representation of the same curve, we see that there is a 1:1 correspondence between the curve points in both examples. This is no accident. In fact if $M_{A,B}$ is a Montgomery curve and $E_{a,b}$ a Weierstraß curve with $a = \frac{3-A^2}{3B^2}$ and $b = \frac{2A^2-9A}{27B^3}$ then the function

$$\Phi : M_{A,B} \rightarrow E_{a,b} : (x, y) \mapsto \left(\frac{3x+A}{3B}, \frac{y}{B} \right) \quad (5.8)$$

maps all points in Montgomery representation onto the points in Weierstraß representation. This map is a 1:1 correspondence (an isomorphism) and its inverse map is given by

$$\Phi^{-1} : E_{a,b} \rightarrow M_{A,B} : (x, y) \mapsto (s \cdot (x - z_0), s \cdot y) \quad (5.9)$$

where z_0 is a root of the polynomial $z^3 + az + b \in \mathbb{F}[z]$ and $s = (\sqrt{3z_0^2 + a})^{-1}$. Using this map, it is therefore possible for implementations of Montgomery curves to freely transit between the Weierstraß and the Montgomery representation. Note however that according to *XXX* not every Weierstraß curve is a Montgomery curve, as all of the properties from *XXX* have to be satisfied. The map Φ^{-1} therefore does not always exist.

Example 78. Consider our pen-jubjub curve again. In example XXX we derive its Weierstraß representation and in example XXX we derive its Montgomery representation.

To see how the coordinate transformation Φ works in this example, lets map points from the Montogomery representation onto points from the Weierstraß representation. Inserting for example the point $(0,0)$ from the Montomery representation XXX into Φ gives

$$\begin{aligned}\Phi(0,0) &= \left(\frac{3 \cdot 0 + A}{3B}, \frac{0}{B} \right) \\ &= \left(\frac{3 \cdot 0 + 6}{3 \cdot 7}, \frac{0}{7} \right) \\ &= \left(\frac{6}{8}, 0 \right) \\ &= (4,0)\end{aligned}$$

So the Montgomery point $(0,0)$ maps to the self inverse point $(4,0)$ of the Weierstraß representation. On the other hand we can use our computations of $s = 7$ and $z_0 = 4$ from XXX, to compute the inverse map Φ^{-1} , which maps point on the Weiertraß representation to points on the Mongomery form. Inserting for example $(4,0)$ we get

$$\begin{aligned}\Phi^{-1}(4,0) &= (s \cdot (4 - z_0), s \cdot 0) \\ &= (7 \cdot (4 - 4), 0) \\ &= (0,0)\end{aligned}$$

So as expected, the inverse maps maps the Weierstraß point back to where it came from on the Montgomery form. We can invoke sage to proof that our computation of Φ is correct: ??

Montgomery group law So we see that Montgomery curves a special cases of short Weierstrass curves. As such they have a group structure defined on the set of their points, which can also be derived from a chord and tangent rule. In accordance with short Weierstrass curves, it can be shown that the identity $x_1 = x_2$ implies $y_2 = \pm y_1$, which shows that the following rules are a complete description of the affine addition law.

- (Neutral element) Point at infinity \mathcal{O} is the neutral element.
- (Additive inverse) The additive inverse of \mathcal{O} is \mathcal{O} and for any other curve point $(x,y) \in M(\mathbb{F}_q) \setminus \{\mathcal{O}\}$, the additive inverse is given by $(x, -y)$.
- (Addition rule) For any two curve points $P, Q \in M(\mathbb{F}_q)$ addition is defined by one of the following cases:
 1. (Adding the neutral element) If $Q = \mathcal{O}$, then the sum is defined as $P + Q = P$.
 2. (Adding inverse elements) If $P = (x,y)$ and $Q = (x, -y)$, the sum is defined as $P + Q = \mathcal{O}$.
 3. (Adding non self-inverse equal points) If $P = (x,y)$ and $Q = (x,y)$ with $y \neq 0$, the sum $2P = (x', y')$ is defined by

$$x' = \left(\frac{3x_1^2 + 2Ax_1 + 1}{2By_1} \right)^2 \cdot B - (x_1 + x_2) - A \quad , \quad y' = \frac{3x_1^2 + 2Ax_1 + 1}{2By_1} (x_1 - x') - y_1$$

4. (Adding non inverse differen points) If $P = (x_1, y_1)$ and $Q = (x_2, y_2)$ such that $x_1 \neq x_2$, the sum $R = P + Q$ with $R = (x_3, y_3)$ is defined by

$$x' = \left(\frac{y_2 - y_1}{x_2 - x_1}\right)^2 B - (x_1 + x_2) - A, \quad y' = \frac{y_2 - y_1}{x_2 - x_1}(x_1 - x') - y_1$$

5.1.3 Twisted Edwards Curves

As we have seen in XXX both Weierstrass and Montgomery curves have somewhat complicated addition and doubling laws as many cases have to be distinguished. Those cases translate to branches in computer programs.

In the context of SNARK development two computational models for bounded computations, called *circuits* and *rank-1 constraint systems*, are used and program-branches are undesireably costly, when implemented in those models. It is therefore advantageous to look for curves with an addition/doubling rule, that requires no branches and as few field operations as possible.

Twisted Edwards curves are particular useful here as a subclass of these curves has a compact and easy to implement addition law that works for all point, including the point at infinity. Implementing that rule therefore needs no branching.

Twisted Edwards Form To see what an affine **twisted Edwards curve** looks like, let \mathbb{F} be a finite field of characteristic > 2 and $a, d \in \mathbb{F} \setminus \{0\}$ two non zero field elements with $a \neq d$. Then a **twisted Edwards ellipti curve** in its affine representation is the set

$$E(\mathbb{F}) = \{(x, y) \in \mathbb{F} \times \mathbb{F} \mid a \cdot x^2 + y^2 = 1 + d \cdot x^2 y^2\} \quad (5.10)$$

of all pairs (x, y) from $\mathbb{F} \times \mathbb{F}$, that satisfy the twisted Edwards equation $a \cdot x^2 + y^2 = 1 + d \cdot x^2 y^2$. A twisted Edwards curve is called an Edwards curve (non twisted), if the parameter a is equal to 1 and 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 curve look somewhat different from Weierstraß curves as their affine representation does not need a special symbol to represent the point at infinity. In fact we we will see that the pair $(0, 1)$ is always a point on any twisted Edwards curve and that it takes the role of the point at infinity.

Despite the different looks 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 $a \cdot x^2 + y^2 = 1 + d \cdot x^2 y^2$ is given. The associated Montgomery curve is then defined by the Montgomery equation

$$\frac{4}{a-d} y^2 = x^3 + \frac{2(a+d)}{a-d} \cdot x^2 + x \quad (5.11)$$

On the other hand a Montgomery curve $By^2 = x^3 + Ax^2 + x$ with $B \neq 0$ and $A^2 \neq 4$ can gives rise to a twisted Edwards curve defined by the equation

$$\left(\frac{A+2}{B}\right)x^2 + y^2 = 1 + \left(\frac{A-2}{B}\right)x^2 y^2 \quad (5.12)$$

Recalling from XXX that Montgomery curves are just a special class of Weierstraß, we now know that twisted Edwards curve are special Weierstraß curves too. So the more general way to describe elliptic curves are Weierstraß curves.

Example 79. Consider the pen jubjub curve from example XXX again. We know from XXX that it is a Montgomery curve and since Montgomery curves are equivalent to twisted Edwards curve, we want to write that curve in twisted Edwards form. We use XXX and compute the parameters a and d as

$$\begin{aligned} a &= \frac{A+2}{B} && \# \text{ insert } A=6 \text{ and } B=7 \\ &= \frac{8}{7} = 3 && \# 7^{-1} = 2 \\ \\ d &= \frac{A-2}{B} \\ &= \frac{4}{7} = 8 \end{aligned}$$

So 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's show that tiny-jubjub is moreover 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 the Euler criterium. We get

$$\begin{aligned} \left(\frac{3}{13} \right) &= 3^{\frac{13-1}{2}} \\ &= 3^6 = 1 \end{aligned}$$

$$\begin{aligned} \left(\frac{8}{13} \right) &= 8^{\frac{13-1}{2}} \\ &= 8^6 = 12 = -1 \end{aligned}$$

which proofs that tiny-jubjub is snark friendly. We can write the tiny-jubjub curve in its affine twisted Edwards representation as

$$TJJ_{13} = \{(x, y) \in \mathbb{F}_{13} \times \mathbb{F}_{13} \mid 3 \cdot x^2 + y^2 = 1 + 8 \cdot x^2 \cdot y^2\}$$

Now that we have the abstract definition of our pen-jubjub curve in twisted Edwards form, we can compute the set of points, by inserting all pairs $(x, y) \in \mathbb{F}_{13} \times \mathbb{F}_{13}$ similar to how we computed the curve points in its Weierstraß or Edwards representation. We get

$$\begin{aligned} PJJ_{13} = \{ &(0, 1), (0, 12), (1, 2), (1, 11), (2, 6), (2, 7), (3, 0), (5, 5), (5, 8), (6, 4), \\ &(6, 9), (7, 4), (7, 9), (8, 5), (8, 8), (10, 0), (11, 6), (11, 7), (12, 2), (12, 11) \} \end{aligned}$$

??

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 Weierstraß curves, the group law of snark friendly twisted Edwards curves can be described by single computation, that works in all cases, no matter if we add the neutral element, inverse, or if have to double a point. To see how the group law looks like, first observe that the point

$(0, 1)$ is a solution to $a \cdot x^2 + y^2 = 1 + d \cdot x^2 \cdot y^2$ for any curve. The sum of any two points (x_1, y_1) , (x_2, y_2) on an Edwards curve $E(\mathbb{F})$ is then given by

$$(x_1, y_1) \oplus (x_2, y_2) = \left(\frac{x_1 y_2 + y_1 x_2}{1 + d x_1 x_2 y_1 y_2}, \frac{y_1 y_2 - a x_1 x_2}{1 - d x_1 x_2 y_1 y_2} \right)$$

and it can be shown that the point $(0, 1)$ serves as the neutral element and the inverse of a point (x_1, y_1) is given by $(-x_1, y_1)$.

Example 80. *Lets look at the tiny-jubjub curve in Edwards form from example XXX again. As we have seen, this curve is given by*

$$PJJ_13 = \{(0, 1), (0, 12), (1, 2), (1, 11), (2, 6), (2, 7), (3, 0), (5, 5), (5, 8), (6, 4), \\ (6, 9), (7, 4), (7, 9), (8, 5), (8, 8), (10, 0), (11, 6), (11, 7), (12, 2), (12, 11)\}$$

To get an undertanding of the twisted Edwards addition law, lets first add the neutral element $(0, 1)$ to itself. We apply the group law XXX and get

$$(0, 1) \oplus (0, 1) = \left(\frac{0 \cdot 1 + 1 \cdot 0}{1 + 8 \cdot 0 \cdot 0 \cdot 1 \cdot 1}, \frac{1 \cdot 1 - 3 \cdot 0 \cdot 0}{1 - 8 \cdot 0 \cdot 0 \cdot 1 \cdot 1} \right) \\ = (0, 1)$$

So as expected, adding the neutral element to itself gives the neutral element again. Now lets add the neutral element to some other curve point. We get

$$(0, 1) \oplus (8, 5) = \left(\frac{0 \cdot 5 + 1 \cdot 8}{1 + 8 \cdot 0 \cdot 8 \cdot 1 \cdot 5}, \frac{1 \cdot 5 - 3 \cdot 0 \cdot 8}{1 - 8 \cdot 0 \cdot 8 \cdot 1 \cdot 5} \right) \\ = (8, 5)$$

Again as expected adding the neutral element to any element will give the element again. Given any curve point (x, y) , we know that the inverse is given by $(-x, y)$. To see how the addition of a point to its inverse works out we therefore compute

$$(5, 5) \oplus (8, 5) = \left(\frac{5 \cdot 5 + 5 \cdot 8}{1 + 8 \cdot 5 \cdot 8 \cdot 5 \cdot 5}, \frac{5 \cdot 5 - 3 \cdot 5 \cdot 8}{1 - 8 \cdot 5 \cdot 8 \cdot 5 \cdot 5} \right) \\ = \left(\frac{12 + 1}{1 + 5}, \frac{12 - 3}{1 - 5} \right) \\ = \left(\frac{0}{6}, \frac{12 + 10}{1 + 8} \right) \\ = \left(0, \frac{9}{9} \right) \\ = (0, 1)$$

So 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 particulary nice and in a unified way.

5.2 Elliptic Curves Pairings

As we have seen in XXX some groups comes with the notation of a so called pairing map, which is a non-degenerate bilinear map, from two groups into another group.

In this section, we discuss *pairings on elliptic curves*, which form the basis of several zk-SNARKs and other zero knowledge proof schemes. The SNARKs derived from pairings have the advantage of constant-sized proof sizes, which is crucial to blockchains.

We start out by defining elliptic curve pairings and discussing a simple application which bears some resemblance to the more advanced SNARKs. We then introduce the pairings arising from elliptic curves and describe Miller's algorithm which makes these pairings practical rather than just theoretically interesting.

Elliptic curves have a few structures, like the Weil or the Tate map, that qualifies as pairing.

Embedding Degrees As we will see in what follows, every elliptic curve gives rise to a pairing map. However as we will see in example XXX, not every such pairing is efficiently computable. So 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 understand this term, let \mathbb{F} be a finite field, $E(\mathbb{F})$ an elliptic curve over \mathbb{F} , and n a prime number that divides the order of $E(\mathbb{F})$. The embedding degree of $E(\mathbb{F})$ with respect to n is then the smallest integer k such that n divides $q^k - 1$.

Fermat's little theorem XXX implies, that every curve has at least *some* embedding degree k , since at least $k = n - 1$ is always a solution to the congruency $q^k \equiv 1 \pmod{n}$ which implies that the remainder of the integer division of $q^k - 1$ by n is 0.

Example 81. *To get a better intuition of the embedding degree, lets consider the elliptic curve $E_1(\mathbb{F}_5)$ from example XXX. We know from XXX that the order of $E_1(\mathbb{F}_5)$ is 9 and since the only prime factor of 9 is 3, we compute the ebedding degree of $E_1(\mathbb{F}_5)$ with respect to 3.*

To find that 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 .

$$\begin{array}{ll} k = 1: 5^1 - 1 = 4 & \text{not divisible by 3} \\ k = 2: 5^2 - 1 = 24 & \text{divisible by 3} \end{array}$$

So we know that the embedding degree of $E_1(\mathbb{F}_5)$ is 2 relative to the the prime factor 3.

Example 82. *Lets consider the tiny jubjub curve TJJ_13 from example XXX. We know from XXX that the order of TJJ_13 is 20 and that the order therefore has two prime factors. A "large" prime factor 5 and a small prime factor 2.*

We start by computing the ebedding 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 .

$$\begin{array}{ll} k = 1: 13^1 - 1 = 12 & \text{not divisible by 5} \\ k = 2: 13^2 - 1 = 168 & \text{not divisible by 5} \\ k = 3: 13^3 - 1 = 2196 & \text{not divisible by 5} \\ k = 4: 13^4 - 1 = 28560 & \text{divisible by 5} \end{array}$$

So we know that the embedding degree of TJJ_13 is 4 relative to the the prime factor 5.

In real world applications, like on pairing friendly elliptic curves as for example BLS_12-381, usually only the embedding degree of the large prime factor are relevant, which in case of out tiny-jubjub curve, is represented by 5. It should however be noted that every prime factor of a curves order has its own notation of embedding degree despite the fact that this is mostly 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 .

$$k = 1: 13^1 - 1 = 12 \quad \text{divisible by 2}$$

So we know that the embedding degree of TJJ_13 is 1 relative to the the prime factor 2. So as we have seen, different prime factors can have different embedding degrees in general. ??

Example 83. To give an example of a cryptographically secure real worl elliptic curve that does not have a small embedding degree lets look at curve secp256k1 again. We know from XXX that the order of this curve is a prime number, so we only have a single embedding degree.

To test potential embedding degrees k , say in the range $1 \dots 1000$, we can invoke sage and compute: ?? So we see that secp256k1 has at least no embedding degree $k < 1000$, which renders secp256k1 as a curve that has no small embedding degree. A property that is of importance later on.

Elliptic Curves over extension fields Suppose that p is a prime number and \mathbb{F}_p its associated prime field. We know from XXX, that the fields \mathbb{F}_{p^m} are extensions of \mathbb{F}_p in the sense that \mathbb{F}_p is a subfield of \mathbb{F}_{p^m} . This implies that we can extend the affine plane an elliptic curve is defined on, by changing the base field to any extension field. To be more precise let $E(\mathbb{F}) = \{(x, y) \in \mathbb{F} \times \mathbb{F} \mid y^2 = x^3 + a \cdot x + b\}$ be an affine short Weierstrass curve, with parameters a and b taken from \mathbb{F} . If \mathbb{F}' is any extension field of \mathbb{F} , then we extend the domain of the curve by defining

$$E(\mathbb{F}') = \{(x, y) \in \mathbb{F}' \times \mathbb{F}' \mid y^2 = x^3 + a \cdot x + b\} \quad (5.13)$$

So while we did not change the defining parameters, we consider curve points from the affine plane over the extension field now. Since $\mathbb{F} \subset \mathbb{F}'$ it can be shown that the original elliptic curve $E(\mathbb{F})$ is a sub curve of the extension curve $E(\mathbb{F}')$.

Example 84. Consider the prime field \mathbb{F}_5 from example XXX and the elliptic curve $E_1(\mathbb{F}_5)$ from example XXX. Since we know from XXX that \mathbb{F}_{5^2} is an extension field of \mathbb{F}_5 , we can extend the definition of $E_1(\mathbb{F}_5)$ to define a curve over \mathbb{F}_{5^2} :

$$E_1(\mathbb{F}_{5^2}) = \{(x, y) \in \mathbb{F} \times \mathbb{F} \mid y^2 = x^3 + x + 1\}$$

Since \mathbb{F}_{5^2} contains 25 points, in order to compute the set $E_1(\mathbb{F}_{5^2})$, we have to try $25 \cdot 25 = 625$ pairs, which is probably a bit to much for the avarage motivated reader. Instaed we involve sage to compute the curve for us. To do so choose the representation of \mathbb{F}_{5^2} from XXX. We get: ?? So 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. Printing the points gives

$$\begin{aligned} E_1(\mathbb{F}_{5^2}) = \{ & \mathcal{O}, (0, 4), (0, 1), (3, 4), (3, 1), (4, 3), (4, 2), (2, 4), (2, 1), \\ & (4t + 3, 3t + 4), (4t + 3, 2t + 1), (3t + 2, t), (3t + 2, 4t), \\ & (2t + 2, t), (2t + 2, 4t), (2t + 1, 4t + 4), (2t + 1, t + 1), \\ & (2t + 3, 3), (2t + 3, 2), (t + 3, 2t + 4), (t + 3, 3t + 1), \\ & (3t + 1, t + 4), (3t + 1, 4t + 1), (3t + 3, 3), (3t + 3, 2), (1, 4t) \} \end{aligned}$$

As we can see, curve $E_1(\mathbb{F}_5)$ sits inside curve $E(\mathbb{F}_{5^2})$, which is implied from \mathbb{F}_5 being a subfield of \mathbb{F}_{5^2} .

Full Torsion groups The fundamental theorem of finite cyclic groups XXX implies, that every prime factor n of a cyclic groups order defines a subgroup of the size of the prime factor. We called such a subgroup an n -torsion group. We have seen many of those subgroups in the examples XXX and XXX.

Now when we consider elliptic curve extensions as defined in XXX, we could ask, what happens to the n -torsion groups in the extension. One might intuitively think that their extension just parallels the extension of the curve. For example when $E(\mathbb{F}_p)$ is a curve over prime field \mathbb{F}_p , with some n -torsion group \mathbb{G} and when we extend the curve to $E(\mathbb{F}_{p^m})$, then there is a bigger n -torsion group, such that \mathbb{G} is a subgroup. Naively this would make sense, as $E(\mathbb{F}_p)$ is a subcurve of $E(\mathbb{F}_{p^m})$.

However the real situation is a bit more surprising then that. To see that, let \mathbb{F}_p be a prime field and $E(\mathbb{F}_p)$ an elliptic curve of order r , with embedding degree k and n -torsion group $E(\mathbb{F}_p)[n]$ for same prime factor n of r . Then it can be shown that the n -torsion group $E(\mathbb{F}_{p^m})[n]$ of a curve extension is equal to $E(\mathbb{F}_p)[n]$, as long as the power m is less then the embedding degree k of $E(\mathbb{F}_p)$.

However for the prime power p^m , for any $m \geq k$, $E(\mathbb{F}_{p^m})[n]$ is strictly larger then $E(\mathbb{F}_p)[n]$ and contains $E(\mathbb{F}_p)[n]$ as a subgroup. We call the n -torsion group $E(\mathbb{F}_{p^k})[n]$ of the extension of E over \mathbb{F}_{p^k} the **full n -torsion group** of that elliptic curve. It can be shown that it contains n^2 many elements and consists of $n + 1$ subgroups, one of which is $E(\mathbb{F}_p)[n]$.

