zkay: **Specifying and Enforcing Data Privacy in Smart Contracts**

Samuel Steffen

Benjamin Bichsel

Mario Gersbach

Noa Melchior

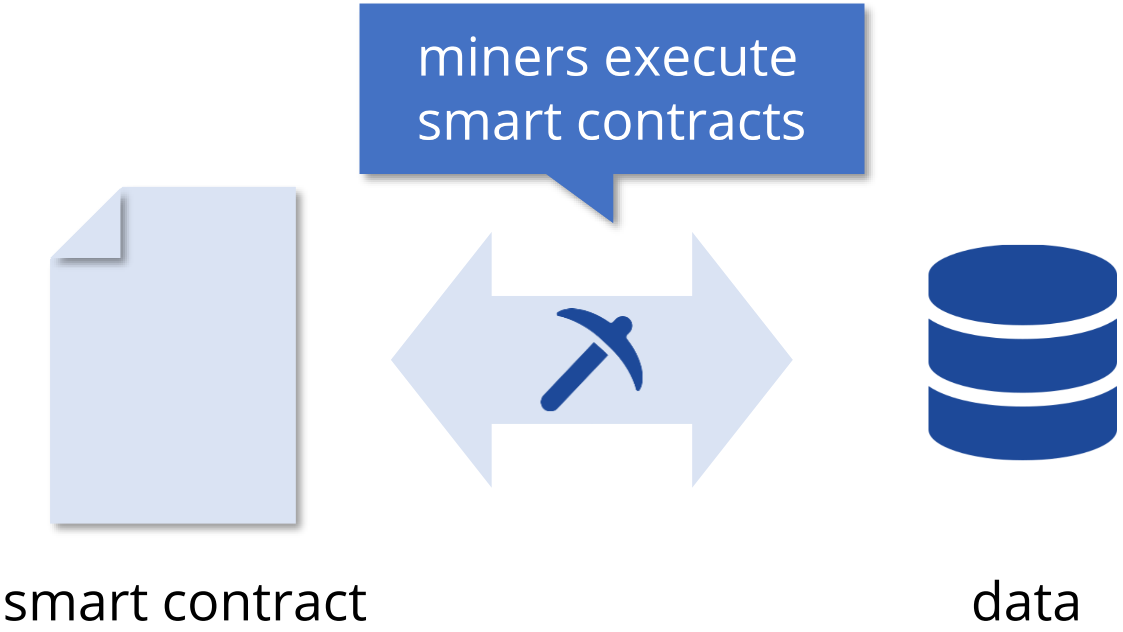
Petar Tsankov

Martin Vechev

ETH zürich

SRILAB

Smart Contracts



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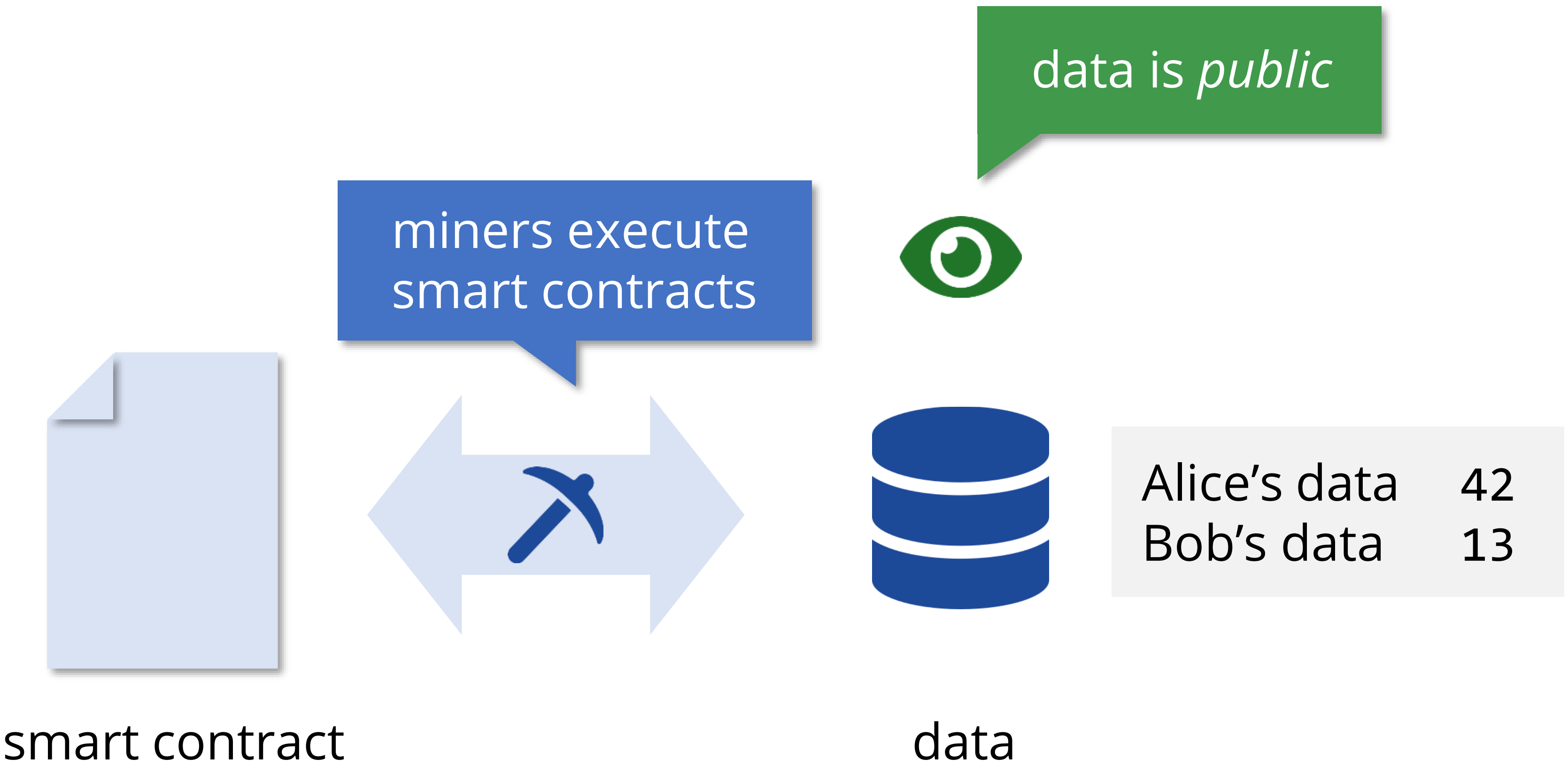
Smart Contracts



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Privacy?

Medical data and the rise of blockchain

6th July 2018

http://www.pharmatimes.com/web_exclusives/medical_data_and_the_rise_of_blockchain_1243441

Privacy?

Blockchain / Smart Contracts

How Blockchain Could Give Us a Smarter Energy Grid

Energy experts believe that blockchain technology can solve a maze of red tape and data management problems.

by Mike Orcutt Oct 16, 2017

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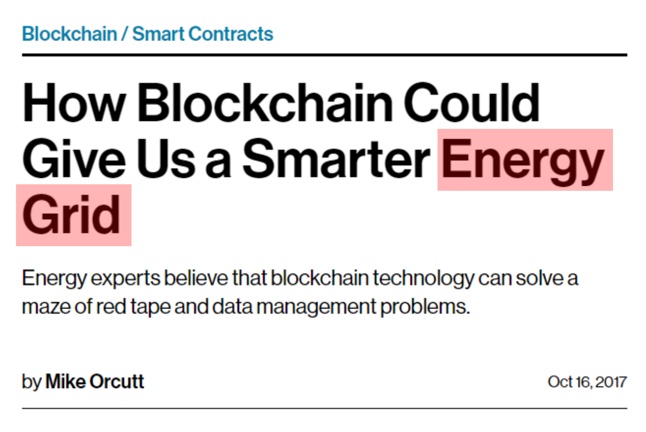
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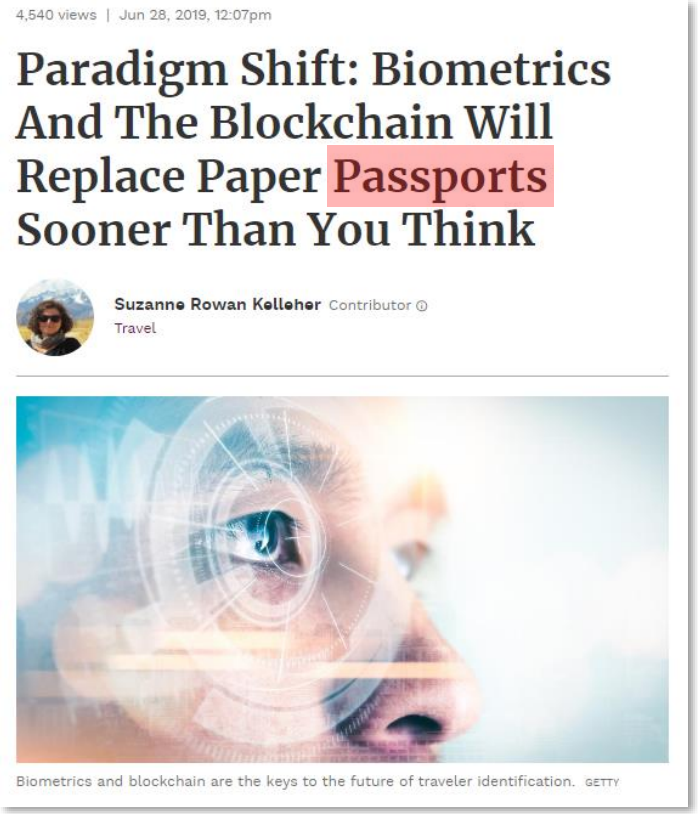
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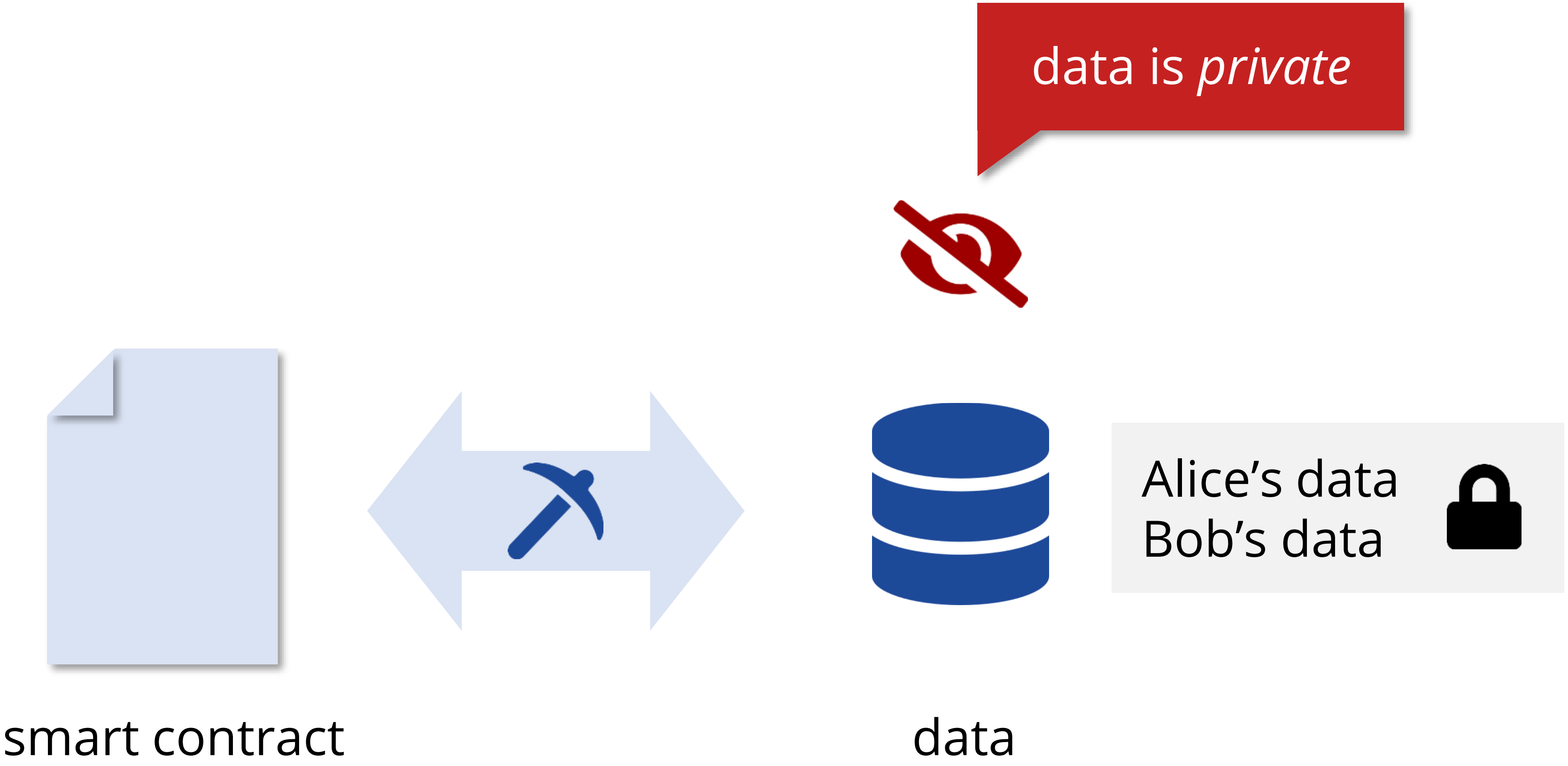
Paradigm Shift: Biometrics And The Blockchain Will Replace Paper Passports Sooner Than You Think

