zkay v0.2: Practical Data Privacy for Smart Contracts

Technical Report

NICK BAUMANN, ETH Zürich, Switzerland
SAMUEL STEFFEN, ETH Zürich, Switzerland
BENJAMIN BICHSEL, ETH Zürich, Switzerland
PETAR TSANKOV, ETH Zürich, Switzerland
MARTIN VECHEV, ETH Zürich, Switzerland
ABSTRACT

Recent work introduces zkay, a system for specifying and enforcing data privacy in smart contracts. While the original prototype implementation of zkay (v0.1) demonstrates the feasibility of the approach, its proof-of-concept implementation suffers from severe limitations such as insecure encryption and lack of important language features.

In this report, we present zkay v0.2, which addresses its predecessor’s limitations. The new implementation significantly improves security, usability, modularity, and performance of the system. In particular, zkay v0.2 supports state-of-the-art asymmetric and hybrid encryption, introduces many new language features (such as function calls, private control flow, and extended type support), allows for different zk-SNARKs backends, and reduces both compilation time and on-chain costs.
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1 INTRODUCTION

1.1 An Improved Implementation of zkay

Zkay [31] is a system for specifying and enforcing data privacy in smart contracts. The original publication comes with a prototype implementation of zkay [10], which however suffers from various limitations. We refer to this prototype implementation as zkay v0.1.

This technical report presents zkay v0.2 [11], a significantly improved implementation of zkay in terms of security, usability, modularity, and performance. The report describes features and implementation details of zkay v0.2, and is targeted at both users and developers. It assumes that the reader is familiar with the language and key ideas of zkay according to the original publication [31].

In summary, zkay v0.2:

- Adds support for state-of-the-art asymmetric and hybrid encryption;
- introduces essential language features including function calls, cryptocurrency-related functionality, private control flow, extended type support, and many more;
- supports different zk-SNARKs backends;
- provides a live transaction runtime automatically transforming transactions, computing the necessary zero-knowledge proofs, and directly interacting with a blockchain;
- features various usability improvements such as improved error messages and simplified installation; and
- reduces both compilation time and on-chain costs.

1.2 Terminology

We now introduce some terms which are commonly used in this report.

- \textbf{Zkay v0.1}: The proof-of-concept implementation from [10].
- \textbf{Zkay v0.2}: The new version of zkay [11] described in this report.
- \textbf{Public computation/value}: An expression/value whose owner is all.
- \textbf{Private computation/value}: An expression/value which is not public.
- \textbf{Public function}: A function whose arguments and return values are public, and whose body only contains public computations and calls to public functions. Note that unless explicitly stated otherwise, this does \textit{not} refer to the visibility modifier of the function.
- \textbf{Private function}: A function which is not public. Note that unless explicitly stated otherwise, this does \textit{not} refer to the visibility modifier of the function.
- \textbf{Internal function call}: Calling a contract function from within the same contract.
- \textbf{External function call}: Calling a contract function from an external account (i.e., a user or a different contract).
- \textbf{On-chain}: Execution on the blockchain as part of a smart contract transaction. Increased on-chain computation results in higher Ethereum gas costs.
- \textbf{Off-chain}: Local execution on a machine of a single user.
- \textbf{Non-interactive zero-knowledge (NIZK) proof}: A proof of a statement about secret values which does not leak any information about these values besides their existence [3, 13]. The
statement can be parameterized by public values. A NIZK proof is generated by a prover knowing the secret values, and verified by a verifier. In particular, NIZK proofs can be used to prove the correct execution of a computation $out_{pub} = \phi(in_{pub}, in_{priv})$ accepting public and private inputs $in_{pub}$ resp. $in_{priv}$, and producing a public result $out_{pub}$.

- **Zk-SNARKs**: An efficient instantiation of NIZKs [2]. Zk-SNARKS require a trusted setup phase, which generates a common reference string for proof generation and verification. In practice, most proving schemes generate a keypair $(k_{p}, k_{v})$ from a constraint system representing the proof statement $\phi$ and secret randomness during the trusted setup phase. The keypair $(k_{p}, k_{v})$ is publicly known: the prover key $k_{p}$ is used to generate proofs for $\phi$ and arbitrary inputs, while the verification key $k_{v}$ is required to verify such proofs.

- **Abstract proof circuit**: A high-level, NIZK-framework agnostic representation of a proof statement (the computation $\phi$ to be proven) internally used by zkay. Such circuits are compiled to framework-specific concrete proof circuits (see below) by different backends.

- **(Concrete) proof circuit**: An arithmetic prime field circuit expressing a proof statement. A circuit can have multiple input parameters, which can be private or public (see below). Zk-SNARK frameworks such as jsnark [23] generate low-level constraint systems from such circuits, which are then used to generate NIZK key pairs and proofs.

- **Private (circuit) input**: Input representing a secret to be hidden from the verifier. Private inputs are known to the prover.

- **Public (circuit) input**: Input representing public knowledge, which is supplied to verifiers on the blockchain.
2 LIMITATIONS OF ZKAY V0.1

This section summarizes the main limitations of zkay v0.1 [10]. The key design goal of zkay v0.2 is to address these limitations.

2.1 Security

Insecure Encryption. A major limitation of zkay v0.1 is its lack of secure encryption. In particular, it uses the surrogate encryption function $\text{Enc}(v, k) = v + k$ to encrypt plaintext $v$ with key $k$, which does not ensure confidentiality. Zkay v0.1 leverages the ZoKrates framework [5, 32] for NIZK proof generation and verification, which at the time of development did not support more realistic encryption functions.

Missing Integrity Verification. zkay v0.1 does not provide tool support for verifying whether the bytecode of a deployed smart contract corresponds to a given zkay contract. Doing this manually is challenging due to the involvement of multiple contracts (main, library, and verification contracts), and because exactly reproducing the bytecode compilation output requires the same verification keys to be used.

Undefined Behavior. The transaction transformation in zkay v0.1 uses arbitrary-precision integers instead of emulating the under- and overflow semantics of fixed-sized integers. The user is required to ensure the absence of under- and overflows as these may result in security vulnerabilities such as the possibility of permanently locking the funds of a contract.

Additionally, zkay v0.1 assumes that variables are always initialized and does not model the zero-initialization semantics of Solidity. When reading an uninitialized variable, transaction transformation in zkay v0.1 may therefore produce an invalid proof.

2.2 Language Fragment

zkay v0.1 only supports a small subset of Solidity as indicated below. This significantly restricts expressivity of zkay contracts.

- only bool, uint (256-bit unsigned integer) and mapping types; no integer variant, enum, or private address types
- no user-defined types
- no tuples or multiple return values
- only basic statements (require and assignment); no control flow except return at the end of function bodies
- only a basic set of operators; no bitwise or shift operators
- no function calls
- no cryptocurrency features (e.g., transfer and payable)

2.3 Usability

Transaction Transformation. Automatic transformation of transactions in zkay v0.1 is very limited and does involve direct interaction with a blockchain. In particular, the public keys of all involved parties and the current blockchain state need to be manually provided to zkay together with the transaction parameters. Issuing the resulting transformed transaction is not part of zkay v0.1 and
needs to be done separately. Overall, issuing a zkay v0.1 transaction is much more complicated than issuing a standard Ethereum transaction.

Uninterpretable Compiler Errors. In general, error reporting in zkay v0.1 is very limited and error messages often only consist of internal stack traces not easily interpretable for users.

No Standardized Contract Distribution. zkay v0.1 does not provide a specification how to distribute a zkay contract to its users. Each user of a contract at least needs access to the original zkay source code and all involved NIZK proving keys, which need to be distributed using off-chain communication.

2.4 Modularity and Extensibility

The implementation of zkay v0.1 is not very modular, which impedes extensibility of the tool. In particular, the compiler is tightly coupled to ZoKrates [32], making it difficult to integrate other NIZK frameworks. Additionally, key and cipher text sizes are hard-coded.

2.5 Performance

Off-chain computation and compilation performance of zkay v0.1 is suboptimal and reduces development productivity. In particular, compiling a simple contract can take up to several minutes.
3 ARCHITECTURE

This section describes the architecture of zkay v0.2, which consists of a compiler compiling zkay to Ethereum contracts (Section 3.1) and a runtime for transaction transformation (Section 3.2). Fig. 1 provides an overview of the architecture and the interactions between the different components.

3.1 Compiler

The compiler accepts a zkay contract and produces various output files as described below (see dark green items in Fig. 1).

- **contract.sol**: The main transformed Solidity contract performing on-chain computation (except proof verification, see next). This contract is deployed to the blockchain.
- **verifier.sol**: Solidity contracts (one per proof circuit) performing NIZK proof verification on-chain, also deployed to the blockchain. The main contract calls these verification contracts.
- **Proving.key, Verifying.key**: NIZK proof key pairs (one key pair per verification contract). The prover keys are used by users of the main contract to generate valid NIZK proofs. The verification keys are integrated into the verification contracts (see previous).
- **manifest.json**: A manifest file storing all zkay compiler settings such that the compiler output can be exactly reproduced later.
The input contract is parsed using an extension of the grammar used in zkay v0.1, supporting the whitespace replacement, the source code locations match the locations in the zkay contract.