So roughly speaking, when we consider towers of curve extensions $E(\mathbb{F}_{p^m})$, ordered by the prime power m , then the n -torsion group stays constant for every level m small then the embedding degree, while it suddenly blossoms into a larger group on level k , with $n + 1$ subgroups and it then stays like that for any level m larger then k . In other words, once the extension field is big enough to find on emore point of order n (that is not defined over the base field), then we actually find all of the points in the full torsion group.

Example 85. Consider curve $E_1(\mathbb{F}_5)$ again. We know that it contains a 3-torsion group and that the embedding degree of 3 is 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 XXX.

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 check the defining equation $[3]P = \mathcal{O}$. Invoking sage we compute `??we get`

$$E_1[3] = \{ \mathcal{O}, (1, t), (1, 4t), (2, 1), (2, 4), (2t + 1, t + 1), (2t + 1, 4t + 4), (3t + 1, t + 4), (3t + 1, 4t + 1) \}$$

Example 86. Consider the tiny jubjub curve from example XXX. we know from XXX 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 element, 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 to slow even on a computer.

Fortunate sage has a way to loop through points of given order efficiently. The following sage code then gives a way to compute the full torsion group: `??` So as expected we get a group that contains $5^2 = 25$ elements. As its rather tedious to write this group down and as we don't need in what follows we skip writing it. To see that the embedding degree 4 is actually the smallerst prime power to find the full 5-torsion group, lets compute the 5-torsion group over of the tiny-jubjub curve the extension field \mathbb{F}_{13^3} . We get `??` So as we can see the 5-torsion group of tiny-jubjub over \mathbb{F}_{13^3} is equal to the 5-torsion group of tiny-jubjub over \mathbb{F}_{13} itself.

Example 87. Lets look at curve *Secp256k1*. We know from XXX that the curve is of some prime order r and hence the only n -torsion group to consider is the curve itself. So the curve group is the r -torsion.

However in order to find the full r -torsion of *Secp256k1*, we need to compute the embedding degree k and as we have seen in XXX it is at least not small. We know from Fermat's little theorem that a finite embedding degree must exist, though. It can be shown that it is given by

$$k = 192986815395526992372618308347813175472927379845817397100860523586360249056$$

which is a 256bit number. So the embedding degree is huge, which implies that the field extension \mathbb{F}_{p^k} is huge too. To understand how big \mathbb{F}_{p^k} is, recall that an element of \mathbb{F}_{p^m} can be represented as a string $[x_0, \dots, x_m]$ of m elements, each containing a number from the prime field \mathbb{F}_p . Now in the case of *Secp256k1*, such a representation has k -many entries, each of 256 bits in size. So without any optimizations, representing such an element would need $k \cdot 256$ bits, which is too much to be represented in the observable universe.

Torsion-Subgroups As we have stated above, any full n -torsion group contains $n + 1$ cyclic subgroups, two of which are of particular interest in pairing based elliptic curve cryptography. To characterize these groups we need to consider the so called *Frobenius* endomorphism

$$\pi : E(\mathbb{F}) \rightarrow E(\mathbb{F}) : \begin{array}{ccc} (x, y) & \mapsto & (x^p, y^p) \\ \mathcal{O} & \mapsto & \mathcal{O} \end{array} \quad (5.14)$$

of an elliptic curve $E(\mathbb{F})$ over some finite field \mathbb{F} of characteristic p . It can be shown that π maps curve points to curve points. The first thing to note is that in case that \mathbb{F} is a prime field, the Frobenius endomorphism acts trivially, since $(x^p, y^p) = (x, y)$ on prime fields, due to Fermat's little theorem XX. So the Frobenius map is more interesting over prime field extensions.

With the Frobenius map at hand, we can now characterise two important subgroups of the full n -torsion. The first subgroup is the n -torsion group that already exists in the curve over the base field. In pairing based cryptography this group is usually written as \mathbb{G}_1 , assuming that the prime factor ' n ' in the definition is implicitly given. Since we know that the Frobenius map, acts trivially on curve over the prime field we can define \mathbb{G}_1 as:

$$\mathbb{G}_1[n] := \{(x, y) \in E[n] \mid \pi(x, y) = (x, y)\} \quad (5.15)$$

In more mathematical terms this definition means, that \mathbb{G}_1 is the *Eigenspace* of the Frobenius map with respect to the *Eigenvalue* 1.

Now it can be shown, that there is another subgroup of the full n -torsion group that can be characterized by the Frobenius map. In the context of so called type 3 pairing based cryptography this subgroup is usually called \mathbb{G}_2 and it defined as

$$\mathbb{G}_2[n] := \{(x, y) \in E[n] \mid \pi(x, y) = [p](x, y)\} \quad (5.16)$$

So in mathematical terms \mathbb{G}_2 is the *Eigenspace* of the Frobenius map with respect to the *Eigenvalue* p .

Notation and Symbols 9. If the prime factor n of the curves order is clear from the context, we sometimes simply write \mathbb{G}_1 and \mathbb{G}_2 to mean $\mathbb{G}_1[n]$ and $\mathbb{G}_2[n]$, respectively.

It should be noted however that sometimes other definitions of \mathbb{G}_2 appear in the literature, however in the context of pairing based cryptography, this is the most common one. It is particularly useful, as we can define hash functions that map into \mathbb{G}_2 , which is not possible for all subgroups of the full n -torsion.

Example 88. Consider the curve $E_1(\mathbb{F}_5)$ from example XXX again. As we have seen this curve has embedding degree $k = 2$ and a full 3-torsion group is given by

$$E_1[3] = \{\mathcal{O}, (2, 1), (2, 4), (1, t), (1, 4t), (2t+1, t+1), (2t+1, 4t+4), (3t+1, t+4), (3t+1, 4t+1)\}$$

According to the general theory, $E_1[3]$ contains 4 subgroups and we can characterise the subgroups \mathbb{G}_1 and \mathbb{G}_2 using the Frobenius endomorphism. Unfortunately at the time of this writing sage did not have a predefined Frobenius endomorphism for elliptic curves, so we have to use the Frobenius endomorphism of the underlying field as a temporary workaround. We compute $\mathbb{G}_1 = \{\mathcal{O}, (2, 4), (2, 1)\}$ is identical to the 3-torsion group of the (unextended) curve over the prime field $E_1(\mathbb{F}_5)$. We can use almost the same algorithm to compute the group \mathbb{G}_2 and get $\mathbb{G}_2 = \{\mathcal{O}, (1, t), (1, 4t)\}$.

Example 89. Considering the tiny-jubjub curve TJJ_13 from example XXX. In example XXX we computed its full 5 torsion, which is a group that has 6 subgroups. We compute \mathbb{G}_1 using sage as: $\mathbb{G}_1 = \{\mathcal{O}, (7, 2), (8, 8), (8, 5), (7, 11)\}$ $\mathbb{G}_2 = \{\mathcal{O}, (9t^2 + 7, t^3 + 11t), (9t^2 + 7, 12t^3 + 2t), (4t^2 + 7, 5t^3 + 10t), (4t^2 + 7, 8t^3 + 3t)\}$

Example 90. 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 . It is however infeasible not just to compute \mathbb{G}_2 itself, but to even compute an average element of \mathbb{G}_2 as elements need too much storage to be representable in this universe.

The Weil Pairing 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 a bilinear, non-degenerate map

$$e(\cdot, \cdot) : \mathbb{G}_1[r] \times \mathbb{G}_2[r] \rightarrow \mathbb{F}_{p^k} ; (P, Q) \mapsto (-1)^r \cdot \frac{f_{r,P}(Q)}{f_{r,Q}(P)} \quad (5.17)$$

where the extension field elements $f_{r,P}(Q), f_{r,Q}(P) \in \mathbb{F}_{p^k}$ are computed by **Miller's algorithm**: Understanding in detail how the algorithm works requires the concept of *divisors*, which we don't really need in this book. The interested reader might look at [REFERENCES]

In real world application 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 curves order.

Example 91. Consider curve $E_1(\mathbb{F}_5)$ from example XXX. Since the only prime factor of the groups order is 3 we can not 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 `if` statement on line XXX will lead to a division by zero error in the computation of the slope m .

Example 92. Consider the tiny-jubjub curve $TJJ_13(\mathbb{F}_{13})$ from example XXX again. We want to instantiate the general definition of the Weil pairing for this example. To do so, recall that we have seen in example XXX, its embedding degree is 4 and that we have the following type-3 pairing groups:

$$\mathbb{G}_1 = \{\mathcal{O}, (7, 2), (8, 8), (8, 5), (7, 11)\}$$

$$\mathbb{G}_2 = \{\mathcal{O}, (9t^2 + 7, t^3 + 11t), (9t^2 + 7, 12t^3 + 2t), (4t^2 + 7, 5t^3 + 10t), (4t^2 + 7, 8t^3 + 3t)\}$$

Algorithm 7 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

where \mathbb{G}_1 and \mathbb{G}_2 are subgroups of the full 5-torsion found in the curve $TJJ_13(\mathbb{F}_{13^4})$. The type-3 Weil pairing is a map $e(\cdot, \cdot) : \mathbb{G}_1 \times \mathbb{G}_2 \rightarrow \mathbb{F}_{13^4}$. From the first if-statement in Miller's algorithm, we can deduce that $e(\mathcal{O}, Q) = 1$ as well as $e(P, \mathcal{O}) = 1$ for all arguments $P \in \mathbb{G}_1$ and $Q \in \mathbb{G}_2$. So in order to compute a non-trivial Weil pairing we choose the arguments $P = (7, 2)$ and $Q = (9t^2 + 7, 12t^3 + 2t)$.

In order to compute the pairing $e((7, 2), (9t^2 + 7, 12t^3 + 2t))$ we have to compute the extension field elements $f_{5,P}(Q)$ and $f_{5,Q}(P)$ applying Miller's algorithm. Do do so first observe that we have $5 = 1 \cdot 2^0 + 0 \cdot 2^1 + 1 \cdot 2^2$, so we get $t = 2$ as well as $b_0 = 1$, $b_1 = 0$ and $b_2 = 1$. The loop therefore needs to be executed two times.

Computing $f_{5,P}(Q)$, we initiate $(x_T, y_T) = (7, 2)$ as well as $f_1 = 1$ and $f_2 = 1$. Then

j	b_j	m	f_1	f_2	x_{2T}	y_{2T}	x_{T+P}	y_{T+P}
1	.							

$$\begin{aligned}
 m &= \frac{3 \cdot x_T^2 + a}{2 \cdot y_T} \\
 &= \frac{3 \cdot 2^2 + 1}{2 \cdot 4} = \frac{3}{3} \\
 &= 1
 \end{aligned}$$

$$\begin{aligned}
 f_1 &= f_1^2 \cdot (y_Q - y_T - m \cdot (x_Q - x_T)) \\
 &= 1^2 \cdot (t - 4 - 1 \cdot (1 - 2)) = t - 4 + 1 \\
 &= t + 2
 \end{aligned}$$

$$\begin{aligned}
 f_2 &= f_2^2 \cdot (x_Q + 2x_T - m^2) \\
 &= 1^2 \cdot (1 + 2 \cdot 2 - 1^2) = (1 + 4 - 1) \\
 &= 4
 \end{aligned}$$

$$\begin{aligned}
 x_{2T} &= m^2 - 2x_T \\
 &= 1^2 - 2 \cdot 2 = -3 \\
 &= 2
 \end{aligned}$$

$$\begin{aligned}
 y_{2T} &= -y_T - m \cdot (x_{2T} - x_T) \\
 &= -4 - 1 \cdot (2 - 2) = -4 \\
 &= 1
 \end{aligned}$$

So we update $(x_T, y_T) = (2, 1)$ and since $b_0 = 1$ we have to execute the if statement on line XXX in the for loop. However since we only loop a single time, we don't need to compute y_{T+P} , since

we only need the updated x_T in the final step. We get:

$$\begin{aligned} m &= \frac{y_T - y_P}{x_T - x_P} \\ &= \frac{1 - 4}{2 - x_P} \end{aligned}$$

$$f_1 = f_1 \cdot (y_Q - y_T - m \cdot (x_Q - x_T))$$

$$f_2 = f_2 \cdot (x_Q + (x_P + x_T) - m^2)$$

$$x_{T+P} = m^2 - x_T - x_P$$

5.3 Hashing to Curves

Elliptic curve cryptography frequently requires the ability to hash data onto elliptic curves. If the order of the curve is not a prime number hashing to prime number subgroups is also of importance. In the context of pairing friendly curves it is also sometimes necessary to hash specifically onto the group \mathbb{G}_1 or \mathbb{G}_2 .

As we have seen in XXX, many general methods are known to hash into groups in general and finite cyclic groups in particular. As elliptic groups are cyclic those methods can be utilized in this case, too. However in what follows we want to describe some methods special to elliptic curves, that are frequently used in applications.

Try and increment hash functions One of the most straight forward ways to hash a bitstring onto an elliptic curve point, in a secure way, is to use a cryptographic hash function together with one of the methods we described in XXX to hash to the modular arithmetic base field of the curve. Ideally the hash function generates an image that is at least one bit longer than the bit representation of the base field modulus.

The image in the base field can then be interpreted as the x -coordinate of the curve point and the two possible y -coordinates are then derived from the curve equation, while one of the bits that exceeded the modulus determines which of the two y -coordinates to choose.

Such an approach would be easy to implement and deterministic and it will conserve the cryptographic properties of the original hash function. However not all x -coordinates generated in such a way, will result in quadratic residues, when inserted into the defining equation. It follows that not all field elements give rise to actual curve points. In fact on a prime field, only half of the field elements are quadratic residues and hence assuming an even distribution of the hash values in the field, this method would fail to generate a curve point in about half of the attempts.

One way to account for this problem is the so called *try and increment* method. Its basic assumption is, that hashing different values, the result will eventually lead to a valid curve point.

Therefore instead of simply hashing a string s to the field the concatenation of s with additional bytes is hashed to the field instead, that is a try and increment hash as described in XXX is used. If the first *try* of hashing to the field does not result in a valid curve point, the counter

Algorithm 8 Hash-to- $E(\mathbb{F}_r)$ **Require:** $r \in \mathbb{Z}$ with $r.\text{nbits}() = k$ and $s \in \{0, 1\}^*$ **Require:** Curve equation $y^2 = x^3 + ax + b$ over \mathbb{F}_r **procedure** TRY-AND-INCREMENT(r, k, s) $c \leftarrow 0$ **repeat** $s' \leftarrow s || c.\text{bits}()$ $z \leftarrow H(s')_0 \cdot 2^0 + H(s')_1 \cdot 2^1 + \dots + H(s')_k \cdot 2^k$ $x \leftarrow z^3 + a \cdot z + b$ $c \leftarrow c + 1$ **until** $z < r$ and $x^{\frac{r-1}{2}} \bmod r = 1$ **if** $H(s')_{k+1} == 0$ **then** $y \leftarrow \sqrt{x} \#(\text{root in } \mathbb{F}_r)$ **else** $y \leftarrow r - \sqrt{x} \#(\text{root in } \mathbb{F}_r)$ **end if****return** (x, y) **end procedure****Ensure:** $(x, y) \in E(\mathbb{F}_r)$

is *incremented* and the hashing is repeated again. This is done until a valid curve point is found eventually.

This method has the advantage that is relatively easy to implement in code and that it preserves the cryptographic properties of the original hash function. However it is not guaranteed to find a valid curve point, as there is a chance that all possible values in the chosen size of the counter will fail to generate a quadratic residue. Fortunately it is possible to make the probability for this arbitrarily small by choosing large enough counters and relying on the (approximate) uniformity of the hash-to-field function.

If the curve is not of prime order, the result will be a general curve point that might not be in the "large" prime order subgroup. A so called *cofactor clearing* step is then necessary to project the curve point onto the subgroup. This is done by scalar multiplication with the cofactor of prime order with respect to the curves order.

Example 93. Consider the tiny jubjub curve from example XXX. We want to construct a try and increment hash function, that hashes a binary string s of arbitrary length onto the large prime order subgroup of size 5.

Since the curve as well as our target subgroup are defined over the field \mathbb{F}_{13} and the binary representation of 13 is $13.\text{bits}() = 1101$, we apply SHA256 from sage's crypto library on the concatenation $s || c$ for some binary counter string 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 z , such that $z^3 + 8 \cdot z + 8$ is a quadratic residue in \mathbb{F}_{13} , we use the 5-th bit to decide which of the two possible roots of $z^3 + 8 \cdot z + 8$ we will choose as the y-coordinate. The result is then a curve point different from the point at infinity. To project it to a point of \mathbb{G}_1 , we multiply it with the cofactor 4. If the result is still not the point at infinity, it is the result of the hash.

To make this concrete let $s = '10011001111010110100000111'$ be our binary string that we want to hash onto \mathbb{G}_1 . We use a 4-bit binary counter, starting at zero, i.e we choose $c = 0000$. Invoking sage we define the try-hash function as ?? As we can see, our first attempt to hash into \mathbb{F}_{13} was not successful as 15 is not a number in \mathbb{F}_{13} , so we increment the binary counter by

1 and try again: ??And we find a hash into \mathbb{F}_{13} . However this point is not guranteed to define a curve point. To see that we insert $z = 3$ into the right side of the Weierstraß equation of the tiny.jubjub curve and compute $3^3 + 8 \cdot 3 + 8 = 7$, but 7 is not a quadratic residue in \mathbb{F}_{13} since $7^{\frac{13-1}{2}} = 7^6 = 12 = -1$. So 3 is a not a suteable point and we have to increment the counter two more times: ??Since $6^3 + 8 \cdot 6 + 8 = 12$ and we have $\sqrt{12} \in \{5, 8\}$, we finally found the valid x coordinate $x = 6$ for the curve point hash. Now since the sign bit of this hash is 1, we choose the larger root $y = 8$ as the y -coordinate and get the hash

$$H('10011001111010110100000111') = (6, 8)$$

which is a valid curve point point on the tiny jubjub curve. Now in order to project it onto the "large" prime order subgroup we have to do cofactor clearing, that is we have to multiply the point with the cofactor 4. We get

$$[4](6, 8) = \mathcal{O}$$

so the hash value is still not right. We therefore have to increment the counter two times again, until we finally find a correct hash to \mathbb{G}_1 ??Since $12^3 + 8 \cdot 12 + 8 = 12$ and we have $\sqrt{12} \in \{5, 8\}$, we found another valid x coordinate $x = 12$ for the curve point hash. Now since the sign bit of this hash is 0, we choose the smaller root $y = 5$ as the y -coordinate and get the hash

$$H('10011001111010110100000111') = (12, 5)$$

which is a valid curve point point on the tiny jubjub curve and in order to project it onto the "large" prime order subgroup we have to do cofactor clearing, that is we have to multiply the point with the cofactor 4. We get

$$[4](12, 5) = (8, 5)$$

So hashing the binary string '10011001111010110100000111' onto \mathbb{G}_1 gives the hash value $(8, 5)$ as a result.

5.4 Constructing elliptic curves

Cryptographically secure elliptic curves like Secp256k1 from example XXX are known for quite some time. In the latest advancements of cryptography, it is however 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 was necessary to design a curve that can be efficiently implemented incide of a so called circuit, in order to enable primitives like elliptic curve signature schemes in a zero knowledge proof. Such a curve is give by the Baby-JubJub curve [XXX] and we have paralld its definition by introducing the tiny-JubJub curve from example XX. 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 existing of a suitable, pairing friendly curve with a specified security level and a low embedding degree as defined in XXX. Famous examples are the BLS_12 or the NMT curves.

The major goal of this section is to explain the most important method to design elliptic curves with predefined properties from sratch, called the *complex multiplication method*. We will apply this method in section to synthesize a particular BLS_6 curve, the most insecure

BLS_6 curve, which will 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 the complex multiplication method.

The Trace of Frobenius To understand the complex multiplication method of elliptic curve, we have to define the so called *trace* of an elliptic curve first.

We know from XXX that elliptic curves over finite fields are cyclic groups of finite order. An interesting question therefore is, if it is possible to estimate the number of elements that 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 can not 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

$$|E(\mathbb{F}_q)| = q + 1 - t \quad (5.18)$$

A positive trace therefore implies, that the curve contains less points than the underlying field and a 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 basefield.

Example 94. Consider the elliptic curve $E_1(\mathbb{F}_5)$ from example XXX. We know that it contains 9 curve points. Since the order of \mathbb{F}_5 is 5 we compute the trace of $E_1(\mathbb{F})$ to be $t = -3$, since the Hasse bound is given by

$$9 = 5 + 1 - (-3)$$

And indeed we have $|t| \leq 2\sqrt{q}$, since $\sqrt{5} > 2.23$ and $|-3| = 3 \leq 4.46 = 2 \cdot 2.23 < 2 \cdot \sqrt{5}$.