Suzanne Rowan Kelleher Contributor
Travel

Biometrics and blockchain are the keys to the future of traveler identification. GETTY

https://www.forbes.com/sites/suzannerowankelleher/2019/06/28/paradigm-shift-biometrics-and-the-blockchain-will-replace-paper-passports-sooner-than-you-think/

Data Privacy for Smart Contracts



Existing Work

Zerocoin [S&P 13]
Zerocash [S&P 14]
Bolt [CCS 17]

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only for payments

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introduce trusted third parties / HW

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introduce trusted third parties / HW

Our work: Leverage *cryptographic primitives* on *existing public* blockchains

Existing Work

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introduce trusted third parties / HW

Our work: Leverage *cryptographic primitives* on *existing public* blockchains

asymmetric encryption

NIZK proofs

Data Privacy with NIZK Proofs

42

Alice’s data	`0x3025…`
Bob’s data	`0x2543…`

Data Privacy with NIZK Proofs

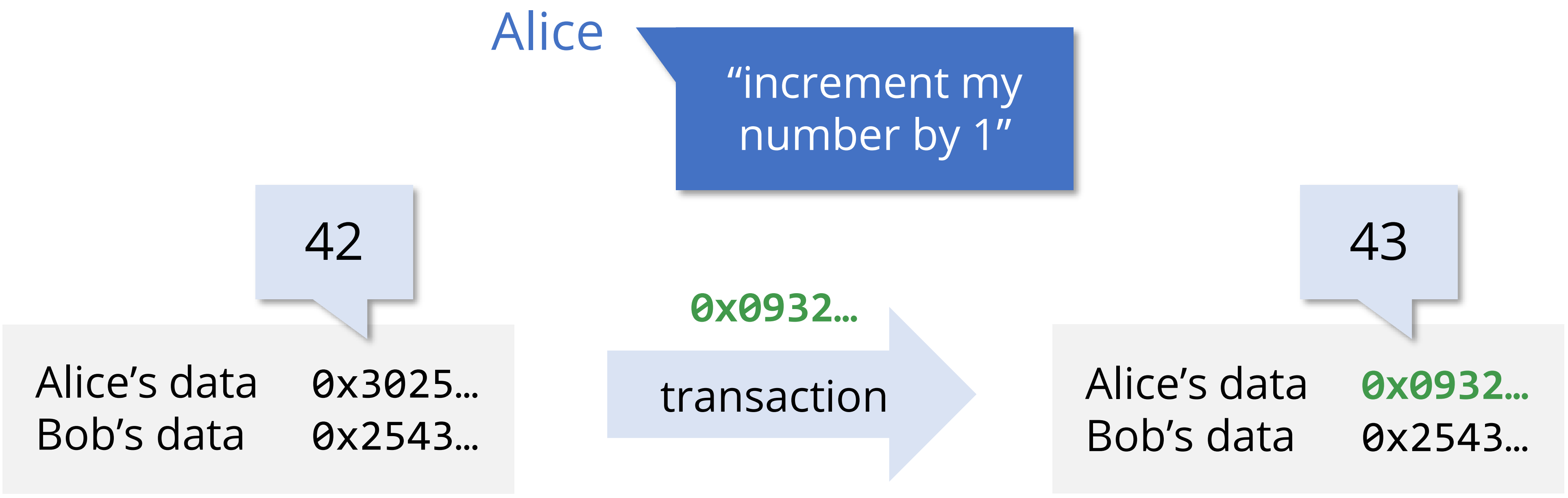
Alice

“increment my number by 1”

42

Alice’s data	`0x3025…`
Bob’s data	`0x2543…`

Data Privacy with NIZK Proofs



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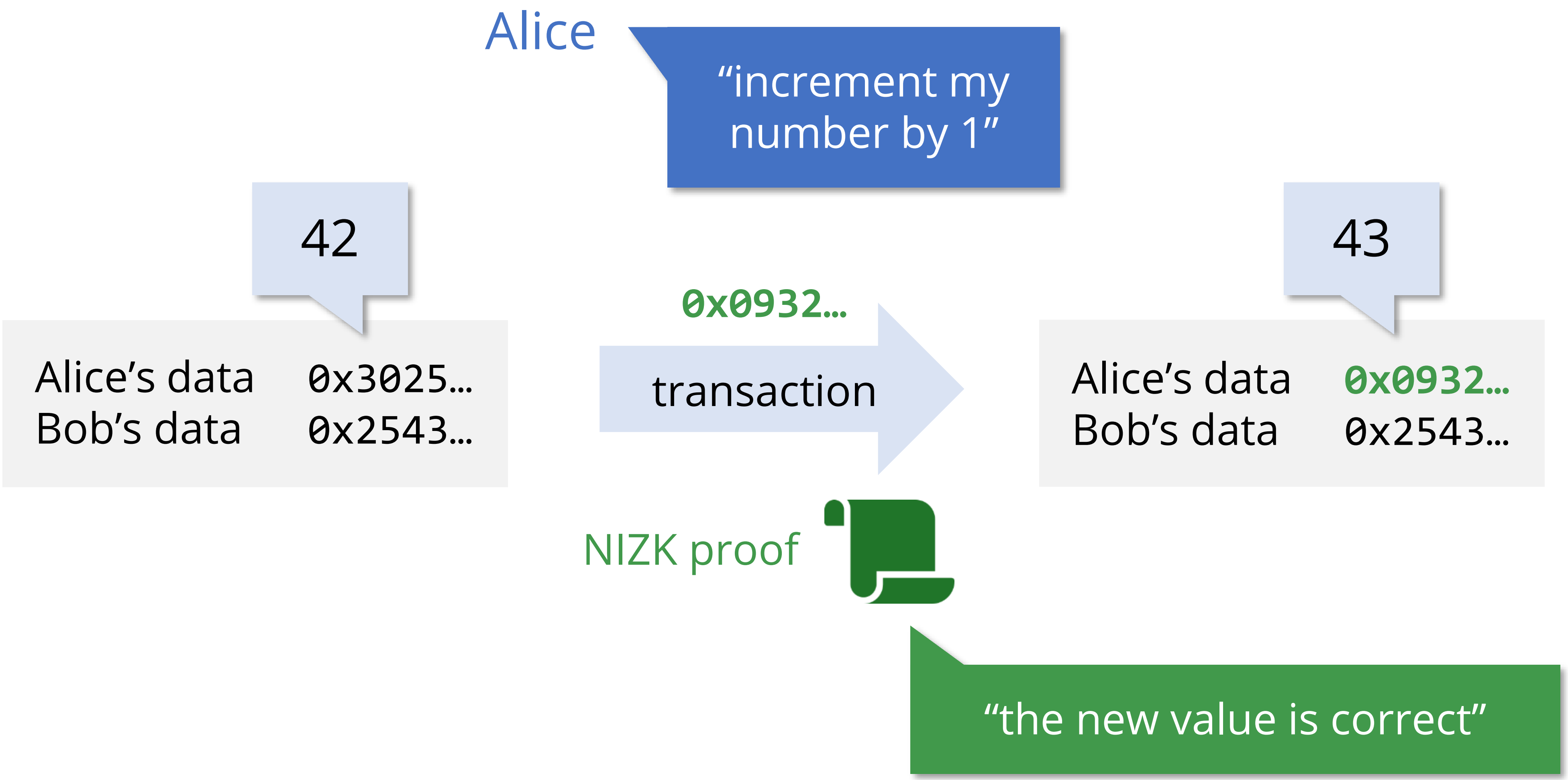

