

Auditable Decentralized Confidential Payment System

Yu Chen
Shandong University

based on works on ESORICS 2020 and FinCrypto 2020 competition

<http://eprint.iacr.org/2019/319>

<https://github.com/yuchen1024/libPGC>

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Outline

- 1 Background
- 2 Framework of Auditable DCP System
- 3 An Efficient Instantiation: PGC
- 4 Experimental Results
- 5 Summary
- 6 Backup
 - Formal Security Model
 - Key Reuse vs. Key Separation
 - Generic Framework and Security Proof

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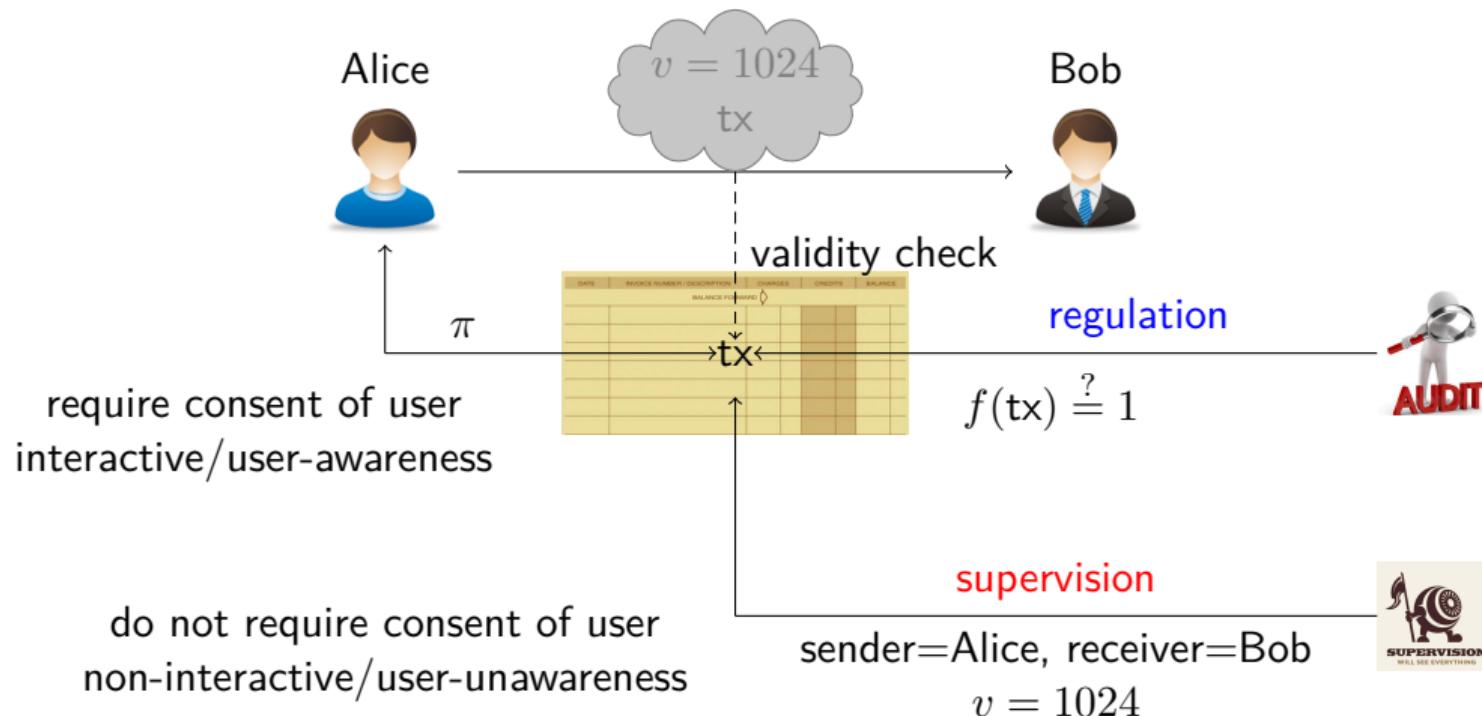
Privacy in Payment System

external observer cannot learn the transfer amount

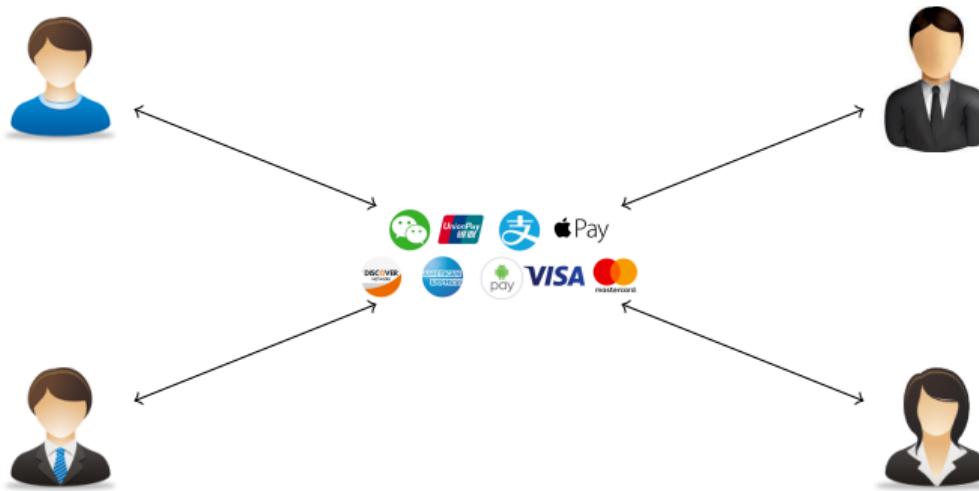


external observer cannot identify the sender and recipient

Auditing in Payment System



Centralized Payment System



- txs are kept on a private ledger only known to the center
- the center is in charge of validity check as well as **protecting privacy** and **conducting audit**

Decentralized Payment System (Blockchain-based Cryptocurrencies)

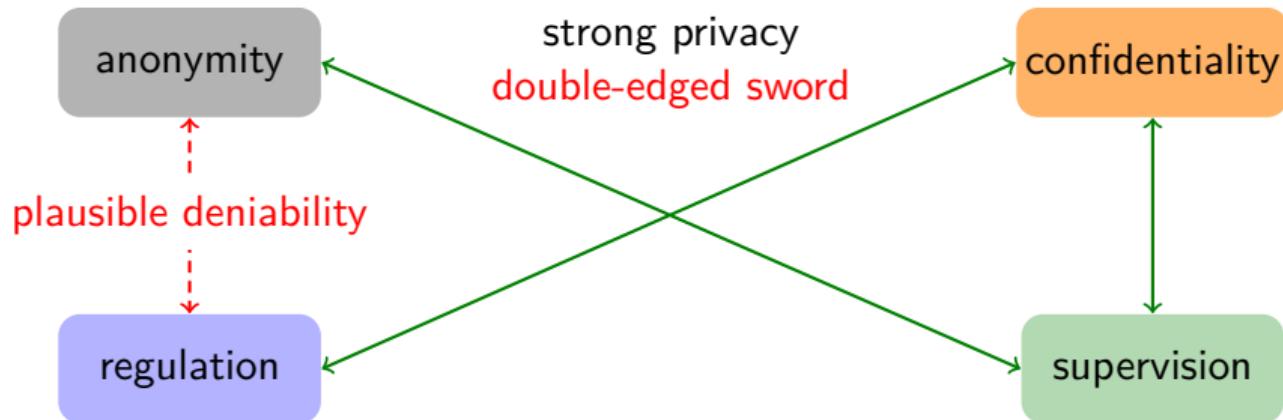


- txs are kept on a global distributed public ledger — the blockchain
- to ensure public verifiability, Bitcoin and Ethereum simply expose all tx information in public \leadsto no privacy

Motivation

Privacy and Auditability are crucial in any financial system, we want to know:

In the decentralized setting, can we have the good of both?



In this work, we trade **anonymity** for **auditing**, propose the first

decentralized **confidential** payment (DCP) system (in the account-based model)
support **regulation** and **supervision**

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Desired Functionality and Security

Verifiability

validity of txs are publicly verifiable

Authenticity

only owner can generate tx; nobody else can forge

Confidentiality

external observer learns the transfer amount

Soundness

nobody cannot generate an illegal tx that passes validity check

Auditability

user cannot cheat and regulation does not leak more info
other than auditing result

Supervision

auditor can see everything, but unable to breach authenticity

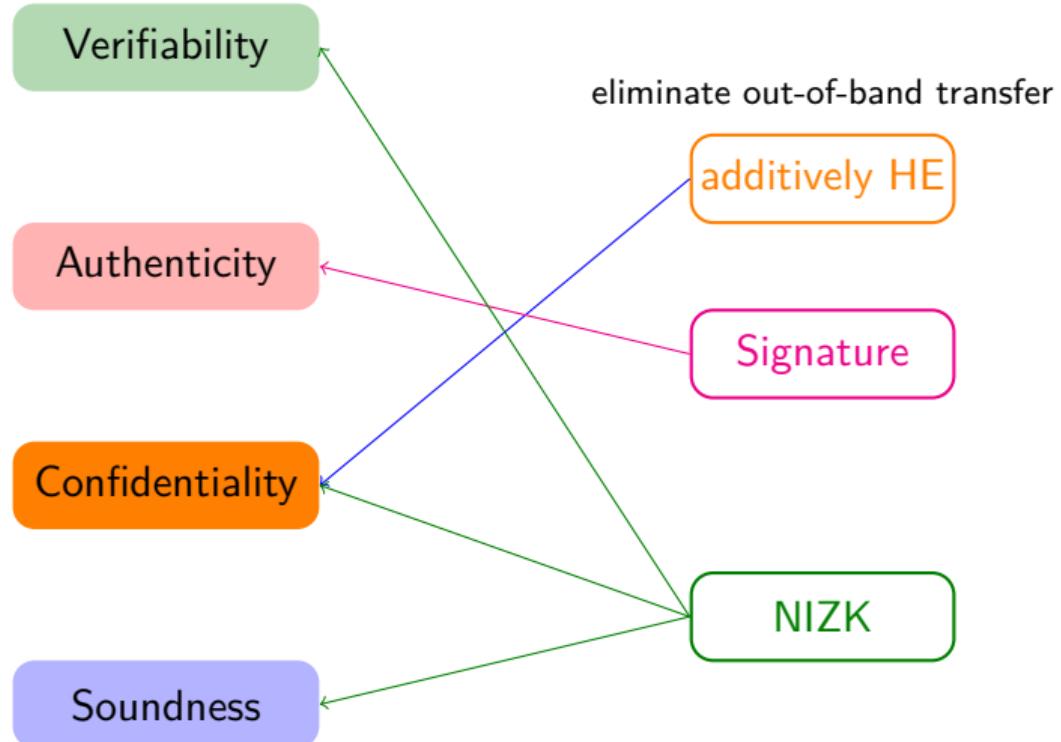
The Devil is in the Details

Formal security model for ADCP is quite challenging

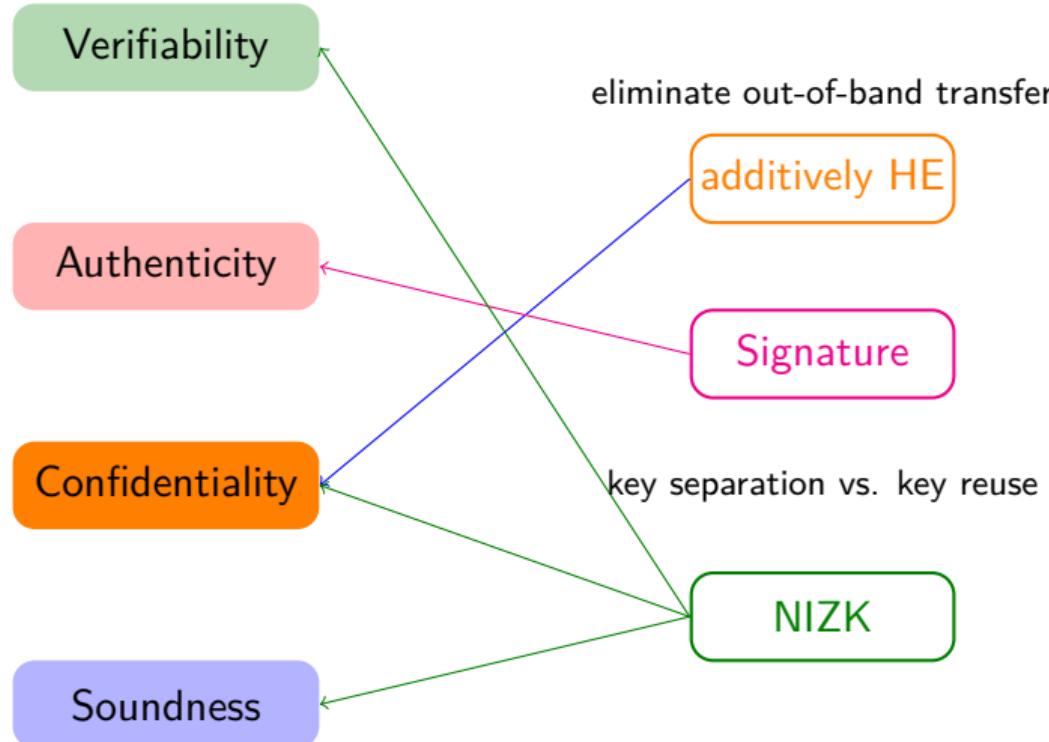
- powerful enough to capture all possible real-world attacks
- clean and handy to use

We refer to the backup slides for the details.