Example 95. To compute the trace of the tiny-jubjub curve, observe from example XXX, that the order of PJJ_13 is 20. Since the order of \mathbb{F}_{13} is 13, we can therefore use the Hasse bound and compute the trace as $t = -6$, since

$$20 = 13 + 1 - (-6)$$

Again we have $|t| \leq 2\sqrt{q}$, since $\sqrt{13} > 3.60$ and $|-6| = 6 \leq 7.20 = 2 \cdot 3.60 < 2 \cdot \sqrt{13}$.

Example 96. To compute the trace of Secp256k1, recall from example XXX, that this curve is defined over a prime field with p elements and that the order of that group is given by r , with

$$p = 115792089237316195423570985008687907853269984665640564039457584007908834671663$$

$$r = 115792089237316195423570985008687907852837564279074904382605163141518161494337$$

Using the Hasse bound $r = p + 1 - t$, we therefore compute $t = p + 1 - r$, which gives the trace of curve Secp256k1 as

$$t = 43242038656559656852420866390673177327$$

So 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 , t is tiny. ??

The j -invariant As we have seen in XXX two elliptic curve $E_1(\mathbb{F})$ 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 $b' = bd^3$.

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:

$$j(E(\mathbb{F}_q)) = (1728 \bmod q) \frac{4 \cdot a^3}{4 \cdot a^3 + (27 \bmod q) \cdot b^2} \quad (5.19)$$

with $j(E(\mathbb{F}_q)) \in \mathbb{F}_q$. We will not go into the details of the j -invariant, but state only, 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 $j(E_1) = j(E_2)$.

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 97. Consider the elliptic curve $E_1(\mathbb{F}_5)$ from example XXX. We compute its j -invariant as

$$\begin{aligned} j(E_1(\mathbb{F}_5)) &= (1728 \bmod 5) \frac{4 \cdot 1^3}{4 \cdot 1^3 + (27 \bmod 5) \cdot 1^2} \\ &= 3 \frac{4}{4+2} \\ &= 3 \cdot 4 = 2 \end{aligned}$$

Example 98. Consider the elliptic curve PJJ_13 from example XXX. We compute its j -invariant as

$$\begin{aligned} j(E_1(\mathbb{F}_5)) &= (1728 \bmod 13) \frac{4 \cdot 8^3}{4 \cdot 8^3 + (27 \bmod 13) \cdot 8^2} \\ &= 12 \cdot \frac{4 \cdot 5}{4 \cdot 5 + 1 \cdot 12} \\ &= 12 \cdot \frac{7}{7+12} \\ &= 12 \cdot 7 \cdot 6^{-1} \\ &= 12 \cdot 7 \cdot 11 \\ &01 \end{aligned}$$

Example 99. Consider *Secp256k1* from example XXX. We compute its j -invariant using sage: ??

The Complex Multiplication Method As we have seen in the previous sections, elliptic curves have various defining properties, like their order and their prime factors, the embedding degree, or the cardinality of the base field. The so called *complex multiplication* (CM) gives a practical method for constructing elliptic curves with pre-defined restrictions on the order and the base field.

The method usually 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 counting number $m \in \mathbb{N}$ with $m \geq 1$. 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, i.e. such that $\gcd(p, t) = 1$ holds true. The choice of t also defines the curve's order r , since $r = p + 1 - t$ by the Hasse bound XXX, so choosing t , will define the large order subgroup as well as all small cofactors. r has to be defined in such a way, that the elliptic curve meets the security requirements of the application it is designed for.

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 $q^k - 1$.

In order for the complex multiplication method to work, both q and t can not be arbitrary, but must be chosen in such a way that two additional integers $D \in \mathbb{Z}$ and $v \in \mathbb{Z}$ exist, such that $D < 0$ as well as $D \bmod 4 = 0$ or $D \bmod 4 = 1$ and the equation

$$4q = t^2 + |D|v^2 \quad (5.20)$$

holds. If those numbers exist, we call D the *CM-discriminant* and we know that we can construct a curve $E(\mathbb{F}_q)$ over a finite field \mathbb{F}_q , such that the order of the curve is $|E(\mathbb{F}_q)| = q + 1 - t$.

It is the content of the complex multiplication method to actually construct such a curve, that is finding the parameters a and b from \mathbb{F}_q in the defining Weierstraß equation, such that the curve has the desired order r .

Finding solutions to equation XXX, can be achieved in different ways, which we will not look much into. In general it can be said, that there are well known constructions for elliptic curve families like the BLS (ECT) families, that provides families of solutions. In what follows we will look at one type of curves the BLS-family, which gives an entire range of solutions.

Assuming that proper parameters q, t, D and v are found, we have to compute the so called *Hilbert class polynomial* $H_D \in \mathbb{Z}[x]$ of the CM-discriminant D , which is a polynomial with integer coefficients. To do so, we first have to compute the following set:

$$\begin{aligned} ICG(D) = \{ (A, B, C) \mid A, B, C \in \mathbb{Z}, D = B^2 - 4AC, \gcd(A, B, C) = 1, \\ |B| \leq A \leq \sqrt{\frac{|D|}{3}}, A \leq C, \text{ if } B < 0 \text{ then } |B| < A < C \} \end{aligned}$$

One way to compute this set, is to first compute the integer $A_{max} = \text{Floor}(\sqrt{\frac{|D|}{3}})$, then loop through all the integers A in the range $[0, \dots, A_{max}]$ as well as through all the integers B in the range $[-A_{max}, \dots, A_{max}]$ and to see if there is an integer C , that satisfies $D = B^2 - 4AC$ and the rest of the requirements in XXX.

To compute the Hilbert class polynomial, the so called *j-function* (or *j-invariant*) is needed, which is a complex function defined on the upper half \mathbb{H} of the complex plane \mathbb{C} , usually written as

$$j : \mathbb{H} \rightarrow \mathbb{C} \quad (5.21)$$

Roughly speaking what this means is that the *j-functions* takes complex numbers $(x + i \cdot y)$ with positive imaginary part $y > 0$ as inputs and returns a complex number $j(x + i \cdot y)$ as result.

For the sake of this book it is not important to actually understand the *j-function* and we can use sage to compute it in a similar way as we would use sage to compute any other well known function. It should be noted however, that the computation of the *j-function* in sage is sometimes prone to precision errors. For example the *j-function* has a root in $\frac{-1+i\sqrt{3}}{2}$, which sage only approximates. Therefore using sage to compute the *j-function*, we need to take precision loss into account and eventually round to the nearest integer. ??With a way

to compute the j -function and the precomputed set $ICG(D)$ at hand, we can now compute the Hilbert class polynomial as

$$H_D(x) = \prod_{(A,B,C) \in ICG(D)} \left(x - j \left(\frac{-B + \sqrt{D}}{2A} \right) \right) \quad (5.22)$$

So what we do is we loop over all elements (A, B, C) from the set $ICG(D)$ and compute the j -function at the point $\frac{-B + \sqrt{D}}{2A}$, where D is the CM-discriminant that we decided in a previous step. The result then defines a factor of the Hilbert class polynomial and all factors are multiplied together.

It can be shown, that the Hilbert class polynomial is an integer polynomial, but actual computations need high precision arithmetics to avoid approximation errors, that usually occur in computer approximations of the j -function as shown above. So in case the calculated Hilbert class polynomial does not have integer coefficients, we need to round the result to the nearest integer. Given that the precision we used was high enough, the result will be correct.

In the next step we use the Hilbert class polynomial $H_D \in \mathbb{Z}[x]$ and project it to a polynomial $H_{D,q} \in \mathbb{F}_q[x]$ with coefficients in the base field \mathbb{F}_q as chosen in the first step. We do this by simply computing the new coefficients as the old coefficients modulus p , that is if $H_D(x) = a_m x^m + a_{m-1} x^{m-1} + \dots + a_1 x + a_0$ we compute the q -modulus of each coefficient $\tilde{a}_j = a_j \bmod p$ which defines the *projected Hilbert class polynomial* as

$$H_{D,p}(x) = \tilde{a}_m x^m + \tilde{a}_{m-1} x^{m-1} + \dots + \tilde{a}_1 x + \tilde{a}_0$$

We then search for roots of $H_{D,p}$, since every root j_0 of $H_{D,p}$ defines a family of elliptic curves over \mathbb{F}_q , which all have a j -invariant XXX equal to j_0 . We can pick any root and all of them will lead to proper curves eventually.

However some of the curves with the correct j -invariant might have an order different from the one we initially decided on. So we need a way to decide on a curve with the correct order.

To compute such a curve, we have to distinguish a few different cases, based on our choice of the root j_0 and of the CM-discriminant D . If $j_0 \neq 0$ or $j_0 \neq 1728 \bmod q$ we compute $c_1 = \frac{j_0}{(1728 \bmod q) - j_0}$ and then we chose some arbitrary quadratic non-residue $c_2 \in \mathbb{F}_q$ and some arbitrary cubic non residue $c_3 \in \mathbb{F}_q$.

The following table is guaranteed to define a curve with the correct order $r = q + 1 - t$, for 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

$$y^2 = x^3 + 3c_1 x + 2c_1 \quad \text{or} \quad y^2 = x^3 + 3c_1 c_2^2 x + 2c_1 c_2^3 \quad (5.23)$$

- Case $j_0 = 0$ and $D \neq -3$. A curve with the correct order is defined by one of the following equations

$$y^2 = x^3 + 1 \quad \text{or} \quad y^2 = x^3 + c_2^3 \quad (5.24)$$

- Case $j_0 = 0$ and $D = -3$. A curve with the correct order is defined by one of the following equations

$$\begin{aligned} y^2 &= x^3 + 1 \quad \text{or} \quad y^2 = x^3 + c_2^3 \quad \text{or} \\ y^2 &= x^3 + c_3^2 \quad \text{or} \quad y^2 = c_3^2 c_2^3 \quad \text{or} \\ y^2 &= x^3 + c_3^{-2} \quad \text{or} \quad y^2 = x^3 + c_3^{-2} c_2^3 \end{aligned}$$

- Case $j_0 = 1728 \bmod q$ and $D \neq -4$. A curve with the correct order is defined by one of the following equations

$$y^2 = x^3 + x \quad \text{or} \quad y^2 = x^3 + c_2^2 x \quad (5.25)$$

- Case $j_0 = 1728 \bmod q$ and $D = -4$. A curve with the correct order is defined by one of the following equations

$$\begin{aligned} y^2 &= x^3 + x \quad \text{or} \quad y^2 = x^3 + c_2 x \quad \text{or} \\ y^2 &= x^3 + c_2^2 x \quad \text{or} \quad y^2 = x^3 + c_2^3 x \end{aligned}$$

To decide the proper defining Weierstraß equation, we therefore have to compute the order of any of the potential curves above and then choose the one that fits out initial requirements. Since it can be shown that the Hilbert class polynomials for the CM-discriminants $D = -3$ and $D = -4$ are given by $H_{-3,q}(x) = x$ and $H_{-4,q} = x - (1728 \bmod q)$ (EXERCISE) the previous cases are exhaustive.

To summarize, using the complex multiplication method, it is possible to synthesize elliptic curve 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. In applications it is therefore sometimes more advantageous to choose a different representative from that class. To do so recall from XXX, that any curve defined by the Weierstraß equation $y^2 = x^3 + ax + b$ is isomorphic to a curve of the form $y^2 = x^3 + ad^2x + bd^3$ for some quadratic residue $d \in \mathbb{F}_q$.

So in order to find a nice representative (e.g. with small parameters a and b) in a last step, the designer might choose a quadratic residue d such that the transformed curve looks the way they wanted it.

Example 100. Consider curve $E_1(\mathbb{F}_5)$ from example XXX. We want to use the complex multiplication method to derive that curve from scratch. Since $E_1(\mathbb{F}_5)$ is a curve of order $r = 9$ over the prime field of order $q = 5$, we know from example XX that its trace of Frobenius is $t = -3$, which also implies that q and $|t|$ are coprime.

We then have to find parameters $D, v \in \mathbb{Z}$ with $D < 0$ and $D \bmod 4 = 0$ or $D \bmod 4 = 1$, such that $4q = t^2 + |D|v^2$ holds. We get

$$\begin{aligned} 4q &= t^2 + |D|v^2 && \Rightarrow \\ 20 &= (-3)^2 + |D|v^2 && \Leftrightarrow \\ 11 &= |D|v^2 \end{aligned}$$

Now since 11 is a prime number, the only solution is $|D| = 11$ and $v = 1$ here. So $D = -11$ and since the Euklidean division of -11 by 4 is $-11 = -3 \cdot 4 + 1$ we have $-11 \bmod 4 = 1$, which shows that $D = -11$ is a proper choice.

In the next step, we have to compute the Hilbert class polynomial H_{-11} and to do so, we first have to find the set $ICG(D)$. To compute that set, observe, that since $\sqrt{\frac{|D|}{3}} \approx 1.915 < 2$, we know from $A \leq \sqrt{\frac{|D|}{3}}$ and $A \in \mathbb{Z}$ that A must be either 0 or 1.

For $A = 0$, we know $B = 0$ from the constraint $|B| \leq A$, but in this case there can be no C satisfying $-11 = B^2 - 4AC$. So we try $A = 1$ and deduce $B \in \{-1, 0, 1\}$ from the constraint $|B| \leq A$. The case $B = -1$ can be excluded since then $B < 0$ has to imply $|B| < A$. In addition, the case $B = 0$ can be excluded as there can be integer C with $-11 = -4C$ since 11 is a prime number.

This leaves the case $B = 1$ and we compute $C = 3$ from the equation $-11 = 1^2 - 4C$, which gives the solution $(A, B, C) = (1, 1, 3)$ and we get

$$ICG(D) = \{(1, 1, 3)\}$$

With the set $ICG(D)$ at hand we can compute the Hilbert class polynomial of $D = -11$. To do so, we have to insert the term $\frac{-1+\sqrt{-11}}{2}$ 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 `sagemath` to compute the j -invariant and get

$$H_{-11}(x) = x - j\left(\frac{-1+i\sqrt{11}}{2}\right) = x + 32768$$

So 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 follows that the projected Hilbert class polynomial is

$$H_{-11,5}(x) = x + 3$$

considered as a polynomial from $\mathbb{F}_5[x]$. 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

$$c_1 = \frac{2}{1728 - 2}$$

in modular 5 arithmetics. Since $1728 \bmod 5 = 3$, we get $c_1 = 2$. Then we have to check if the curve $E(\mathbb{F}_5)$ defined by the Weierstraß $y^2 = x^3 + 3 \cdot 2x + 2 \cdot 2$ has the correct order. We invoke `sage` and find that the order is indeed 9, so it is a curve with the required parameters and we are done.

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

$$y^2 = x^3 + x + 1$$

which is the curve $E_1(\mathbb{F}_5)$, that we used extensively throughout this book. So using the complex multiplication method, we were able to derive a curve with specific properties from scratch.

Example 101. Consider the tiny jubjub curve `TJJ_13` from example XXX. We want to use the complex multiplication method to derive that curve from scratch. Since `TJJ_13` is a curve of order $r = 20$ over the prime field of order $q = 13$, we know from example XX that its trace of Frobenius is $t = -6$, which also implies that q and $|t|$ are coprime.

We then have to find parameters $D, v \in \mathbb{Z}$ with $D < 0$ and $D \bmod 4 = 0$ or $D \bmod 4 = 1$, such that $4q = t^2 + |D|v^2$ holds. We get

$$\begin{aligned} 4q &= t^2 + |D|v^2 && \Rightarrow \\ 4 \cdot 13 &= (-6)^2 + |D|v^2 && \Rightarrow \\ 52 &= 36 + |D|v^2 && \Leftrightarrow \\ 16 &= |D|v^2 \end{aligned}$$

This equation has two solutions for (D, v) , given by $(-4, \pm 2)$ and $(-16, \pm 1)$. Now looking at the first solution, we know that the case $D = -4$ implies $j = 1728$ and the constructed curve is defined by a Weierstraß equation XXX that has a vanishing parameter $b = 0$. We can therefore conclude that choosing $D = -4$ will not help us reconstructing TJJ_13 . It will produce curves with order 20, just not the one we are looking for.

So we choose the second solution $D = -16$ and in the next step, we have to compute the Hilbert class polynomial H_{-16} . To do so, we first have to find the set $ICG(D)$. 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 $|B| < A$ and the compute potential C 's from $-16 = B^2 - 4AC$. We get the following two solution $(1, 0, 4)$ and $(2, 0, 2)$, giving we get

$$ICG(D) = \{(1, 0, 4), (2, 0, 2)\}$$

With the set $ICG(D)$ at hand we can compute the Hilbert class polynomial of $D = -16$. We can invoke `sagemath` to compute the j -invariant and get

$$\begin{aligned} H_{-16}(x) &= \left(x - j \left(\frac{i\sqrt{16}}{2} \right) \right) \left(x - j \left(\frac{i\sqrt{16}}{4} \right) \right) \\ &= (x - 287496)(x - 1728) \end{aligned}$$

So 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 $287496 \bmod 13 = 1$ and $1728 \bmod 13 = 2$ from which follows that the projected Hilbert class polynomial is

$$H_{-11,5}(x) = (x - 1)(x - 12) = (x + 12)(x + 1)$$

considered as a polynomial from $\mathbb{F}_5[x]$. So we have two roots given by $j = 1$ and $j = 12$. We already know that $j = 12$ is the wrong root to construct the tiny jubjub curve, since $1728 \bmod 13 = 2$ and that case can not construct 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

$$\begin{aligned} j(TJJ_13) &= 12 \frac{4 \cdot 8^3}{4 \cdot 8^3 + 1 \cdot 8^2} \\ &= 12 \frac{4 \cdot 5}{4 \cdot 5 + 12} \\ &= 12 \frac{7}{7 + 12} \\ &= 12 \frac{7}{7 + 12} \\ &= 1 \end{aligned}$$

which 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

$$c_1 = \frac{1}{12 - 1} = 6$$

in modular 5 arithmetics. 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 Weierstraß $y^2 = x^3 + 3 \cdot 6x + 2 \cdot 6$ 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 Weierstraß equation $y^2 = x^3 + 5c_2^2 + 12c_2^3$ as

$$y^2 = x^3 + 8x + 5$$

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

$$y^2 = x^3 + 8x + 8$$

which is the ziny jubjub curve, that we used extensively throughout this book. So using the complex multiplication method, we were able to derive a curve with specific properties from scratch.

Example 102. To consider a real world example, we want to use the complex multiplication method in combination with sage to compute Secp256k1 from scratch. So by example XXX, we decided to compute an elliptic curve over a prime field \mathbb{F}_p of order r for the security parameters

$$p = 115792089237316195423570985008687907853269984665640564039457584007908834671663$$

$$r = 115792089237316195423570985008687907852837564279074904382605163141518161494337$$

which, according to example XXX gives the trace of Frobeniois $t = 4324203865659656852420866390673177327$. 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, 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 ??So indeed the pair $(D, v) = (-3, 3034144394672465435952507756676)$ solves the equation, which tells us that there is a curve of order r over a prime field of order p , defined by a Weierstraß equation $y^2 = x^3 + b$ for some $b \in \mathbb{F}_p$. So we need to compute b .

Now 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 into table XXX, we see that there are 6 possible cases to construct a curve with the correct order r . In order to construct the curves of those case we have to choose some arbitrary quadratic and cubic non residue. So we loop through \mathbb{F}_p to find them, invoking sage: ??So we found the quadratic non residue $c_2 = 3$ and the cubic non residue $c_3 = 2$. Using those numbers we check the six cases against the expected order r of the curve we want to synthesize: ??So as expected we found an elliptic curve of the correct order r over a prime field of size p . So in principal we are done, as we have

found a curve with the same basic properties as *Secp256k1*. However the curve is defined by the equation

$$y^2 = x^3 + 86844066927987146567678238756515930889952488499230423029593188005931626003754$$

that use a very large parameter b_1 , which might perform slow in certain algorithms. 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 . So 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

$$d = \sqrt[3]{\frac{b_2}{b_1}}$$

and then invoke sage to loop through values $b_2 \in \mathbb{F}_p$ until it finds some number such that the quotient $\frac{b_2}{b_1}$ has a cube root d and this cube root itself is a quadratic residue. ??So indeed the smallest possible value is $b_2 = 7$ and the defining 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 seen the complex multiplication method is powerful enough to derive cryptographically secure curves like *Secp256k1* from scratch.

The BLS6_6 pen& paper curve In this paragraph we to summarize our understanding of elliptic curves to derive our main pen & 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&paper examples, which mostly means that the curve should contain only a few points, such that we are able to derive exhaustive addition and pairing tables.

A well understood family of pairing friendly curves are the BLS curves (STUFF ABOUT THE HISTORY AND THE NAMING CONVENTION), which are derived in [XXX]. BLS curves are particular 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&paper example.

To apply the complex multiplication method from XXX, 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 what is necessary to control is the order r of the largest prime factor group.

In the case of BLS_6 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

$$\begin{aligned} r(x) &= \Phi_6(x) \\ t(x) &= x + 1 \\ q(x) &= \frac{1}{3}(x-1)^2(x^2 - x + 1) + x \end{aligned}$$

where 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 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 $D = -3$ and 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, most unsecure BLS_6 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 $r(x) > 3$.