Due to the transformed abstract syntax tree (AST) of the contract to generate Solidity code and abstract proof circuits. These circuits are then transformed to concrete circuits used as inputs for the zk-SNARK tools jsnark [23] and libsnark [24]. After generating NIZK key pairs, the compiler generates the verification contracts. From the transformed AST, the compiler also generates a transaction interface that will later be used together with the transaction runtime. Finally, the compiler also generates a manifest file.

Fig. 2 depicts the building blocks realising these phases. The following sections discuss the compiler phases in more detail.

### 3.1.1 Parsing, Analysis and Type Checks

The input contract is parsed using an extension of the grammar used in zkay v0.1, supporting the new language features described in Section 4. Then, we run several type checks and analyses on the constructed AST (see steps 1 and 2 in Fig. 2).

**Socl Type Check.** This check ensures that when ignoring all privacy features specific to zkay, the contract is a valid Solidity contract. It (i) replaces all comments and privacy features in the input contract by a matching amount of whitespace, (ii) invokes the solc Solidity compiler via its json interface, and (iii) displays any warnings or errors from solc in the context of the original code. Due to the whitespace replacement, the source code locations match the locations in the zkay contract.

Users can perform the “stripping” of zkay features in isolation using the zkay solify command. This allows easy use of linters and other program analysis tools designed for Solidity.

The remaining analyses only have to deal with zkay’s privacy types and features. For example, we don’t need to re-implement Solidities data type checks.
Alias Analysis. Like in zkay v0.1, the compiler performs alias analysis on the contract to determine references which are guaranteed to point to the caller’s address at runtime. This information is later used by the privacy type check. Compared to zkay v0.1, the precision of the alias analysis in zkay v0.2 is slightly more precise. For example, the join operation no longer removes final address variables from equivalence sets.

Undefined Behavior Check. This check ensures that the zkay contract is free of undefined behavior due to expressions relying on subexpression evaluation order. In particular, the check forbids expressions where two subexpressions have side-effects on the same variable, or where a variable is written and read in two different subexpressions.

Privacy Type Check. Here, the compiler checks zkay’s privacy types as described in [31]. For instance, it ensures that no implicit information leaks are possible and that the zkay contract is realizable using encryption and NIZK proofs. The typing rules of zkay v0.1 have been extended to account for the new language features of zkay v0.2 (see Section 4). Circuit compatibility and loops are analyzed in two separate checks, see below.

Circuit Compatibility Check. This check ensures that private expressions do not contain private operations that are not expressible inside a NIZK proof circuit. Since zkay v0.2 supports function calls (see Section 4.1), this involves (i) recursively checking the bodies of any called functions, and (ii) ensuring that the body of any function called within a private expression does not involve recursion or loops. Also, the compiler enforces private expressions to be side-effect free in order to simplify circuit optimization.

Loop Check. Finally, the compiler checks that all loops in the contract are fully public, meaning that no private expressions appear within any loop exit condition or body.

3.1.2 AST Transformation and Abstract Circuit Generation

Next, the analyzed AST is transformed to yield abstract proof circuits and Solidity code for the main contract as described below (see Fig. 1 and step 3 in Fig. 2).

AST Transformation. Zkay v0.2 transforms the AST using an extension of the translation rules from [31] to produce representations of the on-chain computation and proof circuits.

Code Generation. During code generation, zkay traverses the on-chain computation AST and emits Solidity code. The resulting Solidity file is the main contract to be deployed on the blockchain. Due to the improved modularity, additional target languages can easily be incorporated in zkay v0.2 by adapting the code generator.

Abstract Circuit Generation. Unlike zkay v0.1, where contract transformation is heavily coupled with the ZoKrates framework [5, 32], zkay v0.2 constructs framework-agnostic abstract representations of proof circuits from the transformed AST. Such an abstract proof circuit maintains a list of public and private circuit inputs, and holds a sequence of abstract circuit statements from the following list.

- Variable Declaration and Assignment: Assigns the (plaintext) value of a private expression to a new temporary circuit variable.
- Guard Condition Modification: Adds or removes a boolean circuit variable to resp. from the guard condition (see §5.3 in [31] for more information on guard conditions).
Encryption/Decryption Constraint: An assertion of the form $\text{cipher} == \text{Enc}($plain$, \text{rnd}, k)$, ensuring correct encryption of a plaintext plain using key $k$ and randomness rnd. Such constraints are used for private function arguments and whenever the result of a private expression is stored to a private variable.

An analogous decryption assertion exists, which is used whenever a private variable is read within a private expression.

Equality Constraint: An assertion of the form $\text{val}_1 == \text{val}_2$. Such constraints are used whenever a private value is declassified.

Function Call: A pointer to the abstract circuit of a called function. The concrete circuit generator (see below) will inline the target circuit at this position.

Note that there is no arbitrary assignment statement for proof circuits. Zkay v0.2 relies on static single assignments, using the "Variable Declaration and Assignment" statement. For simplicity, only this type of statement can contain arbitrary expressions. All other statements may only reference variables directly. Therefore, any compound expression is first assigned to a temporary circuit variable before being used in any of the other statement types.

3.1.3 Transaction Interface Generation

The transformed AST is further processed to generate a transaction interface for the contract. More specifically, this step generates Python code serving as a user interface to the contract and transforming transactions by generating NIZK proofs and encrypting function arguments.

Listings 1 and 2 show the structure of the generated Python code for an example contract. At a high level, zkay creates a Python class which matches the original contract structure, where each method internally performs transaction transformation (transaction simulation, argument encryption, proof generation) for the corresponding contract function. Users can naturally interact with objects of this python class as if they would interact with the contract directly. The generated class makes heavy use of transaction runtime functionality provided by the superclass ContractSimulator. See Section 3.2.1 for more details.

This design has some important advantages over the design of zkay v0.1.
Interpretability: The generated Python code can be manually inspected by users to see how transactions are transformed.

Simplified Debugging: To debug contracts (and also the zkay implementation itself), one can use standard Python debugging tools.

Improved Performance: Since there is no additional overhead for interpreting zkay code (as done in zkay v0.1), performance is slightly better.

3.1.4 Concrete Circuit Generation and Compilation

In this step, abstract proof circuits are compiled to a NIZK-framework-specific concrete circuit representation. Zkay v0.2 uses different circuit compilation backends to target different NIZK frameworks. Each backend must implement zkay’s abstract CircuitGenerator interface, which provides functions for (i) transforming abstract circuits into a backend-specific representation with equivalent semantics, (ii) generating prover and verification keys for a given circuit and proving scheme, and (iii) marshalling generated verification keys into a standard format only depending on the proving scheme (but not the particular backend).

Zkay v0.2 currently supports only one circuit compilation backend, which relies on the jsnark framework [23] and is described below. The ZoKrates integration from zkay v0.1 has been removed due to ZoKrates’ lack of cryptographic primitives.

Jsnark Backend. Jsnark is one of the few currently available frameworks with comprehensive built-in support for cryptographic primitives. In zkay v0.2, a concrete jsnark circuit is represented as a Java subclass of CircuitGenerator. It uses a Java API (see below) to (i) define public and private circuit input wires, and (ii) combine wires using a variety of boolean, arithmetic, and bitwise operations. The jsnark backend generates this Java class and executes it to generate an output file (circuit.arith in Fig. 1) in libsnark-specific format. Then, a separate libsnark [24] interface binary (see below) is used to generate prover and verification keys for the circuit.

Zkay Jsnark API. To increase readability and reduce the amount of boilerplate code in the generated circuit files, zkay v0.2 implements a higher-level Java API [8] on top of jsnark. In particular, the API provides the following items.

(i) A custom abstract CircuitGenerator subclass ZkayCircuitBase, which includes helper functions to define encryption constraints, add circuit inputs with a specific emulated type, and reference input wires by name.

(ii) Adapter classes for jsnark’s cryptographic primitive gadgets, which unpack/pack the inputs/outputs as required for zkay.

(iii) A TypedWire wrapper class, which associates data types to wires and correctly emulates the semantics of arithmetic overflows, signed operations, etc. (see Section 4.7).

As an example, Listing 4 shows the jsnark Java circuit corresponding to the zkay function in Listing 3 and making use of the jsnark Java API.

Zkay Libsnark Interface. The original libsnark interface included in jsnark is not very flexible as it e.g. does not support the GM17 [17] proving scheme. For that reason, zkay v0.2 uses its own custom C++ libsnark interface [9], which extends the existing interface with further proving schemes and serialization of verification keys.
Listing 3. Example zkay code.

```java
public class ZkayCircuit extends ZkayCircuitBase {
    public ZkayCircuit() {
        super("zk__Verify_Token_buy", "dummy", 248, 3, 1, 3, true);
    }

    private void __zk__buy() {
        stepIn("_zk__buy");
        addS("secret0_plain", 1, ZkUint(256));
        addS("zk__in0_cipher_R", 1, ZkUint(256));
        addS("zk__out0_cipher_R", 1, ZkUint(256));
        addIn("zk__in0_cipher", 1, ZkUint(256));
        addIn("zk__in1_plain_amount", 1, ZkUint(256));
        addOut("zk__out0_cipher", 1, ZkUint(256));

        // secret0_plain = dec(balance[me]) [zk__in0_cipher]
        checkDec("secret0_plain", "glob_key_me", "zk__in0_cipher_R", "zk__in0_cipher");
        // zk__in1_plain_amount = amount
        dec1("tmp0_plain", o_((get("secret0_plain")), '+', get("zk__in1_plain_amount")));
        // zk__out0_cipher = enc(tmp0_plain, glob_key_me)
        checkEnc("tmp0_plain", "glob_key_me", "zk__out0_cipher_R", "zk__out0_cipher");

        stepOut();
    }

    @Override
    protected void buildCircuit() {
        super.buildCircuit();
        addK("glob_key_me", 1);
        __zk__buy();
    }

    public static void main(String[] args) {
        ZkayCircuit circuit = new ZkayCircuit();
        circuit.run(args);
    }
}
```

Listing 4. Circuit using high-level jsnark Java API.