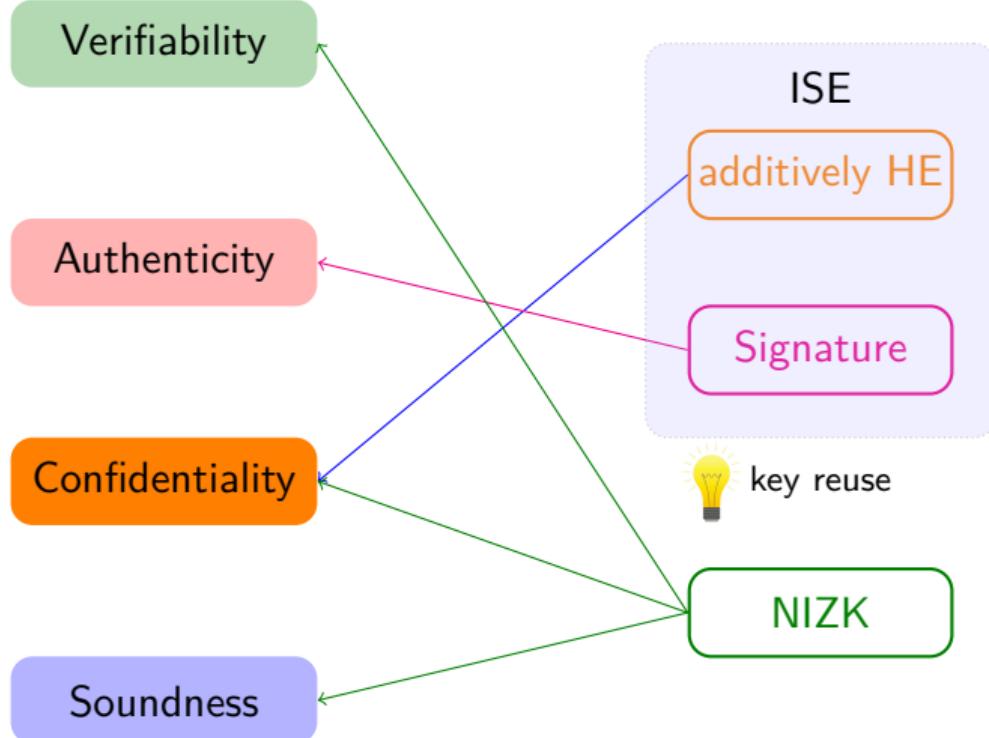
Choice of Building Blocks



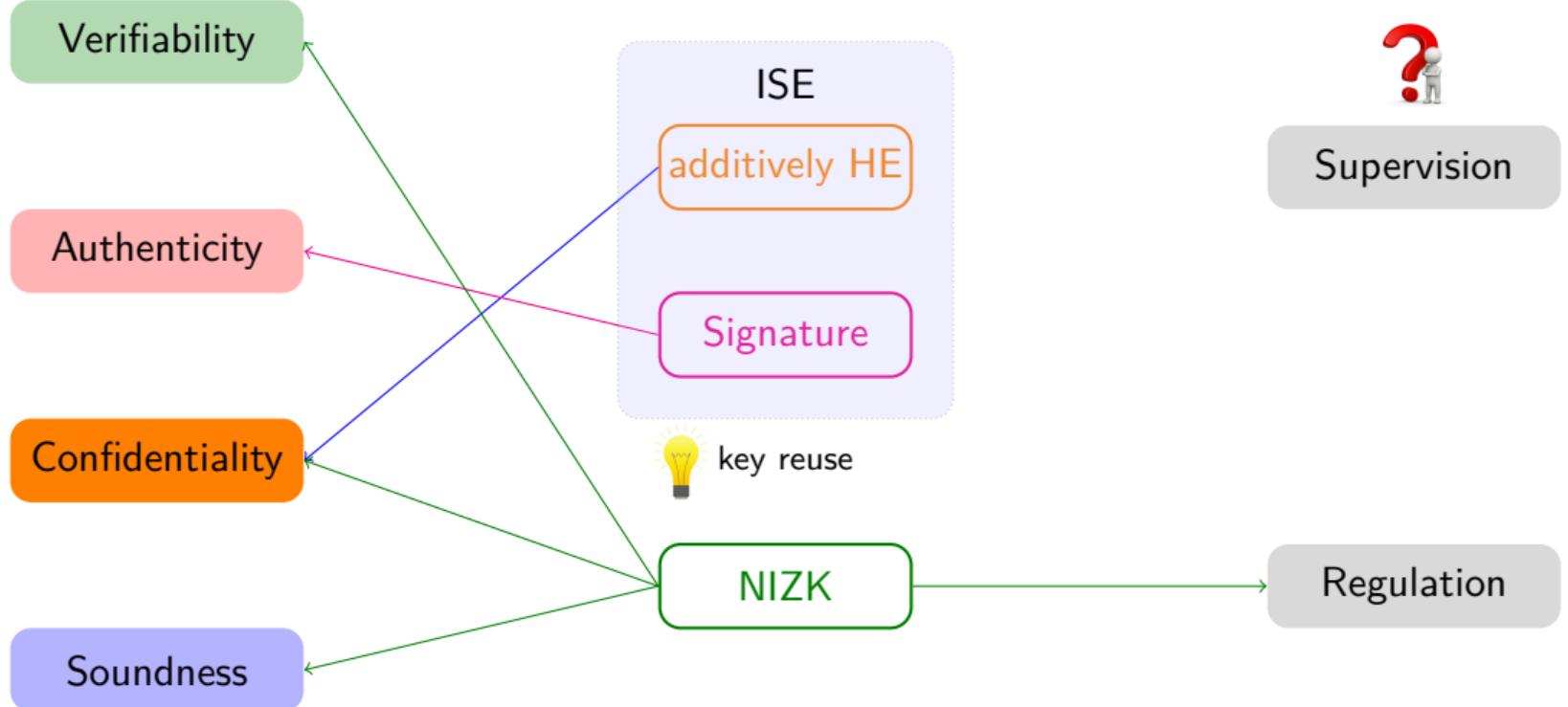
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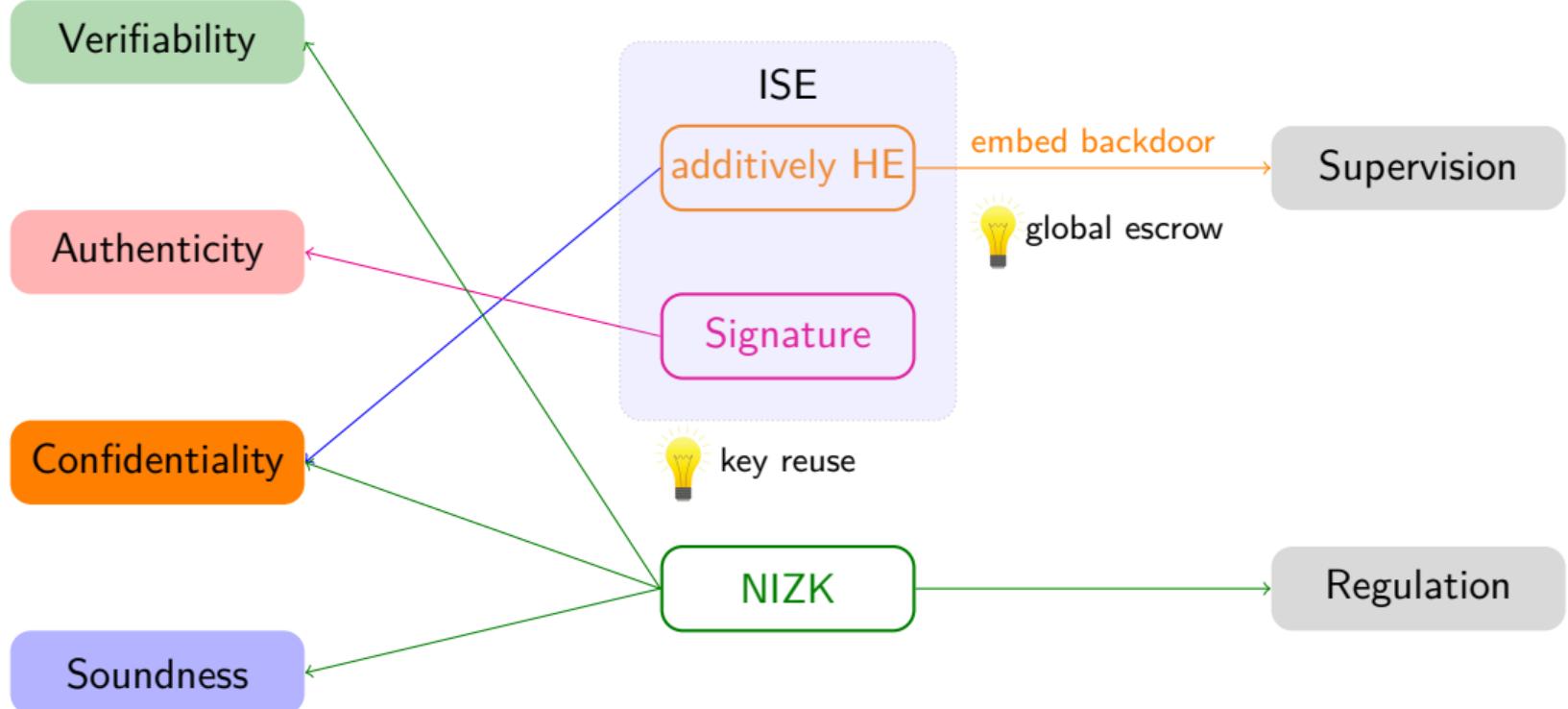
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Choice of Building Blocks



Generic Construction of ADCP

$\text{Setup}(1^\lambda) \rightarrow (pp, sp)$

$\text{ISE}.\text{Setup}(1^\lambda) \rightarrow pp_{\text{ise}}, \text{NIZK}.\text{Setup}(1^\lambda) \rightarrow pp_{\text{nizk}}$
 $\text{ISE}.\text{Gen}(pp_{\text{ise}}) \rightarrow (pk_a, sk_a)$

embed backdoor for supervision

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$\text{CreateAcct}(v_s, \text{sn}_s)$

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 $\text{ISE}.\text{Enc}(pk_s, v_s) \rightarrow \tilde{C}_s$

$pk_s, sk_s, \tilde{C}_s, \text{sn}_s$



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$\text{CreateCTx}(pk_s, sk_s, pk_r, v) \rightarrow \text{ctx}$



$\text{CreateAcct}(v_s, \text{sn}_s)$

$\text{ISE}.\text{Enc} \rightarrow \text{memo} = (pk_s, C_s, pk_r, C_r, pk_a, C_a)$
 $\text{NIZK}.\text{Prove} \rightarrow \pi_{\text{valid}} = \pi_{\text{equal}} \circ \pi_{\text{right}} \circ \pi_{\text{solvent}}$
 $\text{ISE}.\text{Sign}(sk_s, (\text{sn}, \text{memo}, \pi_{\text{valid}})) \rightarrow \sigma$

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$\text{VerifyCTx}(\text{ctx}) \stackrel{?}{=} 1$

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$$pk_s, sk_s, \tilde{C}_s, sn_s \leftarrow \begin{array}{l} \tilde{C}_s = \tilde{C}_s - C_s \\ sn_s ++ \end{array}$$



$$\tilde{C}_r = \tilde{C}_r + C_r \rightarrow pk_r, sk_r, \tilde{C}_r, sn_r$$

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$\text{AuditCTx}(\pi_f, \{\text{ctx}_i\}, f)$

