UniCrypt – A Mathematical Crypto-Library for Java

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- Layer 1: Mathematics
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Introduction

Introductory Example: JCA

```
KeyGenerator keyGenerator =
    KeyGenerator.getInstance(”AES”);
keyGenerator.init(128);
SecretKey key = keyGenerator.generateKey();

Cipher cipher =
    Cipher.getInstance(”AES/ECB/PKCS5Padding”);
cipher.init(Cipher.ENCRYPT_MODE, key);

byte[] message = new Random().getBytes(new byte[20]);
byte[] encrypted = cipher.doFinal(message);

cipher.init(Cipher.DECRYPT_MODE, key);
byte[] decrypted = cipher.doFinal(encrypted);
```

Introductory Example: UniCrypt

```
AESEncryptionScheme aes =
    AESEncryptionScheme.getInstance();

Element key = aes.getKeyGenerator().generateKey();

Element message =
    aes.getMessageSpace().getRandomElement(20);

Element encryption = aes.encrypt(key, message);

Element decryption = aes.decrypt(key, encryption);
```

Motivation

- Multiple e-voting projects since 2008
- Various protocols implemented [CGS97, JCJ05, ...]
- Cryptographic primitives re-implemented
  - Secret-sharing
  - Pedersen commitments
  - ElGamal encryption and re-encryption
  - Zero-knowledge proofs
  - Cryptographic mixing
  - Elliptic curves

  ...
- No suitable library available off the shelf

Project Milestones

- February'12: UniVote project launched (student board elections)
- July'12: First inofficial UniCrypt release (student project)
- February'13: Second inofficial release (part of UniVote)
- March – June'13: Multiple elections in Berne, Zürich, Lucerne
- August'13: Independent project on GitHub
- September'13 – February'14: Complete re-design
- December'13: Proof of shuffle implemented (Wikström)
- February'14: Beta-version used in MobiVote

Project Team

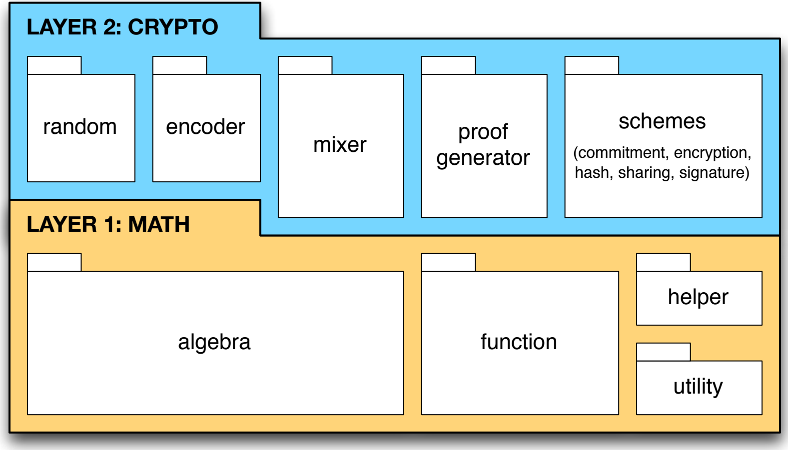
- Prof. Rolf Haenni: Project coordinator, design, development
- Prof. Reto E. Koenig: design, random generators
- MSc Philipp Locher: Cryptographic mixing, zero-knowledge proofs
- BSc Jürg Ritter: First inofficial release
- BSc Philémon von Bergen: Zero-knowledge proofs
- BSc Christian Lutz: Elliptic curves
- Gina-Maria Musaelyan: Documentation

Design Principles and Architecture

Design Principles

- Full coherence with mathematical and cryptographic concepts
- Consistent and self-explanatory nomenclature
- Clean and intuitive APIs
- Generic types (hidden from the developer if possible)
- Consistent coding style
- Immutable objects only
- Design patterns (only) if useful
- No cryptographic black-boxes (e.g. random generator)
- Java 6 compatibiliy

Architecture



LAYER 2: CRYPTO

random

encoder

mixer

proof generator

schemes (commitment, encryption, hash, sharing, signature)