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 are 6 digits, the name of our pen&paper curve should be BLS6_6, since its is common behaviour 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**.

Racalling from XXX, 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 $43^k - 1$. ??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 XXX. 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 equation

$$\begin{array}{ll} 4p = t^2 + |D|v^2 & \Rightarrow \\ 4 \cdot 43 = 5^2 + |D|v^2 & \Rightarrow \\ 172 = 25 + |D|v^2 & \Leftrightarrow \\ 49 = |D|v^2 & \end{array}$$

has the four solutions $(D, v) \in \{(-3, -7), (-3, 7), (-49, -1), (-49, 1)\}$ if D is required to be negative, as expected. So $D = -3$ 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 $j(\text{BLS6_6}) = 0$. We therefore have to look at case XXX in table XXX to derive a parameter b . To decide the proper case for $j_0 = 0$

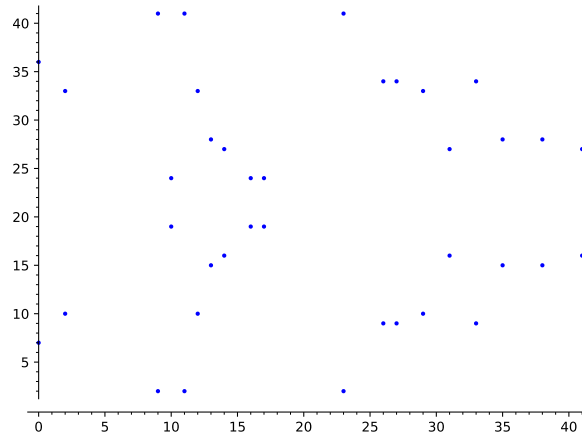
and $D = -3$, we therefore have to choose some arbitrary quadratic non residue c_2 and cubic non residue c_3 in \mathbb{F}_{43} . We choose $c_2 = 5$ and $c_3 = 36$. We check ??

Using those numbers we check the six possible cases from XXX against the the expected order 39 of the curve we want to syntesize:

??So as expeced we found an elliptic curve of the correct order 39 over a prime field of size 43, defined by the equation

$$BLS6_6 := \{(x, y) \mid y^2 = x^3 + 6 \text{ for all } x, y \in \mathbb{F}_{43}\} \quad (5.26)$$

There are other choice for b like $b = 10$ or $b = 23$, but all these curves are isomorphic and hence represent the same curve really but in a different way only. Since BLS6-6 only contains 39 points it is possible to give a visual impression of the curve:



As we can see our curve is somewhat nice, as it does not contain self inverse points that is points with $y = 0$. It follows that the addition law can be optimized, since the branch for those cases can be eliminated.

Summarizing the previous procedure, we have used the method of Barreto, Lynn and Scott to construct a pairing friendly elliptic curve of embedding degree 6. However in order to do elliptic curve cryptography on this curve note that since the order of $BLS6_6$ is 39 its group of rational points is not a finite cyclic group of prime order. We therefore have to find a suitable subgroup as our main target and since $39 = 13 \cdot 3$, we know that the curve must contain a "large" prime order group of size 13 and a small cofactor group of order 3.

It is the content of the following step to construct this group. One way to do so is to find a generator. We can achieve this by choosing an abitrary element of the group that is not the point at infinity and then multiply that point with the cofactor of the groups order. If the result is not the point at infinity, the result will be a generator and if it is the point at infinity we have to choose a different element.

So 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 arbitray 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 ssolution $y \in \mathbb{F}_{43}$ that satisfies the defining Weierstrass equation $y^2 = x^3 + 6$. We choose $x = 9$. Then $y = 2$ is a proper solution, since

$$\begin{aligned} y^2 &= x^3 + 6 && \Rightarrow \\ 2^2 &= 9^3 + 6 && \Leftrightarrow \\ 4 &= 4 \end{aligned}$$

and this implies that $P = (9, 2)$ is therefore a point on $BLS6_6$. To see if we can project this point onto a generator of the large order prim group $BLS6_6[13]$, we have to multiply P with the cofactor, that is we have to compute $[3](9, 2)$. After some computation (EXERCISE) we get $[3](9, 2) = (13, 15)$ and since this is not the point at infinity we know that $(13, 15)$ must be a generator of $BLS6_6[13]$. We write

$$g_{BLS6_6[13]} = (13, 15) \quad (5.27)$$

as we will need this generator in pairing computations all over the book. Since $g_{BLS6_6[13]}$ is a generator, we can use it to construct the subgroup $BLS6_6[13]$, by repeatedly adding the generator to itself. We use sage and get `??` Repeatedly adding a generator to itself as we just did, will generate small groups in logarithmic order with respect to the generator as explained in XXX. We therefore get the following description of the large prime order subgroup of $BLS6_6$:

$$\begin{aligned} BLS6_6[13] = \\ \{ (13, 15) \rightarrow (33, 34) \rightarrow (38, 15) \rightarrow (35, 28) \rightarrow (26, 34) \rightarrow (27, 34) \rightarrow \\ (27, 9) \rightarrow (26, 9) \rightarrow (35, 15) \rightarrow (38, 28) \rightarrow (33, 9) \rightarrow (13, 28) \rightarrow \mathcal{O} \} \end{aligned} \quad (5.28)$$

Having a logarithmic description of this group is tremendously helpfull 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

$$[\cdot]_{(13,15)} : \mathbb{F}_{13} \rightarrow BLS6_6[13] ; x \mapsto [x](13, 15)$$

which generates the group in logarithmic order. 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 point for our purposes is, that we can use this representation to do computations in $BLS6_6[13]$ efficiently in our head using XXX. For example

$$\begin{aligned} (27, 34) \oplus (33, 9) &= [6](13, 15) \oplus [11](13, 15) \\ &= [6 + 11](13, 15) \\ &= [4](13, 15) \\ &= (35, 28) \end{aligned}$$

So XXX is really all we need to do computations in $BLS6_6[13]$ in this book efficiently. However out of convinience, the following picture lists the entire addition table of that group. It 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 XXX.

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

$$\mathbb{G}_1[13] = \{(13, 15) \rightarrow (33, 34) \rightarrow (38, 15) \rightarrow (35, 28) \rightarrow (26, 34) \rightarrow (27, 34) \rightarrow (27, 9) \rightarrow (26, 9) \rightarrow (35, 15) \rightarrow (38, 28) \rightarrow (33, 9) \rightarrow (13, 28) \rightarrow \mathcal{O}\}$$

as the first argument for the Weil pairing function.

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 XXX.

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

$$BLS6_6 := \{(x, y) \mid y^2 = x^3 + 6 \text{ for all } x, y \in \mathbb{F}_{43^6}\} \quad (5.29)$$

over the extension field \mathbb{F}_{43^6} , since the embedding degree of $BLS6_6$ is 6. So we have to construct \mathbb{F}_{43^6} , a field that contains 6321363049 many 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 ?? 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 $t^6 + 6$.

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 defining equation but extend the domain from \mathbb{F}_{43} to \mathbb{F}_{43^6} . After that we have to find at least one element P from that curve, that is not the point at infinity, that is in the full 13-torsion and that satisfies the identity $\pi(P) = [43]P$. We can then use this element as our generator of $\mathbb{G}_2[13]$ and construct all other elements by repeated addition to itself.

Since $BLS6(\mathbb{F}_{43^6})$ contains 6321251664 elements, its not a good strategy to simply loop through all elements. Fortunately sage has a way to loop through elements from the torsion group directly. We get ?? So we found an element from the full 13-torsion, that is in the Eigenspace of the Eigenvalue 43, which implies that it is an element of $\mathbb{G}_2[13]$. As $\mathbb{G}_2[13]$ is cyclic of prime order this element must be a generator and we write

$$g_{\mathbb{G}_2[13]} = (7v^2, 16v^3) \quad (5.30)$$

We can use this generator to compute \mathbb{G}_2 is logarithmic order with respect to $g_{\mathbb{G}_2[13]}$. Using sage we get ??

$$\begin{aligned} \mathbb{G}_2 = \{ & (7v^2, 16v^3) \rightarrow (10v^2, 28v^3) \rightarrow (42v^2, 16v^3) \rightarrow (37v^2, 27v^3) \rightarrow \\ & (16v^2, 28v^3) \rightarrow (17v^2, 28v^3) \rightarrow (17v^2, 15v^3) \rightarrow (16v^2, 15v^3) \rightarrow \\ & (37v^2, 16v^3) \rightarrow (42v^2, 27v^3) \rightarrow (10v^2, 15v^3) \rightarrow (7v^2, 27v^3) \rightarrow \mathcal{O} \} \end{aligned}$$

Again, having a logarithmic description of $\mathbb{G}_2[13]$ is tremendously helpfull in pen and paper computations, as it reduces complicated computation in the extended curve to modular 13 arithmetics. For 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 summerize the previous steps, we have found two subgroups $\mathbb{G}_1[13]$ as well as $\mathbb{G}_2[13]$ suitable to do Weil pairings on *BLS6_6* as explained in XXX. Using the logarithmic order XXX of $\mathbb{G}_1[13]$, the logarithmic order XXX of $\mathbb{G}_2[13]$ and the bilinearity

$$e([k_1]g_{BLS6_6[13]}, [k_2]g_{\mathbb{G}_2[13]}) = e(g_{BLS6_6[13]}, g_{\mathbb{G}_2[13]})^{k_1 \cdot k_2}$$

we can do Weil pairings on *BLS6_6* in a pen and paper style, observing that the Weil pairing between our two generators is given by the identity

$$e(g_{BLS6_6[13]}, g_{\mathbb{G}_2[13]}) = 5v^5 + 16v^4 + 16v^3 + 15v^2 + 3v + 41$$

??

Hashing to the 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

Non 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. For every genrator we therefore have to choose a set of 4 randomly generated invertible elements from \mathbb{F}_{13} . We choose

$$\begin{aligned} (38, 15) &: \{2, 7, 5, 9\} \\ (35, 28) &: \{11, 4, 7, 7\} \\ (27, 34) &: \{5, 3, 7, 12\} \\ (38, 28) &: \{6, 5, 1, 8\} \end{aligned}$$

So our hash function is computed like this:

$$\begin{aligned} H_1(x_{11}, x_1, \dots, x_0) &= [2 \cdot 7^{x_{11}} \cdot 5^{x_{10}} \cdot 9^{x_9}](38, 15) + [11 \cdot 4^{x_8} \cdot 7^{x_7} \cdot 7^{x_6}](35, 28) + \\ &\quad [5 \cdot 3^{x_5} \cdot 7^{x_4} \cdot 12^{x_3}](27, 34) + [6 \cdot 5^{x_2} \cdot 1^{x_1} \cdot 8^{x_0}](38, 28) \end{aligned}$$

Note that $a^x = 1$ whe $x = 0$ and hence those terms can be omitted in the computation. In particular the hash of the 12-bit zero string is given by

$$\begin{aligned} \text{WRONG} - \text{ORDERING} - \text{REDO} H_1(0) &= [2](38, 15) + [11](35, 28) + [5](27, 34) + [6](38, 28) = \\ &= (27, 34) + (26, 34) + (35, 28) + (26, 9) = (33, 9) + (13, 28) = (38, 28) \end{aligned}$$

The hash of 011010101100 is given by

$$\begin{aligned}
 H_1(011010101100) &= \text{WRONG} - \text{ORDERING} - \text{REDO} \\
 [2 \cdot 7^0 \cdot 5^1 \cdot 9^1](38, 15) &+ [11 \cdot 4^0 \cdot 7^1 \cdot 7^0](35, 28) + [5 \cdot 3^1 \cdot 7^0 \cdot 12^1](27, 34) + [6 \cdot 5^1 \cdot 1^0 \cdot 8^0](38, 28) = \\
 [2 \cdot 5 \cdot 9](38, 15) &+ [11 \cdot 7](35, 28) + [5 \cdot 3 \cdot 12](27, 34) + [6 \cdot 5](38, 28) = \\
 [12](38, 15) &+ [12](35, 28) + [11](27, 34) + [4](38, 28) = \\
 &\text{TO}_A\text{PPEAR}
 \end{aligned}$$

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. For every generator we therefore have to choose a set of 4 randomly generated invertible elements from \mathbb{F}_{13} . We choose

$$\begin{aligned}
 (7v^2, 16v^3) &: \{8, 4, 5, 7\} \\
 (42v^2, 16v^3) &: \{12, 1, 3, 8\} \\
 (17v^2, 15v^3) &: \{2, 3, 9, 11\} \\
 (10v^2, 15v^3) &: \{3, 6, 9, 10\}
 \end{aligned}$$

So our hash function is computed like this:

$$\begin{aligned}
 H_1(x_{11}, x_{10}, \dots, x_0) &= [8 \cdot 4^{x_{11}} \cdot 5^{x_{10}} \cdot 7^{x_9}](7v^2, 16v^3) + [12 \cdot 1^{x_8} \cdot 3^{x_7} \cdot 8^{x_6}](42v^2, 16v^3) + \\
 &[2 \cdot 3^{x_5} \cdot 9^{x_4} \cdot 11^{x_3}](17v^2, 15v^3) + [3 \cdot 6^{x_2} \cdot 9^{x_1} \cdot 10^{x_0}](10v^2, 15v^3)
 \end{aligned}$$

We extend this to a hash function that maps unbounded bitstring 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.

$$\text{TinyMD5}_{\mathbb{G}_2} : \{0, 1\}^* \rightarrow \mathbb{G}_2$$

with $\text{TinyMD5}_{\mathbb{G}_2}(s) = H_2(\text{MD5}(s)_0, \dots, \text{MD5}(s)_{11})$. For example, since $\text{MD5}("") = 0\text{xd}41\text{d}8\text{cd}98\text{f}00\text{b}204\text{e}98$ and the binary representation of the hexadecimal number $0\text{x}27\text{e}$ is 001001111110 we compute $\text{TinyMD5}_{\mathbb{G}_2}$ of the empty string as $\text{TinyMD5}_{\mathbb{G}_2}("") = H_2(\text{MD5}(s)_{11}, \dots, \text{MD5}(s)_0) = H_2(001001111110) =$

Chapter 6

Statements

As we have seen in the informal introduction XXX, a snarks is a short non-interactive argument of knowledge, where the knowledge-proof attests to the correctness of statements like "I know the prime factorization of a given number" or "I know the preimage to a given SHA3 digest value" and similar things. However human readable statements like those 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. We will then look at algebraic circuits and rank-1 constraint systems as two particular useful ways to define statements in certain formal languages.

As in many other parts of the book the emphasis is on an introduction from the developers point of view. 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 attacks on the applications of snarks.

6.1 Formal Languages

Formal languages provide the theoretical backround in which logical statements can be formulated in a logically regious way. Roughly speaking a formal language is nothing but a set of words, that are strings of letters taken from some alphabet and formed according to some defining rules of that language.

To be more precise, let Σ be any set and Σ^* the set of all finite tupels (x_1, \dots, x_n) of elements x_j from Σ including the empty tupel $() \in \Sigma^*$. Then a **formal language** L is in its most general definition nothing but a subset of 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**. The rules that specify which tupels from Σ^* belong to the language and which don't, are called the **grammar** of the language.

Checking Relations In the context of snark development it is common to formalize the grammar of a language by a so called **checking relation**, which can be interpreted as a map

$$R : \Sigma^* \rightarrow \{TRUE, FALSE\} \quad (6.1)$$

that decides if a tupel $x \in \Sigma^*$ is an element of the language or not. In this case the language itself can be written as the set of all tupels that satisfies the grammar, i.e as:

$$L := \{x \in \Sigma^* \mid R(x) = TRUE\} \quad (6.2)$$

In our context a **statement** is then a claim, that language L contains a word x , i.e a statement claims $x \in L$ and one way to constructively *proof* a staitment is to provided an actual **instance**, that is an actual word of the language.

Of course formal languages should not be confused with the more intuitive concept of a natural languag. The following examples will provide some intuition about formal languages.

Example 103 (Alternating Binary strings). *To consider a very basic formal language with an almost trivial grammar consider the set $\{0, 1\}$ of the two letters 0 and 1 as our alphabet Σ and imply the rule that a proper word must consist of alternating binary letters of arbitrary length.*

Then the associated language L_{alt} is the set of all finite binary tupels, where a 1 must follow a 0 and vice versa. So for example $(1, 0, 1, 0, 1, 0, 1, 0, 1) \in L_{alt}$ is a proper word as well as $(0) \in L_{alt}$ or the empty word $() \in L_{alt}$. However the binary tupel $(1, 0, 1, 0, 1, 0, 1, 1, 1) \in \{0, 1\}^$ is not a proper word as it violates the grammer of L_{alt} . In addition the tupel $(0, A, 0, A, 0, A, 0)$ is not a proper word as its letter are not from the proper alphabet.*

Inside language L_{alt} it makes sense to claim the following statement: "There exists an alternating string." One way to proof this statement would be by proving an actual instance, that is finding actual alternating string like $x = (1, 0, 1)$. Constructing a string like $(1, 0, 1)$ therefore proofs that statement "There exists an alternating string."

Attempting to write the grammar of this language in a more formal way, we can define the following checking relation:

$$R : \{0, 1\}^* \rightarrow \{TRUE, FALSE\} ; (x_1, x_2, \dots, x_n) \mapsto \begin{cases} TRUE & x_j \neq x_{j+1} \text{ for all } 1 \leq j < n \\ FALSE & \text{else} \end{cases}$$

We can use this relation to check if arbitrary binary tupels are words in L_{alt} or not. For example $R(1, 0, 1) = TRUE$, $R(0) = TRUE$ and $R() = TRUE$, but $R(1, 1) = FALSE$ and so on.

Example 104 (Programing Language). *Programming languages are a very important class of formal languages. In this case 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 are then nothing but properly written computer programm that the compiler accepts. The compiler can therefore be interpreted as the checking relation.*

To give an unusual example strange enough to highlight the point, consider the programing 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 intersting claim is therefore the statement: "There exists a computer program in Malbolge". As it turned out proofing this statement by providing an actual instance was 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 proof the statement.

To look at this high level description more formally, we write $L_{Malbolge}$ for the language, that uses the ASCII table as its alphabet and words are tuples of ASCII letters that the Malbolge compiler accepts. Prooving the statement "There exists a computer program in Malbolge" is the equivalent to the task of finding some word $x \in L_{Malbolge}$. The string

`(=<#9] 6ZY327Uv4-QsqpMn&+Ij''E%e{Ab w=_:]Kw%o44Uqp0/Q?xNvL:H%c#DD2^WV>gY;dtS76qKJImZkj`

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)

Example 105 (3-Factorization). *As one of our main running examples in this book, we want to develop a snark that proofs knowledge of the factorization of elements of the finite field \mathbb{F}_{13} into exactly three factors.*

Formalizing such a high level description, we can define $\Sigma := \mathbb{F}_{13}$ as the alphabet of our language and then define a language $L_{3.fac}$ to consists of those tuples of field elements from \mathbb{F}_{13} , that contain exactly 4 letters w_1, w_2, w_3, w_4 which satisfy the equation $w_1 \cdot w_2 \cdot w_3 = w_4$.

So for example the tuple $(2, 12, 4, 5)$ is a word in $L_{3.fac}$, while neither $(2, 12, 11)$, nor $(2, 12, 4, 7)$ nor $(2, 12, 7, 168)$ are words in $L_{3.fac}$ as they dont satisfy the grammar or are not define over the proper alphabet.

We can describe the language $L_{3.fac}$ more formally by introducing a checking relation as described in XXX:

$$R_{3.fac} : \mathbb{F}_{13}^* \rightarrow \{TRUE, FALSE\} ; (x_1, \dots, x_n) \mapsto \begin{cases} TRUE & n = 4 \text{ and } x_1 \cdot x_2 \cdot x_3 = x_4 \\ FALSE & \text{else} \end{cases}$$

Having defined the language $L_{3.fac}$ it then makes sense to claim the statement like "There is a word in $L_{3.fac}$ " which is logically equivalent to say "There are four elements w_1, w_2, w_3, w_4 from the finite field \mathbb{F}_{13} " such that the equation $w_1 \cdot w_2 \cdot w_3 = w_4$ holds. Proving the correctness of this statement could then be achieved by finding actual field elements like $x_1 = 2$, $x_2 = 12$, $x_3 = 4$ and $x_4 = 5$ giving the $L_{3.fac}$ instance $(2, 12, 4, 5)$, which is a proof for our statement.

Instance and Witness As we have seen statements can formulated as membership claims in formal languages and instances can serve as constructive proofs for those claims. However, in the context of *zero-knowledge* proofs its possible to hide parts of the proofing instance and still be able to proof the statement. In such a context the instance is therefore split into a *public part* which again is called the **instance** and a not publically known part (a private part) called the **witness**.