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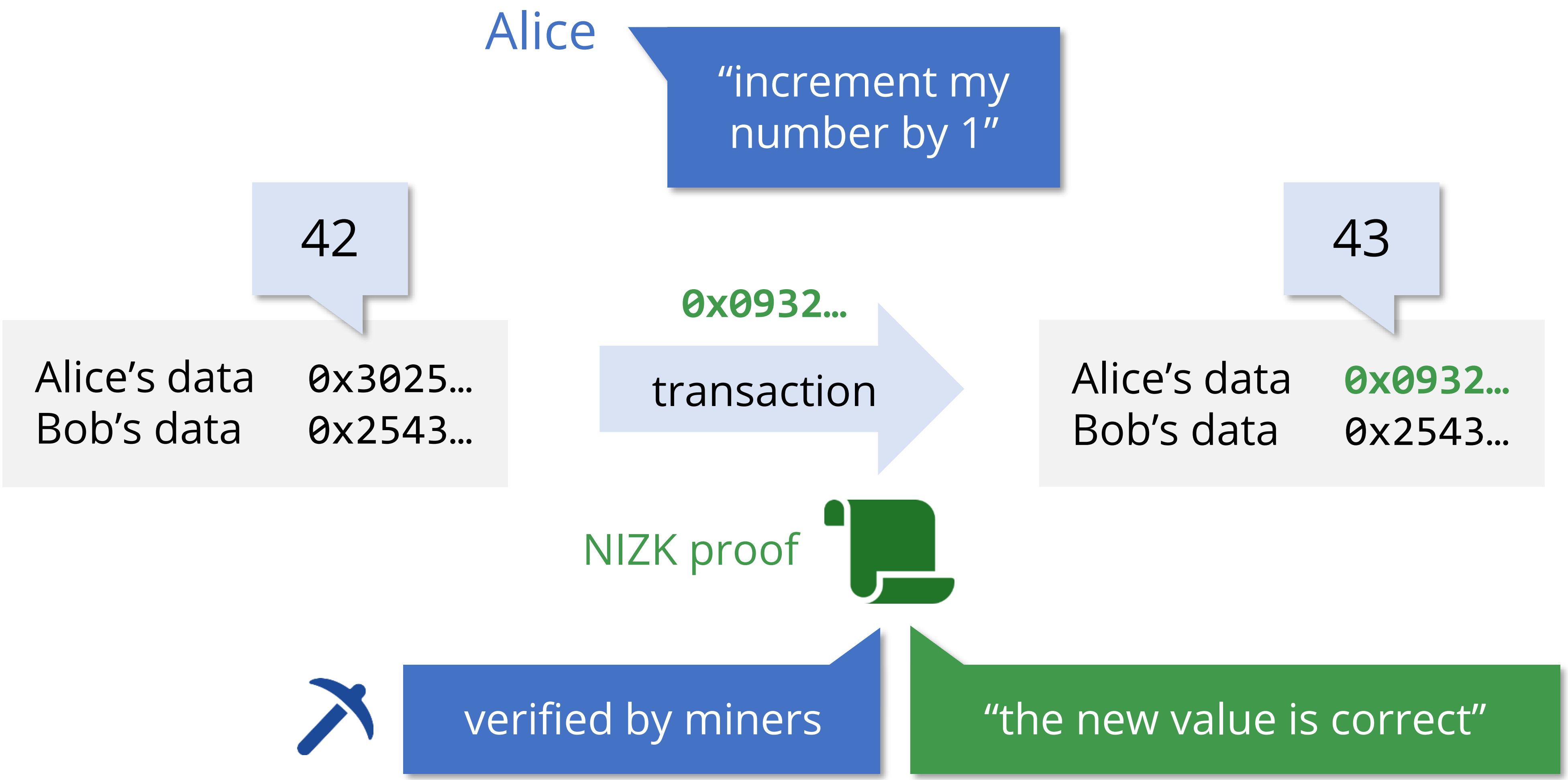

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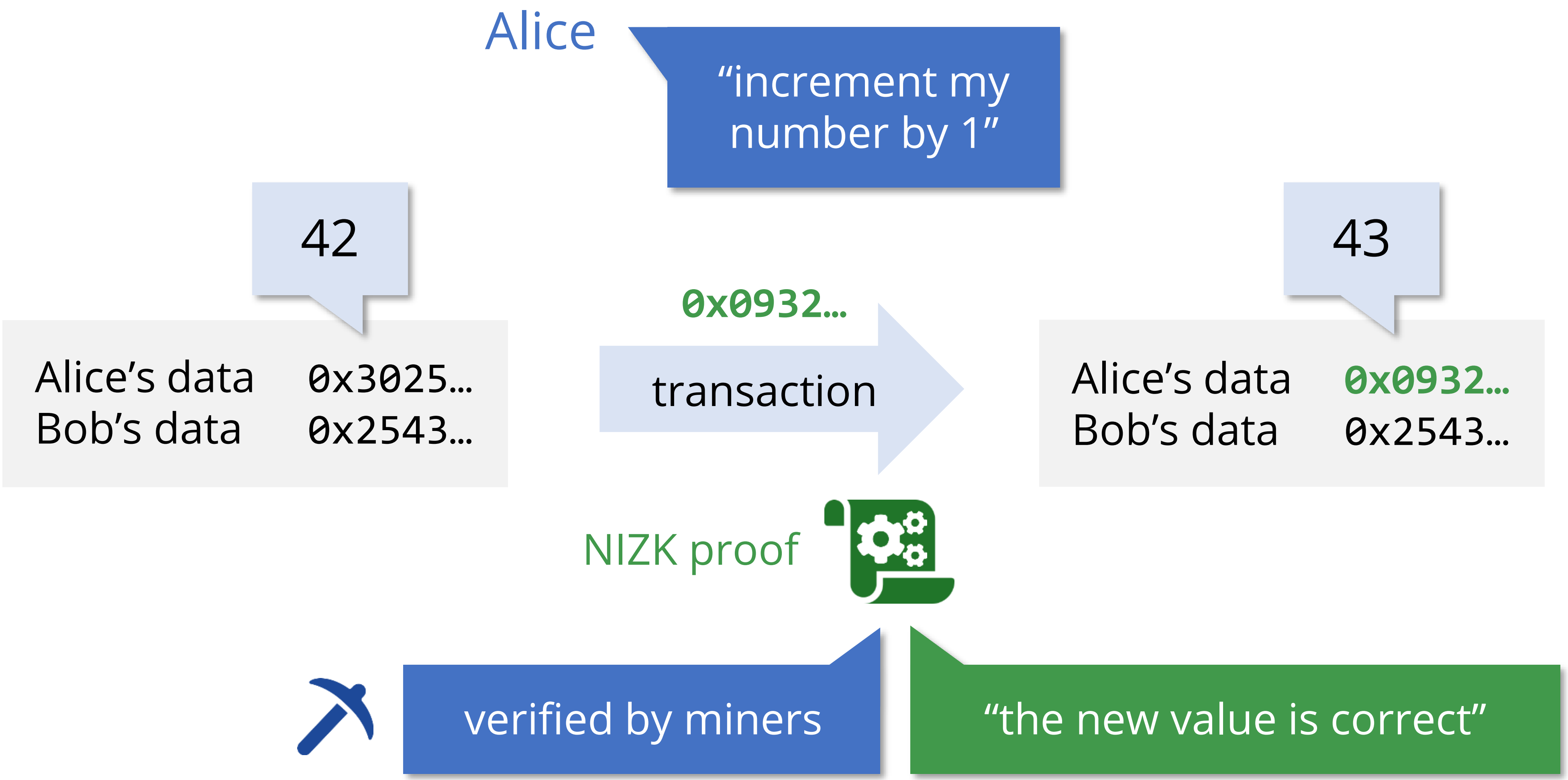
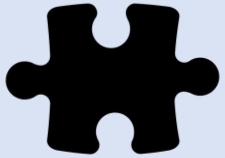


Challenges

Incompleteness of
NIZK Proofs

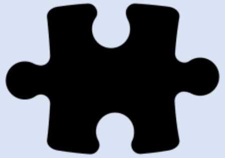


"Puzzle" by jeff from thenounproject.com

Challenges

e.g., can only incorporate fixed-size state

Incompleteness of NIZK Proofs



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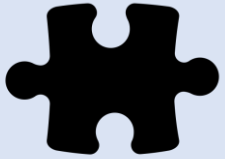


e.g., can only incorporate
fixed-size state

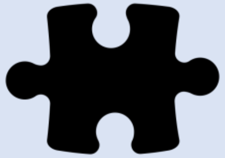
Dynamic arrays?

Entry *lookup*
in contract

Entry *decryption*
in proof

Challenges

Incompleteness of NIZK Proofs



e.g., can only incorporate fixed-size state

Dynamic arrays?

Entry *lookup* in contract

Entry *decryption* in proof

scattered logic

"Puzzle" by jeff from thenounproject.com

Challenges

e.g., can only incorporate fixed-size state

Incompleteness of NIZK Proofs

Dynamic arrays?

Entry *lookup* in contract

scattered logic

Entry *decryption* in proof

Obfuscated Logic ?

"Puzzle" by jeff from thenounproject.com

Challenges

Knowledge
Restrictions

Alice: “increase Bob’s value by 1”

Challenges

Knowledge Restrictions

Alice: “increase Bob’s value by 1”

can not generate proof

Challenges

Obfuscated
Information Leaks  ?

Alice: “overwrite Bob’s value with my value”

"leak" by Quentin B. from thenounproject.com

Challenges

Obfuscated Information Leaks 

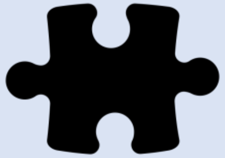
Alice: “overwrite Bob’s value with my value”

did Alice really want this?

"leak" by Quentin B. from thenounproject.com

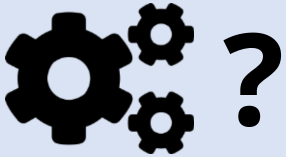
Challenges

Incompleteness of NIZK Proofs



Knowledge Restrictions

Obfuscated Logic



Obfuscated Information Leaks

Challenges

Incompleteness of NIZK Proofs

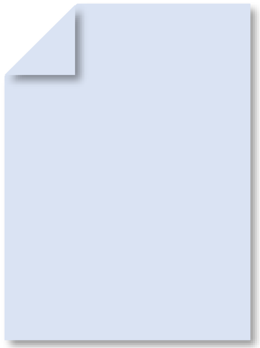
Knowledge Restrictions

This work: zkay

Obfuscated Logic ?