LAYER 1: MATH

algebra

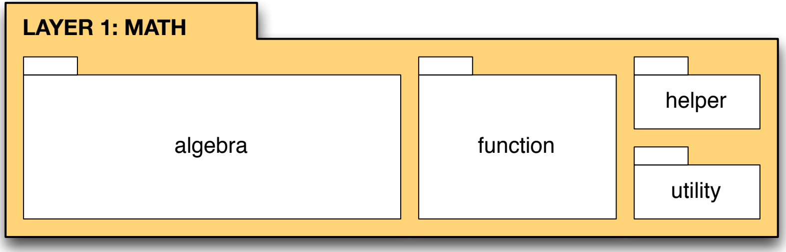
function

helper

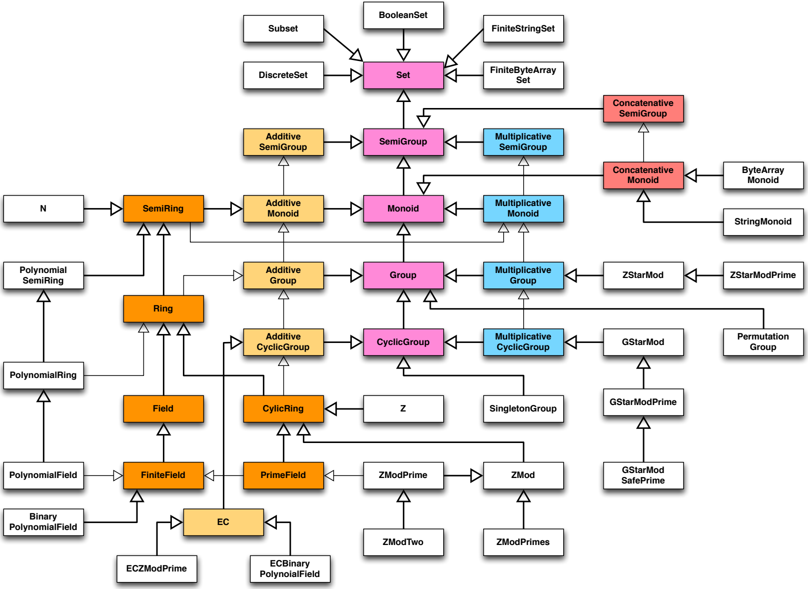
utility

Layer 1: Mathematics

Architecture: Layer 1



Algebra Package



Subset
BooleanSet
FiniteStringSet
DiscreteSet
Set
FiniteByteArray Set
Concatenative SemiGroup
Additive SemiGroup
SemiGroup
Multiplicative SemiGroup
Concatenative Monoid
ByteArray Monoid
N
SemiRing
Additive Monoid
Monoid
Multiplicative Monoid
StringMonoid
Polynomial SemiRing
Additive Group
Group
Multiplicative Group
ZStarMod
ZStarModPrime
Ring
Additive CyclicGroup
CyclicGroup
Multiplicative CyclicGroup
GStarMod
Permutation Group
PolynomialRing
Field
CylicRing
Z
SingletonGroup
GStarModPrime
PolynomialField
FiniteField
PrimeField
ZModPrime
ZMod
GStarMod SafePrime
Binary PolynomialField
EC
ZModTwo
ZModPrimes
ECZModPrime
ECBinary PolynoialField

Basic Algebraic Structures

- No operation
  - `Set`: Membership test $e \overset{?}{\in} S$, order $q = |S|$
  - `Element`: Container for elements $e \in S$
- Single operation $\circ$
  - `SemiGroup`: Associative binary operation $e_1 \circ e_2$
  - `Monoid`: Identity element $i \circ e = e \circ i = e$
  - `Group`: Inverse element $Inv(e) \circ e = i$
  - `CyclicGroup`: Generator $\langle g \rangle = \{\underbrace{g \circ \cdots \circ g}_{i \text{ times}} : 1 \leq i \leq q\} = S$
- Examples
  - `DiscreteSet`: $S = \{s_1, \ldots, s_q\}$
  - `FiniteStringSet`: $S_n = \mathcal{A}^0 \cup \mathcal{A}^1 \cup \cdots \cup \mathcal{A}^n$ for alphabet $\mathcal{A}$
  - `PermutationGroup`: $\Pi_n = \{\pi : \text{ permutation of order } n\}$

Example: PermutationGroup

```java
// Generate permutation group of size 5
PermutationGroup group =
    PermutationGroup.getInstance(5);

// Compute order |group| = 5! = 120
BigInteger order = group.getOrder();

// Pick random permutation and invert it
Element p1 = group.getRandomElement();
Element p2 = group.invert(p1);

// Combine p1 and p2 into p12 = (0,1,2,3,4)
Element p12 = group.apply(p1, p2);
```