### 3.1.5 Verification Contract Generation

In this step, zkay generates Solidity contracts performing on-chain NIZK proof verification. As the format of such verification contracts depends on the used proving scheme, zkay v0.2 uses different proving scheme backends for this task. Each backend implements the abstract ProvingScheme interface and is responsible for (i) defining a verification key data structure, and (ii) generating verification contracts for a given verification key and list of public circuit inputs. Zkay v0.2 provides backends for two proving schemes: GM17 [17], which is already used by zkay v0.1, and the more efficient Groth16 [16] scheme (default in zkay v0.2).

In contrast to zkay v0.1, where verification contracts are directly generated by ZoKrates, the proving scheme backends in zkay v0.2 have full control over the verification contracts and can apply specific optimizations such as loop unrolling, avoiding unnecessary copy operations, and hashing optimizations (see Section 6.1.1).
3.2 Transaction Transformation Runtime

The second core component of zkay v0.2 is a transaction runtime which transforms function calls and executes them on the blockchain. It consists of two parts: the Python contract interface generated by the compiler (see Section 3.2.1) and the actual runtime providing core functionality via an API (see Section 3.2.2). In Section 3.2.3, we describe how users can interact with a zkay contract using its Python interface, either programmatically or via an interactive shell.

3.2.1 Python Contract Interface

The Python contract interface (contract.py in Fig. 1) transforms and forwards function calls to the Solidity contract deployed on the blockchain (contract.sol). Its goal is to prepare encrypted function arguments and generate NIZK proofs to be accepted by the verifier contracts. Because these generally depend on blockchain state and the results of public or private operations in the zkay contract, the interface needs to simulate the execution of the zkay contract in Python.

For many simple operations, the compiler simply emits the transformed AST as equivalent Python code. However, the contract interface also performs more complex operations as described below, often leveraging the zkay runtime API (see Section 3.2.2).

- To make transaction transformation transparent to users, the signature of each external function matches the original zkay function. Its body encrypts private arguments and adds their plaintext values to the secret circuit arguments. At the beginning of the function, the msg, block and tx objects are populated with current blockchain data using the runtime API.
- At the end of each external function that requires verification, the interface uses the runtime API to generate a NIZK proof for the collected circuit arguments. Then, the transformed transaction is issued using the runtime API.
- Parameter or function names conflicting with Python keywords or other reserved names are sanitized by adding a special suffix that is prevented to be used in user code.
- Key lookups in the PKI are replaced by a runtime API call retrieving the requested key from the blockchain state.
- The values of state variables are lazily retrieved from the blockchain and cached for repeated access. Each state variable reference is replaced by an index operation into a dedicated state dictionary that requests the value from the blockchain (via the runtime API) if it is not cached.
- Due to the missing support for nested local scopes in Python, zkay v0.2 uses context managers and a special local variable dictionary aware of scoping (provided by the runtime API) to emulate nested block scopes.
- Whenever a private circuit value is included in the circuit inputs, it is immediately decrypted (using the runtime API) and its plaintext value is added to the secret circuit arguments.
- For each private expression, the simulator computes the expression’s output value, encrypts it (using the runtime API) if required, and stores it in the corresponding circuit output variable.
- Each require statement is replaced by an if-statement raising a RequireException if the condition does not hold.
- For all arithmetic operations and type casts, correct over-/underflow behavior is emulated using the runtime API (see Section 4.7 for details).
- Two additional static methods connect and deploy are added to the contract interface. The function connect verifies the integrity of the remote Solidity contract at the specified address.
Fig. 3. Architecture of the zkay transaction runtime.

(see Section 5.4) and creates a Python interface for it. The function deploy calls the contract constructor, which results in a deployment transaction. See Section 3.2.3 for details.

3.2.2 zkay Runtime

The interface contract.py extends the base class ContractSimulator, which provides access to the zkay runtime API and maintains the transaction simulation’s internal state. The API provides core functionality such as access to local and state variables, type casting and under-/overflow emulation, blockchain interaction, cryptographic operations, and key management (see Section 3.2.1).

Fig. 3 shows an overview of the transaction runtime architecture. Zkay v0.2 supports different encryption schemes, which are realized using different crypto backends. To generate NIZK proofs, the runtime further uses a prover backend. The runtime can interact with a variety of Ethereum blockchain interfaces, which are exposed to the runtime as blockchain backends. We next describe these backends.

Crypto backends. These backends implement key generation, encryption and decryption operations for different encryption schemes. Zkay v0.2 includes 5 crypto backends: “dummy encryption” (the insecure surrogate encryption function used in zkay v0.1), RSA with either PKCS1.5 ([26], section 7.2) or OAEP ([26], section 7.1), as well as ECDH [4, 22, 25] in combination with AES [14] or Chaskey LTS [27] block ciphers. See Section 5 for details.
**Prover backends.** A prover backend is responsible for generating NIZK proofs for a given circuit and input values. Zkay v0.2 supports only one prover backend, which is based on jsnark. To construct a NIZK proof, the jsnark backend first executes the Java circuit (`circuit.java` in Fig. 3) produced by the jsnark circuit generator in proof generation mode to create a jsnark input file (`circuit.in`). This input file is then passed to the libsnark interface, which performs the actual proof generation.

**Blockchain backends.** These backends connect zkay with different Ethereum blockchain interfaces. They implement contract deployment, transactions, state queries (e.g., state variable and account balance queries), and integrity checks (see Section 5.4). All five currently supported blockchain backends are based on web3py [19]. The `w3-eth-tester` [12] and `w3-ganache` [18] backends are used for testing with local blockchains, while the remaining backends are used to connect zkay with real Ethereum nodes over IPC, HTTP, or WebSocket. For security reasons, zkay prevents using dummy encryption for non-local blockchains.

### 3.2.3 Using the Contract Interface

Users can use the `deploy` and `connect` commands of zkay’s command-line interface to easily create and interact with zkay v0.2 contracts. Using `deploy`, a user can deploy a zkay contract to the configured Ethereum blockchain. Then, an instance of the contract interface can be obtained using the `connect` command. When running this command, zkay enters an interactive shell in the context of the created interface object, which allows users to issue transactions in an interactive manner. All external contract functions are available with identical signature as in the zkay contract. When calling any such function, zkay v0.2 transparently transforms the transaction (see Section 3.2.1) and issues it on the configured Ethereum blockchain.

The `deploy` and `connect` functions can also be accessed using the programmatic interface in the module `zkay.zkay_frontend`.
4 NEW LANGUAGE FEATURES

In this section, we describe the new language features introduced in zkay v0.2.

4.1 Function Calls

As a major extension of zkay v0.1, zkay v0.2 supports internal function calls.

4.1.1 Restrictions

Expressions with side-effects (e.g., an expression modifying a state variable) cannot be moved to the proof circuit. Inside private expressions (i.e., if there exists a non-public ancestor in the expression tree), zkay v0.2 hence enforces called functions to be annotated as pure or view.

In general, calls to functions with private return value are inlined in the proof circuit if they occur within a private expression. As a result, the called function bodies may not contain any operations unsupported in the proof circuit (such as loops or recursive function calls). This is enforced by the type system of zkay v0.2. In contrast, calls to functions with public return value are generally not integrated in the proof circuit. If such a function call appears inside a private expression, the return value is computed on-chain and passed to the proof circuit as a public input.

4.1.2 Function Calls not Requiring Verification

There are two cases where an internal function call does not require any verification, namely if (i) the function is fully public, or (ii) the only private expressions in the function are its private arguments. There are no restrictions on such function calls, as they are not transformed by zkay v0.2 in any way.

4.1.3 Function Calls Requiring Verification

Internal function calls outside private expressions require verification if the called function contains private expressions beyond any private arguments. In general, there are two ways to ensure that the required proof circuit is included in a NIZK proof and verified:

(i) **Callee-driven.** Here, the callee is responsible for verifying the proof circuit induced by its own body, excluding nested function calls. With each nested function call, an additional NIZK proof is introduced that has to be tunneled through the caller.

(ii) **Caller-driven.** Here, the caller is responsible for verifying the proof circuit induced by any transitively called function. In this case, the external top-level function performs verification of a single large proof circuit combined from smaller sub-circuits induced by nested function calls. Only a single NIZK proof is introduced per external function.

As the gas cost for verifying a NIZK proof on the blockchain is virtually independent of the proof circuit size (see Section 6.1.1), option (ii), which induces less proof verifications, is more efficient. Accordingly, zkay v0.2 follows the caller-driven approach. For this approach, the following items have to be considered.