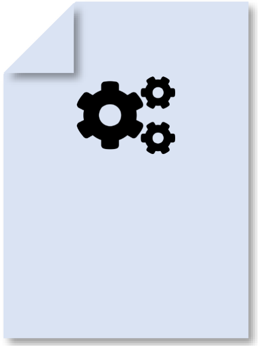
Obfuscated Information Leaks ?

zkay **Overview**



zkay contract

zkay **Overview**



zkay contract

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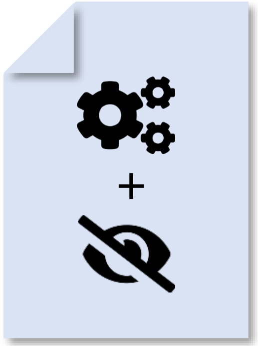

zkay contract

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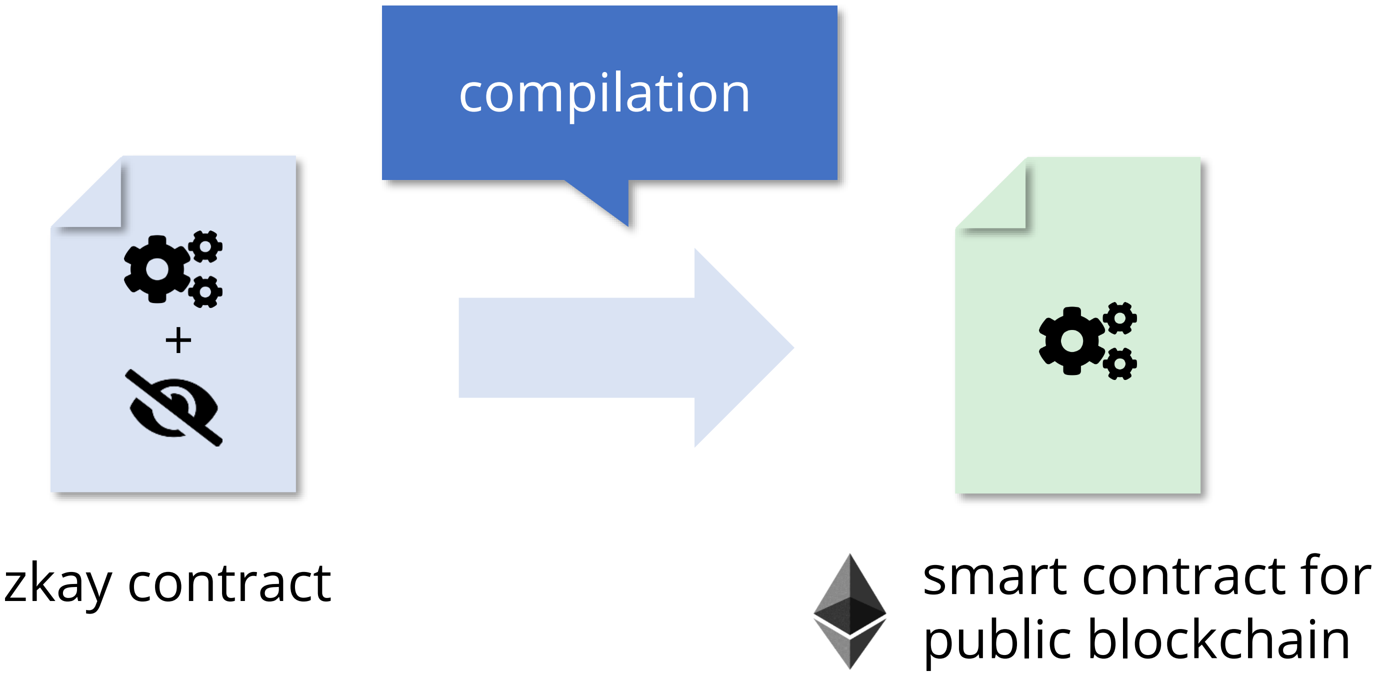

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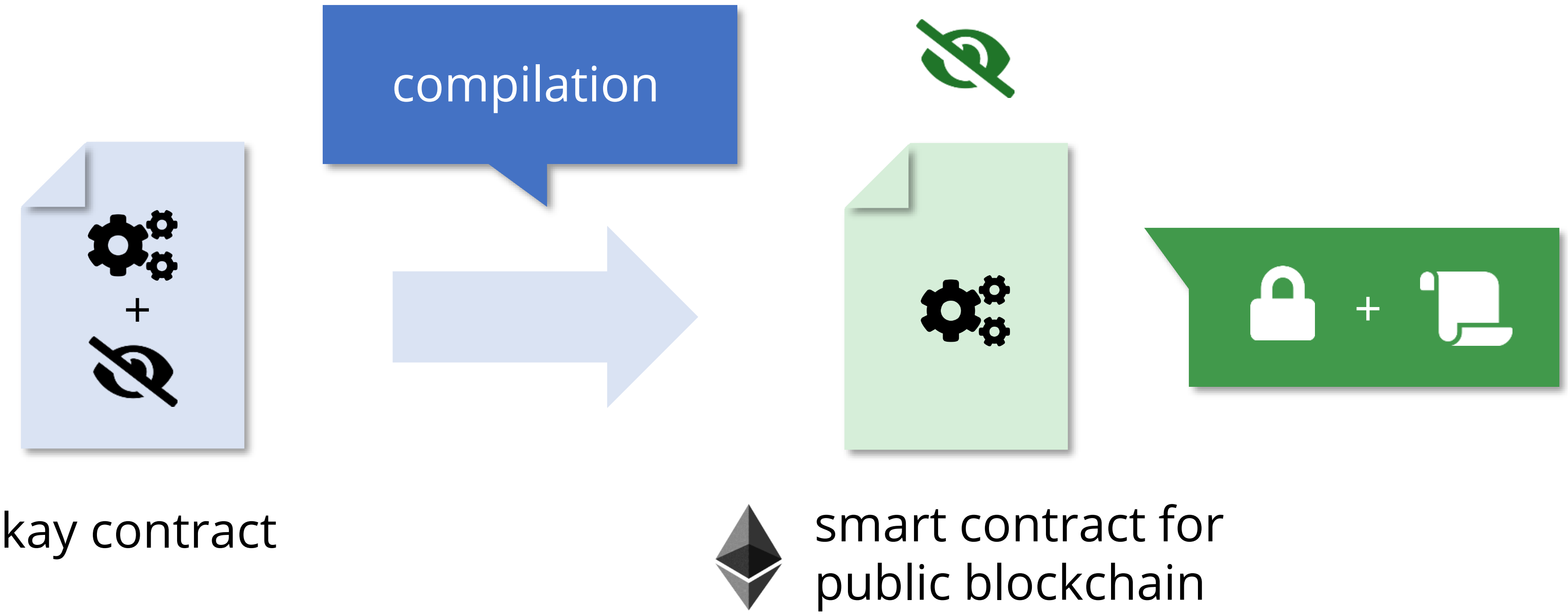
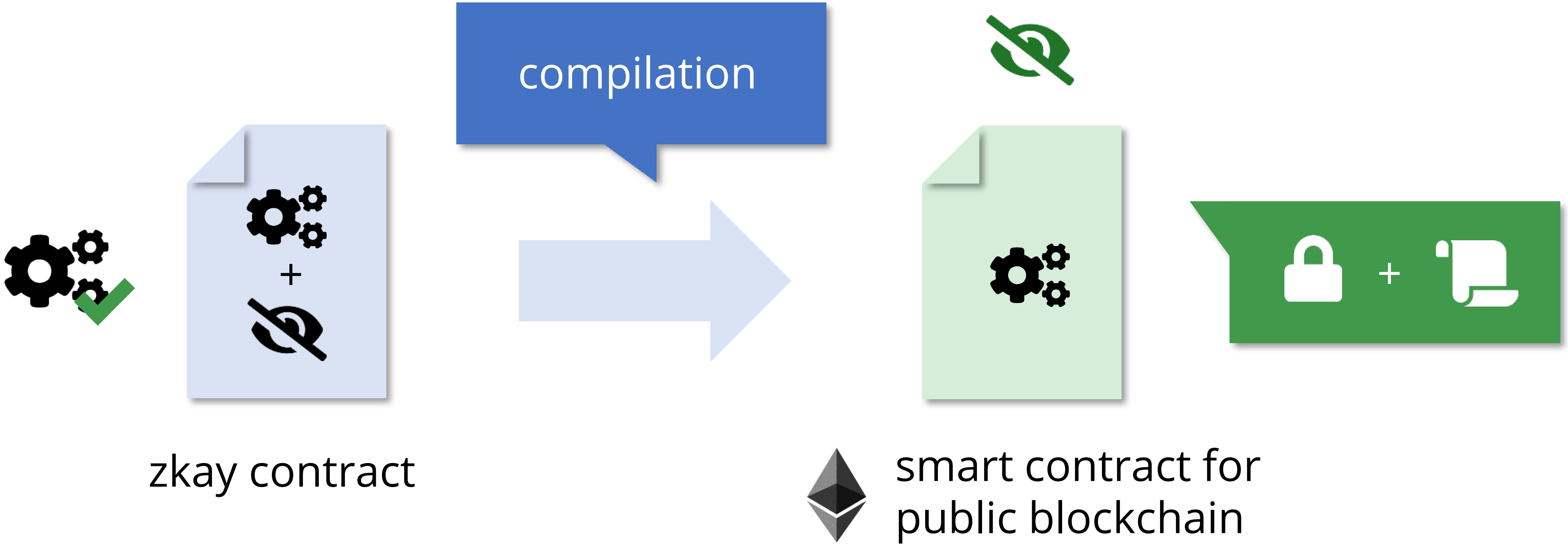