Multiplicative Algebraic Structures

- Set with $*$ as operation
  - `MultiplicativeSemiGroup`: $e_1 * e_2$
  - `MultiplicativeMonoid`: $1 * e = e * 1 = e$
  - `MultiplicativeGroup`: $e^{-1} * e = 1$
  - `MultiplicativeCyclicGroup`: $\langle g \rangle = \{g^i : 1 \leq i \leq q\} = S$
- Examples
  - `ZStarMod`: $\mathbb{Z}_n^* = \{x \in \mathbb{Z}_n : gcd(x, n) = 1\}$
  - `ZStarModPrime`: $\mathbb{Z}_p^* = \{1, \ldots, p-1\}$
  - `GStarMod`: $\mathbb{G}_q \subset Z_n^*$ (cyclic subgroup of prime order q)
  - `GStarModPrime`: $\mathbb{G}_q \subset Z_p^*$
  - `GStarModSafePrime`: $\mathbb{G}_q \subset Z_p^*$ for $p = 2q + 1$

Example: GStarModSafePrime

```
// Generate cyclic subgroup G_11 for p = 23
GStarMod g11 = GStarModSafePrime.getInstance(23);

// Compute order (23-1)/2 = 11
BigInteger order = g11.getOrder();

// Multiply two group elements: 3*9 mod 23 = 4
Element e1 = g11.getElement(3);
Element e2 = g11.getElement(9);
Element e12 = g11.multiply(e1, e2);

// Select default generator g and compute g^5
Element generator = g11.getDefaultGenerator();
Element result = g11.power(generator, 5);
```

Additive Algebraic Structures

- Set with $+$ as operation
  - `AdditiveSemiGroup`: $e_1 + e_2$
  - `AdditiveMonoid`: $0 + e = e + 0 = e$
  - `AdditiveGroup`: $-e + e = 0$
  - `AdditiveCyclicGroup`: $\langle g \rangle = \{i \cdot g : 1 \leq i \leq q\} = S$

- Examples
  - `ECZModPrime`: $E(\mathbb{Z}_p) = \{(x, y) : x^2 = y^3 + ax + b\} \cup \{\infty\}$
  - `ECBinaryPolynomialField`: $E(\mathbb{Z}_{2^p})$

Concatenative Algebraic Structures

- Concatenation as operation
  - `ConcatenativeSemiGroup`: $e_1 \,||\, e_2$
  - `ConcatenativeMonoid`: $\langle\rangle \,||\, e = e \,||\, \langle\rangle = e$

- Examples
  - `StringMonoid`: $S = \mathcal{A}^0 \cup \mathcal{A}^1 \cup \cdots = \mathcal{A}^*$
  - `ByteArrayMonoid`: $B = (\{0,1\}^8)^*$

Example: StringMonoid

```
// Define alphabet and generate string monoid
Alphabet alphabet = Alphabet.getInstance("ADEHLORW–");
StringMonoid monoid =
    StringMonoid.getInstance(alphabet);

// Generate "HELLO–WORLD" from 3 strings
Element s1 = monoid.getElement("HELLO");
Element s2 = monoid.getElement("–");
Element s3 = monoid.getElement("WORLD");
Element s123 = monoid.concatenate(s1, s2, s3);

// Generate random string of length 10
Element s = monoid.getRandomElement(10);
```

Structures with Two Operations

- Set with two operations $+$ and $*$
  - `SemiRing`: $*$ distributes over $+$ with identity elements 1 and 0
  - `Ring`: Additive inverse $-e + e = 0$
  - `Field`: Multiplicative inverse $e^{-1} * e = 1$
  - `FiniteField`: $|S| < \infty$
  - `PrimeField`: $|S| = prime$

- Examples
  - `N`: Semiring of natural numbers $\mathbb{N} = \{0, 1, 2, \ldots\}$
  - `Z`: Ring of integers $\mathbb{Z} = \{0, \pm 1, \pm 2, \ldots\}$
  - `ZMod`: Ring $\mathbb{Z}_n$ of integers modulo n
  - `ZModPrime`: Prime field $\mathbb{Z}_p$
  - `PolynomialRing`: Polynomial ring $R[x]$ over a ring R