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2Case (ii) particularly applies to a function that merely stores the value of its private argument in a state variable. While calls to such functions require verification when being called externally (the correct encryption of private user-provided arguments is checked in the proof circuit), this is not the case for internal calls.
▷ For each external function, the compiler needs to statically determine all transitively called internal functions and construct the required proof circuit. For this to work, the type system has to guarantee the absence of recursive calls and function calls within loops (see Section 3.1.1).

▷ External functions need access to the public proof circuit inputs and outputs for all transitively called internal functions.

▷ Each internally called function needs access to its own circuit outputs.

▷ Verifying correct encryption of private function parameters is required if and only if the function is called externally. In all other cases (internal or private functions), the function can rely on the fact that its arguments have already been verified by the caller.

**Circuit Input and Output Arrays.** In order to manage public circuit inputs, zkay v0.2 uses a large dynamic array shared by transitively called functions. This array is (implicitly) divided into a hierarchy of sections according to the tree of nested function calls. Each section stores the function’s own circuit inputs as well as the sections of all called functions. An analogous second array is used for circuit outputs.

Fig. 4 visualizes the input array memory layout for an example call tree. Here, function $f$ is called externally and calls functions $g$ and $p$ in its function body.

**Functions with Private or Internal Visibility Modifier.** These functions cannot be called externally. Zkay v0.2 adds four parameters to the signature of such functions: dynamic arrays $\text{in}$ and $\text{out}$ used to propagate circuit inputs (resp. outputs) along the call tree, and two integer indices $\text{in\_idx}$ and $\text{out\_idx}$ used to indicate the section start offsets for the current function.

The indices $\text{in\_idx}$ and $\text{out\_idx}$ act as relocation base addresses and are set by the caller of the function. The transformed Solidity code accesses entries of the $\text{in}$ and $\text{out}$ array relative to these offsets, which makes it possible to use the same function definition independently of the function’s location in the call tree.

To work around Solidity’s stack size limit and lack of array slice operators, the circuit outputs are deserialized from the $\text{out}$ array into a struct at the beginning of the function body. Analogously, the public circuit inputs are serialized from a struct into the $\text{in}$ array before the function returns. Within the function body, all circuit outputs resp. inputs are read from resp. stored into the corresponding struct.
Functions with Public Visibility Modifier. Functions with public visibility modifier may be called both internally and externally. Hence, these are split into two functions during compilation.

▷ An internal function, which is simply a copy of the original function transformed as any other internal function (see above).

▷ An external function with two additional parameters proof and out, allowing the user to pass a NIZK proof and a circuit output array according to the memory layout described above. The body of the external function performs the following steps.

(i) Allocate an array large enough to store the circuit inputs of all transitively called functions.

(ii) Request all encryption keys required by any transitively called function from the PKI contract.

(iii) Store all encrypted parameters in the circuit input array (the correct encryption of these parameters will be verified).

(iv) Call the corresponding internal function (see above), passing the in and out arrays with initial indices. The called function will populate the in array.

(v) Invoke the NIZK proof verifier for proof, in and out.

Incorporating Circuits of Nested Calls. The zkay compiler generates a separate abstract proof circuit (see Section 3.1.2) for each function definition. Abstract proof circuits use a special CircuitCall statement to include (sub-)circuits of nested function calls. The circuit compilation backend (see Section 3.1.4) is then responsible for inlining the sub-circuits into the main top-level proof circuit, respecting the memory layout of the in and out arrays.

Example. Figure 5 demonstrates how zkay v0.2 complies function calls to Solidity. To remove clutter, range checks are omitted and a Python-style slicing syntax is used to indicate array ranges.

4.2 Cryptocurrency Functionality

Zkay v0.2 allows functions to be declared payable. Further, it supports address types (see Section 4.8) and querying the balance of an address using the member function balance. Outside private expressions, payable addresses can be used to transfer funds using the member functions send and transfer.

Further, zkay v0.2 provides access to the msg (only sender and value), block, and tx globals. During transaction simulation (see Section 3.2), they are represented as Python objects, which are populated by the blockchain backend.

4.3 If-Statements

Zkay v0.2 supports control-flow using if-statements, both with public and private conditions.

4.3.1 Public Conditions

Zkay v0.2 adds support for if-statements with public conditions and makes use of guard conditions as introduced in [31]: if any of the branches contains private expressions, an appropriate guard condition is added to all proof circuit constraints generated for that branch.
In particular, no branch is allowed to contain operations unsupported in proof circuits or any

For example, consider the zkay code in Listing 5. Its transformed version and generated proof circuit are shown in Listing 6. Using the implication guard \( \implies (\text{enc}(3) == \text{out}[0]) \) for the assertion ensures that the condition \( \text{enc}(3) == \text{out}[0] \) is only checked in the proof circuit if the guard condition \( p == 2 \) is true.

### 4.3.2 Private Conditions

If-statements with private conditions are supported, however with some restrictions making sure that the visible trace of a transaction does not leak any information about the value of the condition. In particular, no branch is allowed to contain operations unsupported in proof circuits or any side-effects apart from assignments to primitive type variables which are private to the caller.
Zkay first collects the set $X$ of all variables which are assigned in at least one branch. Then, it replaces the if-condition by an assignment to all variables in $X$. The correctness of the right-hand side is verified in the proof circuit, which (i) evaluates both branches of the if-statement, and (ii) uses conditional assignment expressions to select the appropriate values for the variables in $X$ according to the value of the condition. In particular, all variables in $X$ get assigned new re-encrypted values, even if the underlying plaintext values were not modified in the branch taken.

4.4 Short-circuit Evaluation

Certain operators such as `||` and `&&` are subject to short-circuit evaluation in Solidity (i.e., not all operands are necessarily evaluated). Zkay v0.2 correctly handles this using appropriate guard conditions in the proof circuits.

For example, consider the zkay code in Listing 7, where the function call `priv()` is skipped if `b` is true due to short-circuit evaluation. When creating the proof circuit for `test`, zkay adds a guard condition to the encryption assertion in `priv` to make sure it is only checked if `b` is false.

```solidity
function priv() returns(bool) {
    uint@me v = 2; // encryption assertion is only checked in the proof circuit if !b
    return true;
}

function test(bool b) {
    bool val = b || priv();
}
```

Listing 7. Guard condition necessary due to short-circuit evaluation.

4.5 Public Loops

Zkay v0.2 supports `while`, `do ... while` and `for` loops whose condition, update statement and body do not contain any private expressions or calls to functions requiring verification (see Section 4.1).

4.6 Tuples

Zkay v0.2 supports Solidity tuples. This can e.g. be used to pack multiple return values or swap variables. Nesting and mixing values with different privacy types is supported. As a tuple is only a syntactic group, it does not have a privacy type itself.

4.7 Integer Variants

Zkay v0.2 provides advanced support for integer variants, including fixed-sized (see Section 4.7.1) and signed (see Section 4.7.2) integers.

The zk-SNARKs frameworks underlying the circuit compilation backends require all proof circuit operations to be expressed using finite arithmetic in a prime field. Prime field numbers are inherently unsigned and restricted in size by the field prime. For instance, the field prime involved in the elliptic Barreto-Naehrig curve “alt_bn128” used in libsnark \(^3\) is roughly 253.5 bits in size.

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\(^3\)https://github.com/scipr-lab/libff/tree/master/libff/algebra/curves/alt_bn128 (accessed 2020-08-25).
making it impossible to accurately represent 256-bit operations. Directly translating Solidity uint
operations to operations in the prime field (as done in zkay v0.1) is hence incorrect.

Zkay v0.2 correctly emulates the semantics of different integer variants (e.g., signed arithmetic, under- and overflow behavior) in the used prime field whenever possible. Otherwise, compiler errors or warnings are raised.

4.7.1 Integer Sizes
Like Solidity, zkay v0.2 supports different integer sizes (i.e., uint8, uint16, ..., uint248, uint256).

Up to 248 bits. For sizes up to 248 bits, the jsnark circuit compilation backend emulates correct overflow behavior using the low-level finite field operation primitives provided by jsnark.

- **Addition**: Emulated by restricting the field addition output (which can have at most 249 bits and hence does not overflow at the field prime) to the desired bit width.
- **Negation**: Emulated by constructing the “two’s complement”, see Section 4.7.2.
- **Subtraction**: Emulated by adding the negated value.
- **Multiplication**: The result of multiplying two n-bit integers can have up to $2n$ bits, which means that a field prime overflow can already occur when multiplying integers with as little as $n \geq 128$ bits. For this reason, multiplication of $(n \geq 128)$-integers is emulated using multiple $\frac{n}{2}$-bit multiplications, whose results do not overflow.

256 bits. Zkay v0.2 uses a single prime field element to represent 256-bit integers, even though this leads to a semantic mismatch between prime field and Solidity operations. In particular:

(i) all private arithmetic operations overflow at the field prime, and
(ii) private comparison operations fail for values $\geq 2^{252}$.

Because private 256-bit operations are safe as long as they only involve values below $2^{252}$, zkay v0.2 does not generally forbid such operations. Instead, it raises an according compiler warning to make developers aware of potential issues.