$\text{JustifyCTx}(sk, \{\text{ctx}_i\}, f) \rightarrow \pi_f$



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$\text{AuditCTx}(\pi_f, \{\text{ctx}_i\}, f)$
 $\text{JustifyCTx}(sk, \{\text{ctx}_i\}, f) \rightarrow \pi_f$



$\text{OpenCTx}(sp, \text{ctx}) \rightarrow v$



Regulation

expressiveness of NIZK in use \leadsto supported regulation policies

$$f_{\text{limit}} : \sum_{i=1}^n v_i < \ell$$

anti-money laundering



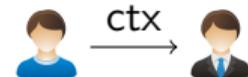
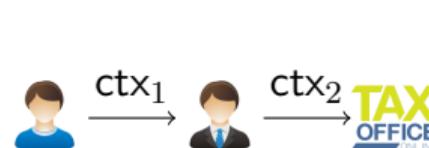
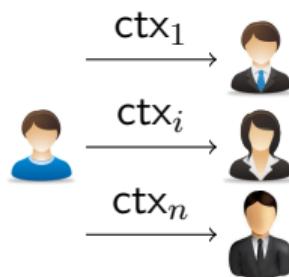
$$f_{\text{rate}} : v_1/v_2 = \rho$$

pay tax



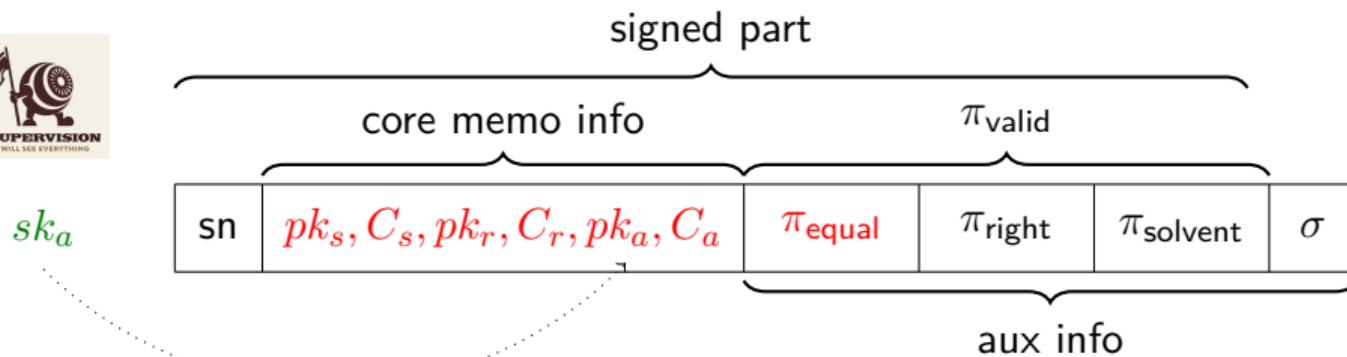
$$f_{\text{open}} : v = v^*$$

selective opening



Supervision

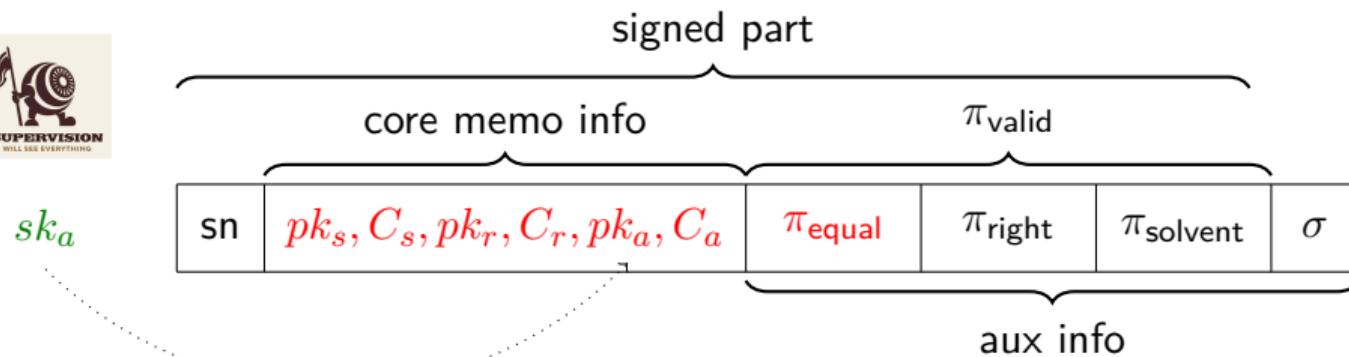
data structure of ctx



Supervision



data structure of ctx



STOC 1990



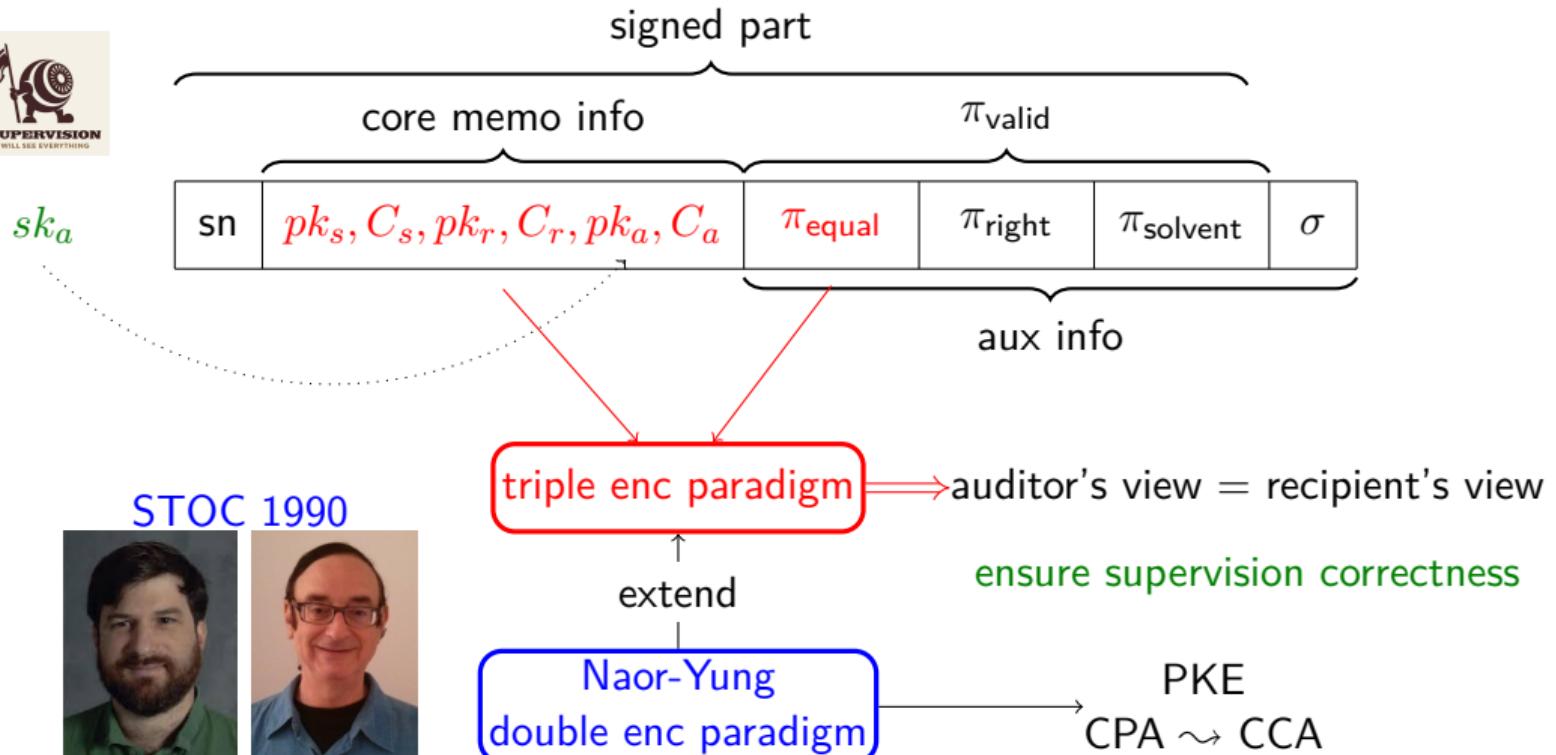
Naor-Yung
double enc paradigm

PKE
CPA \sim CCA

Supervision



data structure of ctx



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Disciplines in Mind

While ADCP framework is intuitive, secure and efficient instantiation requires **clever choice and design** of building blocks.

efficient



efficient ctx generation/verification
compact ctx size

transparent setup



system does not require a trusted setup
design case-tailored NIZK

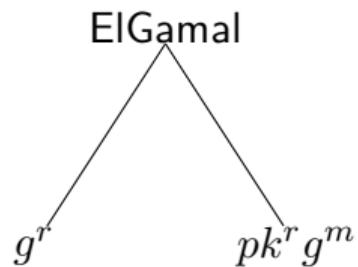
simple & modular



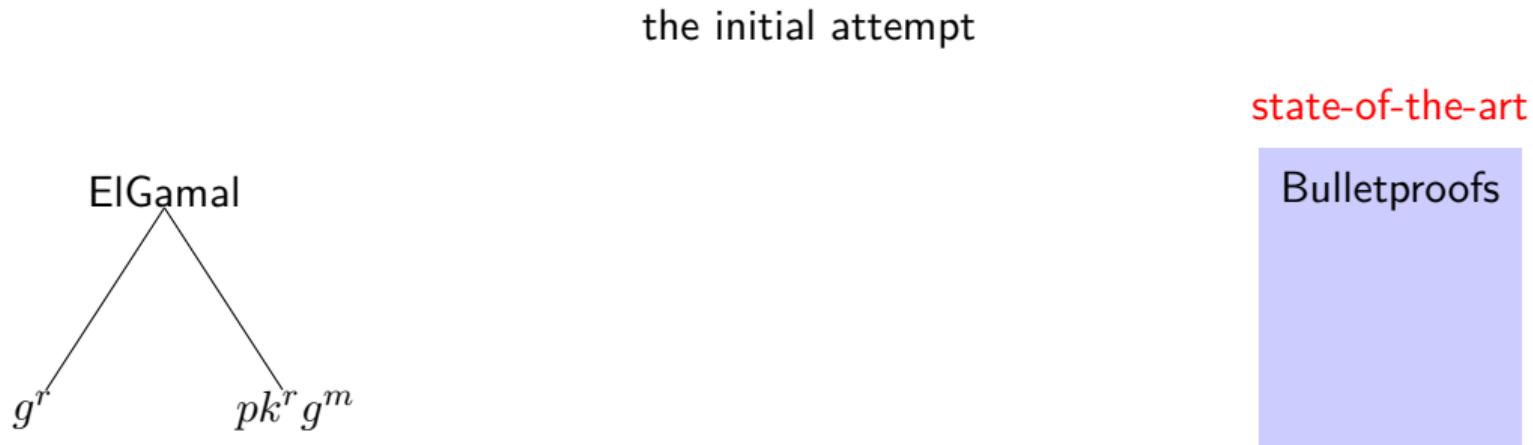
build the system from reusable gadgets
can be reused in other places

Encryption Component of ISE

the initial attempt

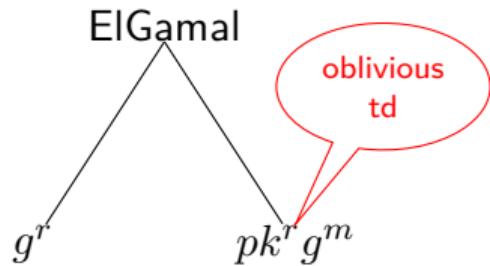


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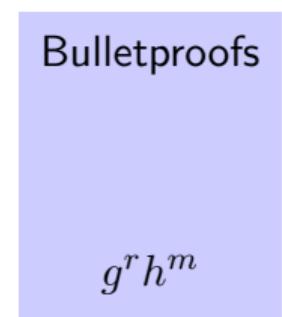


