Efficient Leakage Resilient Circuit Compilers

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Theory

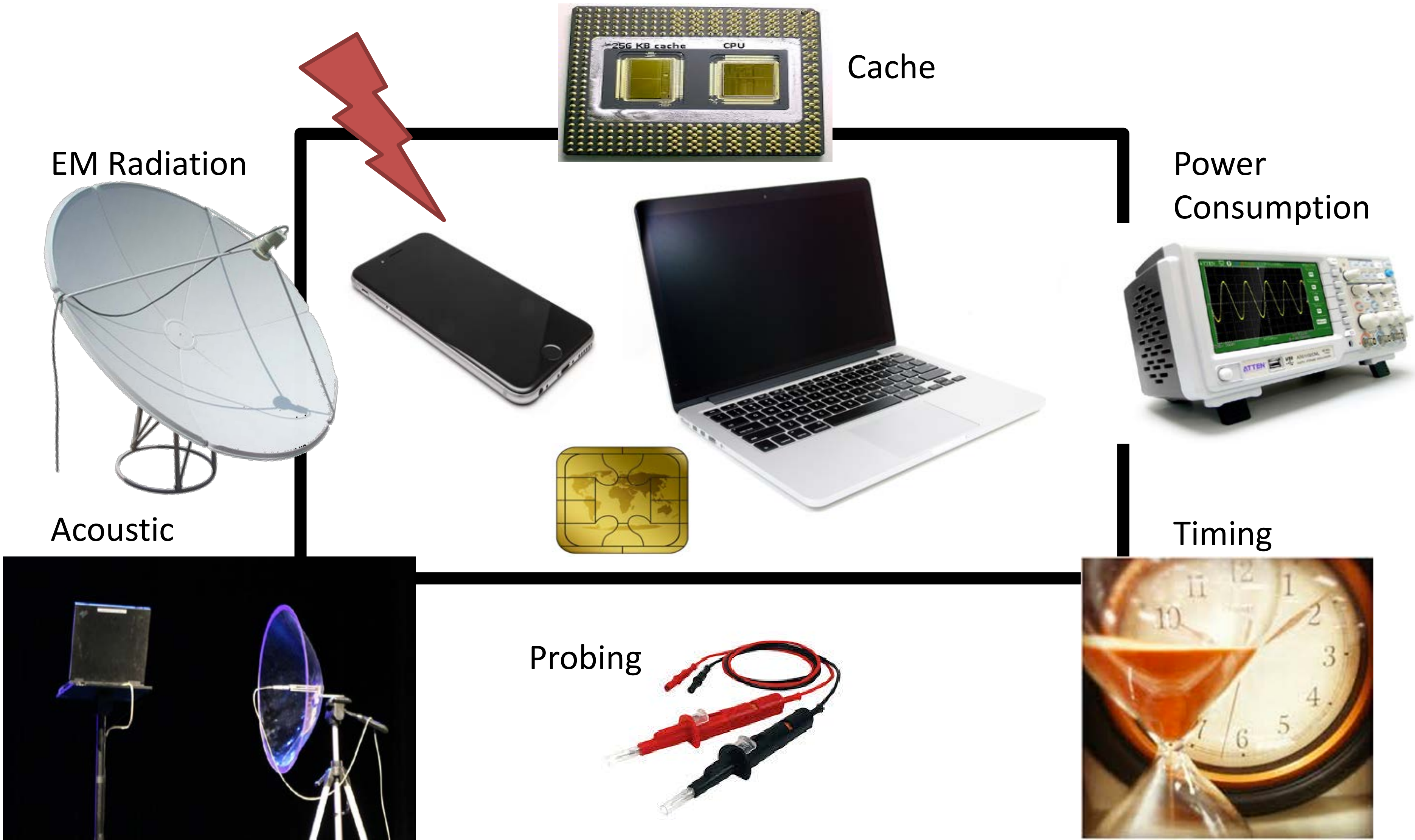
Cryptographic algorithms are often modeled as 'black boxes'

E.g. Internal computation is opaque to external adversaries.

Security is proven under various hardness assumptions.

Reality

Computation Internals **Leak**



Motivation

Many provably secure cryptosystems can be broken by side-channel attacks

Two Paradigms to Fight Leakage Attacks

1. Consider Leakage at design level

   Only security of specific schemes.