4.7.2 Signed Integers
Zkay v0.2 uses the “two’s complement” representation for signed integers and correctly emulates signed integer arithmetic for at most 248 bits. Private 256-bit signed integers are not supported.

4.8 Address and Enum Types
Zkay v0.2 supports address and address payable variables, both of which can be private. Cryptocurrency-related members such as balance (see Section 4.2) are only accessible on public addresses.

Further, zkay v0.2 supports declaring and using custom enum types. These are fully supported inside private expressions.

4.9 Type Casts
Like Solidity, zkay v0.2 allows explicit type conversions between many primitive types. Also, zkay v0.2 reflects the implicit type conversions of Solidity (e.g., conversions from smaller to larger integer
sizes). Type casts are valid operations inside private expressions. The privacy type of a type cast expression is inherited from its source expression.

4.10 More Operators

Assignment Operators. Zkay v0.2 introduces assignment operators such as += and *=. These are syntactic sugar and can only appear as statements (i.e., they are not expressions). One notable exception are loop update expressions, where assignment operators can be used for convenience.

Pre- and Post-increments. Zkay v0.2 supports ++ and -- as prefix or postfix operators. Similarly as assignment operators, pre- and post-increments are statements and cannot be used as expressions, except for loop update expressions.

Bitwise Operators. The bitwise operators & , | , ~ and ^ are supported by zkay v0.2, except for private 256-bit integers.

Shifts. The shift operators << and >> are supported by zkay v0.2, except for private 256-bit integers. For public operands, there are no further restrictions. When shifting private values, the shift amount must be a public constant.

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4Because of Solidity’s unspecified expression evaluation order, treating assignment operators as expressions would lead to unspecified behavior and side-effects.
5 SECURITY FEATURES

In this section, we present the security features of zkay v0.2. In particular, we show how zkay employs asymmetric (Section 5.1) and hybrid (Section 5.2) encryption to protect private data, and how private variables are initialized in this context (Section 5.3). Further, we describe how zkay checks the integrity of deployed contracts (Section 5.4).

5.1 Asymmetric Encryption

Zkay v0.2 supports asymmetric encryption, where data is encrypted under the owner’s public key.

5.1.1 Public Key Infrastructure

Each user account $a$ creates an asymmetric key pair $(sk_a, pk_a)$, whose public part $pk_a$ is published to a dedicated zkay public key infrastructure (PKI) contract. Whenever a compiled zkay contract requires the public key of an address, it requests the key from the PKI contract.

5.1.2 Verifying Encryption

Often, a compiled zkay contract needs to verify that some plaintext $m$ was correctly encrypted for some target address $a$. More specifically, for a given ciphertext $c$, the contract must ensure that $c$ was obtained by encrypting the plaintext $m$ with $a$’s public key $pk_a$ and some secret randomness $r$.

Fig. 6 exemplifies how zkay v0.2 verifies correctness of encryption for an asymmetric encryption backend. The code in Listing 8 is compiled to the Solidity code in Listing 9, which verifies that $c$ is the result of encrypting $m$ under the public key of $other$ and some secret randomness $rnd$. This is captured in the proof circuit shown in Listing 11, which takes public circuit inputs $m$ and $pk$, the private circuit input $rnd$, and returns the (public) output $c$. 

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Listing 8. Example zkay code.
```plaintext
function f(uint val) {
    uint other x = val;
}
```

Listing 9. Transformed Solidity code.
```plaintext
function f(uint val, Cipher c, proof) {
    uint m = val;
    Key pk = PKI.get(other);
    Cipher x = c; // $c == enc(val)$
    verify([m, pk], [c], proof);
}
```

Listing 10. Python contract interface.
```plaintext
def f(val):
    m = val
    pk = request_key(other)
    c, rnd = enc(m, pk)
    x = c
    proof = prove_f([rnd], [m, pk, [c]])
    transact('f', [val, c, proof])
```

Listing 11. Proof circuit (pseudocode).
```plaintext
priv_in: rnd
pub_in: m, pk
pub_out: c
proof:
    - assert $c == enc(m, pk, rnd)$
```
5.1.3 Verifying Decryption

Whenever a private variable \( c \) is used in a private expression \( e \), the value of \( c \) must be decrypted to its plaintext value \( m \) by the contract interface to allow local computation of the (plaintext) value of \( e \). The correctness of this decryption operation is checked in the proof circuit.

For many asymmetric encryption schemes, decryption is more expensive than encryption. Hence, zkay v0.2 checks correctness using the inverse encryption operation in the proof circuit. More specifically, it checks whether the value of \( c \) can be obtained by encrypting the plaintext \( m \) with the owner’s public key and some secret randomness. This is exemplified in Fig. 7.

5.1.4 Available Backends

Zkay v0.2 supports two asymmetric crypto backends described below, both of which are based on RSA [30]. The backends rely on PyCryptodome’s [29] RSA implementation for the contract interfaces, and jsnark’s RSA gadgets for the proof circuits.

**RSA PKCS1.5.** This backend uses RSA encryption with PKCS#1 v1.5 padding (see [26], section 7.2). In comparison to OAEP padding (see below), PKCS1.5 padding offers better off-chain performance (see Section 6.2).

**RSA OAEP.** This backend uses RSA encryption with PKCS#1 v2.0 OAEP padding (see [26], section 7.1).
5.1.5 Limitations

RSA crypto backends come with some efficiency drawbacks (see Section 6.2 for an experimental evaluation). In particular:

▷ RSA requires large key and cipher text sizes. In particular, these items have at least 2048 bits, which amounts to 9 proof circuit inputs. As the cost for NIZK proof verification is linear in the number of public proof circuit inputs, this leads to high gas costs.

▷ RSA encryption, particularly with OAEP, is a very expensive operation in the proof circuit. This leads to high memory consumption and long execution times for proof generation.

For these reasons, zkay v0.2 also offers hybrid encryption as described in the next section.

5.2 Hybrid Encryption

Zkay v0.2 supports hybrid encryption, where an elliptic curve (EC) key exchange is used in combination with a symmetric block cipher. At a high level, hybrid encryption in zkay v0.2 works as follows.

▷ Each account $a$ creates an asymmetric EC key pair $(sk_a, pk_a)$, whose public part $pk_a$ is published in the PKI.

▷ Whenever an account $a$ wants to encrypt data for a target account $b$, it uses elliptic curve Diffie-Hellman (ECDH) [4, 22, 25] to obtain a shared secret from $sk_a$ and $pk_b$. From this shared secret, a shared symmetric key $k_{a,b} = k_{b,a}$ is derived.

▷ Account $a$ then uses a symmetric block cipher to encrypt the plaintext using key $k_{a,b}$ and obtain the ciphertext $c$, which includes an initialization vector (IV). The ciphertext is extended by the public key of $a$ to obtain the tuple $(c, pk_a)$, which is stored on the blockchain.

▷ When decrypting a ciphertext tuple $(c, pk_a)$, account $b$ uses ECDH to obtain $k_{a,b}$ from $sk_b$ and the public key $pk_a$ in the tuple. Then, $b$ can decrypt $c$ using $k_{a,b}$.

5.2.1 Public Key Infrastructure

The PKI for hybrid encryption works analogously as for asymmetric encryption (see Section 5.1.1). EC keys are much smaller than RSA keys for equivalent levels of security. In particular, for the elliptic curve supported by jsnark, a strong EC key equivalent to a 2048-bit RSA key fits within a single proof circuit input.

5.2.2 Verifying Encryption

When verifying that a ciphertext tuple $(c, pk_a)$ is the result of encrypting a plaintext $m$ for a target address $b$, the compiled zkay contract must ensure that (i) $c$ was obtained by encrypting $m$ with the key $k_{a,b}$ derived from $pk_b$ and some secret key $sk_a$, and (ii) $pk_a$ and $sk_a$ form an EC key pair.

Fig. 8 exemplifies how zkay v0.2 verifies correctness of encryption for a hybrid encryption backend. The Solidity code in Listing 17 verifies that $c$ is the result of encrypting $val$ for the account other. In particular, it sets the public key for $c$ to the public key of the sender, \[5 \text{loads the public key of other, and calls the verifier. The proof circuit shown in Listing 19 takes as public arguments the public key pk_me of the sender, the plaintext m, and the public key pk of other. As a private argument, it takes the secret key sk_me of the sender. The circuit (i) asserts that pk_me} \]

\[5 \text{Technically, the implementation uses a uint[3] array to combine the IV, actual cipher text c and public key pk_a of the originator a instead of a ciphertext tuple (c, pk_a).} \]
function f(uint val) {
    uint@other x = val;
}

Listing 16. Example zkay code.

def f(val):
    pk_me = request_key(msg.sender)
    sk_me = get_sk(msg.sender)

    m = val
    pk = request_key(other)
    iv_c = enc(m, ecdh(pk, sk_me))
    x = iv_c

    proof = prove_f(
        [sk_me], [pk_me, m, pk], [iv_c]
    )
    transact('f', [val, iv_c, proof])

Listing 18. Python contract interface.

function f(uint val, IvCipher c, proof) {
    Key pk_me = PKI.get(msg.sender);

    c.src = pk_me;
    uint m = val;
    Key pk = PKI.get(other);
    IvCipher x = c; // c == enc(val)

    verify([pk_me, m, pk], [c], proof);
}

Listing 17. Transformed Solidity code.

priv_in: sk_me
pub_in: pk_me, m, pk
pub_out: iv_c
proof:
    - # once per circuit
      - assert pk_me == G · sk_me
    - # once per pk per circuit
      - k = ECDH(sk_me, pk)
    - # for each encryption
      - iv = iv_c[:128] # first 128 bits
      - assert iv_c == [iv, enc(m, k, iv)]

Listing 19. Proof circuit (pseudocode).

and sk_me form an EC key pair, (ii) constructs the symmetric key k shared between the sender and other using ECDH, and (iii) asserts c has been encrypted correctly.