To acknowledge for this seperation of a proof instance into a public and a private part, our previous definition of a formal language needs a refinement in the context of zero-knowledge proofs. Instead of a single alphabet we consider two alphabets Σ_I and Σ_W , such that the words of the languages are tuples $(i|w) \in \Sigma_I^* \times \Sigma_W^*$ subject to a checking relation

$$R : \Sigma_I^* \times \Sigma_W^* \rightarrow \{TRUE, FALSE\} \quad (6.3)$$

that decides if a tuple $(i|w) \in \Sigma_I^* \times \Sigma_W^*$ is an element of the language or not. Again the language itself can be written as the set of all tuples that satisfies the grammar, i.e as:

$$L := \{(i, w) \in \Sigma_I^* \times \Sigma_W^* \in \Sigma^* \mid R(i|w) = TRUE\} \quad (6.4)$$

In this case we call a public input i an **instance** and a private input w a **witness** of the relation R .

In this context a **statement** is the claim, that given an instance $i \in \Sigma_I^*$ there is a witness $w \in \Sigma_W^*$, such that language L contains a word $(i|w)$. As in the situation of more general languages one way to constructively *proof* such a statement is to provided an actual pair $(i|w)$ with $R(i|w)$, however the point of zero-knowledge proofing systems, as we will see in XXX, is to proof such a statement, without revealing any knowledge about w .

So while statements in the sense of the previous chapter can be seen as membership proofs, statements in this refined definition in combination with publically known instances are knowledge-proofs rather.

Example 106 (3-factorization). Consider the language $L_{3, \text{fac}}$ from example XXX again. Providing instances for the membership statement in this language is equivalent to providing knowledge of 4 elements x_1, x_2, x_3 and x_4 from \mathbb{F}_{13} , such that the modular 13 product of the first three elements is equal to the 4'th element.

Splitting instances into private and public parts, we can reformulate the problem introducing different levels of zero-knowledge into the problem. For example we could reformulate the non-hiding membership statement "there are 4 field elements x_1, x_2, x_3 and x_4 from \mathbb{F}_{13} , such that $x_1 \cdot x_2 \cdot x_3 = x_4$ into a statement, where all factors x_1, x_2, x_3 of x_4 are private and only the product x_4 is public.

A statement would then be something like "There are three factors of x_4 " and as we will see in XXX a zero-knowledge proofing system is able to proof this statement without revealing anything about the factors x_1, x_2 , or x_3 .

Formalizing this new language, which we might call $L_{3, \text{fac_zk}}$ we define a checking relation by

$$R_{3, \text{fac_zk}} : \mathbb{F}_{13}^* \times \mathbb{F}_{13}^* \rightarrow \{TRUE, FALSE\} ;$$

$$((i_1, \dots, i_n) | (w_1, \dots, w_m)) \mapsto \begin{cases} TRUE & n = 1, m = 3, i_1 = w_1 \cdot w_2 \cdot w_3 \\ FALSE & \text{else} \end{cases}$$

and as usual $L_{3, \text{fac_zk}}$ is then defined by all tuples from $\mathbb{F}_{13}^* \times \mathbb{F}_{13}^*$ that are mapped onto TRUE under $R_{3, \text{fac_zk}}$.

Since words in $L_{3, \text{fac_zk}}$ are tuples $(i|w)$ consisting of an instance and a witness, there are different possibilities to formulate statements. The most general one would be equivalent to the one in XXX claiming "there are words in $L_{3, \text{fac_zk}}$ " and a proof, could be given by a concrete pair $(i|w) \in L_{3, \text{fac_zk}}$, such as $(5|2, 12, 4)$.

However as explained in XXX, in the context of zero knowledge proofs, statements are rather knowledge-claims like "Given public input i , there is a private input w . So for example in $L_{3, \text{fac_zk}}$ with public input $i = 5$ a proof for the associated statement could be given by $w = (2, 12, 4)$.

As we will see in XXX, zero-knowledge proofing systems provide techniques to statements like this without revealing anything about the witness.

One question that arises in this context might be why we decided the factors x_1, x_2 and x_3 to be the witness and the product x_4 to be the instance. This of course was just an arbitrary choice and we could have decided on any other constellation. For example nothing stops us from declaring all variables as private or just x_1 or whatever. The actual choice is determined by the application only.

Example 107 (SHA256 – Knowledge of Preimage). A standard example to show the power of zero knowledge proofs is proving the knowledge of some preimage of a cryptographic hash function like the SHA256 function, without actually revealing it.

To understand this example in detail, let's start with introducing a language well suited to build a snark for this problem. Since SHA256 is a function

$$SHA256 : \{0, 1\}^* \rightarrow 0, 1^{256}$$

that maps binary string of arbitrary length onto binary strings of length 256 and we want to proof 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 for both the set of all witnesses and the set of all instances is therefore the set $\{0, 1\}$ of the two binary letters. We then define a checking relation by

$$R_{SHA256} : \{0, 1\}^* \times \{0, 1\}^* \rightarrow \{TRUE, FALSE\} ;$$

$$(i|w) \mapsto \begin{cases} TRUE & i.len() = 256, i = SHA256(w) \\ FALSE & \text{else} \end{cases}$$

and we write L_{SHA256} for the associated language that consists of instance, witness pairs $(i|w) \in L_{SHA256}$ where the instance i is the SHA256 image of the witness w .

Given an instance $i \in \{0, 1\}^{256}$ a statements in L_{SHA256} then is the claim, that there is a witness $w \in \{0, 1\}^*$, such that i is the image of SHA256 of w . One way to proof such a statement would therefore be to actually provide some data that hashes onto i .

Example 108 (Knowledge of Private Key). In this example we want to proof knowledge of an elliptic curve secrete key, provided a public key is given as instance. Of course the most common way to proof knowledge of this key, would be to sign something with it. However the purpose of this example is to shift view on the problem a bit.

As an example curve consider the tiny-jubjub curve from example XXX in its Edwards form

Modularity and Gadgets From a developers perspective it is often useful to construct complex statements and their representing languages from simple ones. In the context of zero knowledge proofs those simple building blocks are often called *gadgets* and mature proofing systems usually contain libraries that contain many useful gadgets, like representations of basic types as booleans, unit32, preimage proofs for Hash functions, elliptic curve cryptography and so on. Implementers can then combine these fundamental building blocks to write complex real world applications.

To understand what this means on the level of formal languages defined by checking relations as explained in XXX, we need to look at the *intersection* of two formal languages, which can be constructed whenever both languages are defined over the same alphabet. In this case the intersection language consists of words that are contained in both languages. To be more precise, let L_1 and L_2 be two formal languages defined over the instance and witness alphabets Σ_I and Σ_W . Then

$$L_1 \cap L_2 := \{x \mid x \in L_1 \text{ and } x \in L_2\} \quad (6.5)$$

If both languages are defined by checking functions R_1 and R_2 as explained in XXX, the following function is a checking function for the intersection language $L_1 \cap L_2$:

$$R_{L_1 \cap L_2} : \Sigma_I^* \times \Sigma_W^* \rightarrow \{TRUE, FALSE\} ; (i, w) \mapsto R_1(i, w) \text{ and } R_2(i, w) \quad (6.6)$$

This is an important fact from an implementations point of view as it allows to construct complex checking relations and their statements from simple building blocks. Given a publically known instance $i \in \Sigma_I^*$ a statement in an intersection language 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 definition by checking relations are a powerful tool to describe statements in a formally rigorous manner.

However from the perspective of existing zero knowledge proofing systems not all ways to actually represent checking relations are equally useful. Depending on the proofing system at hand some are more suitable than others. In this section we will therefore describe the most common ways to represent checking relations and their statements.

6.2.1 Circuit Satisfiability

Definition 6.2.1.1 (Circuits). *Let Σ_I and Σ_W be two alphabets. Then a directed, acyclic graph C is called a **circuit** over $\Sigma_I \times \Sigma_W$, if the graph has an ordering and every node has a label in the following way:*

- *Every source node (called input) has a letter from $\Sigma_I \times \Sigma_W$ as label.*
- *Every sink node (called output) has a letter from $\Sigma_I \times \Sigma_W$ as label.*
- *Every other node (called gate) with j incoming edges has a label that consists of a function $f : (\Sigma_I \times \Sigma_W)^j \rightarrow \Sigma_I \times \Sigma_W$.*

Remark 1 (Circuit-SAT). *Every circuit with n input nodes and m output nodes can be seen as a function that transforms strings of size n from $\Sigma_I \times \Sigma_W$ into strings of size m over the same alphabet. The transformation is done by sending the strings from a node along the outgoing edges to other nodes. If those nodes are gates, then the string is transformed according to the label.*

By executing the previous transformation, every node of a circuit has an associated letter from $\Sigma_I \times \Sigma_W$ and this defines a checking relation over $\Sigma_I^ \times \Sigma_W^*$. To be more precise, let C be a circuit with n nodes and $(i, w) \in \Sigma_I^j \times \Sigma_W^k$ a string. Then $R_C(i, w)$ iff THE CIRCUIT IS SATISFIED WHEN ALL LABELS ARE ASSOCIATED TO ALL NODES IN THE CIRCUIT... BUT MORE PRECISE*

MODULO ERRORS. TO BE CONTINUED.....

An Assignment associates field elements to all edges (indices) in an algebraic circuit. An Assignment is valid, if the field elements arise from executing the circuit. Every other assignment is invalid.

The checking relation for circuit-SAT then is satisfied if valid assignment (TODO: THE WITNESS/INSTANCE SPLITTING)

Valid assignments are proofs for proper circuit execution.

So to summarize, algebraic circuits (over a field \mathbb{F}) are directed acyclic graphs, that express arbitrary, but bounded computation. Vertices with only outgoing edges (leaves, sources) represent inputs to the computation, vertices with only incoming edges (roots, sinks) represent outputs from the computation and internal vertices represent field operations (Either addition or multiplication). It should be noted however that there are many circuits that can represent the same language...

Circuits have a notion of execution, where input values are sent from leaves along edges, through internal vertices to roots.

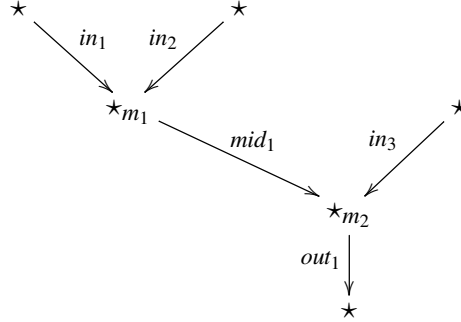
Remark 2. *Algebraic circuits are usually derived by Compilers, that transform higher languages to circuits. An example of such a compiler is XXX. Note: Different Compilers give very different circuit representations and Compiler optimization is important.*

Example 109 (Generalized factorization snark). Consider our generalized factorization example 115 with associated language ??.

To write this example in circuit-SAT, consider the following function

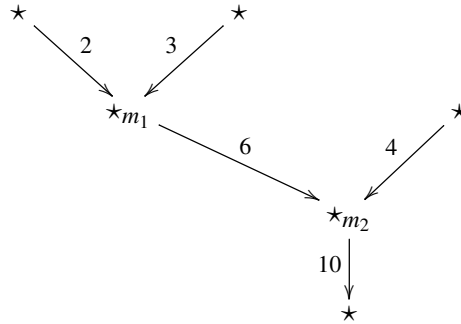
$$f : \mathbb{F}_{13} \times \mathbb{F}_{13} \times \mathbb{F}_{13} \rightarrow \mathbb{F}_{13}; (x_1, x_2, x_3) \mapsto (x_1 \cdot x_2) \cdot x_3$$

A valid circuit for $f : \mathbb{F}_{11} \times \mathbb{F}_{11} \times \mathbb{F}_{11} \rightarrow \mathbb{F}_{11}; (x_1, x_2, x_3) \mapsto (x_1 \cdot x_2) \cdot x_3$ is given by:



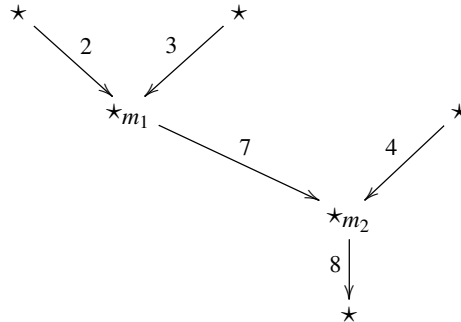
with edge-index set $I := \{in_1, in_2, in_3, mid_1, out_1\}$.

To given a valid assignment, consider the set $I_{valid} := \{in_1, in_2, in_3, mid_1, out_1\} = \{2, 3, 4, 6, 10\}$



Appears from multiplying the input values at m_1, m_2 in \mathbb{F}_{13} , hence by executing the circuit.

Non valid assignment: $I_{err} := \{in_1, in_2, in_3, mid_1, out_1\} = \{2, 3, 4, 7, 8\}$



Can not appear from multiplying the input values at m_1, m_2 in \mathbb{F}_{13}

To match the requirements of the initial task 115, we have to split the statement into instance and witness. So given index set $I := \{in_1, in_2, in_3, mid_1, out_1\}$, we assume that every step in the computation other than in_3 and out_1 are part of the witness. So we choose:

- Instance $S = \{in_3, out_1\}$.
- Witness $W = \{in_1, in_2, mid_1\}$.

Example 110 (Baby JubJub for BLS6-6).

Example 111 (ECDH as a circuit). *over BLS6*

Example 112 (BLS Signature). *example of one layer recursion over MNT4 and MNT6*

Example 113 (Boolean Circuits).

Example 114 (Algebraic (Arithmetic) Circuits).

Any program can be reduced to an arithmetic circuit (a circuit that contains only addition and multiplication gates). A particular reduction can be found for example in [BSCG+13]

6.3 Computational Models

Proofs are the evidence of correctness of the assertions, and people can verify the correctness by reading the proof. However, we obtain much more than the correctness itself: After you read one proof of an assertion, you know not only the correctness, but also why it is correct. Is it possible to solely show the correctness of an assertion without revealing the knowledge of proofs? It turns out that it is indeed possible, and this is the topic of today's lecture: Zero Knowledge Systems.

Example 115 (Generalized factorization snark). *As one of our major running examples we want to derive a zk-SNARK for the following generalized factorization problem:*

Given two numbers $a, b \in \mathbb{F}_{13}$, find two additional numbers $x, y \in \mathbb{F}_{13}$, such that

$$(x \cdot y) \cdot a = b$$

and proof knowledge of those numbers, without actually revealing them.

Of course this example reduces to the classic factorization problem (over \mathbb{F}_{13} by setting $y = 1$)

This zero knowledge system deals with the following situation: "Given two publicly known numbers $a, b \in \mathbb{F}_{13}$ a proofer can show that they know two additional numbers $x, y \in \mathbb{F}_{13}$, such that $(x \cdot y) \cdot a = b$, without actually revealing x or y ."

Of course our choice of what information to hide and what to reveal was completely arbitrary. Every other split would also be possible, but eventually gives a different problem.

For example the task could be to not hide any of the variables. Such a system has no zero knowledge and deals with verifiable computations: "A worker can proof that they multiplied three publicly known numbers $a, b, x \in \mathbb{F}_{13}$ and that the result is $z \in \mathbb{F}_{13}$, in such a way that no verifier has to repeat the computation."

6.3.1 Rank-1 Constraint Systems

The idea of R1CS is that it keeps track of the values that each variable assumes during the computation, and binds the relationships among all those variables that are implied by the computation itself. This way doing a computation properly is enforced by enforcing relations (constraints) between every consecutive steps in the computation.

Definition 6.3.1.1 (Rank-1 Constraint system). *Let \mathbb{F} be a Galois field, i, j, k three numbers and A, B and C three $(i + j + 1) \times k$ matrices with coefficients in \mathbb{F} . Then any vector $x = (1, \phi, w) \in \mathbb{F}^{1+i+j}$ that satisfies the **rank-1 constraint system** (R1CS)*

$$Ax \odot Bx = Cx$$

(where \odot is the Hadamard/Schur product) is called a **statement** of that system, with **instance** ϕ and **witness** w .

We call k the **number of constraints**, i the **instance size** and j the **witness size**.

Remark 3. Any Rank-1 constraint system defines a formal language in the following way: Consider the alphabets $\Sigma_I := \mathbb{F}$ and $\Sigma_W : \mathbb{F}$. Then a checking relation $R_{R1CS} \subset \Sigma_I^i \times \Sigma_W^j \subset \Sigma_I^* \times \Sigma_W^*$ is defined by

$$R_{R1CS}(i, w) \Leftrightarrow (i, w) \text{ satisfies the R1CS}$$

As shown in XXX such a checking relation defines a formal language. We call this language **R1CS satisfiability**.

Example 116 (Generalized factorization snark). *Defining the 5-dimensional affine vector $w = (1, in_1, in_2, in_3, m_1, out_1)$ for $in_1, in_2, in_3, m_1, out_1 \in \mathbb{F}_{13}$ and the 6×7 -matrices*

$$A = \begin{pmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \end{pmatrix}, \quad B = \begin{pmatrix} 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \end{pmatrix}, \quad C = \begin{pmatrix} 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}$$

We can instantiate the general R1CS equation $Aw \odot Bw = Cw$ as

$$\begin{pmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \end{pmatrix} \begin{pmatrix} 1 \\ in_1 \\ in_2 \\ in_3 \\ m_1 \\ out_1 \end{pmatrix} \odot \begin{pmatrix} 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \end{pmatrix} \begin{pmatrix} 1 \\ in_1 \\ in_2 \\ in_3 \\ m_1 \\ out_1 \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 \\ in_1 \\ in_2 \\ in_3 \\ m_1 \\ out_1 \end{pmatrix}$$

So evaluating all three matrix products and the Hadarmat prodoct we get two constraint equations

$$\begin{aligned} in_1 \cdot in_2 &= m_1 \\ m_1 \cdot in_3 &= out_1 \end{aligned}$$

So from the way this R1CS is constructed, we know that whatever the underlying field \mathbb{F} is, the only solutions to this equations are

$$\{(0, 0, 0), (0, 1, 0), (1, 0, 0), (1, 1, 1)\}$$

Gadgets Rank 1 constraints systems can become very large

Boolean Algebra

Sometimes it is necessary to assume that a statement describes boolean variables. However by definition the alphabet of a statement is a finite field, which is often the scalar field of a large prime order cyclic group. So developers need a way to simulate boolean algebra inside other finite fields.

The most common way to do this, is to interpret the additive and multiplicate neutral element $\{0, 1\} \subset F$ as boolean values. This is convinient because they are defined in any field.

In what follows we will define a few of the most basic R1CS to check boolean expressions in R1CS satisfiability. We will leave other basic constructions as exercises to the reader.

We start with actually constraining field elements to boolean values then Once field elements are boolean constraint, we need constraints that are able to enforce boolean algebra on them. We therefore give constraints for the functionally complete set of Boolean operators give by *AND* and *NOT*. As all other boolean operations can be constructed from *AND* and *NOT*, this suffices. However in actual implementations it is of high importance to limit the number of constraints as much as possible. In reality it is therefor advantageous to implement all logic operators in constraints.

Boolean Constraint So when a developer needs boolean variables as part of their statement, a R1CS is required on those variables, that enforces the variable to be either 1 or 0. So to "constrain a field element $x \in \mathbb{F}$ to be 1 or 0 what we need is a system of equation $(A_i x) \cdot (B_i x) = C_i x$ for some $A_i, B_i, C_i \in \mathbb{F}$, such that the only possible solutions for x are 0 or 1. As it turns out such a system can be realized by a single equation $x \cdot (1 - x) = 0$ We see that indeed 0 and 1 are the only solutions here, since for the right side to be zero, at least one factor on the left side needs to be zero and this only happens for 0 and 1.

So now that we have found a correct equation for a boolean constrain, we have to translate it into the associated R1CS format, which is given by

$$\begin{pmatrix} 0 & 1 \end{pmatrix} \begin{pmatrix} 1 \\ x \end{pmatrix} \odot \begin{pmatrix} 1 & -1 \end{pmatrix} \begin{pmatrix} 1 \\ x \end{pmatrix} = \begin{pmatrix} 0 & 0 \end{pmatrix} \begin{pmatrix} 1 \\ x \end{pmatrix}$$

So we get the following statement $\phi = (1, i, w) = (1, x)$, with instance (public input) $i = x$ and now witness (private input) w . In addition we get the matrices $A = \begin{pmatrix} 0 & 1 \end{pmatrix}$, $B = \begin{pmatrix} 1 & -1 \end{pmatrix}$ and $C = \begin{pmatrix} 0 & 0 \end{pmatrix}$.

To make those constraints easily accesable for R1CS developers, a gadget is convinient:

AND-constraints Given three field elements $x, y, z \in \mathbb{F}$ that represent boolean variables, we want to find a R1CS, such that $w = (1, x, y, z)$ satisfies the constraint system if and only if $x \text{ AND } y = z$.

So first we have to constrain x, y and z to be boolean as explained in XXX. The next thin is we need to find a R1CS that enforces the *AND* logic. We can simply choose $x \cdot y = z$, since (for boolean constraint values) $x \cdot y$ equals 1 if and only if both x and y are 1.