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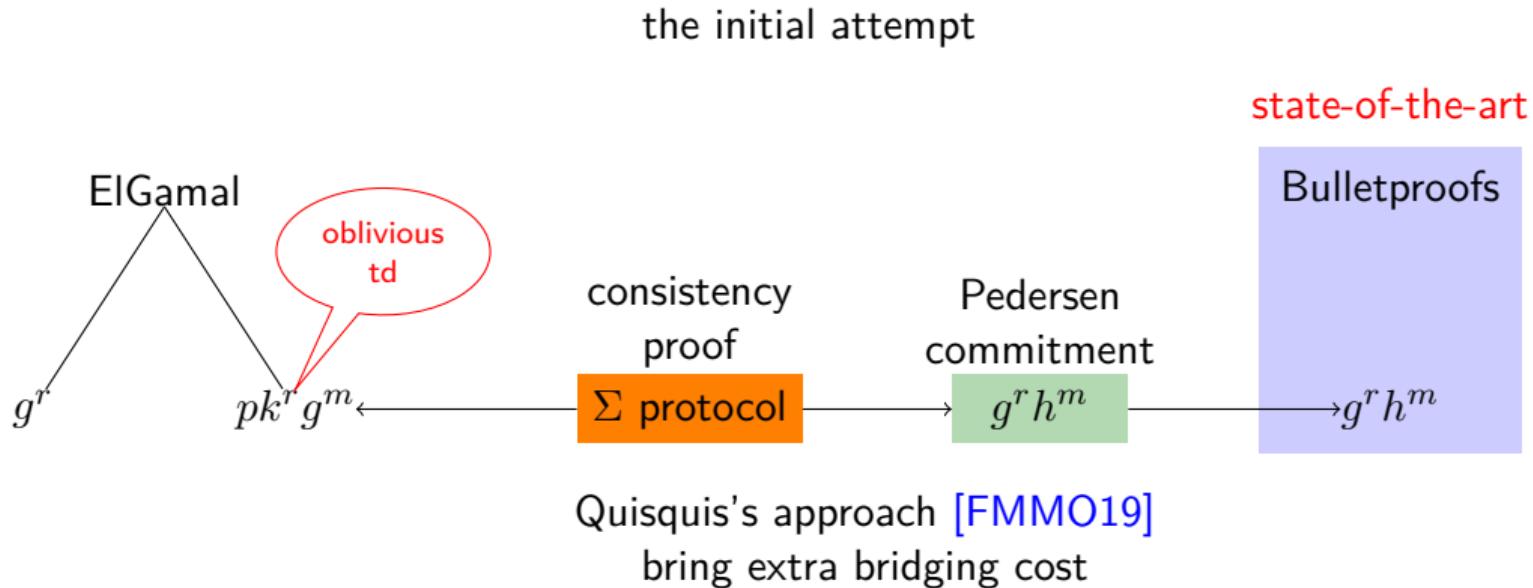
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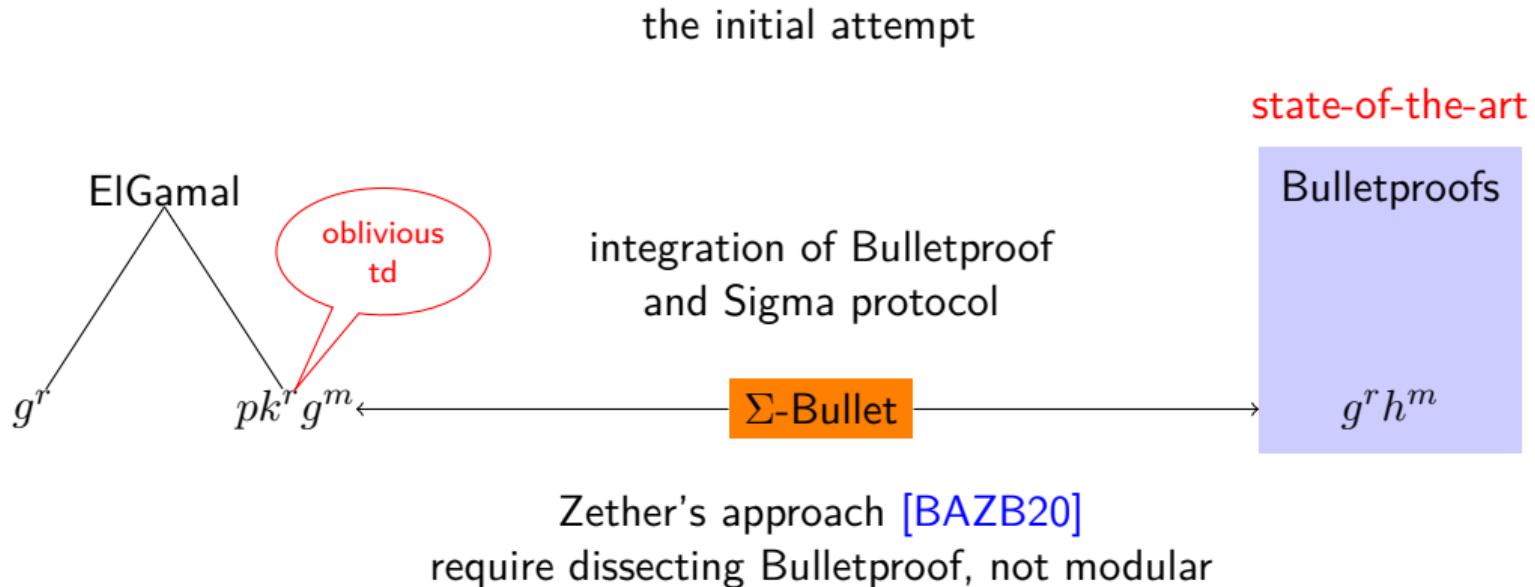
state-of-the-art



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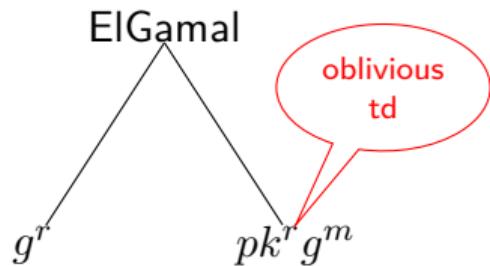


Encryption Component of ISE



Encryption Component of ISE

the initial attempt



state-of-the-art

Bulletproofs

$g^r h^m$

simple and efficient, but not friendly to the state-of-the-art range proofs

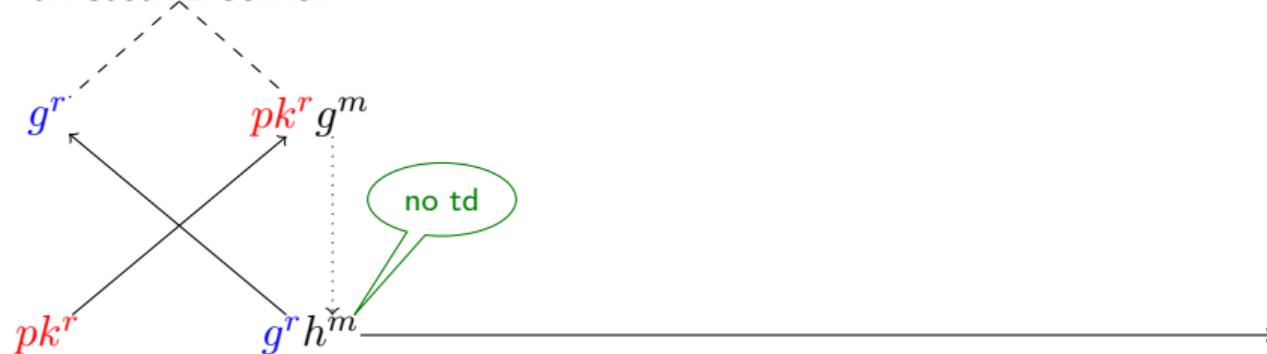
Encryption Component of ISE: Twisted ElGamal

twisted ElGamal

$$g^r \quad \textcolor{red}{pk^r g^m}$$

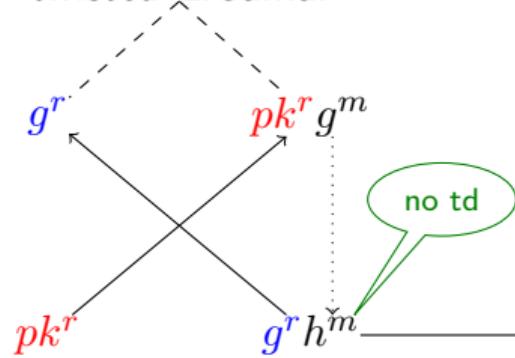
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state-of-the-art

Bulletproofs

$g^r h^m$

Encryption Component of ISE: Twisted ElGamal

twisted ElGamal



- encode message over another generator h
- switch key encapsulation and session key
- advantages
 - ① as secure and efficient as standard ElGamal;
 - ② Bulletproofs-friendly: especially in the aggregated mode
 - ③ also friendly to other range proofs [CCS08, CKLR21] that accept Pedersen commitment as instance

Comparison to ElGamal

| ElGamal | size | | | | efficiency | | |
|----------|-----------------|----------------|------------------|-----------------|------------|-----------|-----------------|
| | pp | pk | sk | C | KeyGen | Enc | Dec |
| standard | $ \mathbb{G} $ | $ \mathbb{G} $ | $ \mathbb{Z}_p $ | $ 2\mathbb{G} $ | 1Exp | 3Exp+2Add | 1Exp+1Add+1DLOG |
| twisted | $2 \mathbb{G} $ | $ \mathbb{G} $ | $ \mathbb{Z}_p $ | $ 2\mathbb{G} $ | 1Exp | 3Exp+2Add | 1Exp+1Add+1DLOG |

Related works [FMMO19, BAZB20] use brute-force algorithm to decrypt, we use Shanks's algorithm to speed decryption \Rightarrow admits flexible time/space trade-off and parallelization!

Table: Costs of working with Bulletproofs between standard ElGamal and twisted ElGamal: an additional Pedersen commitment and a Sigma protocol for consistency.

| ElGamal | size | efficiency |
|----------|----------------------------------|------------|
| standard | $2 \mathbb{G} + \mathbb{Z}_p $ | 4Exp+1Add |
| twisted | 0 | 0 |

the saving could be tremendous when processing millions of data

Comparison to Paillier

Table: Twisted ElGamal vs. Paillier PKE (32-bit message space and 128-bit security)

| timing (ms) | Setup | KeyGen | Enc | Dec | ReRand | Add | Sub | Scalar |
|-------------|--------|---------|--------|--------|--------|--------|--------|--------|
| Paillier | — | 1644.53 | 32.211 | 31.367 | — | 0.0128 | — | — |
| t-ElGamal | 21s+6s | 0.0151 | 0.114 | 1 | 0.157 | 0.0031 | 0.0042 | 0.093 |

4 ~ 300× speed up in computation efficiency

| size (bytes) | public parameters | public key | secret key | ciphertext |
|--------------|-------------------|------------|------------|------------|
| Paillier | — | 384 | 384 | 768 |
| t-ElGamal | 66 | 33 | 32 | 66 |

10× speed up in communication cost

Signature Component of ISE

We choose Schnorr signature as the signature component.

- ① Setup and KeyGen of Schnorr signature are identical to those of twisted ElGamal.
key reuse strategy ✓
- ② Sign of Schnorr signature is irrelevant to Decrypt of twisted ElGamal:
 - $\text{Sign}(sk, m)$: pick $r \xleftarrow{R} \mathbb{Z}_p$, set $A = g^r$, compute $e = H(m, A)$, $z = r + sk \cdot e \bmod p$, output $\sigma = (A, z)$.

recall Schnorr signature is provably secure by modeling H as RO: simulating signature oracle by programming H without using $sk \Rightarrow$ signatures reveals zero-knowledge of sk

joint security ✓

We can also use ECDSA/SM2 signature schemes.

NIZK for L_{equal}

According to our ADCP framework and twisted ElGamal, L_{equal} can be written as:

$$\{(pk_i, X_i, Y_i)_{i \in [3]} \mid \exists r_1, r_2, r_3, v \text{ s.t. } X_i = pk_i^{r_i} \wedge Y_i = g^{r_i} h^v \text{ for } i = 1, 2, 3\}.$$

On statement $(pk_i, X_i, Y_i)_{i \in [3]}$, P and V interact as below:

- ① P picks $a, b \xleftarrow{\text{R}} \mathbb{Z}_p$, sends $A_i = pk_i^{a_i}$, $B = g^a h^b$ to V .
- ② V picks $e \xleftarrow{\text{R}} \mathbb{Z}_p$ and sends it to P as the challenge.
- ③ P computes $z_i = a + er_i$ for $i \in [3]$ and $t = b + ev$ using $w = (r_1, r_2, r_3, v)$, then sends (z_1, z_2, z_3, t) to V . V accepts iff the following four equations hold simultaneously:

$$pk_i^{z_i} = A_i X_i^e \tag{1}$$

$$g^{z_1} h^t = B Y_1^e \tag{2}$$

NIZK for L_{right}

According to our ADCP framework and twisted ElGamal, L_{right} can be written as:

$$\{(pk, X, Y) \mid \exists r, v \text{ s.t. } X = pk^r \wedge Y = g^r h^v \wedge v \in \mathcal{V}\}.$$

For ease of analysis, we additionally define L_{enc} and L_{range} as below:

$$L_{\text{enc}} = \{(pk, X, Y) \mid \exists r, v \text{ s.t. } X = pk^r \wedge Y = g^r h^v\}$$
$$L_{\text{range}} = \{Y \mid \exists r, v \text{ s.t. } Y = g^r h^v \wedge v \in \mathcal{V}\}$$

It is straightforward to verify that $L_{\text{right}} \subset L_{\text{enc}} \wedge L_{\text{range}}$.