How to securely implement any scheme?

Wanted:

2. Leakage resilient Compiler

   Transform any circuit to a leakage resilient circuit secure in a strong black-box sense.

Def.: Circuit Compilers

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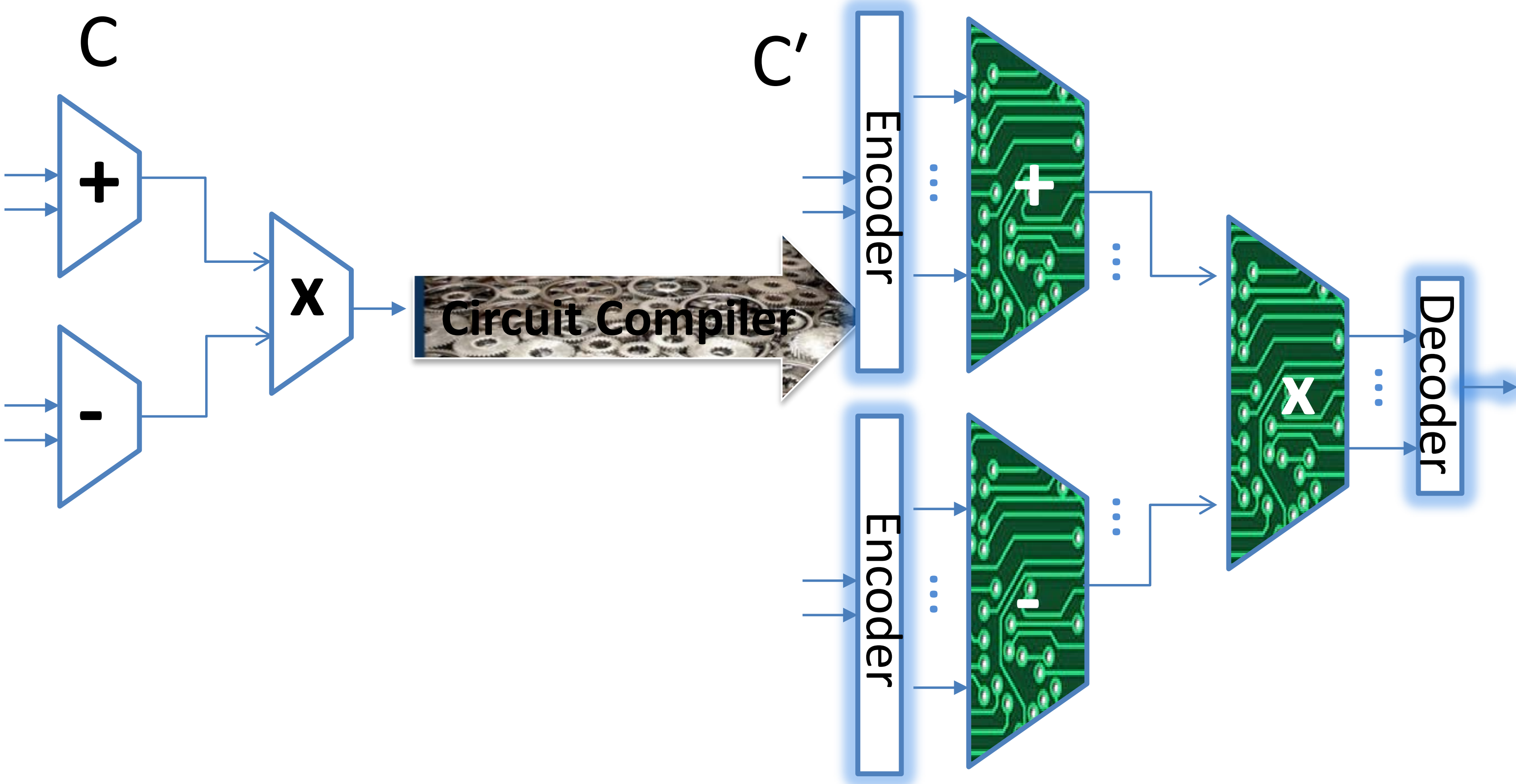