Now that we have found a correct equation for a boolean constrain, we have to translate it into the associated R1CS format, which is given by

$$\begin{pmatrix} 0 & 1 & 0 & 0 \end{pmatrix} \begin{pmatrix} 1 \\ x \\ y \\ z \end{pmatrix} \odot \begin{pmatrix} 0 & 0 & 1 & 0 \end{pmatrix} \begin{pmatrix} 1 \\ x \\ y \\ z \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 \\ x \\ y \\ z \end{pmatrix}$$

Combining this R1CS with the required fthree boolean constraints for x, y and z we get

$$\begin{pmatrix} 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 \\ x \\ y \\ z \end{pmatrix} \odot \begin{pmatrix} 0 & 0 & 1 & 0 \\ 1 & -1 & 0 & 0 \\ 1 & 0 & -1 & 0 \\ 1 & 0 & 0 & -1 \end{pmatrix} \begin{pmatrix} 1 \\ x \\ y \\ z \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} 1 \\ x \\ y \\ z \end{pmatrix}$$

So from the way this R1CS is constructed, we know that whatever the underlying field \mathbb{F} is, the only solutions to this equations are

$$\{(0,0,0), (0,1,0), (1,0,0), (1,1,1)\}$$

which is the set of all $(x,y,z) \in \{0,1\}^3$ such that $x \text{ AND } y = z$.

NOT constraint Given two field elements $x, y \in \mathbb{F}$ that represent boolean variables, we want to find a R1CS, such that $w = (1, x, y)$ satisfies the constraint system if and only if $x = \neg y$.

So again we have to constrain x and y to be boolean as explained in XXX. The next think is we need to find a R1CS that enforces the *NOT* logic. We can simply choose $(1 - x) = y$, since (for boolean constraint values) this enforces that y is always the boolean opposite of x .

Now that we have found a correct equation for a boolean constrain, we have to translate it into the associated R1CS format, which is given by

$$\begin{pmatrix} 1 & -1 & 0 \end{pmatrix} \begin{pmatrix} 1 \\ x \\ y \end{pmatrix} \odot \begin{pmatrix} 1 & 0 & 0 \end{pmatrix} \begin{pmatrix} 1 \\ x \\ y \end{pmatrix} = \begin{pmatrix} 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 \\ x \\ y \end{pmatrix}$$

So actually we wrote the linear equation $1 - x = y$ like $(1 - x) \cdot 1 = y$ and translated that into the matrix equation.

Combining this R1CS with the required three boolean constraints for x , y and z we get

$$\begin{pmatrix} 1 & -1 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 \\ x \\ y \end{pmatrix} \odot \begin{pmatrix} 1 & 0 & 0 \\ 1 & -1 & 0 \\ 1 & 0 & -1 \end{pmatrix} \begin{pmatrix} 1 \\ x \\ y \end{pmatrix} = \begin{pmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} 1 \\ x \\ y \end{pmatrix}$$

So from the way this R1CS is constructed, we know that whatever the underlying field \mathbb{F} is, the only solutions to this equations are

$$\{(0,1), (1,0)\}$$

which is the set of all $(x,y) \in \{0,1\}^2$ such that $x = \neg y$.

EXERCISE: DO OR; XOR; NAND

More complicated logical constraints can then be obtained by combining all sub-R1CS together. For example if the task is to enforce $(in_1 \text{ AND } \neg in_2) \text{ AND } in_3 = out_1$ we first apply the FLATTENING technique from XXX, which gives is

$$\begin{aligned} \neg in_2 &= mid_1 \\ in_1 \text{ AND } mid_1 &= mid_2 \\ mid_2 \text{ AND } in_3 &= out_1 \end{aligned}$$

So we have the statement $w = (1, in_1, in_2, in_3, mid_1, mid_2, out_1)$, 6 boolean constraints for the variables, 2 constraints for the 2 *AND* operations and 1 constraint for the *NOT* operation.

Binary representations

In circuit computations its is often necessary to use the binary representation of a prime field element. Binary representations of prime field elements work exactly like binary representations of ordinary unsigned integers. Only the algebraic operations are different. To compute the binary representation of some number $x \in \mathbb{F}_p$ we need to know the number of bits in the binary representation of p first. We write this as $m = |p_{bin}|$.

Then a bitstring $(b_0, \dots, b_m) \in \{0, 1\}^m$ is the binary representation of the field element x , if and only if

$$x = b_0 \cdot 2^0 + b_1 \cdot 2^1 + \dots + b_m \cdot 2^m$$

Note that, since p is a prime number that has a leading bit 1 at position m . Moreover every prime number $p > 2$ is odd and hence has least significant bit set to 1. Hence all numbers 2^j for $0 \leq j \leq m$ are elements of \mathbb{F}_p and the equation is well defined. We can therefore enforce this equation as a R1CS, by flattening the equation:

$$\begin{array}{rcl} b_0 \cdot 1 & = & mid_0 \\ b_1 \cdot 2 & = & mid_1 \\ \dots & = & \dots \\ b_m \cdot 2^m & = & mid_m \\ (mid_0 + mid_1 + \dots + mid_m) \cdot 1 & = & x \end{array}$$

So we have the statement $w = (1, x, b_0, \dots, b_m, mid_0, \dots, mid_m)$ and we need $(m+1)$ constraints to enforce the binary representation in addition to the m constraints that enforce booleanness.

At this point we see, that writing more complex R1CS becomes clumsy and in actual implementations people therefore use languages to makes the constraint system more readable. In this example we could write for example something like this:

keeping in mind that this is a meta level algorithm to **generate** the R1CS, not the R1CS itself, as constructs like for loops have not direct meaning on the level of the R1CS itself.

Example 117. *Considering the prime field \mathbb{F}_{13} , we want to enforce the binary representation of $7 \in \mathbb{F}_{13}$. To find the number of bits that we need to consider in our R1Cs, we start with the binary representation of 13, which is $(1, 0, 1, 1)$ since $13 = 1 \cdot 2^0 + 0 \cdot 2^1 + 1 \cdot 2^2 + 1 \cdot 2^3$. So $m = 4$ and we have to enforce a 4-bit representation for 7, which is $(1, 1, 1, 0)$, since $7 = 1 \cdot 2^0 + 1 \cdot 2^1 + 1 \cdot 2^2 + 0 \cdot 2^3$.*

A valid statement is then given by $w = (1, 7, 1, 1, 1, 0, 1, 2, 4, 0)$ and indeed we satisfy the 9 required constraints

$$\begin{array}{rcl} 1 \cdot (1 - 1) & = & 0 \quad // \text{boolean constraints} \\ 1 \cdot (1 - 1) & = & 0 \\ 1 \cdot (1 - 1) & = & 0 \\ 0 \cdot (1 - 0) & = & 0 \\ \\ 1 \cdot 1 & = & 1 \\ 1 \cdot 2 & = & 2 \\ 1 \cdot 4 & = & 4 \\ 0 \cdot 8 & = & 0 \\ (1 + 2 + 4 + 0) \cdot 1 & = & 7 \end{array}$$

Conditional (ternary) operator

It is often required to implement the ternary conditional operator $?:$ as a R1CS. In general this operator takes three arguments, a boolean value b and two expressions *if_true* and *if_false*, usually written as $b ? c : d$ and executes c and d according to the value of b .

If we assume all three arguments to be values from a finite field, such that b is boolean constraint (XXX), we can enforce a field element x to be the result of the conditional operator as

$$x = b \cdot c + (1 - b) \cdot d$$

Flattening the code gives

$$\begin{aligned} b \cdot c &= mid_0 \\ (1 - b) \cdot d &= mid_1 \\ (mid_0 + mid_1) \cdot 1 &= x \end{aligned}$$

So we have the statement $w = (1, x, b, c, d, mid_0, mid_1)$ and we need 3 constraints to enforce the conditional operator in addition to 1 constraint that enforces booleanness of b .

NOTE: THERE WAS THIS PODCAST WITH ANNA AND THE GUY JAN TALKE TO WHERE HE SAID; CONDITIONALS CAN BE IMPLEMENTED SUCH THAT NOT BOTH BRANCHES ARE EXECUTED: LOOK THAT UP

Range Proofs

$x > 5 \dots$

UIntN

STUFF ABOUT HOW UINTN COMPUTATIONS ARE NOT STANDARDIZED AND THAT THERE ARE IMPLEMENTATIONS OTHER THEN MOD-N.... WE FIX ON MOD-N. WHAT DO ZEXE CIRCOM ECT FIX ON?

As we know circuits are not defined over integers but over finite fields instead. We therefore have no notation of integers in circuits. However on computers we also not use integers natively but UInt's instead.

As we know a UIntN type is a representation of integers in the range of $0 \dots 2^N$ with the exception that algebraic operations like addition and multiplication deviate from actual integers, whenever the result exceeds the largest representable number $2^N - 1$.

In circuit design it is therefore important to distinguish between various things tht might look like integers, but are actually not. For example Haskell's type NAT is an actual implementation of natural numbers. In particular this means

Example 118 (UInt8). *What is $0xFF0 + 0xFF0$ and so on...*

Bit constraints In prime fields, addition and multiplication behaves exactly like addition and multiplication with integers as long as the result does not exceed the modulus.

This makes the representation of UIntNs in a prime field \mathbb{F}_p potentially ambiguous, as there are two possible representations, whenever $2^N - 1 < p$. In that case any element of *UIntN* could be interpreted as an element of \mathbb{F}_p . This however is dangerous as the algebraic laws like addition and multiplication behave very different in general.

It is therefore common to represent UIntN types in circuits as binary constraints strings of field elements of length N .

Example 119. *Consider the UInt4 type over the prime field \mathbb{F}_{17} . Since $2^4 = 16$, UInt4 can represent the numbers $0, \dots, 15$ and it would be possible to interpret them as elements in \mathbb{F}_{17} . However addition*

Twisted Edwards curves

Sometimes it required to do elliptic curve cryptography "inside of a circuit". This means that we have to implement the algebraic operations (addition, scalar multiplication) of an elliptic curve as a R1CS. To do this efficiently the curve that we want to implement must be defined over the same base field as the field that is used in the R1CS.

Example 120. *So for example when we consider an RICS over the field \mathbb{F}_{13} as we did in example XXX, then we need a curve that is also defined over \mathbb{F}_{13} . Moreover it is advantageous to use a (twisted) Edwards curve inside a circuit, as the addition law contains no branching (See XXX). As we have seen in XXX our Baby-Jubjub curve is an Edwards curve defined over \mathbb{F}_{13} . So it is well suited for elliptic curve cryptography in our pen and paper examples*

Twisted Edwards curves constraints As we have seen in XXX, an Edwards curve over a finite field F is the set of all pairs of points $(x, y) \in \mathbb{F} \times \mathbb{F}$, such that x and y satisfy the equation $a \cdot x^2 + y^2 = 1 + d \cdot x^2 y^2$.

We can interpret this equation as a constraint on x and y and rewrite it as a RICS by applying the flattening technique from XXX.

$$\begin{aligned} x \cdot x &= x_sq \\ y \cdot y &= y_sq \\ x_sq \cdot y_sq &= xy_sq \\ (a \cdot x_sq + y_sq) \cdot 1 &= 1 + d \cdot xy_sq \end{aligned}$$

So we have the statement $w = (1, x, y, x_sq, y_sq, xy_sq)$ and we need 4 constraints to enforce that x and y are points on the Edwards curve $x^2 + y^2 = 1 + d \cdot x^2 y^2$. Writing the constraint system in matrix form, we get:

$$\begin{pmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & a & 1 & 0 \end{pmatrix} \begin{pmatrix} 1 \\ x \\ y \\ x_sq \\ y_sq \\ xy_sq \end{pmatrix} \odot \begin{pmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} 1 \\ x \\ y \\ x_sq \\ y_sq \\ xy_sq \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 & 0 & d \end{pmatrix} \begin{pmatrix} 1 \\ x \\ y \\ x_sq \\ y_sq \\ xy_sq \end{pmatrix}$$

EXERCISE: WRITE THE RICS FOR WEIERSTRASS CURVE POINTS

Example 121 (Baby-JubJub). *Considering our pen and paper Baby JubJub curve over from XXX, we know that the curve is defined over \mathbb{F}_{13} and that $(11, 9)$ is a curve point, while $(2, 3)$ is not a curve point.*

Starting with $(11, 9)$, we can compute the statement $w = (1, 11, 9, 4, 3, 12)$. Substituting this into the constraints we get

$$\begin{aligned} 11 \cdot 11 &= 4 \\ 9 \cdot 9 &= 3 \\ 4 \cdot 3 &= 12 \\ (1 \cdot 4 + 3) \cdot 1 &= 1 + 7 \cdot 12 \end{aligned}$$

which is true in \mathbb{F}_{13} . So our statement is indeed a valid assignment to the twisted Edwards curve constraining system.

Now considering the non valid point $(2, 3)$, we can still come up with some kind of statement w that will satisfy some of the constraints. But fixing $x = 2$ and $y = 3$, we can never satisfy all constraints. For example $w = (1, 2, 3, 4, 9, 10)$ will satisfy the first three constraints, but the last constrain can not be satisfied. Or $w = (1, 2, 3, 4, 3, 12)$ will satisfy the first and the last constrain, but not the others.

Twisted Edwards curves addition As we have seen in XXX one the major advantages of working with (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 "at infinity" but the actual curve poin $(0, 1)$.

As we know from XXX, give two points (x_1, y_1) and (x_2, y_2) on a twisted Edwards curve their sum is given by

$$(x_3, y_3) = \left(\frac{x_1 y_2 + y_1 x_2}{1 + d \cdot x_1 x_2 y_1 y_2}, \frac{y_1 y_2 - a \cdot x_1 x_2}{1 - d \cdot x_1 x_2 y_1 y_2} \right)$$

We can realize this equation as a R1CS as follows: First not that we can rewrite the addition law as

$$\begin{aligned} x_1 \cdot x_2 &= x_{12} \\ y_1 \cdot y_2 &= y_{12} \\ x_1 \cdot y_2 &= xy_{12} \\ y_1 \cdot x_2 &= yx_{12} \\ x_{12} \cdot y_{12} &= xy_{12} y_{12} \\ x_3 \cdot (1 + d \cdot xy_{12} y_{12}) &= xy_{12} + yx_{12} \\ y_3 \cdot (1 - d \cdot xy_{12} y_{12}) &= y_{12} - a \cdot x_{12} \end{aligned}$$

So we have the statement $w = (1, x_1, y_1, x_2, y_2, x_3, y_3, x_{12}, y_{12}, xy_{12}, yx_{12}, xy_{12} y_{12})$ and we need 7 constraints to enforce that $(x_1, y_1) + (x_2, y_2) = (x_3, y_3)$

Example 122 (Baby-JubJub). *Considering our pen and paper Baby JubJub curve over from XXX. We recall from XXX that $(11, 9)$ is a generator for the large prime order subgroup. We therefor already know from XXX that $(11, 9) + (7, 8) = (11, 9) + [3](11, 9) = [4](11, 9) = (2, 9)$. So we compute a valid statement as $w = (1, 11, 9, 7, 8, 2, 9, 12, 7, 10, 11, 6)$. Indeed*

$$\begin{aligned} 11 \cdot 7 &= 12 \\ 9 \cdot 8 &= 7 \\ 11 \cdot 8 &= 10 \\ 9 \cdot 7 &= 11 \\ 10 \cdot 11 &= 6 \\ 2 \cdot (1 + 7 \cdot 6) &= 10 + 11 \\ 9 \cdot (1 - 7 \cdot 6) &= 7 - 1 \cdot 12 \end{aligned}$$

There are optimizations for this using only 6 constraints, available:

Twisted Edwards curves inversion Similar to elliptic curves in Weierstrass form, inversion is cheap on Edwards curve as the negative of a curve point $-(x, y)$ is given by $(-x, y)$. So a curve point (x_2, y_2) is the additive inverse of another curve point (x_1, y_1) precisely if the equation $(x_1, y_1) = (-x_2, y_2)$ holds. We can write this as

$$\begin{aligned} x_1 \cdot 1 &= -x_2 \\ y_1 \cdot 1 &= y_2 \end{aligned}$$

We therefor have a statement of the form $w = (1, x_1, y_1, x_2, y_2)$ and can write the constraints into a matrix equation as

$$\begin{pmatrix} 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \end{pmatrix} \begin{pmatrix} 1 \\ x_1 \\ y_1 \\ x_2 \\ y_2 \end{pmatrix} \odot \begin{pmatrix} 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} 1 \\ x_1 \\ y_1 \\ x_2 \\ y_2 \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 \\ x_1 \\ y_1 \\ x_2 \\ y_2 \end{pmatrix}$$

In addition we need the following constraints:

$$\begin{aligned} x_1 \cdot 1 &= -x_2 \\ y_1 \cdot 1 &= y_2 \end{aligned}$$

Twisted Edwards curves scalar multiplication Although there are highly optimized R1CS implementations for scalar multiplication on elliptic curves, the basic idea is somewhat simple: Given an elliptic curve E/\mathbb{F}_r , a scalar $x \in \mathbb{F}_r$ with binary representation (b_0, \dots, b_m) and a curve point $P \in E/\mathbb{F}_r$, the scalar multiplication $[x]P$ can be written as

$$[x]P = [b_0]P + [b_1]([2]P) + [b_2]([4]P) + \dots + [b_m]([2^m]P)$$

and since b_j is either 0 or 1, $[b_j](kP)$ is either the neutral element of the curve or $[2^j]P$. However $[2^j]P$ can be computed inductively by curve point doubling, since $[2^j]P = [2]([2^{j-1}]P)$.

So scalar multiplication can be reduced to a loop of length m , where the original curve point is repeatedly doubled and added to the result, whenever the appropriate bit in the scalar is equal to one.

So to enforce that a curve point (x_2, y_2) is the scalar product $[k](x_1, y_1)$ of a scalar $x \in \mathbb{F}_r$ and a curve point (x_1, y_1) , we need an R1CS that defines point doubling on the curve (XXX) and an R1CS that enforces the binary representation of x (XXX).

In case of twisted Edwards curve, we can use ordinary addition for doubling, as the constraints work for both cases (doubling is addition, where both arguments are equal). Moreover $[b](x, y) = (b \cdot x, b \cdot y)$ for boolean b . Hence flattening equation XXX gives

$$\begin{aligned} b_0 \cdot x_1 &= x_{0,1} \quad // [b_0]P \\ b_0 \cdot y_1 &= y_{0,1} \end{aligned}$$

In addition we need to constrain (b_0, \dots, b_N) to be the binary representation of x and we need to constrain each b_j to be boolean.

As we can see a R1CS for scalar multiplication utilizes many R1CS that we have introduced before. For efficiency and readability it is therefore useful to apply the concept of a gadget (XXX). A pseudocode method to derive the associated R1CS could look like this:

Curve Cycles A particularly interesting case with far reaching implication is the situation when we have two curves E_1 and E_2 , such that the scalar field of curve E_1 is the base field of curve E_2 and vice versa. In that case it is possible to implement the group laws of one curve in circuits defined over the scalar field of the other curve.

The RAM Model

FROM THE PODCAST WITH ANNA R. AND THE GUY FROM JAN....

Generalizations

many circuits can be found here:

6.3.2 Quadratic Arithmetic Programs

As shown by [Pinocchio] rank-1 constraint systems can be transformed into so called quadratic arithmetic programs assuming \mathbb{F} .

taken from the pinocchio paper. For proving arithmetic circuit-sat. Given a R1CS QAPs transform potential solution vectors into two polynomials p and t , such that p is divisible by t if and only if the vector is a solution to the R1CS.

They are major building blocks for **succinct** proofs, since with high probability, the divisibility check can be performed in a single point of those polynomials. So computationally

expensive polynomial division check is reduced TO WHAT? (IN FIELDS THERE IS ALWAYS DIVISIBILITY)

Definition 6.3.2.1 (Quadratic Arithmetic Program). Assume we have a Galois field \mathbb{F} , three numbers i, j, k as well as three $(i + j + 1) \times k$ matrices A, B and C with coefficients in \mathbb{F} that define the RICS $Ax \odot Bx = Cx$ for some statement $x = (1, i, w)$ and let $m_1, \dots, m_k \in \mathbb{F}$ be arbitrary field elements.

Then a **quadratic arithmetic program** of the RICS is the following set of polynomials over \mathbb{F}

$$QAP = \left\{ t \in \mathbb{F}[x], \{a_h, b_h, c_h \in \mathbb{F}[x]\}_{h=1}^{i+j+1} \right\}$$

where $t(x) := \prod_{l=1}^k (x - m_l)$ is a polynomial of degree k , called the **target polynomial** of the QAP and $a_h(x), b_h(x)$ as well as $c_h(x)$ are the unique degree $k - 1$ polynomials that are defined by the equations

$$a_h(m_l) = A_{h,l} \quad b_h(m_l) = B_{h,l} \quad c_h(m_l) = C_{h,l} \quad h = 1, \dots, i + j + 1, l = 1, \dots, k$$

The major point is that RICS-sat can be reformulated into the divisibility of a polynomials defined by any QAP.

Theorem 6.3.2.2. Assume that an RICS and an associated QAP as defined in XXX are given. Then the affine vector $y = (1, i, w)$ is a solution to the RICS, if and only if the polynomial

$$p(x) = \left(\sum y_h \cdot a_h(x) \right) \cdot \left(\sum y_h \cdot b_h(x) \right) - \sum y_h \cdot c_h(x)$$

is divisible by the target polynomial t .