Example: Ring of Integers $(\bmod\, n)$

```
// Generate Z_25 and compute its order
ZMod z25 = ZMod.getInstance(25);
BigInteger order = z25.getOrder();

// Define 4 element 3, 7, 10, 12
DualisticElement e1 = z25.getElement(3);
DualisticElement e2 = z25.getElement(7);
DualisticElement e3 = z25.getElement(10);
DualisticElement e4 = z25.getElement(12);

// Compute (e1 + e2^2 - e3)/e4 mod 25
Element result =
    e1.add(e2.square()).subtract(e3).divide(e4);
```

Cartesian Products and Tuples

- Cartesian products $S_1 \times \cdots \times S_n$
  - `ProductSet`
  - `ProductSemiGroup`
  - `ProductMonoid`
  - `ProductGroup`
  - `ProductCyclicGroup`
- Corresponding combined elements
  - `Tuple`: general tuples $(e_1, \ldots, e_n) \in S_1 \times \cdots \times S_n$
  - `Pair`: tuples $(e_1, e_2) \in S_1 \times S_2$ of arity 2
  - `Triple`: tuples $(e_1, e_2, e_3) \in S_1 \times S_2 \times S_3$ of arity 3
- Sets and elements can be composed recursively

Example: Products and Tuples

```
// Generate 3 atomic sets
Set s1 = Z.getInstance();
Set s2 = N.getInstance();
Set s3 = StringMonoid.getInstance(Alphabet.LOWER_CASE);

// Generate s1 x s2, (s1 x s2)^3 and (s1 x s2)^3 x s3
ProductSet s4 = ProductSet.getInstance(s1, s2);
ProductSet s5 = ProductSet.getInstance(s4, 3);
ProductSet s6 = s5.add(s3);

// Select random tuple t1 = (e1,e2) from s4
Tuple t1 = s4.getRandomElement();

// Generate tuple t2 = (−5,”hello”) from s1 x s3
Tuple t2 = Tuple.getInstance(s1.getElement(−5),
    s3.getElement(”hello”));
```

Functions

- `Function`: mathematical concept of a function $f : X \to Y$
  - `public Set getDomain();`
  - `public Set getCoDomain();`
  - `public Element apply(Element e);`
- There is a large set of predefined functions
  - `AdapterFunction`, `AdditionFunction`, `ConstantFunction`, `ConvertFunction`, `EqualityFunction`, `HashFunction`, `IdentityFunction`, `InvertFunction`, `ModuloFunction`, `MultiplicationFunction`, `PermutationFunction`, `PowerFunction`, `SelectionFunction`, ...
- Functions can be combined in two ways
  - `ComposedFunction`: $f(x) = f_1 \circ \cdots \circ f_n(x) = f_1(f_2(\cdots f_n(x)))$
  - `ProductFunction`: $f(x_1, \ldots, x_n) = (f_1(x_1), \ldots, f_n(x_n))$

Example: HashFunction

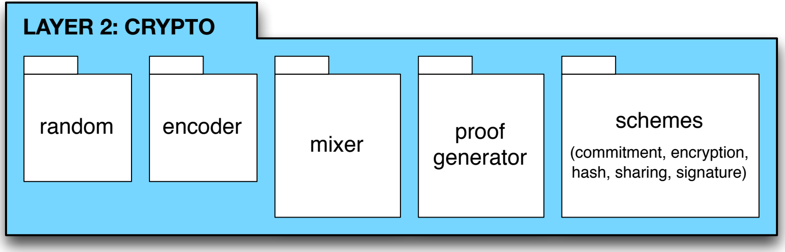
```java
// Generate product group Z23^10 and random element
Group z23 = ZModPrime.getInstance(23);
ProductGroup pg = ProductGroup.getInstance(z23, 10);
Tuple tuple = pg.getRandomElement();

// Define hash function Z23^10 -> {0,1}^256 (SHA256)
Function function = HashFunction.getInstance(pg);

// Apply hash function to tuple (returns byte array)
Element hashValue = function.apply(tuple);
```

Layer 2: Cryptography

Architecture: Layer 2



LAYER 2: CRYPTO

random

encoder

mixer

proof generator

schemes

(commitment, encryption, hash, sharing, signature)