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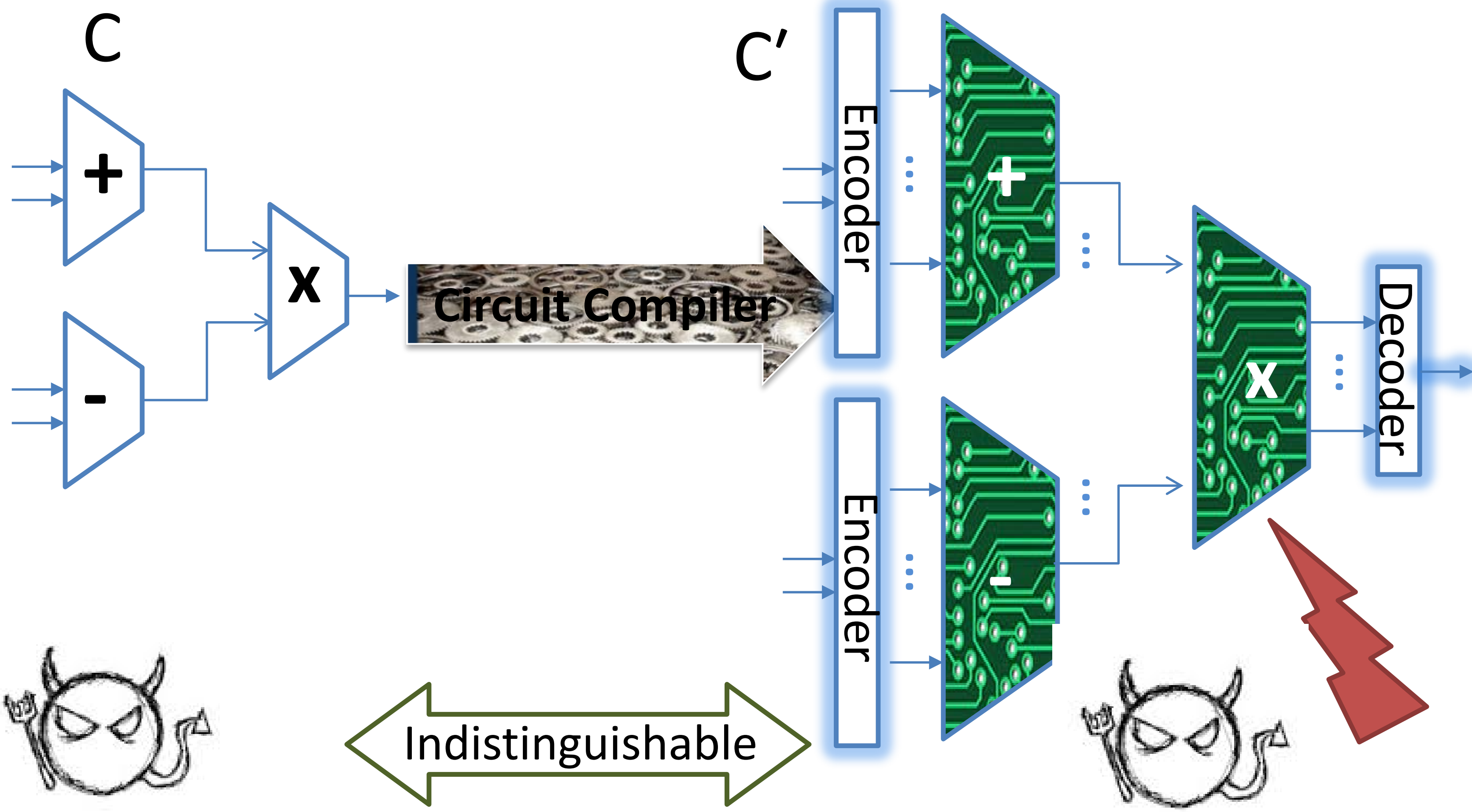

Even given leakage, execution “looks like” black-box access to C(.)