5.2.3 Verifying Decryption

Like for asymmetric encryption (see Section 5.1.3), zkay proves correct decryption using an encryption operation in the proof circuit. Verifying decryption works similarly as for encryption (see Fig. 8), however the shared encryption key is derived from the originator’s public key stored as part of the ciphertext.

5.2.4 Available Backends

Zkay v0.2 supports two hybrid crypto backends described below. The shared key is derived from the ECDH shared secret by taking the 128 leftmost bits of its SHA-256 digest [15]. As an optimization, shared keys are only computed once per proof circuit.

**ECDH AES.** This backend combines SHA-256-ECDH key derivation with AES-128 [14] encryption in CBC mode [6]. The implementation relies on PyCryptodome’s AES-CBC implementation and jsnark’s CBC, AES and ECDH gadgets.
ECDH Chaskey. This backend is a more lightweight alternative to ECDH AES. It uses the Chaskey LTS block cipher [27], which is natively supported by jsnark and allows for more efficient proof circuits than AES. The implementation relies on jsnark’s CBC, Chaskey and ECDH gadgets. The contract interface combines BouncyCastle’s [28] CBC mode with a custom Chaskey LTS block cipher implementation.

5.3 Default Initialization for Private Variables

In Solidity, variables are implicitly initialized with zero-equivalent values (e.g., reading an uninitial-  ized integer variable is guaranteed to return zero). While this is a useful feature often leveraged by Solidity contracts, it is an issue for compiled zkay contracts, where private variables would have to be implicitly initialized with the encryption of zero. For this reason, zkay v0.1 restricts support for default initialization and has undefined behavior when reading uninitialized private variables.

Zkay v0.2 adds support for zero-initialized private variables. The general idea is to rely on Solidity’s initialization but treat private variables with values zero as if they were encrypted. More specifically, proof circuit assertions of the form cipher = enc(plain, k) are actually implemented as (cipher = 0 ⇒ plain = 0) \land (cipher ≠ 0 ⇒ cipher = enc(plain, k)). Also, decrypting the ciphertext 0 in the contract interface is configured to return the plaintext 0. Finally, an additional constraint asserting that user-provided ciphertexts are never 0 is included in proof circuits. In the extremely unlikely event that encrypting a plaintext in the contract interface leads to the ciphertext 0, the plaintext is re-encrypted using fresh randomness.

5.4 Checking Contract Integrity

In order to interact with a compiled zkay contract deployed on the blockchain, a user needs access to the following items: (i) the original zkay contract, (ii) the NIZK prover and verifier keys, and (iii) the manifest file specifying the originally used compiler version and options. These items provide enough information to locally reconstruct the contract interface. Zkay v0.2 comes with utilities to bundle these items in an archive that can be distributed to and imported by users via an out-of-band channel.

Integrity of Remote Contracts. When using a deployed contract, users need to verify that it corresponds to the local archive they have obtained via an out-of-band channel. This is, the remote EVM bytecode must be verified to match the result of compiling (i) using (ii–iii).

Zkay v0.2 automatically performs this verification whenever the Python contract interface is attached to a remote contract C by the connect command (see Section 3.2.3). In particular, it performs the following steps.

(i) Zkay compiles the local zkay contract using the compiler settings in the manifest file and a special mode that uses the existing prover and verifier keys instead of re-generating them. The compiler outputs the transformed Solidity contract C_{local}, all verification contracts, the PKI contract, and any required library contracts.

(ii) The addresses of the remote PKI, library and verification contracts as used by the remote contract are retrieved from bytecode.

(iii) The PKI and verifier address placeholders in C_{local} are replaced with the concrete addresses of the corresponding remote contracts obtained in the previous step. Similarly, the remote library addresses are linked to the local verification contracts.
(iv) $C_{\text{local}}$ and all locally generated verification contracts, PKI contract, and library contracts are compiled with solc using the compiler settings in the manifest file.

(v) The bytecode of $C$, the remote PKI, library and verification contracts is compared to the compilation results from the previous step. If the bytecode is not equal, zkay raises an error and aborts the connection.

Trusted Setup Phase. Like in any NIKZ-proof framework based on zk-SNARKs, prover and verifier key generation in zkay v0.2 relies on a trusted setup phase. The entity running key generation must destroy a secret string generated during this phase, commonly referred to as “toxic waste”. If this string is retained by a malicious user, the user can construct arbitrary fake proofs accepted by the verifier and hence break zkay’s correctness guarantees (however, not it’s privacy guarantees) [20]. The user creating and distributing a zkay contract archive must therefore be trusted to execute the setup phase correctly and destroy the toxic waste.

In practice, trusted setup phases are often implemented using complex ceremonies based on secure multi-party computation in order to weaken trust assumptions [7]. While zkay users can manually establish such ceremonies, zkay v0.2 does not come with built-in support for establishing suchlike.
6 PERFORMANCE

Next, we present the various optimizations employed in zkay v0.2 to reduce compilation time, off-chain runtime and memory requirements, and on-chain gas costs (Section 6.1). Further, we compare the performance of zkay v0.2 to zkay v0.1 using a set of benchmarks (Section 6.2).

6.1 Optimizations

This section presents important optimizations employed by zkay v0.2.

6.1.1 Optimized Input Hashing

The size of the verification key and the gas cost of NIZK proof verification are linear in the number of public circuit inputs and outputs. The number of public circuit inputs can be reduced by (i) making public circuit inputs in₁, . . . , inₙ private, and (ii) providing a hash h over these inputs as a single public circuit input, which is computed on-chain and verified in the proof circuit. This leads to low verification costs that are almost constant in the number of circuit inputs, except for a small linearly-increasing cost for computing h on-chain. ⁶

In zkay v0.1, h was computed as h = sha256(sha256(sha256( . . . , inₙ₋₂), inₙ₋₁), inₙ), which results in 2n SHA-256 compressions for n public 256-bit circuit inputs. ⁷ Zkay v0.2 improves this by using a single SHA-256 hash over the concatenated inputs: h = sha256(in₁, in₂, . . .). This construction only requires ⌊n² / 2⌋ + 1 SHA-256 compressions for n public 256-bit circuit inputs. Further, zkay v0.2 provides a configurable threshold on the number n of public circuit inputs above which this construction should be applied.

6.1.2 Constant Folding

Like in Solidity, zkay v0.2 uses dedicated number literal types for constants and applies constant folding. In particular, the value of a public constant sub-expression within a private expression is computed at compile time and integrated into the proof circuit.

6.1.3 Circuit Input Caching

In zkay v0.1, multiple accesses of the same variable within a proof circuit led to multiple redundant circuit inputs. Zkay v0.2 performs caching of circuit inputs and re-uses these inputs for all accesses of the same variable provided it is not modified. If a variable is modified in the zkay contract, the cache is evicted and the variable is re-imported into the proof circuit.

6.1.4 Public Key Caching

Zkay v0.1 requests the required public key from the PKI and imports it using a new circuit input every time it constructs an encryption or decryption constraint in the proof circuit. If the same public key is required multiple times, this leads to redundant circuit inputs and PKI lookups.

⁶We note that this comes at the cost of increased proof generation runtime and memory consumption.
⁷Each call of sha256 needs to hash a 512 bit payload (input and previous digest) plus another 512-bits due to Merkle-Damgård length padding.
### Table 1. Contract compilation time [s].

| Contract | “dummy encryption” | zkay v0.2 | zkay v0.1 | zkay v0.2 |
|----------|---------------------|-----------|-----------|-----------|
|          |                     | ecdh-chaskey | ecdh-aes | rsa-pkcs1.5 | rsa-oaep |
| exam     | 291.91              | 61.77      | 88.42     | 318.17     | 488.14   |
| income   | 124.27              | 41.23      | 55.50     | 162.82     | 245.37   |
| insurance | 416.16              | 104.74     | 140.07    | 467.49     | 710.10   |
| lottery  | 83.66               | 34.28      | 45.80     | 96.33      | 153.99   |
| med-stats | 235.46              | 51.68      | 70.88     | 236.99     | 356.09   |
| power-grid | 123.05              | 44.75      | 59.49     | 192.59     | 288.25   |
| receipts | 183.11              | 63.54      | 83.30     | 263.37     | 405.42   |
| reviews  | 305.95              | 78.35      | 107.02    | 357.54     | 545.39   |
| sum-ring | 123.17              | 45.69      | 60.15     | 179.96     | 274.94   |
| token    | 295.18              | 72.82      | 98.67     | 331.52     | 508.55   |
| Mean     | 218.19              | 59.88      | 80.93     | 260.68     | 397.62   |
| Speedup  | -                   | 3.64       | 2.70      | 0.84       | 0.55     |

In zkay v0.2, public keys are cached and only imported once whenever possible. In particular, as the owner of a private variable remains constant during an entire transaction, zkay v0.2 imports all public keys required for a transaction once, in the external top-level function.  