zkay contract

smart contract for
public blockchain

zkay **Overview**



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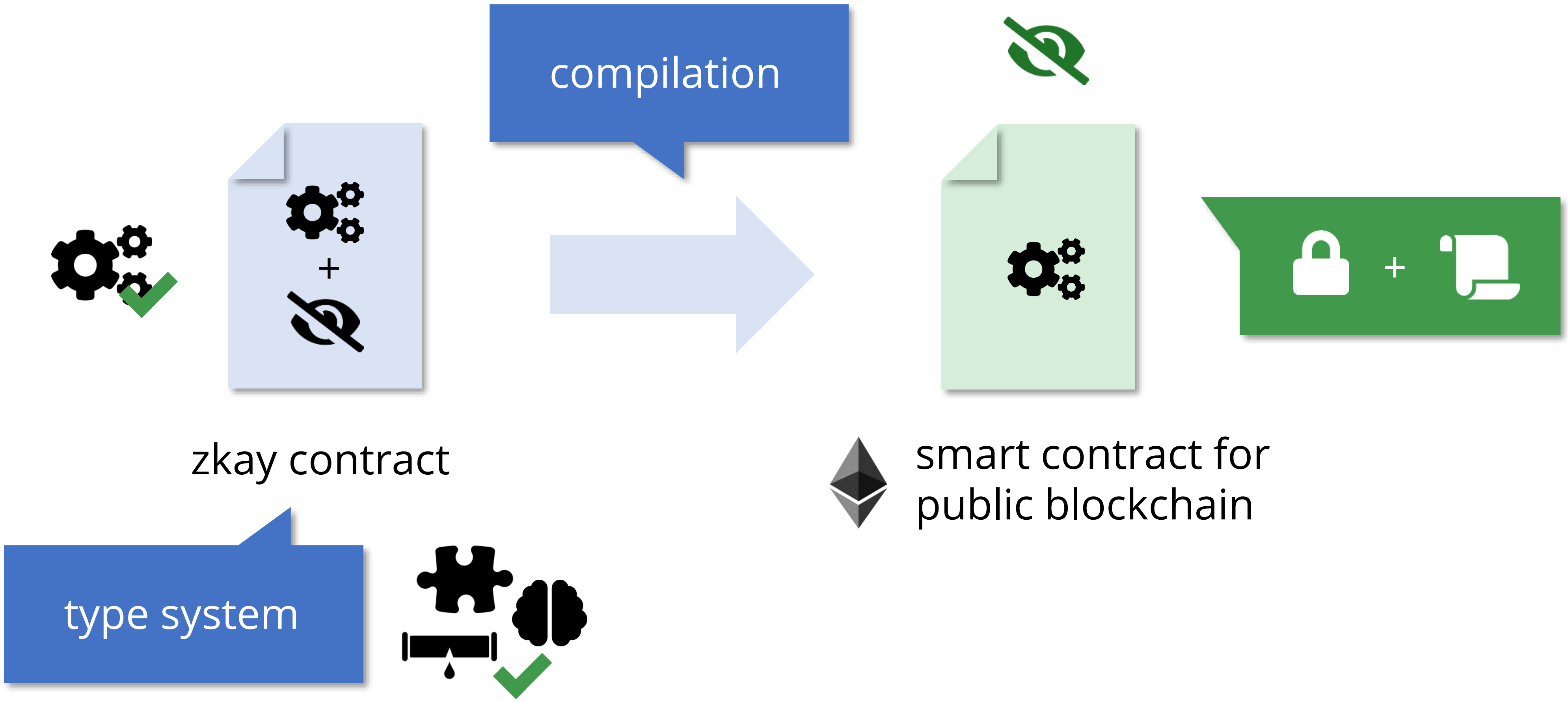


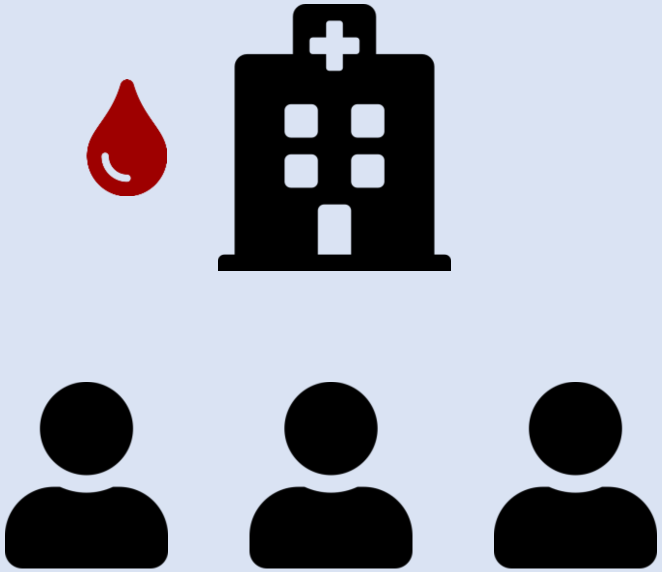
Example

```
contract MedStats {
   address hospital;
   uint count;
   mapping(address => bool) risk;

   constructor() {
      hospital = msg.sender; count = 0;
   }

   function record(address don, bool r) {
      require(hospital == msg.sender);
      risk[don] = r;
      count = count + (r ? 1 : 0);
   }
}
```

Medical Statistics



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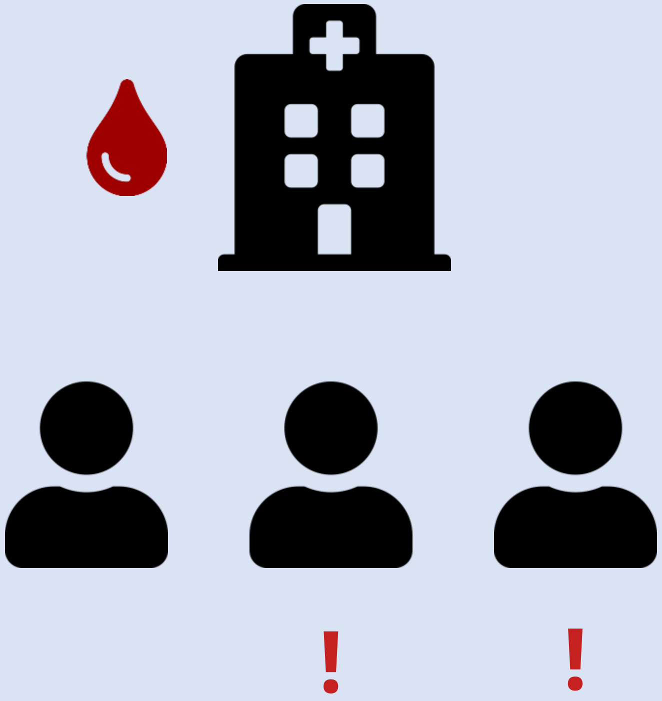

risk

count: 2

Example

Solidity

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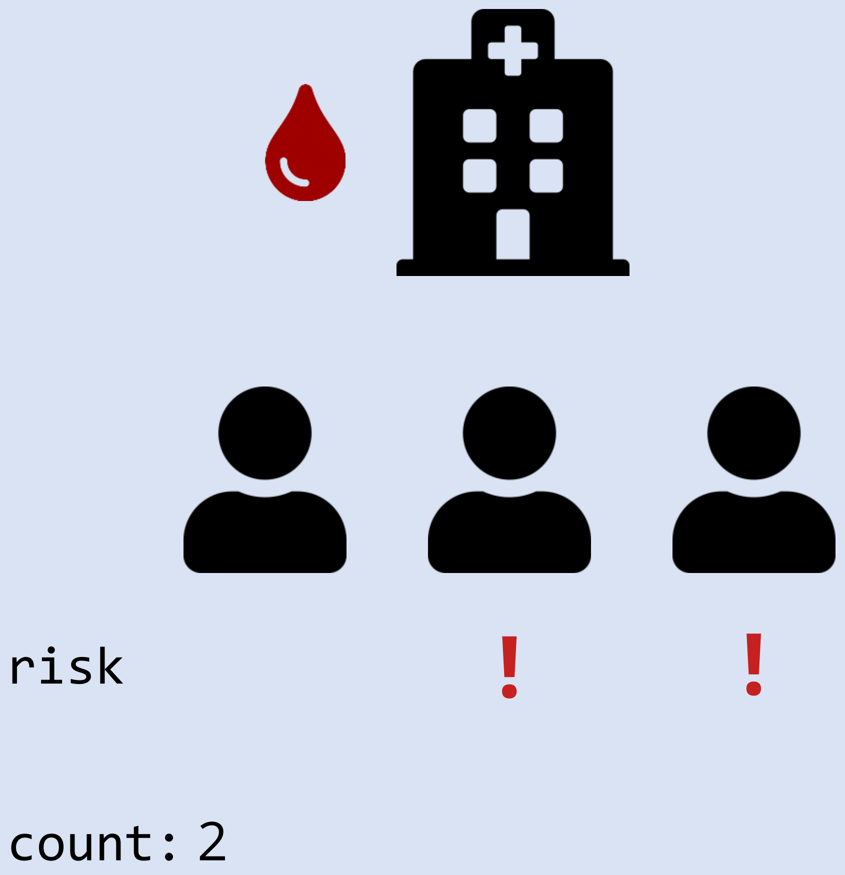
Medical Statistics



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Initialization

Example

Solidity

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```

Record data of donor

Example

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Record data of donor

Privacy?

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      risk[don] = r;
      count = count + (r ? 1 : 0);
   }
}
```

Sensitive information must remain *private*

zkay **Privacy Annotations**

Idea:

```
datatype@owner
```

zkay **Privacy Annotations**

```
contract MedStats {
    final address hospital;
    uint@hospital count;
    mapping(address!x => bool@x) risk;

    constructor() {
        hospital = me; count = 0;
    }

    function record(address don, bool@me r) {
        require(hospital == me);
        risk[don] = reveal(r, don);
        count = count + (r ? 1 : 0);
    }
}
```

count is *private to* hospital
hospital is the *owner* of count

zkay **Privacy Annotations**

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hospital is the *owner* of count

risk[a] is private to address a

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```

count is *private to* hospital
hospital is the *owner* of count

risk[a] is private to address a

r is private to the caller (@me)

zkay **Privacy Annotations**

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        risk[don] = reveal(r, don);
        count = count + (r ? 1 : 0);
    }
}
```

`count` is *private to* `hospital`
`hospital` is the *owner* of `count`

`risk[a]` is private to address `a`

`r` is private to the caller (`@me`)

`don` is public (`@all`)

zkay **Privacy Annotations**

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contract MedStats {
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   }
}
```

count is *private to* hospital
hospital is the *owner* of count

risk[a] is private to address a

r is private to the caller (**@me**)

don is public (**@all**)

reclassify r for don

zkay **Privacy Annotations**

```
contract MedStats {
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      require(hospital == me);
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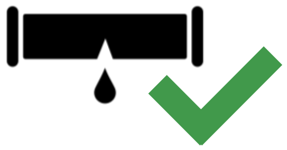
      count = count + (r ? 1 : 0);
   }
}
```

Logic *not obfuscated*

Type System Goals

No unintended information leaks



Type System Goals

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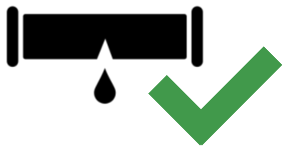
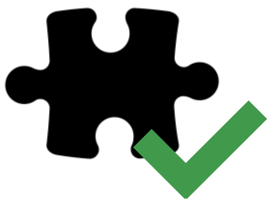


Realizability using NIZK proofs



Preventing Unintended Leaks

```
contract MedStats {
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   }
}
```

@me

@all

Preventing Unintended Leaks

```
contract MedStats {
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   function record(address don, bool@me r) {
      require(hospital == me);
      risk[don] = reveal(r, don);
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   }
}
```

OK

@me

@all

Allow implicit *classification*

Preventing Unintended Leaks