The polynomials a_h, b_h and c_h are uniquely defined by the equations in XXX. However to actually compute them we need some algorithm like the Langrange XXX from XXX.

Example 123 (Generalized factorization snark). In this example we want to transform the RICS from example ?? into an associated QAP.

We start by choosing an arbitrary field element for every constraint in the RICS, since we have 2 constraints we choose $m_1 = 5$ and $m_2 = 7$

With this choice we get the target polynomial $t(x) = (x - m_1)(x - m_2) = (x - 5)(x - 7) = (x + 8)(x + 6) = x^2 + x + 9$.

Since our statement has structure $w = (1, in_1, in_2, in_3, m_1, out_1)$ we have to compute the following degree 1 polynomials

$$\{a_c, a_{in_1}, a_{in_2}, a_{in_3}, a_{mid_1}, a_{out}\} \quad \{b_c, b_{in_1}, b_{in_2}, b_{in_3}, b_{mid_1}, b_{out}\} \quad \{c_c, c_{in_1}, c_{in_2}, c_{in_3}, c_{mid_1}, c_{out}\}$$

Apply QAP rule XXX to the $a_{k \in I}$ polynomials gives

$$\begin{aligned} a_c(5) &= 0, & a_{in_1}(5) &= 1, & a_{in_2}(5) &= 0, & a_{in_3}(5) &= 0, & a_{mid_1}(5) &= 0, & a_{out}(5) &= 0 \\ a_c(7) &= 0, & a_{in_1}(7) &= 0, & a_{in_2}(7) &= 0, & a_{in_3}(7) &= 0, & a_{mid_1}(7) &= 1, & a_{out}(7) &= 0 \end{aligned}$$

$$\begin{aligned} b_c(5) &= 0, & b_{in_1}(5) &= 0, & b_{in_2}(5) &= 1, & b_{in_3}(5) &= 0, & b_{mid_1}(5) &= 0, & b_{out}(5) &= 0 \\ b_c(7) &= 0, & b_{in_1}(7) &= 0, & b_{in_2}(7) &= 0, & b_{in_3}(7) &= 1, & b_{mid_1}(7) &= 0, & b_{out}(7) &= 0 \end{aligned}$$

$$\begin{aligned} c_c(5) &= 0, & c_{in_1}(5) &= 0, & c_{in_2}(5) &= 0, & c_{in_3}(5) &= 0, & c_{mid_1}(5) &= 1, & c_{out}(5) &= 0 \\ c_c(7) &= 0, & c_{in_1}(7) &= 0, & c_{in_2}(7) &= 0, & c_{in_3}(7) &= 0, & c_{mid_1}(7) &= 0, & c_{out}(7) &= 1 \end{aligned}$$

Since our polynomials are of degree 1 only we don't have to invoke Langrange method but can deduce the solutions right away.

Polynomials are defined on the two values 5 and 7 here. Linear Polynomial $f(x) = m \cdot x + b$ is fully determined by this. Derive the general equation:

- $5m + b = f(5)$ and $7m + b = f(7)$
- $b = f(5) - 5m$ and $b = f(7) - 7m$
- $b = f(5) + 8m$ and $b = f(7) + 6m$
- $f(5) + 8m = f(7) + 6m$
- $8m - 6m = f(7) - f(5)$
- $2m = f(7) - f(5)$
- $7 \cdot 2m = 7(f(7) - f(5))$
- $m = f(7) - f(5)$
-
- $b = f(5) + 8m$
- $b = f(5) + 8 \cdot (f(7) - f(5))$
- $b = f(5) + 4(f(7) - f(5))$
- $b = f(5) + 4f(7) - 4f(5)$
- $b = 4f(7) - 3f(5)$

Gives the general equation: $f(x) = 7(f(7) - f(5))x + 10f(5) + 4f(7)$

For a_{in_1} the computation looks like this:

- $a_{in_1}(x) = 7(a_{in_1}(7) - a_{in_1}(5))x + 10a_{in_1}(5) + 4a_{in_1}(7) =$
- $7(0 - 1)x + 10 \cdot 1 + 4 \cdot 0 =$
- $-7x + 10 =$
- $6x + 10$
- $a_{mid_1}(x) = 7(a_{mid_1}(7) - a_{mid_1}(5))x + 10a_{mid_1}(5) + 4a_{mid_1}(7) =$
- $7(1 - 0)x + 10 \cdot 0 + 4 \cdot 1 =$
- $7x + 4 =$
- $7x + 4$

$a_c(x) = 0$	$b_c(x) = 0$	$c_c(x) = 0$
$a_{in_1}(x) = 6x + 10$	$b_{in_1}(x) = 0$	$c_{in_1}(x) = 0$
$a_{in_2}(x) = 0$	$b_{in_2}(x) = 6x + 10$	$c_{in_2}(x) = 0$
$a_{in_3}(x) = 0$	$b_{in_3}(x) = 7x + 4$	$c_{in_3}(x) = 0$
$a_{mid_1}(x) = 7x + 4$	$b_{mid_1}(x) = 0$	$c_{mid_1}(x) = 6x + 10$
$a_{out}(x) = 0$	$b_{out}(x) = 0$	$c_{out}(x) = 7x + 4$

This gives the quadratic arith-

metic program for our generalized factorization snark as

$$QAP = \{x^2 + x + 9, \{0, 6x + 10, 0, 0, 7x + 4, 0\}, \{0, 0, 6x + 10, 7x + 4, 0, 0\}, \{0, 0, 0, 0, 6x + 10, 7x + 4\}\}$$

Now as we recall, the main point for using QAPs in snarks is the fact, that solutions to RICS are in 1:1 correspondence to the divisibility of a polynomial p , constructed from a RICS solution and the polynomials of the QAP and the target polynomial.

So lets see this in our example. We already know from example XXX, that $I = \{1, 2, 3, 4, 6, 11\}$ is a solution to the RICS XXX of our problem. To see how this translates to polynomial divisibility we compute the polynomial p_I by

$$\begin{aligned}
 p_I(x) &= \left(\sum_{h \in |I|} I_h \cdot a_h(x) \right) \cdot \left(\sum_{h \in |I|} I_h \cdot b_h(x) \right) - \left(\sum_{h \in |I|} I_h \cdot c_h(x) \right) \\
 &= (2(6x + 10) + 6(7x + 4)) \cdot (3(6x + 10) + 4(7x + 4)) - (6(6x + 10) + 11(7x + 4)) \\
 &= ((12x + 7) + (3x + 11)) \cdot ((5x + 4) + (2x + 3)) - ((10x + 8) + (12x + 5)) \\
 &= (2x + 5) \cdot (7x + 7) - (9x) \\
 &= (x^2 + 2 \cdot 7x + 5 \cdot 7x + 5 \cdot 7) - (9x) \\
 &= (x^2 + x + 9x + 9) - (9x) \\
 &= x^2 + x + 9
 \end{aligned}$$

And as we can see in this particular example $p_I(x)$ is equal to the target polynomial $t(x)$ and hence it is divisible by t with $p/t = 1$.

To give a counter example we already know from XXX that $I = \{1, 2, 3, 4, 8, 2\}$ is not a solution to our RICS. To see how this translates to polynomial divisibility we compute the polynomial p_I by

$$\begin{aligned}
 p_I(x) &= \left(\sum_{h \in |I|} I_h \cdot a_h(x) \right) \cdot \left(\sum_{h \in |I|} I_h \cdot b_h(x) \right) - \left(\sum_{h \in |I|} I_h \cdot c_h(x) \right) \\
 &= (2(6x + 10) + 6(7x + 4)) \cdot (3(6x + 10) + 4(7x + 4)) - (6(6x + 10) + 11(7x + 4)) \\
 &= 8x^2 + 11x + 3
 \end{aligned}$$

This polynomial is not divisible by the target polynomial t since Not divisible by t : $(8x^2 + 11x + 3)/(x^2 + x + 9) = 8 + \frac{3x+8}{x^2+x+9}$

6.3.3 Quadratic span programs

6.4 proof system

Now a *proof system* is nothing but a game between two parties, where one parties task is to convince the other party, that a given string over some alphabet is a statement is some agreed on language. To be more precise. Such a system is more over *zero knowledge* if this possible without revealing any information about the (parts of) that string.

Definition 6.4.0.1 ((Interactive) Proofing System). *Let L be some formal language over an alphabet Σ . Then an **interactive proof system** for L is a pair (P, V) of two probabilistic interactive algorithms, where P is called the **prover** and V is called the **verifier**.*

Both algorithms are able to send messages to one another. Each algorithm only sees its own state, some shared initial state and the communication 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 in an accept state or in a reject state. We impose no restrictions on the local computation conducted by the prover.

We require that, whenever the verifier is executed the following two conditions hold:

- *(Completeness)* If a string $x \in \Sigma^*$ is a member of language L , that is $x \in L$ and both prover and verifier follow the protocol; the verifier will accept.
- *(Soundness)* If a string $x \in \Sigma^*$ is not a member of language L , that is $x \notin L$ and the verifier follows the protocol; the verifier will not be convinced.
- *(Zero-knowledge)* If a string $x \in \Sigma^*$ is a member of language L , that is $x \in L$ and the prover follows the protocol; the verifier will not learn anything about x but $x \in L$.

In the context of zero knowledge proving systems definition XXX gets a slight adaptation:

- **Instance:** Input commonly known to both prover (P) and verifier (V), and used to support the statement of what needs to be proven. This common input may either be local to the prover-verifier interaction, or public in the sense of being known by external parties (Some scientific articles use "instance" and "statement" interchangeably, but we distinguish between the two.).
- **Witness:** Private input to the prover. Others may or may not know something about the witness.
- **Relation:** Specification of relationship between instances and witness. A relation can be viewed as a set of permissible pairs (instance, witness).
- **Language:** Set of statements that appear as a permissible pair in the given relation.
- **Statement:** Defined by instance and relation. Claims the instance has a witness in the relation (which is either true or false).

The following subsections define ways to describe checking relations that are particularly useful in the context of zero knowledge proofing systems

6.4.1 Succinct NIZK

Preprocessing style: trusted setup, multi party ceremony

Blum, Feldman and Micali extended the notion of non-interactive zero-knowledge (NIZK) proofs in the common reference string model. NIZK proofs are useful in the construction of non-interactive cryptographic schemes, e.g., digital signatures and CCA-secure public key encryption.

Definition 6.4.1.1. Let \mathcal{R} be a relation generator that given a security parameter λ in unary returns a polynomial time decidable binary relation R . For pairs $(i, w) \in R$ we call i the instance¹ and w the witness. We define R_λ to be the set of possible relations R the relation generator may output given 1^λ . We will in the following for notational simplicity assume λ can be deduced from the description of R . The relation generator may also output some side information, an auxiliary input z , which will be given to the adversary. An efficient prover publicly verifiable non-interactive argument for R is a quadruple of probabilistic polynomial algorithms (SETUP, PROVE, VFY, SIM) such

- **Setup:** $(CRS, \tau) \rightarrow \text{Setup}(R)$: The setup produces a common reference string CRS and a simulation trapdoor τ for the relation R .

¹Note that in Groth16 this is called the statement. We think the term instance is more consistent with SOMETHING.

- *Proof*: $\pi \rightarrow \text{Prove}(R, \text{CRS}, i, w)$: The prover algorithm takes as input a common reference string CRS and a statement $(i, w) \in R$ and returns an argument π .
- *Verify*: $0/1 \rightarrow \text{Vfy}(R, \text{CRS}, i, \pi)$: The verification algorithm takes as input a common reference string CRS, an instance i and an argument π and returns 0 (reject) or 1 (accept).
- $\pi \rightarrow \text{Sim}(R, \tau, i)$: The simulator takes as input a simulation trapdoor τ and instance i and returns an argument π .

Common Reference String Generation Also called trusted setup phase. The field elements needed in this step are called toxic waste ...

Trusted third party The most simple approach to generate a common reference string is a so called *trusted third party*. By assumption the entire systems trusts this party to generate the common reference string exactly accoring to the rules and the party will delete all traces of the toxic waste after CRS generation.

Player exchangeable Multi Party Ceremonies Achive soundness if only a single party is honest and correctly deletes toxix waste. Is always zero knowledge.

State of the art works in the random beacon model.

A random beacon produces publicly available and verifiable random values at fixed intervals. The difference between random beacons and random oracles, is that random beacons are not available until certain time slots. Random beacons can be instanciated for example by evaluation of say 2^{40} iterations of SHA256 on some high entropy, publically available data like the closing value of the stock market on a certain date, the output of a selected set of national lotteries and so on.

The assumption is that any given random beacon value contains large amounts of entropy that is independent from the influence of an adversary in previous time slots.

Groth16

Groth's constant size NIZK argument is based on constructing a set of polynomial equations and using pairings to efficiently verify these equations. Gennaro, Gentry, Parno and Raykova [Pinocchio] found an insightful construction of polynomial equations based on Lagrange interpolation polynomials yielding a pairing-based NIZK argument with a common reference string size proportional to the size of the statement and wit-ness.

It constructs a snark for arithmetic circuit satisfiability, where a proof consists of only 3 group elements. In addition to being small, the proof is also easy to verify. The verifier just needs to compute a number of exponentiations proportional to the instance size and check a single pairing product equation, which only has 3 pairings.

The construction can be instantiated with any type of pairings including Type III pairings, which are the most efficient pairings. The argument has perfect completeness and perfect zero-knowledge. For soundness ??

In the common reference string model.

Setup:

- random elements $\alpha, \beta, \gamma, \delta, s \in \mathbb{F}_{\text{scalar}}$

- Common reference string CRS_{QAP} , specific to the QAP and the choice of statement and witness $CRS_{QAP} = (CRS_{\mathbb{G}_1}, CRS_{\mathbb{G}_2})$, with $n = \deg(t)$:

$$CRS_{\mathbb{G}_1} = \left\{ \begin{array}{l} [\alpha]g, [\beta]g, [\delta]g, \{[s^k]g\}_{k=0}^{n-1}, \left\{ \left[\frac{\beta a_k(s) + \alpha b_k(s) + c_k(s)}{\gamma} \right] g \right\}_{k \in I} \\ \left\{ \left[\frac{\beta a_k(s) + \alpha b_k(s) + c_k(s)}{\delta} \right] g \right\}_{k \in W}, \left\{ \left[\frac{s^k t(s)}{\delta} \right] g \right\}_{k=0}^{n-2} \end{array} \right\}$$

$$CRS_{\mathbb{G}_2} = \left\{ [\beta]h, [\gamma]h, [\delta]h, \{[s^k]h\}_{k=0}^{n-1} \right\}$$

- Toxic waste: Must delete random elements after CRS_{QAP} generation.

Example 124 (Generalized factorization snark). *In this example we want to compile our main example in Groth16. Input is the RICS from example 116. We choose the following global parameters*

$$\text{curve} = \text{BLS6-6} \quad \mathbb{G}_1 = \text{BLS6-6}(13) \quad g = (13, 15) \quad \mathbb{G}_2 = \quad h = (7v^2, 16v^3) \text{ and } \mathbb{G}_T = \mathbb{F}_{43^6}^*.$$

Example 125 (Trusted third party for the factorization snark). *We consider ourself as a trusted third part to generate the common reference string for our generalized factorization snark. We therefore choose the following secret field elements $\alpha = 6$, $\beta = 5$, $\gamma = 4$, $\delta = 3$, $s = 2$ from \mathbb{F}_{13} and are very careful to hide them from anyone how hasn't read this book. From those values we can then instantiate the common reference string XXX:*

$$CRS_{\mathbb{G}_1} = \left\{ \begin{array}{l} [6](13, 15), [5](13, 15), [3](13, 15), \{[s^k](13, 15)\}_{k=0}^1, \left\{ \left[\frac{5a_k(2) + 6b_k(2) + c_k(2)}{4} \right] (13, 15) \right\}_{k \in S} \\ \left\{ \left[\frac{5a_k(2) + 6b_k(2) + c_k(2)}{3} \right] (13, 15) \right\}_{k \in W}, \left\{ \left[\frac{s^k t(2)}{3} \right] (13, 15) \right\}_{k=0}^0 \end{array} \right\}$$

Since we have instance indices $I = \{1, in_1, in_2\}$ and witness indices $W = \{in_3, mid_1, out_1\}$ we have The instance parts.

$$\left[\frac{5a_c(2) + 6b_c(2) + c_c(2)}{4} \right] (13, 15) = \left[\frac{5 \cdot 0 + 6 \cdot 0 + 0}{4} \right] (13, 15) = [0](13, 15) = \mathcal{O}$$

$$\left[\frac{5a_{in_3}(2) + 6b_{in_3}(2) + c_{in_3}(2)}{4} \right] (13, 15) = [(5 \cdot 0 + 6 \cdot (7 \cdot 2 + 4) + 0) \cdot 10] (13, 15) =$$

$$[(6 \cdot 5) \cdot 10] (13, 15) = [1] (13, 15) = (13, 15)$$

$$\left[\frac{5a_{out}(2) + 6b_{out}(2) + c_{out}(2)}{4} \right] (13, 15) = [(5 \cdot 0 + 6 \cdot 0 + (7 \cdot 2 + 4)) \cdot 10] (13, 15) =$$

$$[5 \cdot 10] (13, 15) = [11] (13, 15) = (33, 9)$$

Witness part:

$$\left[\frac{5a_{in_1}(2) + 6b_{in_1}(2) + c_{in_1}(2)}{3} \right] (13, 15) = [(5 \cdot (6 \cdot 2 + 10) + 6 \cdot 0 + 0) \cdot 9] (13, 15) =$$

$$[(5 \cdot 9) \cdot 9] (13, 15) = [2] (13, 15) = (33, 34)$$

$$\left[\frac{5a_{in_2}(2) + 6b_{in_2}(2) + c_{in_2}(2)}{3} \right] (13, 15) = [(5 \cdot 0 + 6 \cdot (6 \cdot 2 + 10) + 0) \cdot 9] (13, 15) =$$

$$[(6 \cdot 9) \cdot 9] (13, 15) = [5] (13, 15) = (26, 34)$$

$$\left[\frac{5a_{mid_1}(2) + 6b_{mid_1}(2) + c_{mid_1}(2)}{3} \right] (13, 15) = [(5 \cdot (7 \cdot 2 + 4) + 6 \cdot 0 + 0) \cdot 9] (13, 15) =$$

$$[(5 \cdot 5) \cdot 9] (13, 15) = [4] (13, 15) = (35, 28)$$

For $\left\{ \left[\frac{s^k t(2)}{3} \right] (13, 15) \right\}_{k=0}^0$ we get

$$\left[\frac{2^0 t(2)}{3} \right] (13, 15) = [t(2) \cdot 9] (13, 15) = [(2^2 + 2 + 9) \cdot 9] (13, 15) = [5] (13, 15) = (26, 34)$$

All together, the \mathbb{G}_1 part of the CRS is:

$$CRS_{\mathbb{G}_1} = \left\{ (27, 34), (26, 34), (38, 15), \{(13, 15), (33, 34)\}, \{\emptyset, (13, 15), (33, 9)\}, \right. \\ \left. \{(33, 34), (26, 34), (35, 28)\}, \{(26, 34)\} \right\}$$

To compute the \mathbb{G}_2 part

$$CRS_{\mathbb{G}_2} = \left\{ [5](7v^2, 16v^3), [4](7v^2, 16v^3), [3](7v^2, 16v^3), \left\{ [2^k](7v^2, 16v^3) \right\}_{k=0}^1 \right\}$$

$$CRS_{\mathbb{G}_2} = \{ [5](7v^2, 16v^3), [4](7v^2, 16v^3), [3](7v^2, 16v^3), \{ [1](7v^2, 16v^3), [2](7v^2, 16v^3) \} \}$$

$$CRS_{\mathbb{G}_2} = \{ (16v^2, 28v^3), (37v^2, 27v^3), (42v^2, 16v^3), \{ (7v^2, 16v^3), (10v^2, 28v^3) \} \}$$

So altogether our common reference string is

$$\left(\left\{ (27, 34), (26, 34), (38, 15), \{(13, 15), (33, 34)\}, \{\emptyset, (13, 15), (33, 9)\}, \right. \right. \\ \left. \left. \{(33, 34), (26, 34), (35, 28)\}, \{(26, 34)\} \right\} \right. \\ \left. \left\{ (16v^2, 28v^3), (37v^2, 27v^3), (42v^2, 16v^3), \{ (7v^2, 16v^3), (10v^2, 28v^3) \} \right\} \right)$$

Example 126 (Player exchangeable multi party ceremony for the factorization snark). In this example we want to simulate a real world player exchangeable multi party ceremony for our factorization snark XXX as explained in XXX.

We use our TinyMD5 hash function XXX to hash to \mathbb{G}_2 .