- Σ_{enc} : Sigma protocol for L_{enc}
- Λ_{bullet} : Bulletproofs for L_{range}

DL relation between (g, h) is hard $\Rightarrow \Sigma_{\text{enc}} \circ \Lambda_{\text{bullet}}$ is SHVZK PoK for L_{right}

NIZK for L_{solvent}

According to our ADCP framework, L_{solvent} can be written as:

$$\{(pk, \tilde{C}, C) \mid \exists sk \text{ s.t. } (pk, sk) \in R_{\text{key}} \wedge \text{ISE.Dec}(sk, \tilde{C} - C) \in \mathcal{V}\}.$$

$\tilde{C} = (\tilde{X} = pk^{\tilde{r}}, \tilde{Y} = g^{\tilde{r}}h^{\tilde{m}})$ encrypts \tilde{m} of pk under \tilde{r} , $C = (X = pk^r, Y = g^r h^v)$ encrypts v under r . Let $C' = (X' = pk^{r'}, Y' = g^{r'} h^{m'}) = \tilde{C} - C$, L_{solvent} can be rewritten as:

$$\{(pk, C') \mid \exists r', m' \text{ s.t. } C' = \text{ISE.Enc}(pk, m'; r') \wedge m' \in \mathcal{V}\}.$$

Prove it as L_{right} ? No! r' is unknown.

Solution: refresh-then-prove

- ① refresh C' to C^* under fresh randomness $r^* \Leftarrow$ can be done with sk
- ② prove $(C', C^*) \in L_{\text{equal}} \Leftarrow$ Sigma protocol Σ_{ddh} (do not need r')
- ③ prove $C^* \in L_{\text{right}}$

Bonus: two useful proof gadgets

twisted ElGamal + Bulletproofs: prove an encrypted message lies in specific range

- extremely useful in privacy-preserving applications: confidential transaction and secure machine learning

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-

$$pk^r \quad g^r h^m$$

prover is the sender of C

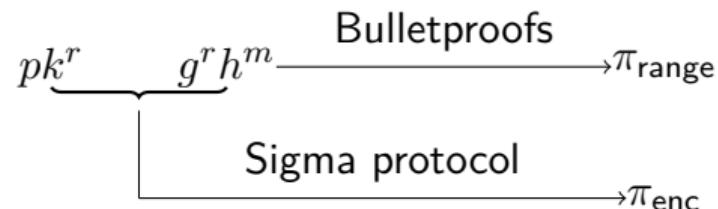
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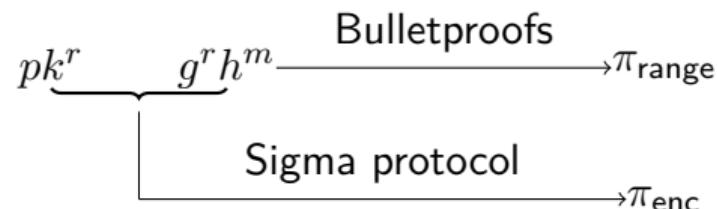


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twisted ElGamal + Bulletproofs: prove an encrypted message lies in specific range

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prover is the sender of C
knows both r and m



$$pk^{\boxed{r}} \quad g^{\boxed{r}} h^m$$

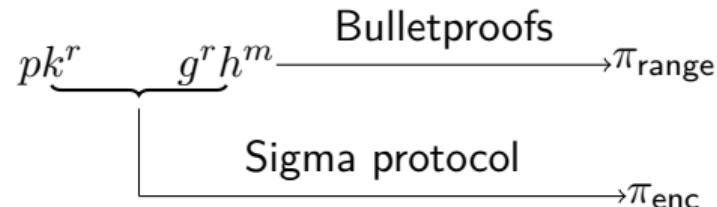
prover is the receiver of C
knows sk and thus m

Bonus: two useful proof gadgets

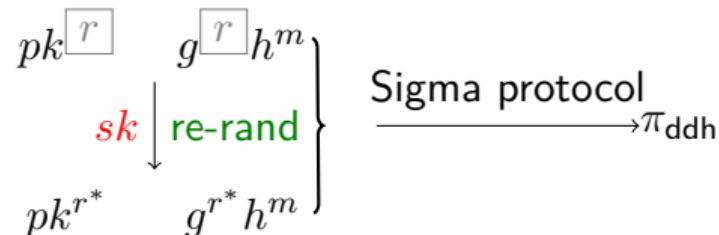
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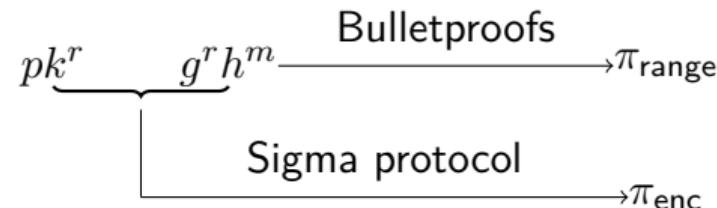


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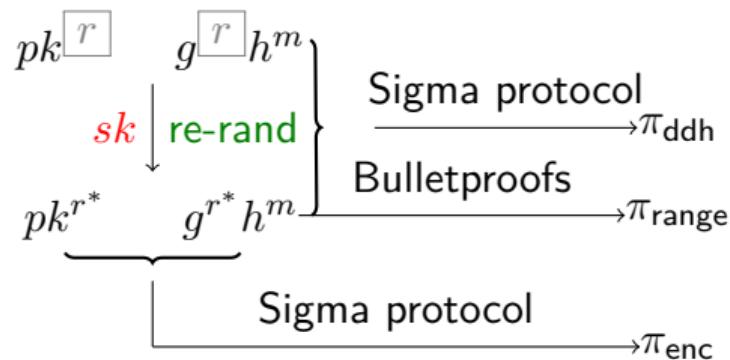
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NIZK for Auditing Policies: (1/2)

$$L_{\text{limit}} = \{(pk, \{C_i\}_{1 \leq i \leq n}, a_{\max}) \mid \exists sk \text{ s.t.} \\ (pk, sk) \in R_{\text{key}} \wedge v_i = \text{ISE.Dec}(sk, C_i) \wedge \sum_{i=1}^n v_i \leq a_{\max}\}$$

P computes $C = \sum_{i=1}^n C_i$, proves $(pk, C) \in L_{\text{solvent}}$ using Gadget-2

$$L_{\text{open}} = \{(pk, C = (X, Y), v) \mid \exists sk \text{ s.t. } X = (Y/h^v)^{sk} \wedge pk = g^{sk}\}$$

$(pk, X, Y, v) \in L_{\text{open}}$ is equivalent to $(Y/h^v, X, g, pk) \in L_{\text{ddh}}$.

NIZK for Auditing Policies: (2/2)

$$L_{\text{rate}} = \{(pk, C_1, C_2, \rho) \mid \exists sk \text{ s.t.} \\ (pk, sk) \in R_{\text{key}} \wedge v_i = \text{ISE.Dec}(sk, C_i) \wedge v_1/v_2 = \rho\}$$

We assume $\rho = \alpha/\beta$, where α, β are positive integer much smaller than p .

Let $C_1 = (pk^{r_1}, g^{r_1}h^{v_1})$, $C_2 = (pk^{r_2}, g^{r_2}h^{v_2})$. P computes

$$C'_1 = \beta \cdot C_1 = (X'_1 = pk^{\beta r_1}, Y'_1 = g^{\beta r_1}h^{\beta v_1}) \\ C'_2 = \alpha \cdot C_2 = (X'_2 = pk^{\alpha r_2}, Y'_2 = g^{\alpha r_2}h^{\alpha v_2})$$

Note $v_1/v_2 = \rho = \alpha/\beta$ iff $h^{\beta v_1} = h^{\alpha v_2}$. $(pk, C_1, C_2, \rho) \in L_{\text{rate}}$ is equivalent to $(Y'_1/Y'_2, X'_1/X'_2, g, pk) \in L_{\text{ddh}}$.

Thanks to nice algebra structure of twisted ElGamal, PGC supports efficient auditing for any policy that can be expressed as linear constraint over transfer amount and balance

Optimizations

| | | | |
|----|-----------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------|
| sn | $pk_s, C_s, pk_r, C_r, pk_a, C_a$ | $\pi_{\text{equal}} \circ (\pi_{\text{enc}}^1 \circ \pi_{\text{bullet}}^1) \circ (C^* \circ \pi_{\text{ddh}} \circ \pi_{\text{enc}}^2 \circ \pi_{\text{bullet}}^2)$ | σ |
|----|-----------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------|

Optimizations

randomness reuse

↓

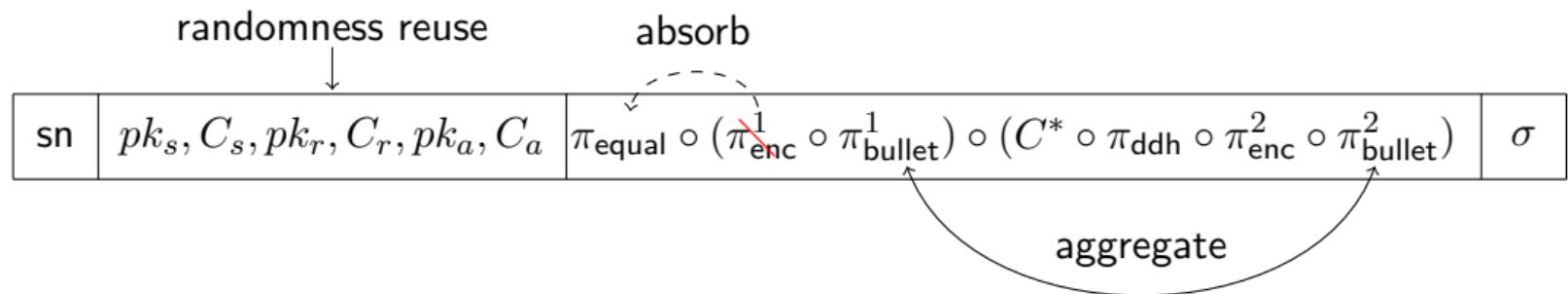
| | | | |
|----|-----------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------|
| sn | $pk_s, C_s, pk_r, C_r, pk_a, C_a$ | $\pi_{\text{equal}} \circ (\pi_{\text{enc}}^1 \circ \pi_{\text{bullet}}^1) \circ (C^* \circ \pi_{\text{ddh}} \circ \pi_{\text{enc}}^2 \circ \pi_{\text{bullet}}^2)$ | σ |
|----|-----------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------|

Randomness-Reusing

- original construction encrypts the same message v under pk_i ($i = \{s, r, a\}$) using independent random coins: $(pk_s, pk_s^{r_1}, g^{r_1} h^v, pk_r, pk_r^{r_2}, g^{r_2} h^v, pk_a, pk_a^{r_3}, g^{r_3} h^v)$
- twisted ElGamal is IND-CPA secure in 1-message/3-recipient setting
even when reusing randomness $\Rightarrow (pk_s, pk_s^r, pk_r, pk_r^r, pk_a, pk_a^r, [g^r h^v])$