```
contract MedStats {
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   function record(address don, bool@me r) {
      require(hospital == me);
      risk[don] = r;
      count = count + (r ? 1 : 0);

   }
}
```

@don

@me

Preventing Unintended Leaks

```
contract MedStats {
   final address hospital;
   uint@hospital count;
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   constructor() {
      hospital = me; count = 0;
   }

   function record(address don, bool@me r) {
      require(hospital =
      risk[don] = r;
      count = count + (r ? 1 : 0);
   }
}
```

disallow

@don

@me

Disallow implicit *re-/declassification*

Preventing Unintended Leaks

```
contract MedStats {
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  constructor() {
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  }

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    require(hospital == me);
    risk[don] = reveal(r, don);
    count = count + (r
  }
}
```

OK

requires **reveal**

Disallow implicit
re-/declassification

Preventing Unintended Leaks

```
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   }
}
```

@me

@all

Preventing Unintended Leaks

```
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    count = count + (r ? 1 : 0);
  }
}
```

@me

@me

@all

Type of compound expressions is *conservative*

Ensuring Realizability

Alice

```
data[bob] = data[bob] + 1;
```

Ensuring Realizability

Alice

```
data[bob] = data[bob] + 1;
```

@bob

Ensuring Realizability

Alice

```
data[bob] = data[bob] + 1;
```

@bob

can only read **`@me`** or **`@all`**

Ensuring Realizability

```
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   final address hospital;
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      hospital = me; count = 0;
   }

   function record(address don, bool@me r) {
      require(hospital == me);
      risk[don] = reveal(r, don);
      count = count + (r ? 1 : 0);
@hospital
}
```

Can only read *self-owned* or *public* variables

Ensuring Realizability

```
contract MedStats {
  final address hospital;
  uint@hospital count;
  mapping(address!x => bool@x) risk;

  constructor() {
    hospital = me; count = 0;
  }

  function record(address don, bool@me r) {
    require(hospita
    risk[don] = re          );
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}
```

?

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`@hospital`

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can prove `hospital == me`

Sometimes, *static analysis* is required

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OK

Sometimes, *static analysis* is required

Compilation

Compilation Example

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function record(bool@me r) {
   require(hospital == me);
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Compilation Example

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function record(bool@me r) {
   require(hospital == me);
   count = count + (r ? 1 : 0);
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```

```
function record(bin r, bin z, bin p) {
   require(hospital == me);
   bin old = count; count = z;
   verify(p, z, r, old, pk(me));
}
```

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   require(hospital == me);
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public

private

I know sk such that

old + (r ? 1 : 0)

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private

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      old     + (     r       ? 1 : 0)
dec(old, sk) + (dec(r, sk) ? 1 : 0)
```

Compilation Example

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   verify(p, z, r, old, pk(me));
}
```

public

private

I know sk such that

```
                old      + (    r        ? 1 : 0)
        dec(old, sk) + (dec(r, sk) ? 1 : 0)
z == enc(dec(old, sk) + (dec(r, sk) ? 1 : 0), pk(me))
```

Compilation