#### 6.1.5 Prover and Verifier Key Caching

Zkay v0.2 caches generated prover and verifier keys to re-use them during compilation if the corresponding proof circuit did not change since the previous compilation. As key generation amounts for a large part of the compilation time, this often leads to significantly lower compilation times and higher development productivity.

#### 6.1.6 Parallelization

Zkay v0.2 compiles different proof circuits in parallel to speed up compilation. Also, it leverages the multi-threading support of libsnark for key and proof generation.

### 6.2 Benchmarks

In this section, we compare the performance of zkay v0.2 to its predecessor zkay v0.1. In particular, we compare compilation time, memory and output size (Section 6.2.1); on-chain gas costs (Section 6.2.2); and off-chain transaction runtime and memory (Section 6.2.3). In Section 6.2.4, we compare the performance for different proving schemes.

For our comparison in Sections 6.2.1 to 6.2.3, we use the GM17 [17] proving scheme available in both implementations. We evaluate zkay v0.2 on all its crypto backends (see Section 5). This includes “dummy encryption”, which enables a direct comparison to zkay v0.1. We evaluate both implementations on the 10 example contracts analyzed in zkay’s original publication [31, Tab. 1].

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For tagged mapping entries (e.g. `mapping (address!x => uint@x)`), this optimization is not applied as the owner depends on the mapping index, which may change dynamically at runtime.
Table 2. Peak memory usage during compilation [MB].

| Contract     | “dummy encryption” | zkay v0.1 | zkay v0.2 | ecdh-chaskey | ecdh-aes | rsa-pkcs1.5 | rsa-oaep |
|--------------|--------------------|-----------|-----------|--------------|----------|-------------|----------|
| exam         | 3299.56            | 774.21    | 2782.38   | 6865.15      | 19700.89 | 19219.52    |
| income       | 1639.13            | 592.68    | 1564.26   | 7070.88      | 8737.90  | 11608.73    |
| insurance    | 3131.96            | 1166.66   | 2713.01   | 11092.28     | 24591.12 | 23332.04    |
| lottery      | 586.27             | 672.40    | 1116.64   | 8201.20      | 4427.00  | 5501.43     |
| med-stats    | 3234.79            | 580.10    | 1899.68   | 6233.57      | 11719.60 | 14476.78    |
| power-grid   | 1505.89            | 768.29    | 1574.00   | 7275.74      | 8329.46  | 11176.63    |
| receipts     | 1411.74            | 739.35    | 1519.86   | 9460.97      | 9652.18  | 16056.25    |
| reviews      | 3820.18            | 874.72    | 3100.03   | 5668.42      | 18955.75 | 22539.82    |
| sum-ring     | 1473.79            | 511.28    | 1831.28   | 6844.18      | 8752.44  | 11597.67    |
| token        | 3230.38            | 946.04    | 2342.00   | 10268.23     | 12664.50 | 17110.29    |
| Mean         | 2333.37            | 762.57    | 2044.31   | 7898.06      | 12753.08 | 15261.92    |
| Reduction Factor | -        | 3.06      | 1.14      | 0.30         | 0.18     | 0.15        |

All experiments are conducted on a system with the following specifications.

- **CPU**: Intel i7-8700K 6x4.7GHz (+SMT)
- **RAM**: 32 GB DDR4-3200
- **OS**: MX Linux 19.1 x64, Kernel 4.19
- **Compiler**: GCC 8.3.0, OpenJDK 11.0.7, Python 3.7.3

### 6.2.1 Compilation Performance

We now analyze zkay’s compilation time and memory requirements, as well as the compilation output size.

**Compilation Time.** Table 1 compares the compilation time of zkay v0.1 and zkay v0.2 with different crypto backends for the 10 evaluated contracts. The majority of compilation time is due to circuit compilation and key generation in the proving scheme backends. As a result, the compilation times for different crypto backends (which induce different proof circuit complexities) vary significantly.

Zkay v0.2 reduces the compilation time for “dummy encryption” by a factor of around 11.6. Even though RSA backends induce much more complex proof circuits, compilation times for these backends in zkay v0.2 are similar than for “dummy encryption” in zkay v0.1. This is due to the strong optimizations performed in zkay v0.2. ECDH based hybrid backends are more efficient and even allow for faster compilation than zkay v0.1 with “dummy encryption”.

**Compilation RAM Usage.** Table 2 compares the peak RAM usage during compilation of the 10 evaluated contracts in zkay v0.1 and zkay v0.2 with different crypto backends. For the insurance contract, the RSA PKCS1.5 backend required almost 25 GB (resp. 10 GB) of RAM during circuit compilation (resp. key generation), which makes compilation on low-end machines impossible. In contrast, hybrid crypto backends are much more memory efficient.
Table 3. Compiled contract storage requirement [MB].

| Contract  | "dummy encryption" | zkay v0.1 | zkay v0.2 | ecdh-chaskey | ecdh-aes | rsa-pkcs1.5 | rsa-oaep |
|-----------|---------------------|-----------|-----------|--------------|----------|-------------|----------|
| exam      | 1447                | 286       | 1299      | 1754         | 7245     | 10940       |
| income    | 581                 | 213       | 795       | 1004         | 3594     | 5276        |
| insurance | 2027                | 553       | 2138      | 2753         | 10604    | 15755       |
| lottery   | 368                 | 137       | 639       | 776          | 2146     | 3266        |
| med-stats | 1157                | 252       | 1057      | 1370         | 5246     | 7790        |
| power-grid| 581                 | 213       | 881       | 1118         | 4231     | 6177        |
| receipts  | 870                 | 299       | 1271      | 1605         | 5959     | 8789        |
| reviews   | 1519                | 369       | 1649      | 2117         | 8198     | 12204       |
| sum-ring  | 581                 | 186       | 928       | 1160         | 3964     | 5912        |
| token     | 1443                | 357       | 1482      | 1923         | 7526     | 11172       |

Mean          | 1057.40          | 286.50    | 1213.90   | 1558.00      | 5871.30  | 8728.10     |
Reduction Factor | -               | 3.69      | 0.87      | 0.68         | 0.18     | 0.12        |

Output Size. Table 3 compares the storage of the compilation output. This is dominated by the prover keys, whose size depends on the complexity of the proof circuit. With RSA backends, prover keys become very large (several GB per circuit), which makes contract distribution expensive. The compilation output of hybrid backends is much smaller, but still in the order of 1 GB.

Summary. In Fig. 9, we visualize the relative differences in compilation time, memory usage, and output size for the different backends in zkay v0.2. All values are normalized with respect to zkay v0.1 (which uses "dummy encryption"). In general, hybrid crypto backends are more efficient than RSA backends for all considered metrics.

6.2.2 On-chain Gas Costs

We now analyze the on-chain costs of zkay transactions for a set of scenarios, which comprise multiple transactions executed on the same contract (see [31] for details). Table 4 compares the average transaction gas costs for the scenarios using zkay v0.1 and zkay v0.2 with different crypto backends. The numbers exclude the (one-time) costs for deployments and public key announcements in the PKI contract. In Fig. 10, we show the mean transaction gas cost per crypto backend.

The "dummy encryption" backend in zkay v0.2 is around 11.7% more gas-efficient than zkay v0.1. Also, the hybrid crypto backends result in lower transaction costs. Only RSA backends lead to increased costs, likely due to the significantly larger ciphertext and key sizes.

6.2.3 Off-chain Transaction Performance

We now analyze zkay’s off-chain performance when creating and issuing transactions. More precisely, we analyze the runtime and peak memory usage of issuing transactions using the contract interface of zkay v0.2 (resp. the transaction transformation of zkay v0.1). Both runtime and memory are dominated by NIZK proof generation.

Runtime. Table 5 compares the total runtime for creating and issuing all transactions in the given scenarios using zkay v0.1 and zkay v0.2 with different crypto primitives. The numbers
Fig. 9. Mean compilation time, memory usage and output size for different backends in zkay v0.2, normalized w.r.t. zkay v0.1.

Table 4. Average transaction gas cost (w/o deployment transactions) [gas].

| Scenario    | “dummy encryption” | zkay v0.2 |              |              |              |              |
|-------------|---------------------|-----------|--------------|--------------|--------------|--------------|
|             | zkay v0.1 | zkay v0.2          | ecdh-chaskey | ecdh-aes     | rsa-pkcs1.5  | rsa-oaep     |
| exam        | 975867   | 867507           | 942841       | 942916       | 1368591      | 1368527      |
| income      | 958761   | 844096           | 862339       | 862323       | 938187       | 938043       |
| insurance   | 863896   | 759457           | 805235       | 805219       | 961517       | 961525       |
| lottery     | 961293   | 870737           | 915360       | 915440       | 1313058      | 1313090      |
| med-stats   | 963358   | 841806           | 874977       | 874897       | 996628       | 996612       |
| power-grid  | 955134   | 842065           | 875727       | 875684       | 998738       | 998674       |
| receipts    | 956674   | 843245           | 878341       | 878266       | 1002490      | 1002565      |
| reviews     | 968579   | 852586           | 901632       | 901632       | 1071598      | 1071521      |
| sum-ring    | 958754   | 846932           | 877017       | 876985       | 983056       | 982944       |
| token       | 971990   | 855217           | 890301       | 890301       | 1025587      | 1025459      |
| Mean        | 953430.56 | 842364.74        | 882376.90    | 882366.24    | 1065945.00   | 1065895.99   |
| Reduction Factor | -         | 1.13             | 1.08         | 1.08         | 0.89         | 0.89         |

The results include deployment transactions, NIZK proof generation, and transaction execution on a local test blockchain (ganache-cli for zkay v0.1, eth-tester with py-evm backend for zkay v0.2). Zkay v0.2 is faster than zkay v0.1 for “dummy encryption” as well as for hybrid crypto backends.
Fig. 10. Mean transaction gas cost (w/o deployment transactions) for different crypto backends.