Benefit: compact ctx size & simpler design of Σ_{enc}

Optimizations

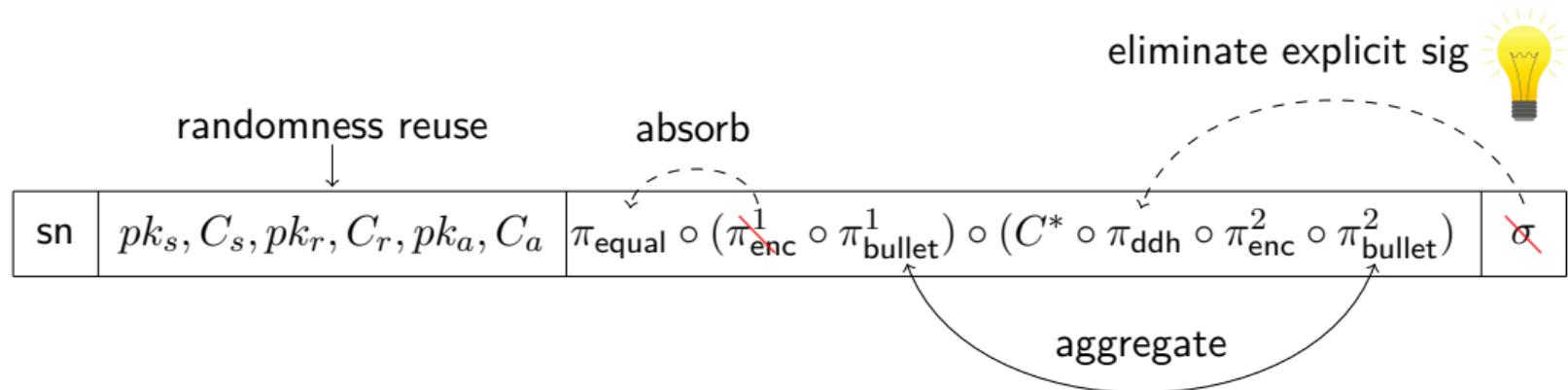


More Efficient Assembly of NIZK

- π_{enc} can be removed since π_{equal} already proves knowledge of C_s
- nice feature of twisted ElGamal \Rightarrow two Bulletproofs can be generated and verified in aggregated mode \leadsto reduce the size of range proof part by half

Benefit: further shrink the ctx size

Optimizations

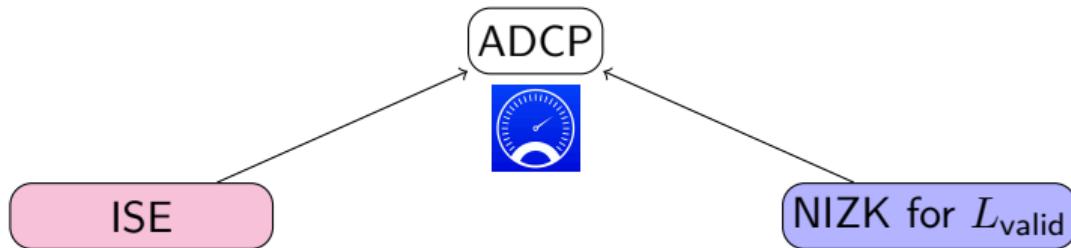


Eliminate Explicit Signature

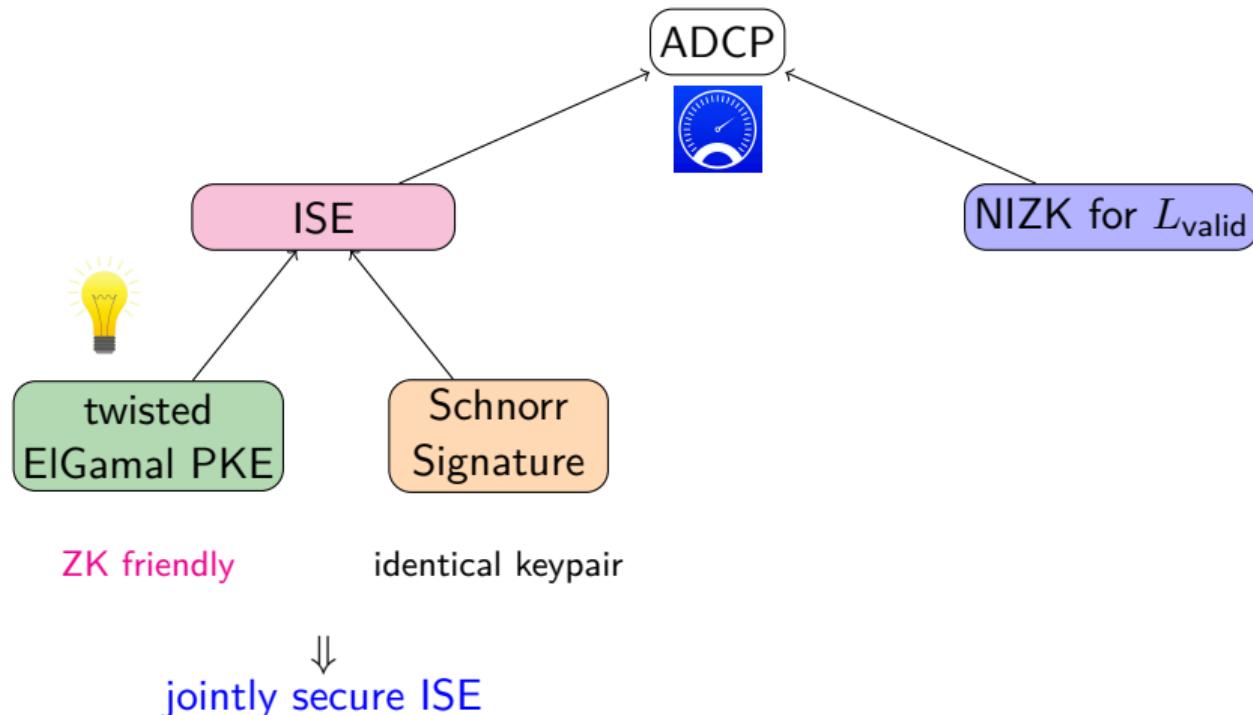
- Σ_{ddh} (3-move public-coin ZKPoK of sk_1) is a sub-protocol of NIZK for L_{solvent}
- apply the Fiat-Shamir transform by appending the rest part to hash input $\sim \pi_{\text{ddh}}$ serves as both a proof of DDH tuple and a sEUF-CMA signature of ctx (jointly secure with twisted ElGamal)

Benefit: further shrink the ctx size & speed ctx generation/verification

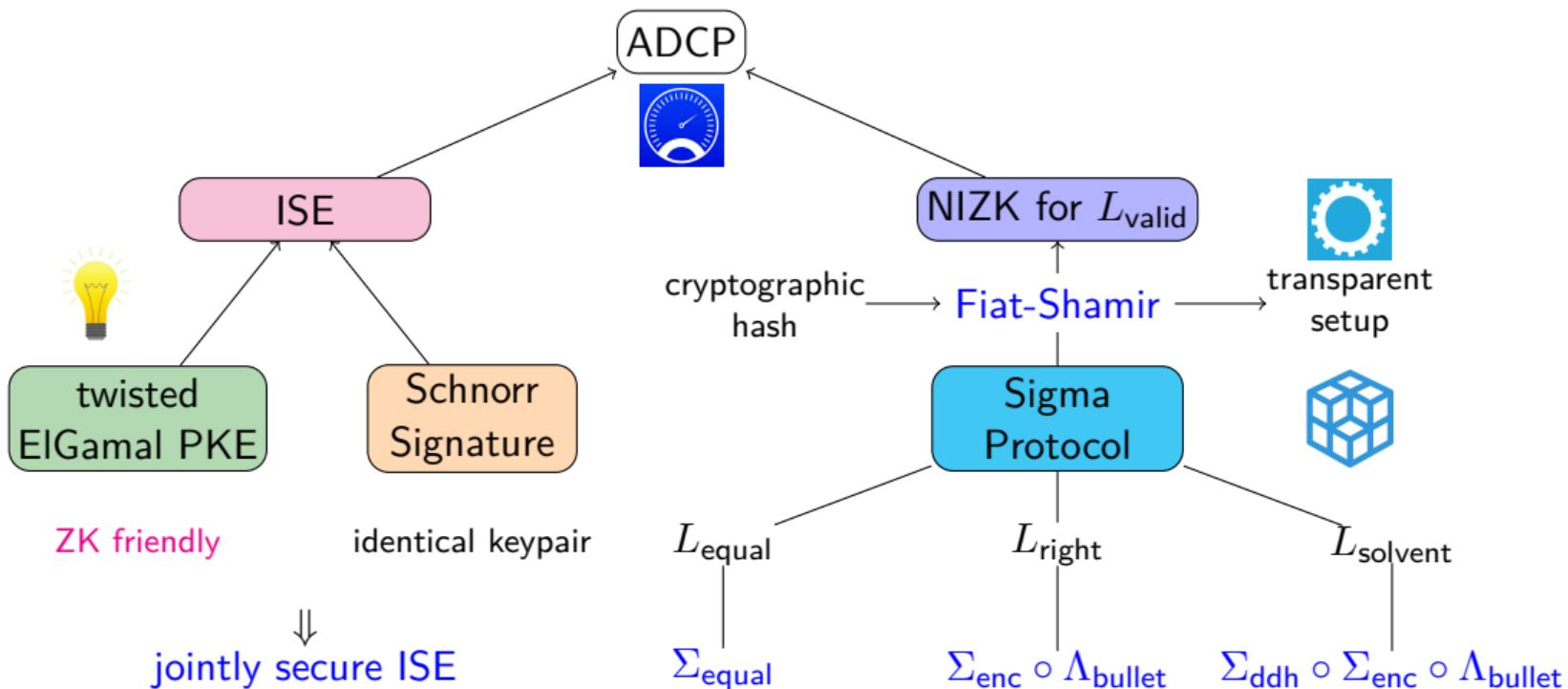
Recap of Efficient Instantiation



Recap of Efficient Instantiation



Recap of Efficient Instantiation



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Deploy as Cryptocurrency

Table: The computation and communication complexity of ADCP.

| ADCP | ctx size | | transaction cost (ms) | |
|--------------|--------------------------------------------------------|-------|-----------------------|--------|
| | big- \mathcal{O} | bytes | generation | verify |
| transaction | $(2 \log_2(\ell) + 22) \mathbb{G} + 11 \mathbb{Z}_p $ | 1408 | 42 | 15 |
| regulation | proof size | | auditing cost (ms) | |
| | big- \mathcal{O} | bytes | generation | verify |
| limit policy | $(2 \log_2(\ell) + 4) \mathbb{G} + 5 \mathbb{Z}_p $ | 622 | 21.5 | 7.5 |
| rate policy | $2 \mathbb{G} + 1 \mathbb{Z}_p $ | 98 | 0.55 | 0.69 |
| open policy | $2 \mathbb{G} + 1 \mathbb{Z}_p $ | 98 | 0.26 | 0.42 |
| supervision | opening $\leq 1\text{ms}$ | | | |

- Set $v_{\max} = 2^\ell - 1$, where $\ell = 32$
- Choose EC curve prime256v1 (128 bit security), $|\mathbb{G}| = 33$ bytes, $|\mathbb{Z}_p| = 32$ bytes.
- MacBook Pro [Intel i7-4870HQ CPU (2.5GHz), 16GB of RAM]

```
Build test enviroment for SDCT >>>
```

```
Setup SDCT system
```

```
Initialize SDCT >>>
```

```
Initialize Twisted ElGamal >>>
```

```
hash map does not exist, begin to build and serialize >>>
```

```
hash map building and serializing takes time = 22646.1 ms
```

```
hash map already exists, begin to load and rebuild >>>
```

```
hash map loading and rebuilding takes time = 6357.54 ms
```

```
Generate two accounts
```

```
Alice's account creation succeeds
```

```
pk = 043764DF55F2F38822FB6367672976107E2EA292C7B51B1FDEF89CD4ABD233A2C4666FB834156DA51139
```

```
AFAAA40C20ACA5B
```

```
Alice's initial balance = 512
```

```
Bob's account creation succeeds
```

```
pk = 04D6F787C791C27900AFB9B883B12495249C25A37AD1AC3FCAD8D9E22AB1138D30F16E509D2B86299B12
```