Shamir Secret Sharing

- Prime field $\mathbb{Z}_p$
- Secret $s \in \mathbb{Z}_p$ to share among n people
- Threshold $t \leq n$
- Polynomial $f(x) = s + a_1 x + a_2 x^2 + \ldots + a_{t-1} x^{t-1}$ for $a_i \in \mathbb{Z}_p$
- Share $s_i = (x_i, f(x_i))$, for $x_i \in \mathbb{Z}_p$ and $i = 1, \ldots, n$
- Recovering of s using Lagrange interpolation

ShamirSecretSharingScheme

```java
// Define prime field
ZModPrime z29 = ZModPrime.getInstance(29);

// Generate (5,3)-threshold secret sharing scheme
SecretSharingScheme sss =
    ShamirSecretSharingScheme.getInstance(z29, 5, 3);

// Create message m=25
Element message = sss.getMessageSpace().getElement(5);

// Compute shares
Tuple shares = sss.share(message);

// Select subset of shares and recover message
Tuple someShares = shares.removeAt(1).removeAt(3);
Element recoveredMessage = sss.recover(someShares);
```

ElGamal Encryption

- Cyclic prime order subgroup $G_q \subset Z_p^*$ for $p = 2q + 1$
- Generator $g \in G_q$
- Private key $x \in \mathbb{Z}_q$
- Public key $y = g^x \in G_q$
- Randomization $r \in \mathbb{Z}_q$
- Message $m \in G_q$
- Encryption: $Enc_y(m, r) = (g^r, m \cdot y^r) \in G_q \times G_q$
- Decryption: $Dec_x(a, b) = b/a^x$

ElGamalEncryptionScheme I

```
// Create cyclic group and get default generator
CyclicGroup g_q = GStarModSafePrime.getInstance(23);
Element generator = g_q.getDefaultGenerator();

// Create ElGamal encryption scheme
ElGamalEncryptionScheme elGamal =
    ElGamalEncryptionScheme.getInstance(generator);

// Create keys
KeyPairGenerator kpg = elGamal.getKeyPairGenerator();
Element privateKey = kpg.generatePrivateKey();
Element publicKey = kpg.generatePublicKey(privateKey);

// Create random message
Element message =
    elGamal.getMessageSpace().getRandomElement();
```

ElGamalEncryptionScheme II

```
// Perform encryption
Element encryption = elGamal.encrypt(publicKey, message);

// Perform decryption
Element decryption = elGamal.decrypt(privateKey, encryption);

// Get encryption and decryption function
Function encFunction elGamal.getEncryptionFunction();
Function decFunction elGamal.getDecryptionFunction();
```

Encoders

- An encoder represents an injective mapping between two sets
  - `public Element encode(Element e)`
  - `public Element decode(Element e)`

- Example: Encrypt string (base-64) with ElGamal
  - recall that $m \in G_q \subset \mathbb{Z}_p^*$
  - for example $G_{11} = \{1, 2, 3, 4, 6, 8, 9, 12, 13, 16, 18\} \subset \mathbb{Z}_{23}^*$
  - we need $f : S_n \rightarrow G_q$ and $f^{-1} : G_q \rightarrow S_n$, possibly constructed as a composed function $f = f_1 \circ f_2$ for
    $f_1 : S_n \rightarrow \mathbb{Z}_q$ (`FiniteStringToZModEncoder`)
    $f_2 : \mathbb{Z}_q \rightarrow G_q$ (`ZModToGStarModSafePrimeEncoder`)

CompositeEncoder

```
// Define underlying groups
Group g_q = GStarModSafePrime.getRandomInstance(256);
Group z_q = g_q.getZModOrder();

// Create alphabet and encoders
Alphabet base64 = Alphabet.BASE64;
Encoder encoder1 =
    FiniteStringToZModEncoder.getInstance(z_q, base64);
Encoder encoder2 =
    ZModToGStarModSafePrimeEncoder.getInstance(g_q);
Encoder encoder12 =
    CompositeEncoder.getInstance(encoder1, encoder2);

// Encode and decode message
Element message =
    encoder12.getDomain().getElement("Hello␣World");
Element encoded = encoder12.encode(message);
Element decoded = encoder12.decode(encoded);
```

Cryptographic Mixing

- Let $E_1, \ldots, E_n$ be a list of ElGamal encryptions of messages m_i with randomisations r_i and public key y
- Re-encryptions $E'_i = E_i * Encrypt_y(1, r'_i) = Encrypt(m, r_i + r'_i)$
- Permutation $\pi \in \Pi_n$
- Cryptographic mixing:

$$shuffle_{\pi}(E_1, \ldots, E_n, r'_1, \ldots, r'_n) = (E'_{\pi(1)}, \ldots, E'_{\pi(n)})$$