Table 5. Total off-chain runtime for executing all scenario transactions [s].

| Scenario    | "dummy encryption" | zkay v0.1 | zkay v0.2 | ecdh-chaskey | ecdh-aes | rsa-pkcs1.5 | rsa-oaep |
|-------------|---------------------|-----------|-----------|--------------|----------|-------------|----------|
| exam        | 243.47              | 28.48     | 102.13    | 158.64       | 512.09   | 708.31      |
| income      | 115.14              | 18.44     | 52.44     | 81.69        | 208.82   | 278.49      |
| insurance   | 229.06              | 41.19     | 115.08    | 173.61       | 484.45   | 661.19      |
| lottery     | 83.04               | 19.11     | 44.60     | 73.59        | 123.06   | 165.33      |
| med-stats   | 198.24              | 26.59     | 83.14     | 126.40       | 360.82   | 491.32      |
| power-grid  | 89.11               | 14.48     | 40.67     | 62.02        | 155.76   | 206.74      |
| receipts    | 167.25              | 34.18     | 104.30    | 155.31       | 410.89   | 558.92      |
| reviews     | 188.67              | 36.17     | 112.62    | 159.67       | 473.02   | 654.75      |
| sum-ring    | 140.72              | 24.83     | 81.75     | 119.67       | 326.09   | 430.86      |
| token       | 154.25              | 24.77     | 70.39     | 109.05       | 298.09   | 410.35      |
| Mean        | 160.89              | 26.82     | 80.71     | 121.97       | 335.31   | 456.63      |
| Speedup     | -                   | 6.00      | 1.99      | 1.32         | 0.48     | 0.35        |

RAM Usage. Table 6 compares the peak memory usage during scenario execution. Like for compilation, RSA backends are very memory-intensive. However, the memory requirements for hybrid crypto backends are moderate.

Summary. In Fig. 11, we visualize the relative differences in the scenario runtime and memory usage for the different backends in zkay v0.2. All values are normalized with respect to zkay v0.1 (which uses "dummy encryption"). In general, hybrid crypto backends are more efficient than RSA backends in terms of both scenario runtime and memory usage.
### Table 6. Peak memory usage during scenario execution [MB].

| Scenario   | “dummy encryption” zkay v0.1 | zkay v0.2 ecdh-chaskey | zkay v0.2 ecdh-aes | zkay v0.2 rsa-pkcs1.5 | zkay v0.2 rsa-oaep |
|------------|-----------------------------|------------------------|-------------------|----------------------|-------------------|
| exam       | 1584.79                     | 2341.76                | 3204.56           | 11348.01             | 17132.19          |
| income     | 1562.11                     | 1205.80                | 3072.60           | 9444.64              | 9543.21           |
| insurance  | 1548.90                     | 2152.11                | 3133.64           | 9789.28              | 12879.11          |
| lottery    | 1222.43                     | 759.79                 | 2608.45           | 2342.67              | 2703.75           |
| med-stats  | 1215.16                     | 1633.88                | 2874.27           | 10100.89             | 11413.27          |
| power-grid | 1861.60                     | 1203.95                | 3105.70           | 9278.91              | 9502.40           |
| receipts   | 1217.36                     | 1261.17                | 2954.74           | 9266.15              | 9434.11           |
| reviews    | 1218.19                     | 2749.75                | 3296.79           | 12893.10             | 18672.79          |
| sum-ring   | 1199.20                     | 1488.59                | 3235.51           | 9609.82              | 9470.62           |
| token      | 1481.12                     | 2024.75                | 3245.45           | 9985.55              | 13182.52          |
| Mean       | 1411.09                     | 1682.15                | 3073.17           | 9405.90              | 11393.40          |
| Reduction Factor | - 3.51 | 0.84 0.46 0.15 0.12 |

![Fig. 11. Mean scenario runtime and peak memory usage for different backends in zkay v0.2, normalized w.r.t. zkay v0.1.](image)

6.2.4 **Comparison of Proving Schemes**

So far, we have analyzed zkay v0.2 with the GM17 [17] proving scheme, which is also available in zkay v0.1. We now demonstrate how using the Groth16 [16] proving scheme improves zkay’s performance.
Table 7. Comparison of zkay v0.2 proving schemes for the ECDH AES crypto backend.

| Metric (mean across all scenarios)          | GM17     | Groth16   |
|--------------------------------------------|----------|-----------|
| Compilation Time [s]                       | 80.93    | 56.59     |
| Compilation Peak Memory [MB]               | 7898.06  | 7025.70   |
| Output Size [MB]                           | 1558.00  | 1081.2    |
| Scenario Time [s]                          | 121.97   | 100.48    |
| Scenario Peak Memory [MB]                  | 3073.17  | 3021.79   |
| Avg. Transaction Cost [gas]                | 882366.24| 626593.67 |

In Table 7, we compare the average performance, memory usage and gas costs over all scenarios for the two proving schemes using the ECDH AES crypto backend. Groth16 is more efficient overall: While there is no significant effect on memory usage, Groth16 decreases average compilation time and output size by roughly 30%, gas costs by 25%, and scenario runtime by 20% compared to GM17. In zkay v0.2, Groth16 is the default proving scheme.
7 USABILITY IMPROVEMENTS

7.1 Installation

Zkay v0.2 can be packaged and installed using setuptools. Package installation automatically compiles the required libsnark interface binary from source and makes the zkay command globally available.

7.2 Error Messages

In contrast to zkay v0.1, zkay v0.2 displays human-readable and descriptive error messages. For example, the command-line interface provides precise source code locations for type errors.

7.3 Contract Distribution

Zkay v0.2 simplifies contract distribution by providing built-in support for bundling and exporting/importing zkay contracts along with all relevant information such as prover keys (see Section 5.4 for details).

For example, Alice can deploy and share a contract `contract.zkay` with Bob as follows.

(i) Alice compiles and deploys `contract.zkay` using her local zkay compiler.

(ii) Next, she bundles the locally compiled contract to an archive `contract.zkp` using zkay’s `export` command.

(iii) Alice then sends the archive `contract.zkp` to Bob using an off-chain channel and informs him about the address of the deployed contract.

(iv) Bob can now import `contract.zkp` on his local computer using zkay’s `import` command. He can then connect to and interact with Alice’s deployed contract.

7.4 Configuration Files

Zkay v0.2 allows rich customization and comes with support for configuration files.

The default settings are configured in `config_user.py`, any of which can be overridden via a hierarchy of configuration files. The user may create the following configuration files: (i) a system-wide configuration file in `$SITE_CONFIG_DIR/zkay/config.json`, (ii) a user-wide configuration file in `$USER_CONFIG_DIR/zkay/config.json`, and (iii) a local configuration file in the working directory or in a location provided using a command line flag.

It is further possible to override any setting via a command-line parameter of the same name, which takes precedence over all configuration files.

7.5 Command-line Interface

The command-line interface of zkay v0.2 is based on sub-commands, which are described below. All commands support context-aware bash-autocompletion powered by argcomplete [21]. Programmatic access to all features is available through the `zkay_frontend` module.

- zkay check: Run the type checker on the given zkay file.

Zkay v0.2 uses the appdirs library [1] to determine the location of `SITE_CONFIG` and `USER_CONFIG`.

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[1]: https://pypi.org/project/appdirs/
[21]: https://argcomplete.readthedocs.io/en/latest/

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zkay solify: Strip zkay-specific features from the given zkay file and output the resulting Solidity code. This makes it possible to analyze zkay code with tools designed for Solidity.

zkay compile: Compile the given zkay file. This includes type-checking, code transformation, circuit construction and compilation, NIZK key generation, and contract interface generation.

zkay update-solc: Download and install the latest compatible version of solc.

Distribution.

zkay export: Package the necessary data (contract, manifest and prover keys) of the given compilation output directory as a *.zkp archive.

zkay import: Import a given *.zkp archive.

Deployment and Interaction.

zkay deploy-pki: Deploy the PKI contract.

zkay deploy-crypto-libs: Deploy library contracts required for the GM17 proving scheme.

zkay run: Open an interactive shell in the context of the contract interface of a given compilation output directory.

zkay deploy: Deploy the contract of a given compilation output directory.

zkay connect: Connect to the contract of a given compilation output directory at a given address and start an interactive shell in the context of the contract interface.
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