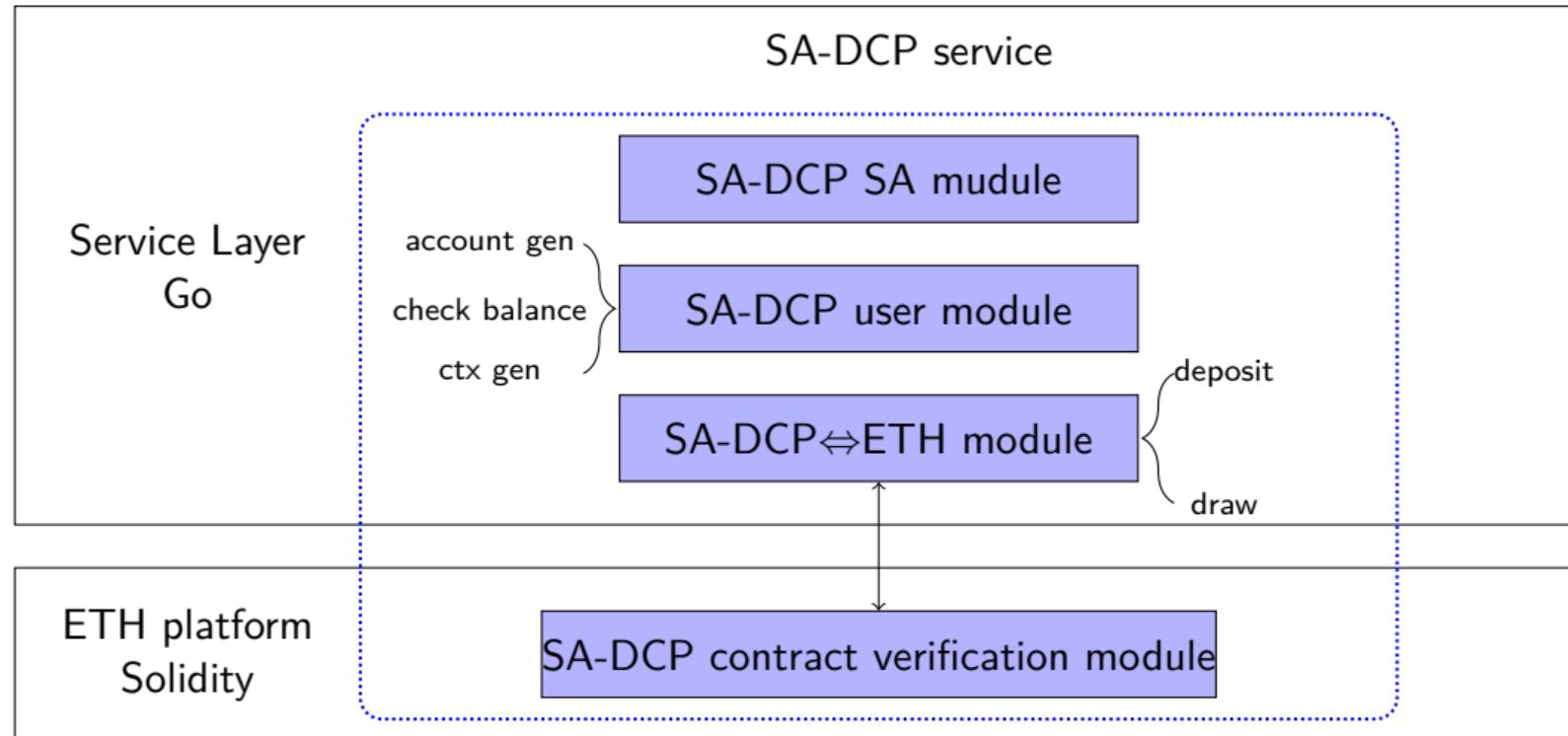
```
AD396330A282586
```

```
Bob's initial balance = 256
```

| | |
|---|------------------------------|
| ✓ | SDCT-CRYPTOCURRENCY |
| > | build |
| └ | depends |
| └ | bulletproofs |
| └ | aggregate_bulletproof.hpp |
| └ | innerproduct_proof.hpp |
| └ | common |
| └ | global.hpp |
| └ | hash.hpp |
| └ | print.hpp |
| └ | routines.hpp |
| └ | nizk |
| └ | nizk_dlog_equality.hpp |
| └ | nizk_plaintext_equality.hpp |
| └ | nizk_plaintext_knowledge.hpp |
| └ | sm |
| └ | sm3hash.hpp |
| └ | twisted_elgamal |
| └ | calculate_dlog.hpp |
| └ | twisted_elgamal.hpp |
| └ | src |
| └ | SDCT.hpp |
| └ | test |
| └ | CMakeLists.txt |
| └ | LICENSE |
| └ | README_cn.md |
| └ | README_cn.pdf |
| └ | README_en.md |

Deploy as a Service

provide **auditable confidential transaction service** for ETH platform.



experimental result on ETH Ganache 2.4.0 ~ SA-DCP service is practical

The screenshot shows the Geth UI interface with the following sections:

- ACCOUNTS**: Shows the current block (0), gas price (0), gas limit (8000000), hardfork (MUIRGLEACIER), network ID (5777), RPC server (HTTP://127.0.0.1:8545), and mining status (AUTOMINING).
- BLOCKS**
- TRANSACTIONS**
- CONTRACTS**
- EVENTS**
- LOGS**
- SEARCH FOR BLOCK NUMBERS OR TX HASHES**: A search bar with a magnifying glass icon.
- WORKSPACE**: Includes a **QUICKSTART** button, a **SAVE** button, a **SWITCH** button, and a gear icon for settings.

MNEMONIC ?

three stock swap matter mutual okay virus guess river behave recall decrease

HD PATH

m/44'/60'/0'/0/account_index

| ADDRESS | BALANCE | TX COUNT | INDEX | |
|--------------------------------------------|------------|----------|-------|---|
| 0xe0CC6D58A344734b9A3e5179C769D005F72BF6C3 | 128.00 ETH | 0 | 0 | 🔑 |
| 0x7402b27f057Cb618F7652d8365e1a3741cC857c6 | 128.00 ETH | 0 | 1 | 🔑 |
| 0x6d7b442e2dA5Ab6e84EF6Ea07BAC0e03e4087bD4 | 128.00 ETH | 0 | 2 | 🔑 |

INFO[06-06|20:45:36] CTx transfer **token**=0x00000000000000000000000000000000

amount=128 **gas**=2537804 **tx**=0xb8e319158cf2996555a50f15e13069b811e85991d856a061abe00f4b5c8d4a3

CTx transfer succeeds: Carol transfer 128 coins to Bob

Carol's current balance 0

Bob's current balance 256

INFO[06-06|20:45:43] CTx transfer **token**=0x00000000000000000000000000000000

amount=128 **gas**=2499341 **tx**=0x58d522f75b0ab940ae0f47eb8c63bf85f89f9be5e4e035370cde0a45c3bc2416

CTx transfer succeeds: Bob transfer 128 coins to Alice

Bob's current balance 128

Alice's current balance 256

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Comparison to Related Works

Table: Comparison to other account-based DCP

| Scheme | transparent setup | scalability | confidentiality | anonymity | regulation | supervision |
|----------|-------------------|-------------|-----------------|-----------|-------------|-------------|
| zkLedger | ✓ + DL | $O(n)$ | ? | ✓ | $O(m, f)$ | ✗ |
| Zether | ✓ + DL | $O(1)$ | ✓ | ✓ | ? | ✗ |
| ADCP | ✓ + DL | $O(1)$ | ✓ | ✗ | $O(f)$ | ✓ |

- n is the number of system users, m is the number of all transactions on the ledger
- zkLedger [NVV18]: (i) ctx size is linear of n , and n is fixed at the very beginning. (ii) confidentiality is questionable due to the use of correlated randomness; (iii) audit efficiency is linear of both m and $|f|$ due to anonymity
- Zether [BAZB20]: (i) possibly support audit when sacrificing anonymity; (ii) security of ZKP is hard to check

Summary

We propose a framework of ADCP from ISE and NIZK **with formal security model and rigorous proof**

- provide strong privacy and security guarantees for normal users
- provide handlers to conduct regulation and supervision for authority

We instantiate the ADCP by carefully designing and combining cryptographic primitives \leadsto PGC

- transparent setup, security solely based on the DLOG assumption
- modular, simple and efficient

Highlights

- twisted ElGamal: efficient, homomorphic and zero-knowledge proof friendly \leadsto a good alternative to **ISO standard HE schemes**: ElGamal and Paillier
- two proof gadgets: widely applicable in privacy-preserving scenarios, e.g. secure machine learning

History of This Work

2019.01: run out of ideas, begin to investigate cryptocurrency

2019.02: brain storming, solve a bunch of technical difficulties

- a simple twist \Rightarrow twisted ElGamal

2019.03: finish a rush draft

2019.04-05: finish demo code based on MIRACL

2019.06-07: finish the security proofs of ZK part

2019.08-09: rewrite the demo code based on OpenSSL

2020.06: ESORICS 2020

2020.09-11: figure out how to conduct supervision, attend 1st FinCrypto competition

CISC 2019

Challenge1

Champion (\$3000)

Team Mugiwara, Zhicong Huang from Alibaba Group

Runner Up (\$1000)

Team Kunlun: Yu Chen from Ant Financial

3rd Place (\$500)

(Vacancy)

CISC 2019



ESORICS 2020

PGC: Decentralized Confidential Payment System with Auditability

Yi Chen^{1,2,3*}, Xianglong He⁴, Cheng Tang⁵, and Hua Bi^{1,2,3}
¹ School of Cyber Science and Technology, China University of Geosciences, Beijing, 100083, China
² State Key Laboratory of Geospatial Information Engineering, China University of Geosciences, Beijing, 100083, China
³ Ministry of Education Key Laboratory of Geo-spatial Information Engineering, China University of Geosciences, Beijing, 100083, China
⁴ State Key Laboratory of Information Security, Institute of Computing Technology, Chinese Academy of Sciences, Beijing, 100190, China
⁵ Chinese Academy of Sciences, Beijing, 100083, China
✉ bihua@cup.edu.cn
* Corresponding author.
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首届金融密码杯 (3/205)



Foteini Baldimtsi @ GMU



We note that zkLedger [51] uses Pedersen commitments but overlooks the connection with twisted ElGamal. A proper use of twisted ElGamal in zkLedger can lead to optimizations as discussed in detail in Appendix D.

By using twisted ElGamal [25], MINILEDGER is fully-compatible with Bulletproofs [17] which can further reduce its concrete storage requirements.

different public keys. PGC is one of the few works that recognizes the problem of efficient small *dlog* lookup tables, and while it highlights the greater efficiency of heuristic approaches like *kangaroo*, it still opts for Shanks to enable easy amortization for the time-space tradeoff and parallelization. In their proof of

Thanks for Your Attention!

Any Questions?

Reference I

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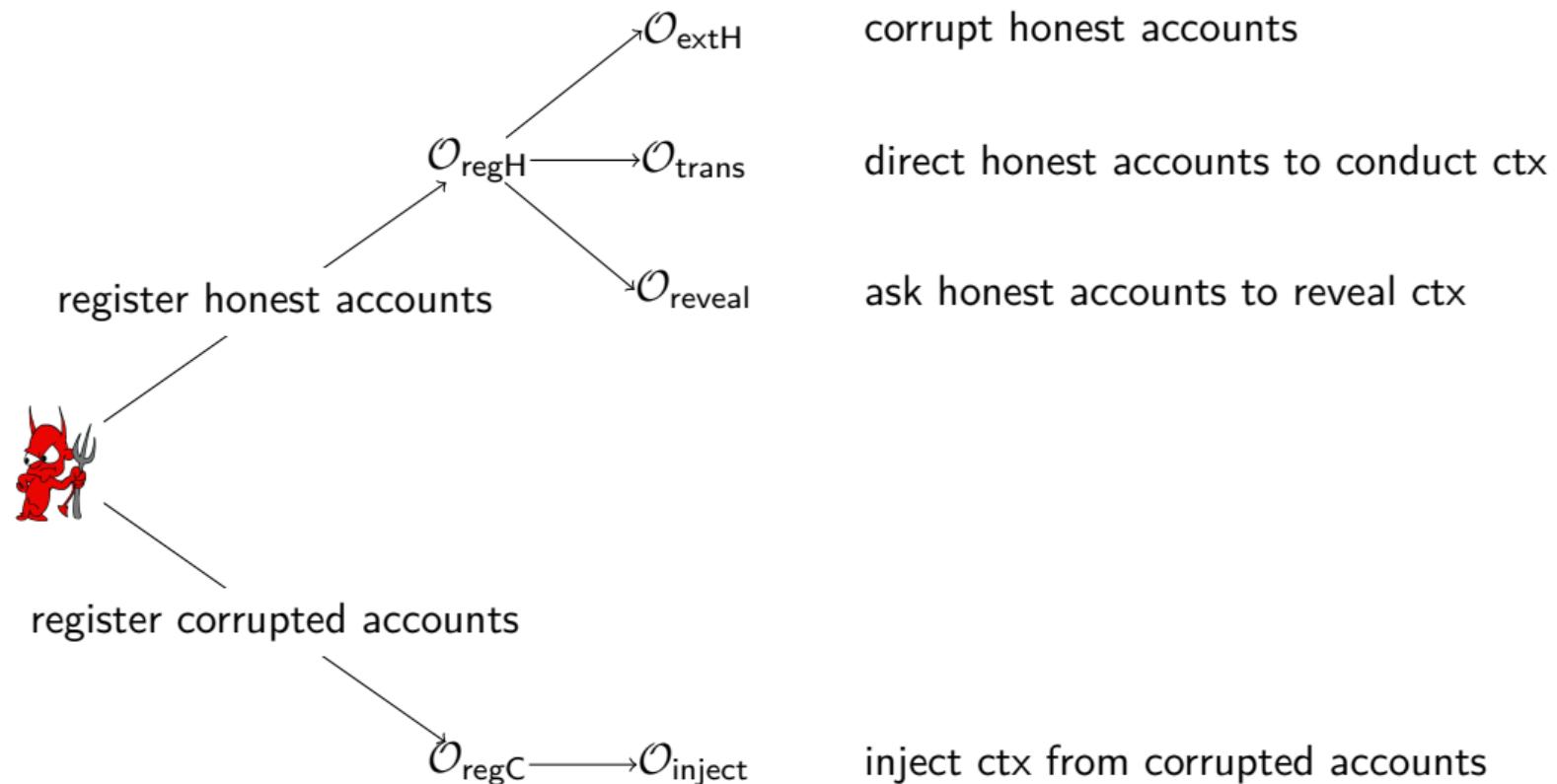
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Formal Security Model (Oracles)