ReEncryptionMixer

```
// Generate encryptions
Element e1 = elGamal.encrypt(publicKey, m1, r1);
Element e2 = elGamal.encrypt(publicKey, m2, r2);
    :           :           :
Element e10 = elGamal.encrypt(publicKey, m10, r10);
Tuple encryptions = Tuple.getInstance(e1, e2, ... e10);

// Create mixer
Mixer mixer = ReEncryptionMixer.getInstance(elGamal,
    publicKey, 10);

// Shuffle the encryptions
Tuple shuffledEncyptions = mixer.shuffle(encryptions);
```

Non-Interactive Preimage Proofs

- Let $f : X \rightarrow Y$ be a homomorphic function (one-way)
- Private input $x \in X$
- Public input $y = f(x) \in Y$
- Prove knowledge of preimage x by computing

  $$(t, c, s) = NIZKP\{x \in X : y = f(x))\}$$

  non-interactively from x and y (without releasing any information about x)
- Example: proof knowledge of private ElGamal key $y = g^x$

PreimageProofGenerator

```
EncryptionScheme elGamal = ElGamalEncryptionScheme... ;

// Generate keys
KeyPairGenerator kpg = elGamal.getKeyPairGenerator();
Element privateKey = kpg.generatePrivateKey();
Element publicKey = kpg.generatePublicKey(privateKey);

// Create proof generator
Function function =
    kpg.getPublicKeyGenerationFunction();
PreimageProofGenerator ppg =
    PreimageProofGenerator.getInstance(function);

// Generate and verify proof
Triple proof = ppg.generate(privateKey, publicKey);
BooleanElement result = ppg.verify(proof, publicKey);
```

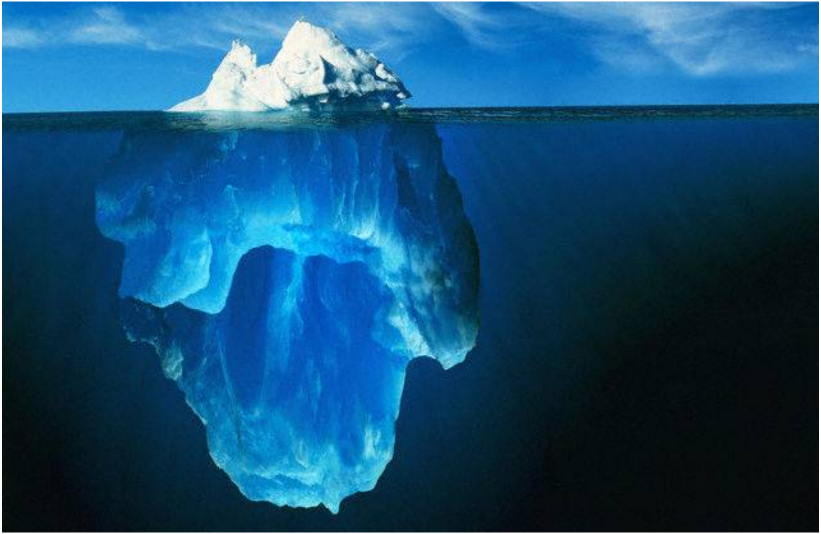
Summary and Outlook

Summary

- UniCrypt = Java library with advanced mathematical and cryptographic primitives
- Offers clean and intuitive APIs
- Growing in size
    - 68 interfaces
    - 217 classes
    - 34553 lines of codes (incl. comments, excl. tests)
- Open-source: abailable on GitHub
- Free for academic or non-commercial usage (dual license)
- Collaborations are welcome

Outlook

- Stage of development: alpha
- Important components under development
    - elliptic curves
    - true random generators
- Important components missing
    - signature schemes
    - certificates
    - further encryption schemes (RSA, Paillier, etc.)
    - further types of zero-knowledge proofs
    - other cryptographic schemes
- Documentation largely missing
- Insufficient code coverage by existing JUnit tests



Source: http://www.djibang.org/wp/wp-content/uploads/eisberg.jpg

Questions?

http://e-voting.bfh.ch

https://github.com/bfh-evg/unicrypt