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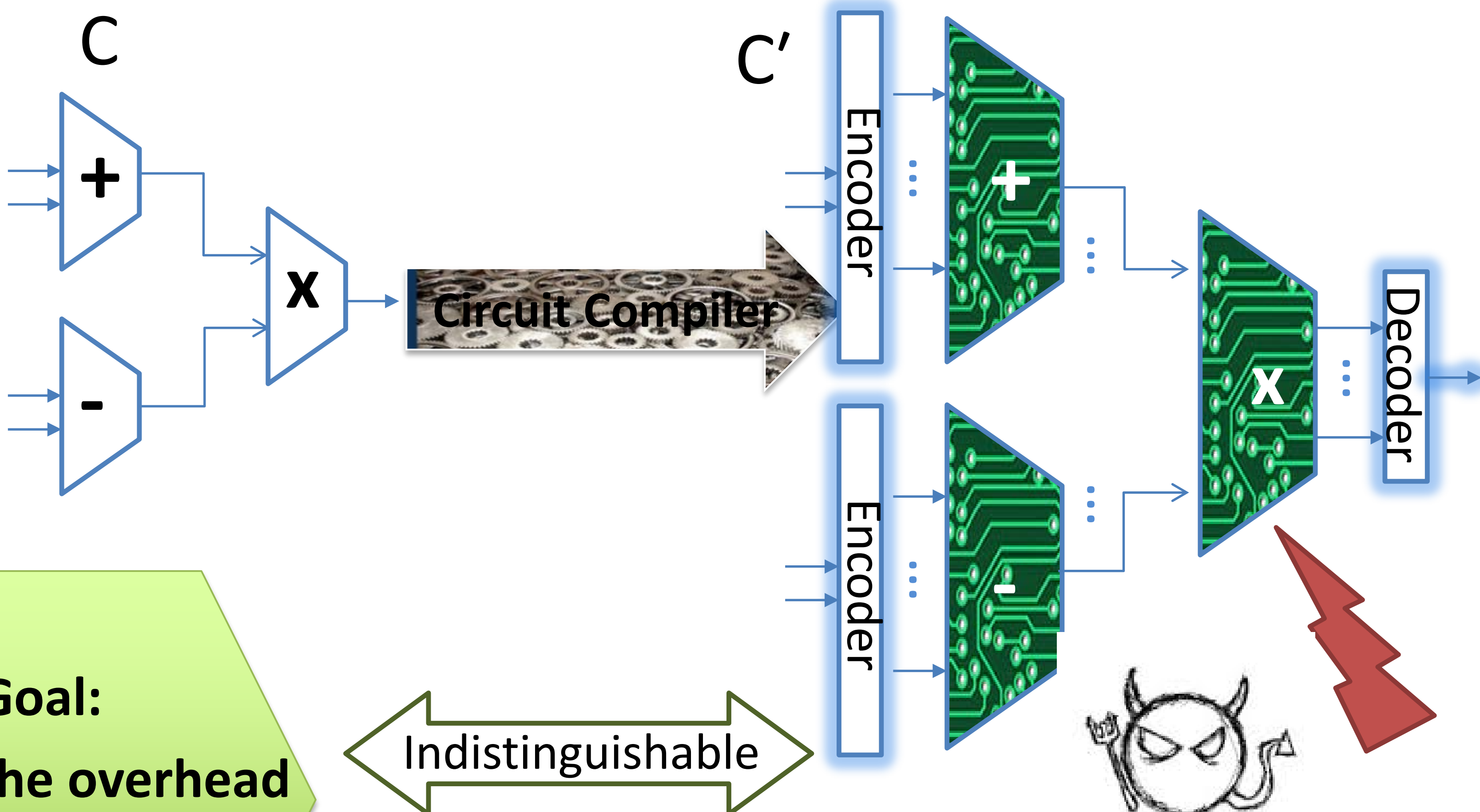