```
function f(...) {
  P;
  return e;
}
```

```
function f̄(..., 𝓕, bin proof) {
  T(P)
  verify_ϕ(proof, 𝓟);
  return T_e(e);
}
```

for ϕ: $(\mathcal{P}, \mathcal{S}) \to \{0, 1\}$

(a) Transformation of a zkay function.

$$out(e, \alpha) ::= v_i \qquad \text{(invariant: } e@\texttt{me} \text{ or } e@\texttt{all})$$

$$\mathcal{F} \leftarrow \mathcal{F}, v_i$$

$$\mathcal{P} \leftarrow \mathcal{P}, v_i, \texttt{pk}(\alpha)$$

$$\mathcal{S} \leftarrow \mathcal{S}, R_i$$

$$\phi \leftarrow \phi;\ v_i == \texttt{enc}(\ T_\phi(e)\ , R_i, \texttt{pk}(\alpha))\ ;$$

(b) Transformation $out(e, \alpha)$. If $\alpha = \texttt{all}$, the highlighted part is omitted.

$$in(e, \alpha) ::= \texttt{dec}_\tau(\ v_i,\ \texttt{sk}) \qquad \text{(invariant: } e@\alpha, \alpha \in \{\texttt{me}, \texttt{all}\})$$

$$\text{add to } T(P) \quad : \quad \tau'@\texttt{all}\ \ v_i = T_e(e); \qquad \text{for } \tau' ::= \begin{cases} \tau & \alpha = \texttt{all} \\ \texttt{bin} & \alpha \neq \texttt{all} \end{cases}$$

$$\mathcal{P} \leftarrow \mathcal{P}, v_i$$

$$\mathcal{S} \leftarrow \mathcal{S}, \texttt{sk}$$

(c) Transformation $in(e, \alpha)$. If $\alpha = \texttt{all}$, the highlighted part is omitted.

$$T(P_1; P_2) ::= T(P_1); T(P_2) \tag{1}$$

$$T(L@\alpha = e@\alpha) ::= T_L(L) = T_e(e) \qquad \text{(we use } T_L = T_e) \tag{2}$$

$$T(L@\alpha = e@\texttt{all}) ::= T_L(L) = out(e, \alpha) \qquad (\alpha \neq \texttt{all}) \tag{3}$$

$$T(\texttt{require}(e)) ::= \texttt{require}(T_e(e)) \tag{4}$$

$$T(\texttt{while}\ e\ \{P\}) ::= \texttt{while}\ e\ \{P\} \qquad (P \text{ is fully public}) \tag{5}$$

$$T(\texttt{if}\ e\ \{P_1\}\ \texttt{else}\ \{P_2\}) ::= \texttt{if}\ T_e(e)\ \{T(P_1, T_e(e))\}\ \texttt{else}\ \{T(P_2, T_e(!e))\} \tag{6}$$

(d) Transforming statements using T.

$$T_e(c) ::= c \qquad \text{const } c \tag{7}$$

$$T_e(\text{id}) ::= \text{id} \qquad \text{var id } (\star) \tag{8}$$

$$T_e(L[e]) ::= T_L(L)[T_e(e)] \qquad \text{mapping entry} \tag{9}$$

$$T_e((e_1 + e_2)@\texttt{all}) ::= T_e(e_1) + T_e(e_2) \qquad \text{native functions} \tag{10}$$

$$T_e(\texttt{reveal}(e, \alpha)) ::= out(e, \alpha) \qquad \text{(invariant: } e@\texttt{me}) \tag{11}$$

$$T_e(e@\alpha) ::= out(e, \alpha) \qquad \text{(invariant: } e@\texttt{me}) \tag{12}$$

(e) Transforming expressions in zkay using T_e. For private function arguments id, $\star$ adds an additional correctness constraint to ϕ.

$$T_\phi(c) ::= c \qquad \text{const } c \tag{13}$$

$$T_\phi(L@\alpha) ::= in(L, \alpha) \qquad \text{(invariant: } \alpha \in \{\texttt{all}, \texttt{me}\}) \tag{14}$$

$$T_\phi(\texttt{reveal}(e, \alpha)) ::= T_\phi(e) \tag{15}$$

$$T_\phi(e_1 + e_2) ::= T_\phi(e_1) + T_\phi(e_2) \qquad \text{native functions} \tag{16}$$