We assume that we have a coordinator Alice together with three parties Bob, Carol and Dave that want to contribute their randomness to the protocol. Since the degree n of the target polynomial is 2, we need to compute the common reference string

$$CRS = \{ \}$$

For contributor $j > 0$ in phase l to compute the proof of knowledge XXX, we need to define the transcript $_{l,j-1}$ of the previous round. We define it as sha256 of MPC $_{l,j-1}$. To be more precise we define

$$transcript_{l,j-1} = MD5(' [s]g_1[s]g_2[s^2]g_1[\alpha]g_1[\alpha \cdot s]g_1[\beta]g_1[\beta]g_2[\beta \cdot s]g_1')$$

The only thing actually important about the transcript, is that it is publically available data that is not accesable for anyone before the MPC-data of round $j - 1$ in phase l exists.

We start with the first round usually called the 'powers of tau' *EXPLAIN THAT TERM...*
The computation is initialized With $s = 1$, $\alpha = 1$, $\beta = 1$. Hence the computation starts with the following data

$$MPC_{1,0} = \left\{ \begin{array}{ll} ([s]g_1, [s]g_2) & = ((13, 15), (7v^2, 16v^3)) \\ [s^2]g_1 & = (13, 15) \\ [\alpha]g_1 & = (13, 15) \\ [\alpha \cdot s]g_1 & = (13, 15) \\ ([\beta]g_1, [\beta]g_2) & = ((13, 15), (7v^2, 16v^3)) \\ [\beta \cdot s]g_1 & = (13, 15) \end{array} \right\}$$

Then

$$\begin{aligned} transcript_{1,0} = \\ MD5(' (13, 15)(7v^2, 16v^3)(13, 15)(13, 15)(13, 15)(13, 15)(7v^2, 16v^3)(13, 15)') = \\ f2baea4d3dba5eef5c63bb210920e7d9 \end{aligned}$$

We obtain that hash by computing

`printf'%s' "(13, 15)(7v^2, 16v^3)(13, 15)(13, 15)(13, 15)(13, 15)(7v^2, 16v^3)(13, 15)" | md5sum`

Everyone agreed, that the MPC starts on the 21.03.2020 and everyone can contribute for exactly a year until the 20.03.2021.

It then proceeds in a round robin style, starting with Bob, who obtains that data in $MPC_{1,0}$ and then computes his contribution. Lets assume that Bob is honest and that bought a 13-sided dice (PICTURE OF 13-SIDED DICE) to randomly find three secret field values from our prime field \mathbb{F}_{13} . He though the dice and got $\alpha = 4$, $\beta = 8$ and $s = 2$. He then updates $MPC_{1,0}$:

$$MPC_{1,1} = \left\{ \begin{array}{lll} ([s]g_1, [s]g_2) & = ([2](13, 15), [2](7v^2, 16v^3)) & = ((33, 34), (10v^2, 28v^3)) \\ [s^2]g_1 & = [4](13, 15) & = (35, 28) \\ [\alpha]g_1 & = [4](13, 15) & = (35, 28) \\ [\alpha \cdot s]g_1 & = [8](13, 15) & = (26, 9) \\ ([\beta]g_1, [\beta]g_2) & = ([8](13, 15), [8](7v^2, 16v^3)) & = ((26, 9), (16v^2, 15v^3)) \\ [\beta \cdot s]g_1 & = [3](13, 15) & = (38, 15) \end{array} \right\}$$

In addition he compute

$$POK_{1,1} \left\{ \begin{array}{ll} y_s & = POK(2, f2baea4d3dba5eef5c63bb210920e7d9) = ((33, 34), (16v^2, 28v^3)) \\ y_\alpha & = POK(4, f2baea4d3dba5eef5c63bb210920e7d9) = ((35, 28), (10v^2, 15v^3)) \\ y_\beta & = POK(8, f2baea4d3dba5eef5c63bb210920e7d9) = ((26, 9), (16v^2, 28v^3)) \end{array} \right\}$$

since $[s]g_1 = (33, 34)$, $[\alpha]g_1 = (35, 28)$ and $[\beta]g_1 = (26, 9)$. as well as

$$\begin{aligned}
 & \text{TinyMD5}_2(' (33, 34) f2baea4d3dba5ee f5c63bb210920e7d9') = \\
 & H_2(\text{MD5}(' (33, 34) f2baea4d3dba5ee f5c63bb210920e7d9').\text{trunc}(3)) = \\
 & H_2(2066b3b6b6d97c46c3ac6ee2ccd23ad9.\text{trunc}(3)) = H_2(ad9) = \\
 & H_2(101011011001) = \\
 & [8 \cdot 4^1 \cdot 5^0 \cdot 7^1](7v^2, 16v^3) + [12 \cdot 1^0 \cdot 3^1 \cdot 8^1](42v^2, 16v^3) + \\
 & [2 \cdot 3^0 \cdot 9^1 \cdot 11^1](17v^2, 15v^3) + [3 \cdot 6^0 \cdot 9^0 \cdot 10^1](10v^2, 15v^3) = \\
 & [8 \cdot 4 \cdot 7](7v^2, 16v^3) + [12 \cdot 3 \cdot 8](42v^2, 16v^3) + [2 \cdot 9 \cdot 11](17v^2, 15v^3) + [3 \cdot 10](10v^2, 15v^3) = \\
 & [8 \cdot 4 \cdot 7](7v^2, 16v^3) + [12 \cdot 3 \cdot 8](42v^2, 16v^3) + [2 \cdot 9 \cdot 11](17v^2, 15v^3) + [3 \cdot 10](10v^2, 15v^3) = \\
 & [3](7v^2, 16v^3) + [2](42v^2, 16v^3) + [3](17v^2, 15v^3) + [4](10v^2, 15v^3) = \\
 & [3](7v^2, 16v^3) + [2 * 3](7v^2, 16v^3) + [3 * 7](7v^2, 16v^3) + [4 * 11](7v^2, 16v^3) = \\
 & (42v^2, 16v^3) + (17v^2, 28v^3) + (16v^2, 15v^3) + (16v^2, 28v^3) = \\
 & [3](7v^2, 16v^3) + [6](7v^2, 16v^3) + [8](7v^2, 16v^3) + [5](7v^2, 16v^3) = \\
 & [3 + 6 + 8 + 5](7v^2, 16v^3) = (37v^2, 16v^3)
 \end{aligned}$$

So we get $[2](37v^2, 16v^3) = (16v^2, 28v^3)$

=====

$$\begin{aligned}
 & \text{TinyMD5}_2(' (35, 28) f2baea4d3dba5ee f5c63bb210920e7d9') = \\
 & H_2(\text{MD5}(' (35, 28) f2baea4d3dba5ee f5c63bb210920e7d9').\text{trunc}(3)) = \\
 & H_2(ad54fa3674f6a84fab9208d7a94c9163.\text{trunc}(3)) = H_2(163) = \\
 & H_2(000101100011) = \\
 & [8 \cdot 4^0 \cdot 5^0 \cdot 7^0](7v^2, 16v^3) + [12 \cdot 1^1 \cdot 3^0 \cdot 8^1](42v^2, 16v^3) + \\
 & [2 \cdot 3^1 \cdot 9^0 \cdot 11^0](17v^2, 15v^3) + [3 \cdot 6^0 \cdot 9^1 \cdot 10^1](10v^2, 15v^3) = \\
 & [8](7v^2, 16v^3) + [12 \cdot 8](42v^2, 16v^3) + [2 \cdot 3](17v^2, 15v^3) + [3 \cdot 9 \cdot 10](10v^2, 15v^3) = \\
 & [8](7v^2, 16v^3) + [5](42v^2, 16v^3) + [6](17v^2, 15v^3) + [10](10v^2, 15v^3) = \\
 & [8](7v^2, 16v^3) + [5 * 3](7v^2, 16v^3) + [6 * 7](7v^2, 16v^3) + [10 * 11](7v^2, 16v^3) = \\
 & (16v^2, 15v^3) + (10v^2, 28v^3) + (42v^2, 16v^3) + (17v^2, 28v^3) = \\
 & [8](7v^2, 16v^3) + [2](7v^2, 16v^3) + [3](7v^2, 16v^3) + [6](7v^2, 16v^3) = \\
 & [8 + 2 + 3 + 6](7v^2, 16v^3) = (17v^2, 28v^3)
 \end{aligned}$$

So we get $[4](17v^2, 28v^3) = (10v^2, 15v^3)$

$$\begin{aligned}
& \text{TinyMD5}_2(' (26,9)f2baea4d3dba5ee f5c63bb210920e7d9') = \\
& H_2(\text{MD5}(' (26,9)f2baea4d3dba5ee f5c63bb210920e7d9').\text{trunc}(3)) = \\
& H_2(b87b632f7027ad78cad c2452beb30e9a.\text{trunc}(3)) = H_2(e9a) = \\
& H_2(111010011010) = \\
& [8 \cdot 4^1 \cdot 5^1 \cdot 7^1](7v^2, 16v^3) + [12 \cdot 1^0 \cdot 3^1 \cdot 8^0](42v^2, 16v^3) + \\
& [2 \cdot 3^0 \cdot 9^1 \cdot 11^1](17v^2, 15v^3) + [3 \cdot 6^0 \cdot 9^1 \cdot 10^0](10v^2, 15v^3) = \\
& [8 \cdot 4 \cdot 5 \cdot 7](7v^2, 16v^3) + [12 \cdot 3](42v^2, 16v^3) + [2 \cdot 9 \cdot 11](17v^2, 15v^3) + [3 \cdot 9](10v^2, 15v^3) = \\
& [2](7v^2, 16v^3) + [10](42v^2, 16v^3) + [3](17v^2, 15v^3) + [1](10v^2, 15v^3) = \\
& [2](7v^2, 16v^3) + [10 \cdot 3](7v^2, 16v^3) + [3 \cdot 7](7v^2, 16v^3) + [1 \cdot 11](7v^2, 16v^3) = \\
& (10v^2, 28v^3) + (37v^2, 27v^3) + (16v^2, 15v^3) + (10v^2, 15v^3) = \\
& [2](7v^2, 16v^3) + [4](7v^2, 16v^3) + [8](7v^2, 16v^3) + [11](7v^2, 16v^3) = \\
& [2 + 4 + 8 + 11](7v^2, 16v^3) = (7v^2, 27v^3)
\end{aligned}$$

So we get $[8](17v^2, 28v^3) = (16v^2, 28v^3)$

So Bob publishes $\text{MPC}_{1,1}$ as well as $\text{POK}_{1,1}$ and after that its Carols turn. Lets also assume that Carol is honest. So Carol looks at Bobs data and compute the transcript according to our rules

$$\begin{aligned}
& \text{transcript}_{1,1} = \\
& \text{MD5}(' (33,34)(10v^2, 28v^3)(35,28)(35,28)(26,9)(26,9)(16v^2, 15v^3)(38,15)') = \\
& \text{fe72e18b90014062682a77136944e362}
\end{aligned}$$

We obtain that hash by computing

`printf'%s' (33,34)(10v^2, 28v^3)(35,28)(35,28)(26,9)(26,9)(16v^2, 15v^3)(38,15)"|md5sum`

Carol then computes here contribution. Since she is honest she chooses randomly three secret field values from our prime field \mathbb{F}_{13} , by invoking her compter. She found $\alpha = 3$, $\beta = 4$ and $s = 9$ and updates $\text{MPC}_{1,1}$:

$$\text{MPC}_{1,2} = \left\{ \begin{array}{lll} ([s]g_1, [s]g_2) & = ([9](33,34), [9](10v^2, 28v^3)) & = ((26,34), (16v^2, 28v^3)) \\ [s^2]g_1 & = [9 \cdot 9](35,28) & = (13,28) \\ [\alpha]g_1 & = [3](35,28) & = (13,28) \\ [\alpha \cdot s]g_1 & = [3 \cdot 9](26,9) & = (26,9) \\ ([\beta]g_1, [\beta]g_2) & = ([4](26,9), [4](16v^2, 15v^3)) & = ((27,34), (17v^2, 28v^3)) \\ [\beta \cdot s]g_1 & = [4 \cdot 9](38,15) & = (35,28) \end{array} \right\}$$

In addition he compute

$$\text{POK}_{1,2} \left\{ \begin{array}{ll} y_s & = \text{POK}(9, \text{fe72e18b90014062682a77136944e362}) = ((35,15), (17v^2, 28v^3)) \\ y_\alpha & = \text{POK}(3, \text{fe72e18b90014062682a77136944e362}) = ((38,15), (17v^2, 15v^3)) \\ y_\beta & = \text{POK}(4, \text{fe72e18b90014062682a77136944e362}) = ((35,28), (42v^2, 27v^3)) \end{array} \right\}$$

$$\begin{aligned}
& \text{TinyMD5}_2(' (35, 15) fe72e18b90014062682a77136944e362') = \\
& H_2(\text{MD5}(' (35, 15) fe72e18b90014062682a77136944e362').\text{trunc}(3)) = \\
& H_2(115f145ceffdda73e916dc5ba8ae7354.\text{trunc}(3)) = H_2(354) = \\
& H_2(001101010100) = \\
& [8 \cdot 4^0 \cdot 5^0 \cdot 7^1](7v^2, 16v^3) + [12 \cdot 1^1 \cdot 3^0 \cdot 8^1](42v^2, 16v^3) + \\
& [2 \cdot 3^0 \cdot 9^1 \cdot 11^0](17v^2, 15v^3) + [3 \cdot 6^1 \cdot 9^0 \cdot 10^0](10v^2, 15v^3) = \\
& [8 \cdot 7](7v^2, 16v^3) + [12 \cdot 8](42v^2, 16v^3) + [2 \cdot 9](17v^2, 15v^3) + [3 \cdot 6](10v^2, 15v^3) = \\
& [4](7v^2, 16v^3) + [5](42v^2, 16v^3) + [5](17v^2, 15v^3) + [5](10v^2, 15v^3) = \\
& [4](7v^2, 16v^3) + [5 * 3](7v^2, 16v^3) + [5 * 7](7v^2, 16v^3) + [5 * 11](7v^2, 16v^3) = \\
& (37v^2, 27v^3) + (10v^2, 28v^3) + (37v^2, 16v^3) + (42v^2, 16v^3) = \\
& [4](7v^2, 16v^3) + [2](7v^2, 16v^3) + [9](7v^2, 16v^3) + [3](7v^2, 16v^3) = \\
& [4 + 2 + 9 + 3](7v^2, 16v^3) = (16v^2, 28v^3)
\end{aligned}$$

So we get $[9](16v^2, 28v^3) = (17v^2, 28v^3)$

$$\begin{aligned}
& \text{TinyMD5}_2(' (38, 15) fe72e18b90014062682a77136944e362') = \\
& H_2(\text{MD5}(' (38, 15) fe72e18b90014062682a77136944e362').\text{trunc}(3)) = \\
& H_2(cc4da0c02c4c1b15e72d6cc6430206ab.\text{trunc}(3)) = H_2(6ab) = \\
& H_2(011010101011) = \\
& [8 \cdot 4^0 \cdot 5^1 \cdot 7^1](7v^2, 16v^3) + [12 \cdot 1^0 \cdot 3^1 \cdot 8^0](42v^2, 16v^3) + \\
& [2 \cdot 3^1 \cdot 9^0 \cdot 11^1](17v^2, 15v^3) + [3 \cdot 6^0 \cdot 9^1 \cdot 10^1](10v^2, 15v^3) = \\
& [8 \cdot 5 \cdot 7](7v^2, 16v^3) + [12 \cdot 3](42v^2, 16v^3) + [2 \cdot 3 \cdot 11](17v^2, 15v^3) + [3 \cdot 9 \cdot 10](10v^2, 15v^3) = \\
& [7](7v^2, 16v^3) + [10](42v^2, 16v^3) + [1](17v^2, 15v^3) + [10](10v^2, 15v^3) = \\
& [7](7v^2, 16v^3) + [10 * 3](7v^2, 16v^3) + [1 * 7](7v^2, 16v^3) + [10 * 11](7v^2, 16v^3) = \\
& (17v^2, 15v^3) + (17v^2, 28v^3) + (17v^2, 15v^3) + (17v^2, 28v^3) = \\
& [7](7v^2, 16v^3) + [4](7v^2, 16v^3) + [7](7v^2, 16v^3) + [6](7v^2, 16v^3) = \\
& [7 + 4 + 7 + 6](7v^2, 16v^3) = (10v^2, 15v^3)
\end{aligned}$$

So we get $[3](10v^2, 15v^3) = (17v^2, 15v^3)$

$$\begin{aligned}
& \text{TinyMD5}_2(' (35,28)fe72e18b90014062682a77136944e362') = \\
& H_2(\text{MD5}(' (35,28)fe72e18b90014062682a77136944e362').\text{trunc}(3)) = \\
& H_2(502323bc55c75f7189fad7999c9f1708.\text{trunc}(3)) = H_2(708) = \\
& H_2(011100001000) = \\
& [8 \cdot 4^0 \cdot 5^1 \cdot 7^1](7v^2, 16v^3) + [12 \cdot 1^1 \cdot 3^0 \cdot 8^0](42v^2, 16v^3) + \\
& [2 \cdot 3^0 \cdot 9^0 \cdot 11^1](17v^2, 15v^3) + [3 \cdot 6^0 \cdot 9^0 \cdot 10^0](10v^2, 15v^3) = \\
& [8 \cdot 5 \cdot 7](7v^2, 16v^3) + [12](42v^2, 16v^3) + [2 \cdot 11](17v^2, 15v^3) + [3](10v^2, 15v^3) = \\
& [7](7v^2, 16v^3) + [12](42v^2, 16v^3) + [9](17v^2, 15v^3) + [3](10v^2, 15v^3) = \\
& [7](7v^2, 16v^3) + [12 * 3](7v^2, 16v^3) + [9 * 7](7v^2, 16v^3) + [3 * 11](7v^2, 16v^3) = \\
& (17v^2, 15v^3) + (42v^2, 27v^3) + (10v^2, 15v^3) + (17v^2, 15v^3) = \\
& [7](7v^2, 16v^3) + [10](7v^2, 16v^3) + [11](7v^2, 16v^3) + [7](7v^2, 16v^3) = \\
& [7 + 10 + 11 + 7](7v^2, 16v^3) = (37v^2, 16v^3)
\end{aligned}$$

So we get $[4](37v^2, 16v^3) = (42v^2, 27v^3)$

Dave thinks he can outsmart the syte, Since he is the last to contribute, he just makes up an entirely new MPC, that does not contain any randomness from the previous contributors. He thinks he can do that because, no one can distinguish his $\text{MPC}_{1,3}$ from a correct one. If this is done in a smart way, he will even be able to compute the correct POKs.

So Dave choses $s = 12$, $\alpha = 11$ and $\beta = 10$ and he will keep those values, hoping to be able to use them later to forge false proofs in the factorization snark. He then compute

$$\text{MPC}_{1,3} = \left\{ \begin{array}{ll} ([s]g_1, [s]g_2) & = ((13, 28), (7v^2, 27v^3)) \\ [s^2]g_1 & = (13, 15) \\ [\alpha]g_1 & = (33, 9) \\ [\alpha \cdot s]g_1 & = (33, 34) \\ ([\beta]g_1, [\beta]g_2) & = ((38, 28), (42v^2, 27v^3)) \\ [\beta \cdot s]g_1 & = (38, 15) \end{array} \right\}$$

Dave does not delete s , α and β , because if this is accepted as phase one of the common reference string computation, Dave controls already 3/4-th of the cheating key to forge proofs. So Dave is careful to get the proofs of knowledge right. He computes the transcript of Carols contribution as

$\text{transcript}_{1,2} =$

$$\begin{aligned}
& \text{MD5}(' (26,34)(16v^2, 28v^3)(13,28)(13,28)(26,9)(27,34)(17v^2, 28v^3)(35,28)') = \\
& c8e6308fffd47009f5f65e773ae4b499
\end{aligned}$$

We obtain that hash by computing

$$\text{printf}'\%s''(26,34)(16v^2, 28v^3)(13,28)(13,28)(26,9)(27,34)(17v^2, 28v^3)(35,28)''|md5sum$$

Chapter 7

Exercises and Solutions

TODO: All exercises we provided should have a solution, which we give here in all detail.

Bibliography

Jens Groth. On the size of pairing-based non-interactive arguments. *IACR Cryptol. ePrint Arch.*, 2016:260, 2016. URL <http://eprint.iacr.org/2016/260>.

David Fifield. The equivalence of the computational diffie–hellman and discrete logarithm problems in certain groups, 2012. URL <https://web.stanford.edu/class/cs259c/finalpapers/dlp-cdh.pdf>.

Torben Pryds Pedersen. Non-interactive and information-theoretic secure verifiable secret sharing. In Joan Feigenbaum, editor, *Advances in Cryptology — CRYPTO '91*, pages 129–140, Berlin, Heidelberg, 1992. Springer Berlin Heidelberg. ISBN 978-3-540-46766-3. URL <https://fmouhart.epheme.re/Crypto-1617/TD08.pdf>.

Martin Albrecht, Lorenzo Grassi, Christian Rechberger, Arnab Roy, and Tyge Tiessen. Mimc: Efficient encryption and cryptographic hashing with minimal multiplicative complexity. Cryptology ePrint Archive, Report 2016/492, 2016. <https://ia.cr/2016/492>.