Goal:
Reduce the overhead induced by the compiler

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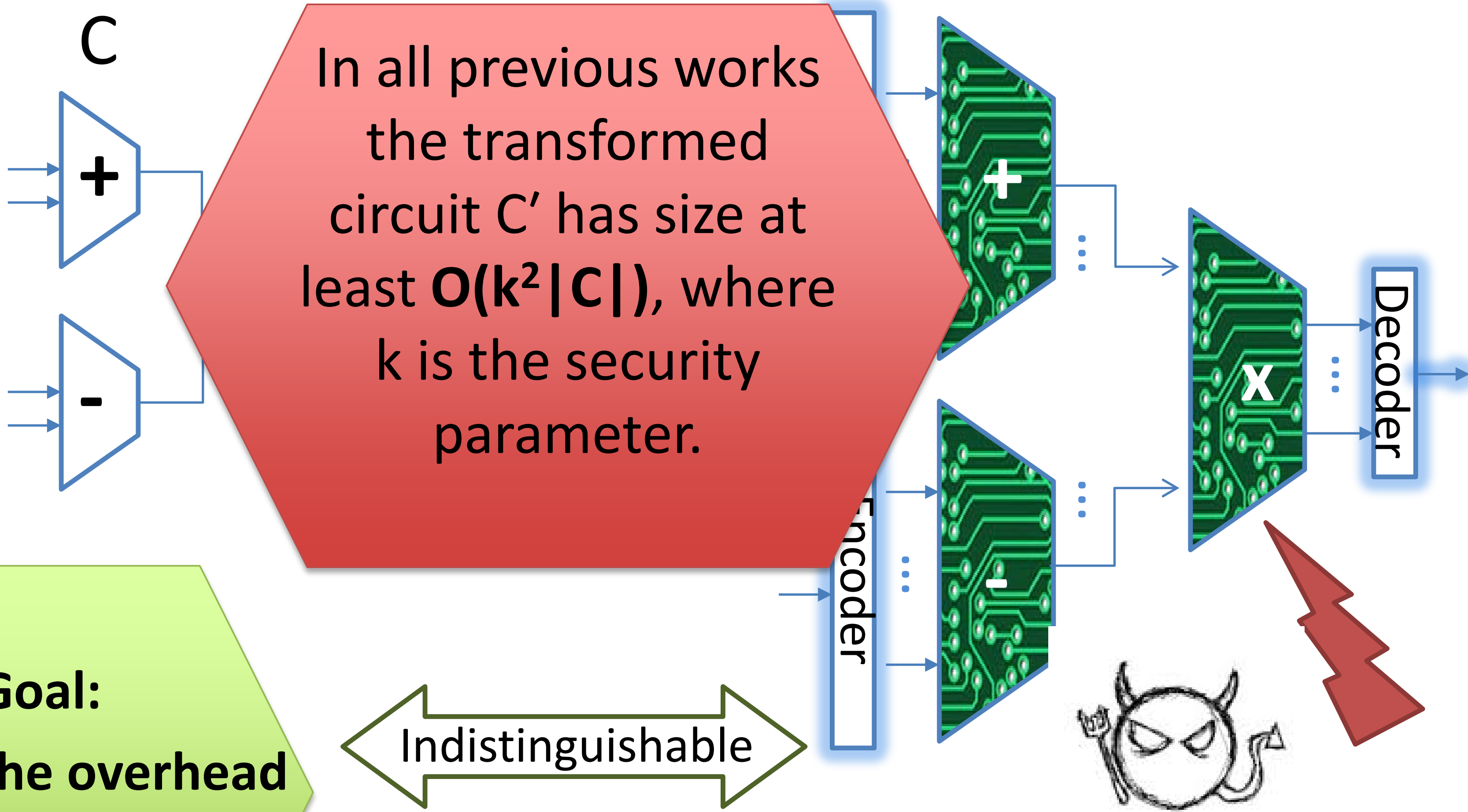
Def.: Circuit Compilers



In all previous works the transformed circuit C′ has size at least **$O(k^2|C|)$**, where k is the security parameter.

Goal:
Reduce the overhead induced by the compiler

Indistinguishable

Even given leakage, execution “looks like” black-box access to C(.)

Our Goal

Build Efficient Leakage Resilient Compilers

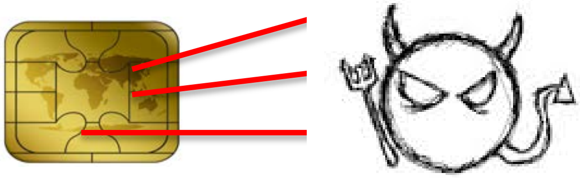
Is it possible to construct leakage resilient compilers with at most linear overhead?

- All previous works introduce at least quadratic overhead.