(f) Transforming expressions in the proof circuit using T_ϕ.

Figure 5: Overview of zkay transformations. We write $e@\alpha$ to indicate that e has privacy type α. The symbol v_i denotes a fresh variable.

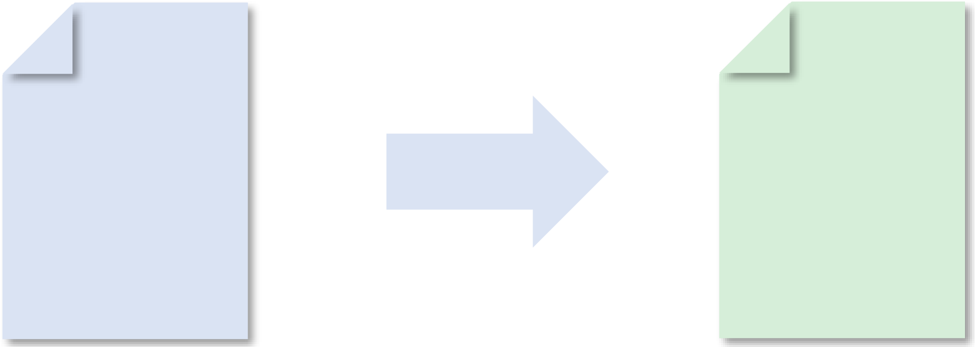
see paper for details

scattered logic

Privacy Guarantees

Data Privacy

ideal world



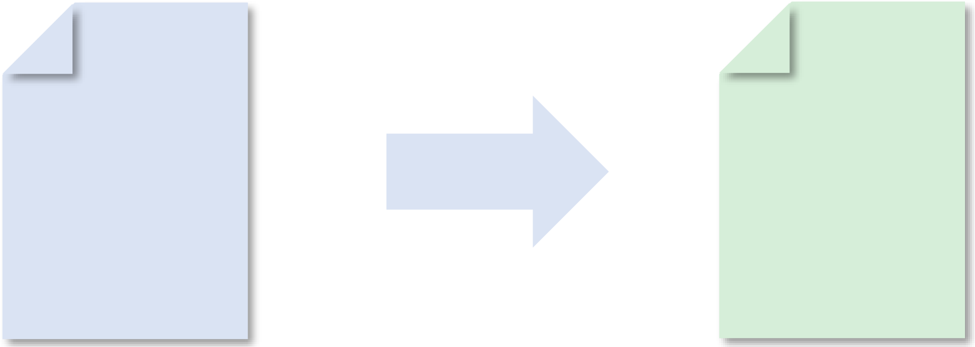
real world

input
(specification)

output
(realization)

Data Privacy

ideal world



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Everything Eve can learn here…

Data Privacy

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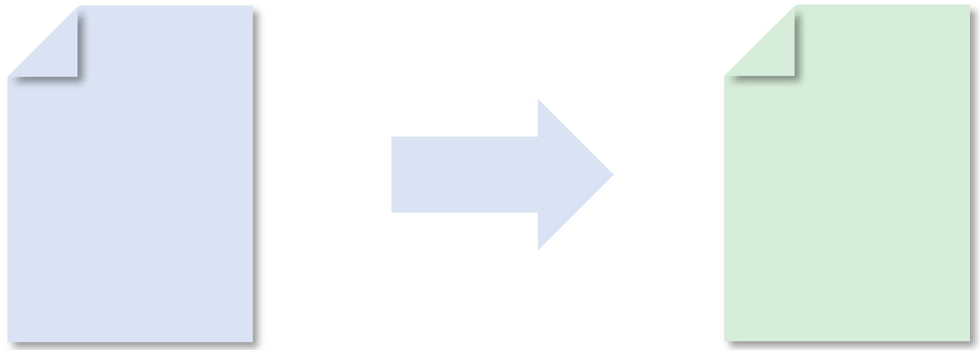

input
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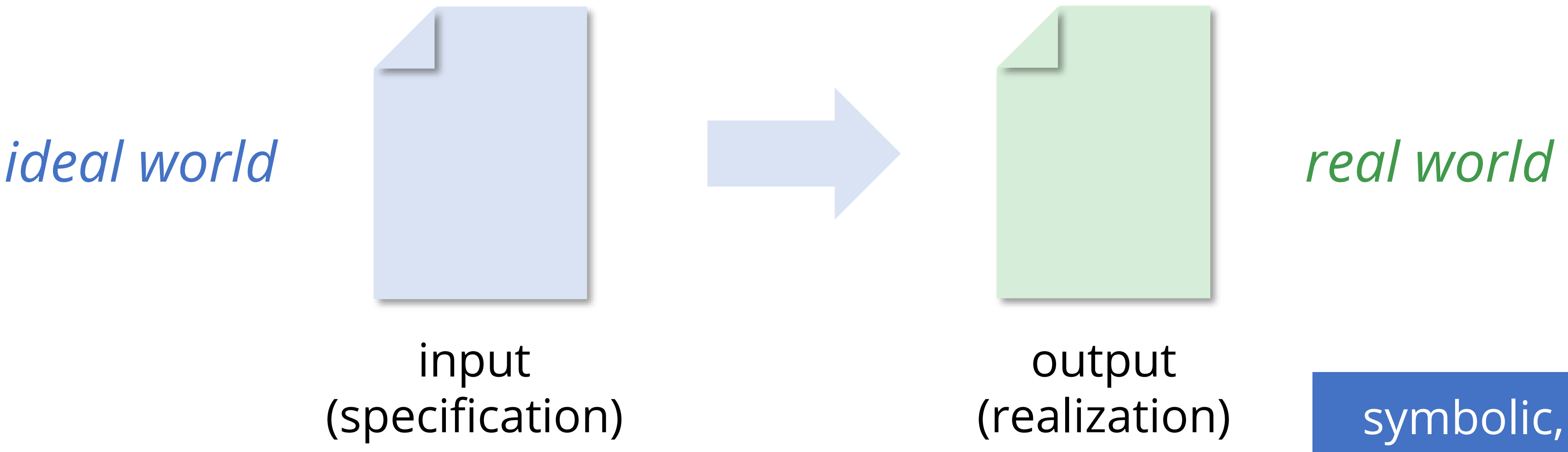
real world

Everything Eve can learn here…

…she can also learn here

Data Privacy



symbolic,
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Data Privacy

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Everything Eve can
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according to privacy types

Data Privacy

Theorem: Compiled contracts are *private* w.r.t. their input contracts

Everything Eve can learn here…

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according to privacy types

Implementation

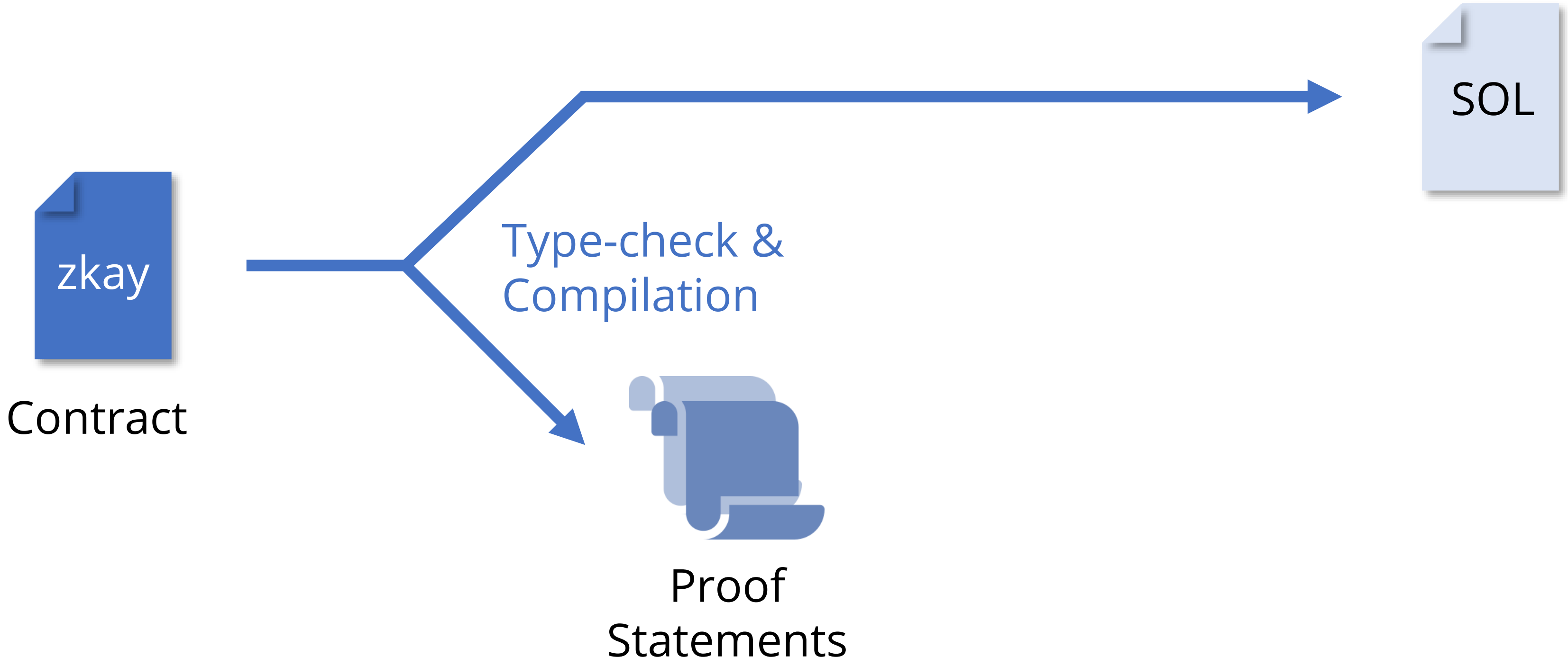
eth-sri/zkay

zkay

Contract

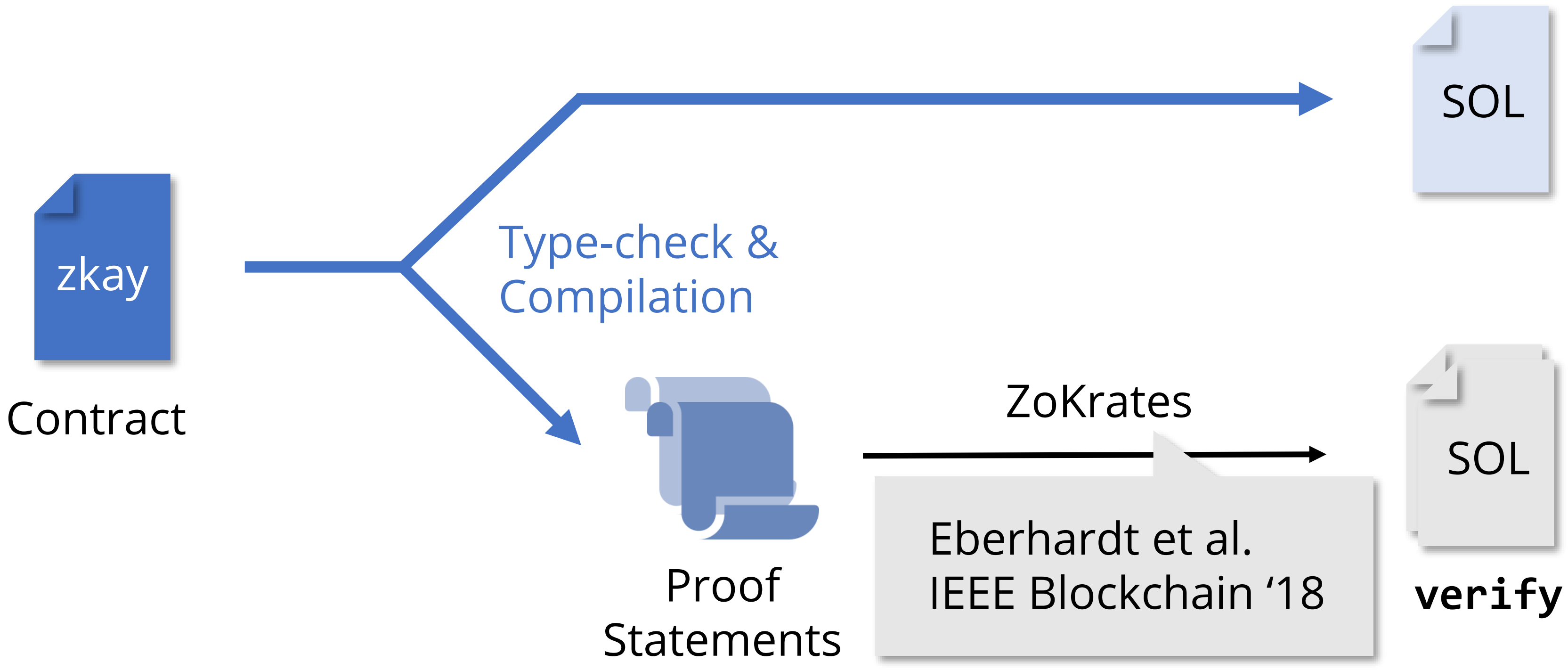
Implementation

eth-sri/zkay



Implementation

eth-sri/zkay



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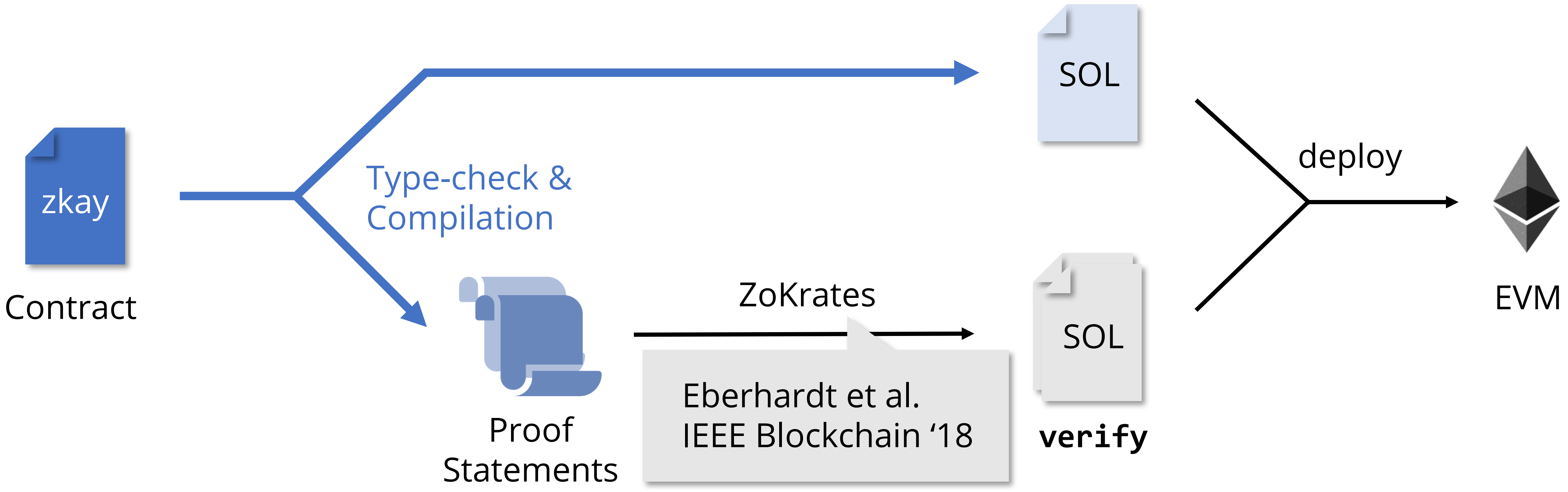
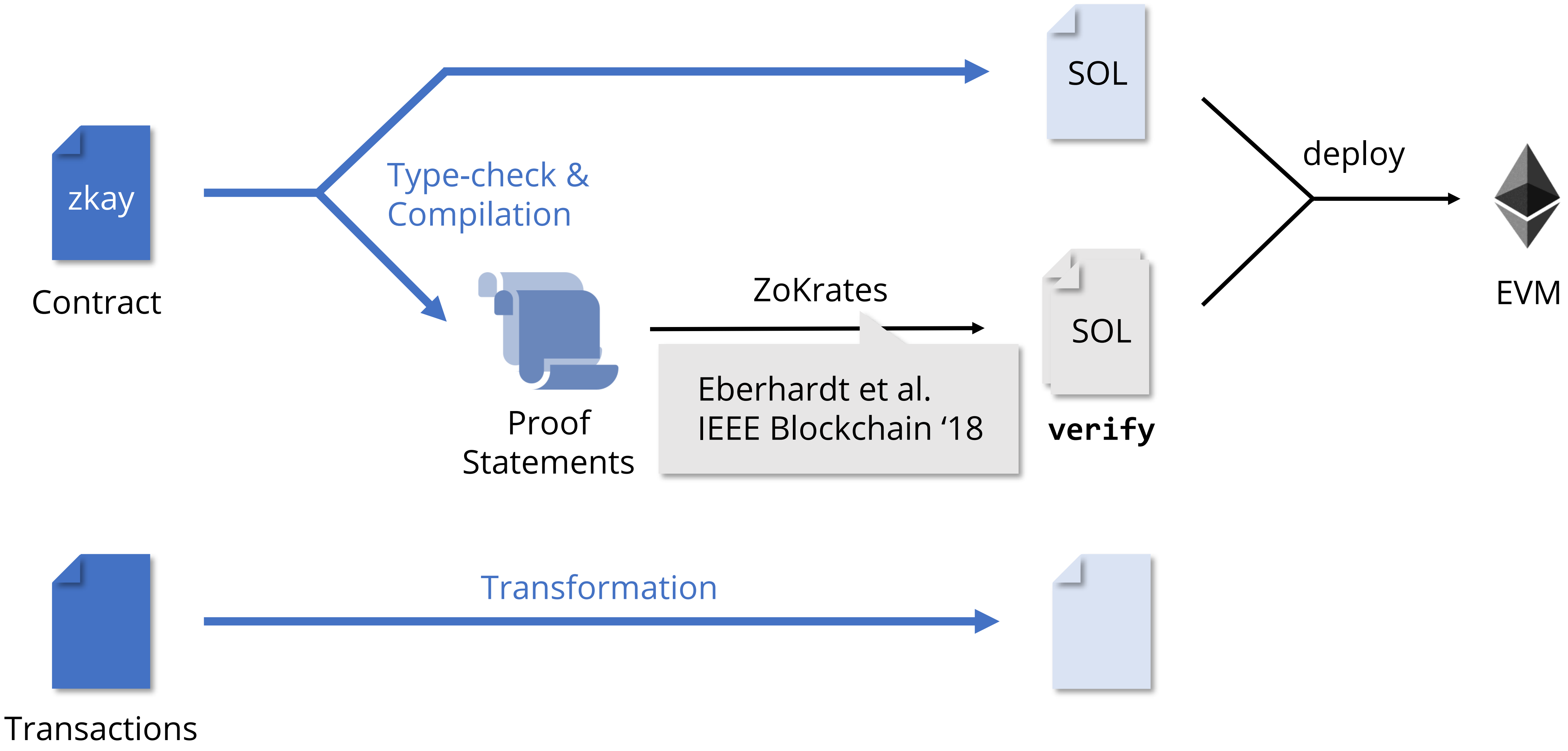
eth-sri/zkay



Implementation

eth-sri/zkay



Evaluation

Expressiveness?

Gas costs?

Evaluation

10 Example Contracts

22 – 79 loc

Evaluation

10 Example Contracts

wide range of domains

22 – 79 loc

Insurance & Finance

Healthcare

Gambling

…

Evaluation

wide range of domains

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10 Example Contracts

22 – 79 loc

Small example scenarios

4 – 9 transactions

Evaluation

wide range of domains

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Small example scenarios

4 – 9 transactions

zkay is expressive

On-Chain Costs

Private Transactions

On-Chain Costs

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dominated by constant-cost*
NIZK proof verification

ca. 10^6 Gas per tx

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ca. 0.50 US$ (1 ETH = 170 US$)

On-Chain Costs

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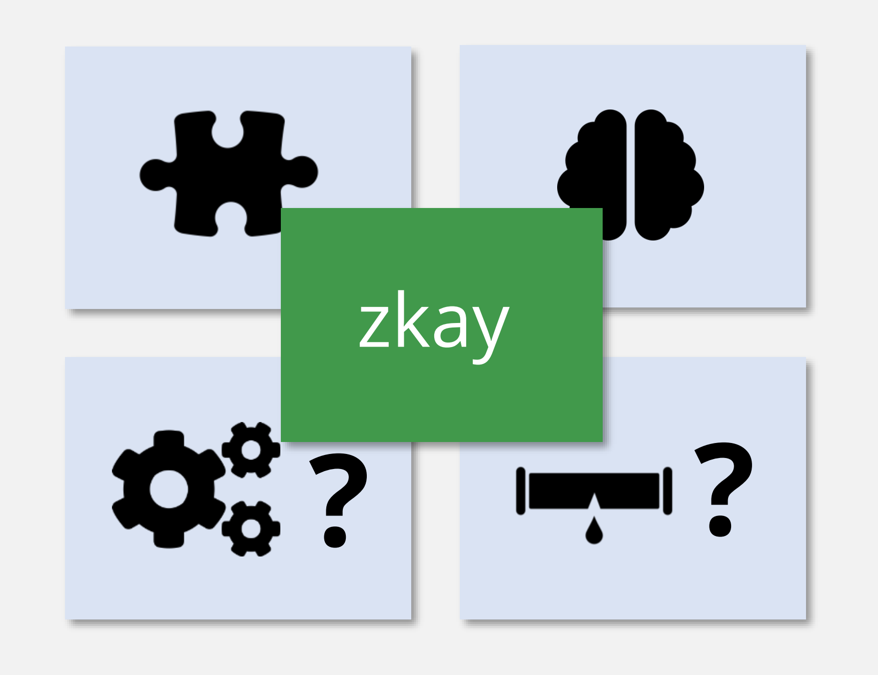
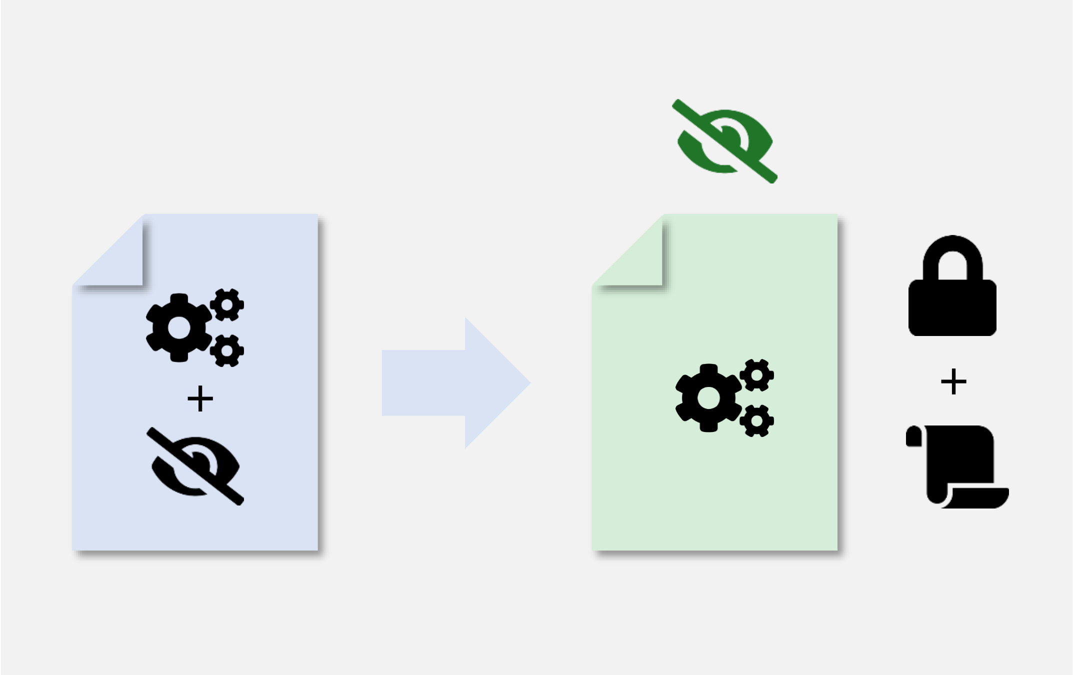
gas costs are moderate

Summary





`datatype@owner`

`eth-sri/zkay`

expressive

moderate costs

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