Formal Security Model: Authenticity

$$\text{Adv}_{\mathcal{A}}(\lambda) = \Pr \left[\begin{array}{l} \text{VerifyCTx}(\text{ctx}^*) = 1 \wedge \\ \text{pk}_s^* \in T_{\text{honest}} \wedge \text{ctx}^* \notin T_{\text{ctx}}(\text{pk}_s^*) \end{array} : \begin{array}{l} pp \leftarrow \text{Setup}(\lambda); \\ \text{ctx}^* \leftarrow \mathcal{A}^{\mathcal{O}}(pp); \end{array} \right].$$

Formal Security Model: Confidentiality

$$\text{Adv}_{\mathcal{A}}(\lambda) = \Pr \left[\beta = \beta' : \begin{array}{l} pp \leftarrow \text{Setup}(\lambda); \\ (state, pk_s^*, pk_r^*, v_0, v_1) \leftarrow \mathcal{A}_1^{\mathcal{O}}(pp); \\ \beta \xleftarrow{\text{R}} \{0, 1\}; \\ \text{ctx}^* \leftarrow \text{CreateCTx}(sk_s^*, pk_s^*, pk_r^*, v_{\beta}); \\ \beta' \leftarrow \mathcal{A}_2^{\mathcal{O}}(state, \text{ctx}^*); \end{array} \right] - \frac{1}{2}.$$

To prevent trivial attacks, \mathcal{A} is subject to the following restrictions:

- ① pk_s^*, pk_r^* chosen by \mathcal{A} are required to be honest accounts, and \mathcal{A} is not allowed to make corrupt queries to either pk_s^* or pk_r^* ;
- ② \mathcal{A} is not allowed to make reveal query to ctx^* .
- ③ let v_{sum} (with initial value 0) be the dynamic sum of the transfer amounts in $\mathcal{O}_{\text{trans}}$ queries related to pk_s^* after ctx^* , both $\tilde{v}_s - v_0 - v_{\text{sum}}$ and $\tilde{v}_s - v_1 - v_{\text{sum}}$ must lie in \mathcal{V} .

Restrictions 1 and 2 prevents trivial attack by decryption, restrictions 3 prevent inferring β by testing whether overdraft happens.

Formal Security Model: Soundness

$$\text{Adv}_{\mathcal{A}}(\lambda) = \Pr \left[\begin{array}{l} \text{VerifyCTx}(\text{ctx}^*) = 1 \\ \wedge \text{memo}^* \notin L_{\text{valid}} \end{array} : \begin{array}{l} pp \leftarrow \text{Setup}(\lambda); \\ \text{ctx}^* \leftarrow \mathcal{A}^{\mathcal{O}}(pp); \end{array} \right].$$

Here, $\text{ctx}^* = (\text{sn}^*, \text{memo}^*, \text{aux}^*)$.

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A Subtle Point: Key reuse vs. Key Separation

We employ PKE and SIG simultaneously to secure auditable DCP.

| | key separation $(pk_1, sk_1), (pk_2, sk_2)$ | key reuse (pk, sk) |
|------|-----------------------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------|
| Pros | | Pros |
| Cons | <ul style="list-style-type: none">• off-the-shelf & easy to analyze• double key size• tricky address derivation | <ul style="list-style-type: none">• greatly simplify DCP system• more efficient• case-tailored design |

We choose **Integrated Signature and Encryption (ISE)**: one keypair for both encryption and sign, while IND-CPA and EUF-CMA hold in the joint sense

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Generic Construction of Auditable DCP: Building blocks

ISE = (Setup, KeyGen, Sign, Verify, Enc, Dec)

- PKE component is additively homomorphic over \mathbb{Z}_p
- Fix pp , KeyGen naturally induces an \mathcal{NP} relation:

$$R_{\text{key}} = \{(pk, sk) : \exists r \text{ s.t. } (pk, sk) = \text{KeyGen}(pp; r)\}$$

NIZK = (Setup, CRSGen, Prove, Verify)

- adaptive soundness
- adaptive ZK

Algorithms of Auditable DCP: 1/4

$\text{Setup}(1^\lambda)$: generate pp for the auditable DCP system

- $pp_{\text{ise}} \leftarrow \text{ISE}.\text{Setup}(1^\lambda)$, $pp_{\text{nizk}} \leftarrow \text{NIZK}.\text{Setup}(1^\lambda)$, $crs \leftarrow \text{NIZK}.\text{CRSGen}(pp_{\text{nizk}})$
- output $pp = (pp_{\text{ise}}, pp_{\text{nizk}}, crs)$, set $\mathcal{V} = [0, v_{\max}]$

$\text{CreateAcct}(\tilde{v}, \text{sn})$: create an account

- $(pk, sk) \leftarrow \text{ISE}.\text{KeyGen}(pp_{\text{ise}})$, pk serves as account address
- $\tilde{C} \leftarrow \text{ISE}.\text{Enc}(pk, \tilde{v}; r)$

$\text{RevealBalance}(sk, \tilde{C})$: reveal the balance of an account

- $\tilde{m} \leftarrow \text{ISE}.\text{Dec}(sk, \tilde{C})$

Algorithms of Auditable DCP: 2/4

CreateCTx(sk_s, pk_s, v, pk_r): transfer v coins from account pk_s to account pk_r .

- $C_s \leftarrow \text{ISE.Enc}(pk_s, v; r_1)$, $C_r \leftarrow \text{ISE.Enc}(pk_r, v; r_2)$, $\text{memo} = (pk_s, pk_r, C_s, C_r)$.
- run NIZK.Prove with witness (sk_s, r_1, r_2, v) to generate a proof π_{valid} for
 $\text{memo} = (pk_s, pk_r, C_s, C_r) \in L_{\text{valid}} \mapsto L_{\text{equal}} \wedge L_{\text{right}} \wedge L_{\text{solvent}}$

$$L_{\text{equal}} = \{(pk_s, pk_r, C_s, C_r) \mid \exists r_1, r_2, v \text{ s.t.}$$

$$C_s = \text{ISE.Enc}(pk_s, v; r_1) \wedge C_r = \text{ISE.Enc}(pk_r, v; r_2)\}$$

$$L_{\text{right}} = \{(pk_s, C_s) \mid \exists r_1, v \text{ s.t. } C_s = \text{ISE.Enc}(pk_s, v; r_1) \wedge v \in \mathcal{V}\}$$

$$L_{\text{solvent}} = \{(pk_s, \tilde{C}_s, C_s) \mid \exists sk_1 \text{ s.t. } (pk_s, sk_s) \in R_{\text{key}} \wedge \text{ISE.Dec}(sk_s, \tilde{C}_s - C_s) \in \mathcal{V}\}$$

- $\sigma \leftarrow \text{ISE.Sign}(sk_s, (\text{sn}, \text{memo}, \pi_{\text{valid}}))$
- output ctx = ($\text{sn}, \text{memo}, \pi_{\text{valid}}, \sigma$)

Algorithms of Auditable DCP: 3/4

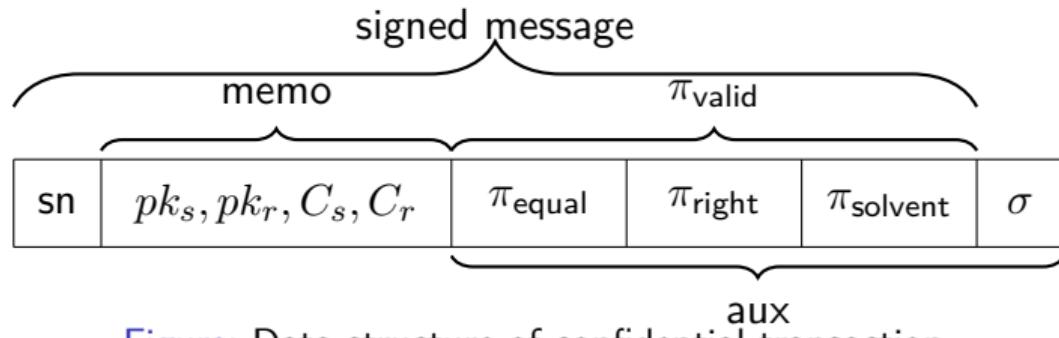


Figure: Data structure of confidential transaction.

VerifyCTx(ctx): check if ctx is valid.

- parse $\text{ctx} = (\text{sn}, \text{memo}, \pi_{\text{valid}}, \sigma)$, $\text{memo} = (pk_s, pk_r, C_s, C_r)$:
 - ① check if sn is a fresh serial number of pk_s (inspect the blockchain);
 - ② check if $\text{ISE.Verify}(pk_s, (\text{sn}, \text{memo}, \pi_{\text{valid}}), \sigma) = 1$;
 - ③ check if $\text{NIZK.Verify}(crs, \text{memo}, \pi_{\text{valid}}) = 1$.
- ctx is recorded on the ledger if validity test passes or discarded otherwise.

Update(ctx): sender updates his balance $\tilde{C}_s = \tilde{C}_s - C_s$ and increments sn, receiver updates his balance $\tilde{C}_r = \tilde{C}_r + C_r$.

Algorithms of Auditable DCP: 4/4

JustifyCTx($pk, sk, \{ctx_i\}_{i=1}^n, f$): user pk runs NIZK.Prove with witness sk to generate a zero-knowledge proof π_f for $f(\{ctx_i\}_{i=1}^n) = 1$.

$$f_{\text{limit}} : \sum_{i=1}^n v_i < \ell$$

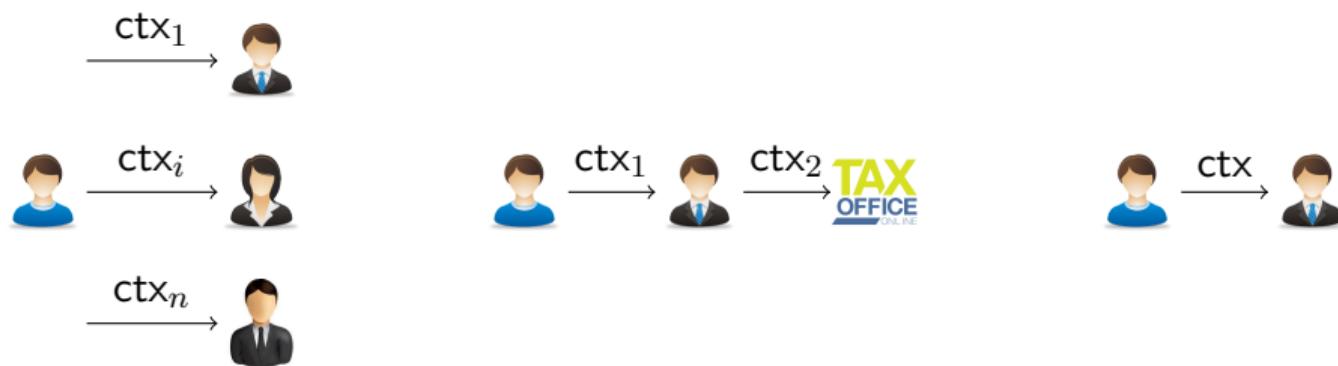
anti-money laundering

$$f_{\text{rate}} : v_1/v_2 = \rho$$

tax payment

$$f_{\text{open}} : v = v^*$$

selective disclosure



AuditCTx($pk, \{ctx_i\}_{i=1}^n, f, \pi_f$): auditor runs NIZK.Verify to check if π_f is valid.

Security Proof

Theorem: Assuming the security of ISE and NIZK, our CTx framework is secure.

- security of ISE's signature component \Rightarrow authenticity
- security of ISE's PKE component + adaptive ZK of NIZK \Rightarrow confidentiality
- adaptive soundness of NIZK \Rightarrow soundness