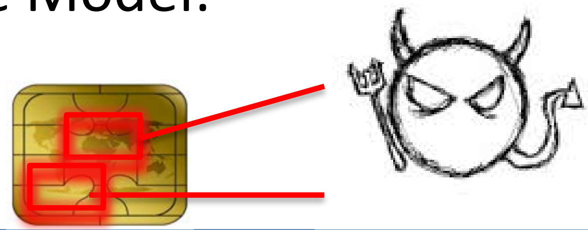
Prior Work on General Compilers

Three Leakage Models:

‘Local’ Bounded Wire-Probing: [ISW03,…]



‘Local’ Only Computation (OC) Leakage/ Split State Model: [MR04,…]



‘Global’ Computational Continuous Weak Leakage i.e. AC^0 leakage Functions [FRRTV10,…]

Our Results

Using Techniques from secure MPC

Efficient Compliers:

'Local' Wire-Probing: **$O(\text{polylog}(k) \cdot |C| \log |C|)$**
Previous Best Overhead: $O(k^2|C|)$ by [ISW03]

'Local' OC Leakage : **$O(k \log k \log\log k |C|)$**

Previous Best Overhead: $\Omega(k^4|C|)$ by [DF12] and $\Omega(k^3|C|)$ by [GR12]

This talk

'Global' Computational Continuous Weak Leakage: **$O(k \cdot |C| \log |C|)$**
Previous Best Overhead: $O(k^2|C|)$ by [FRRTV10] and $O(k^3|C|)$ by [R13]

Our Result on Global Computational Weak Leakage

- **Informal Theorem :** A compiler that makes **any circuit** resilient to **computationally weak leakages**. The compiler increases the circuit size by a factor of **O(k)**.

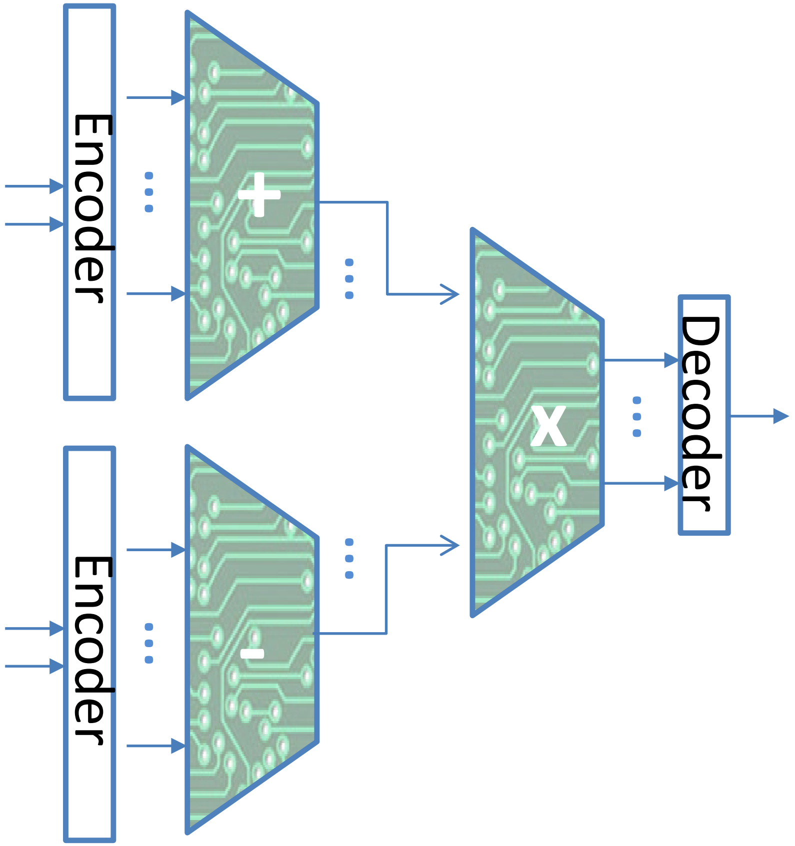
- **Global adaptive leakage**
- **Arbitrary total leakage**

However we must assume something [MR04]:

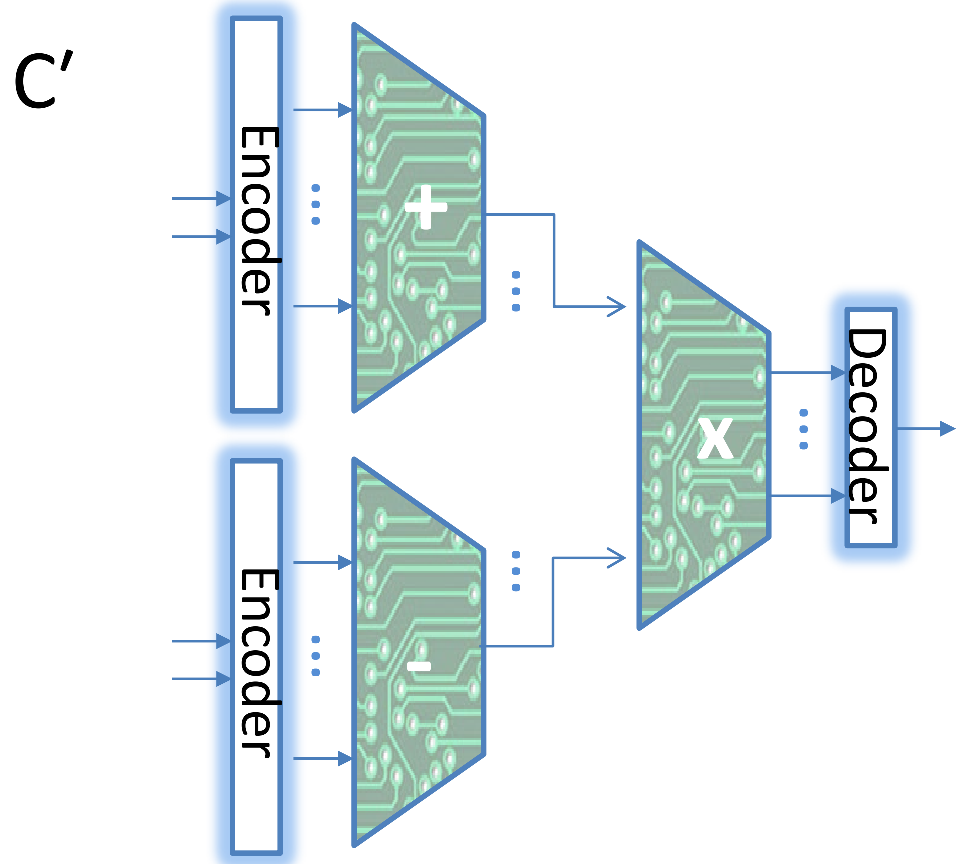
- **Leakage function is computationally weak.**
- **Simple opaque gates.**

The Compiler

C′



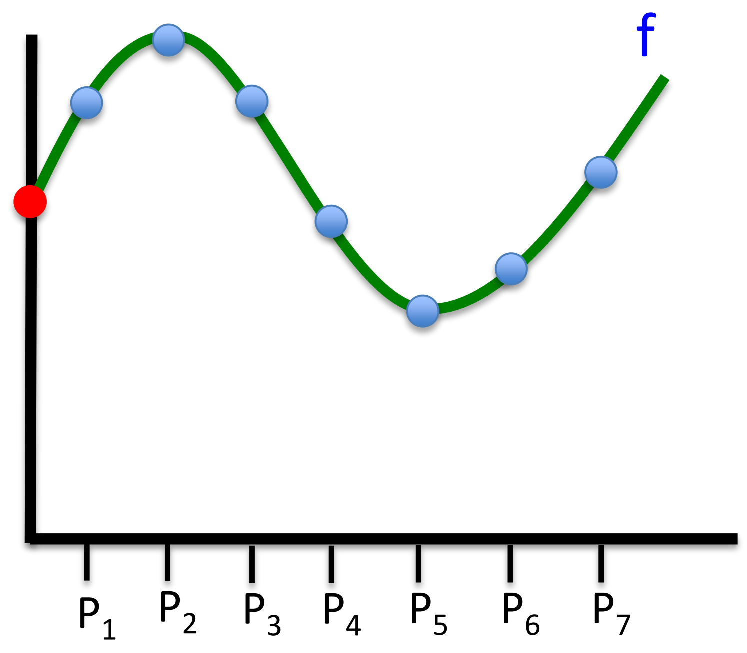
The Compiler:
From Wires to Wire Bundles



Packed Secret Sharing (PSS)

- PSS is a central tool in information theoretic secure MPC protocols.

Standard Secret Sharing :



Degree of f denoted by d

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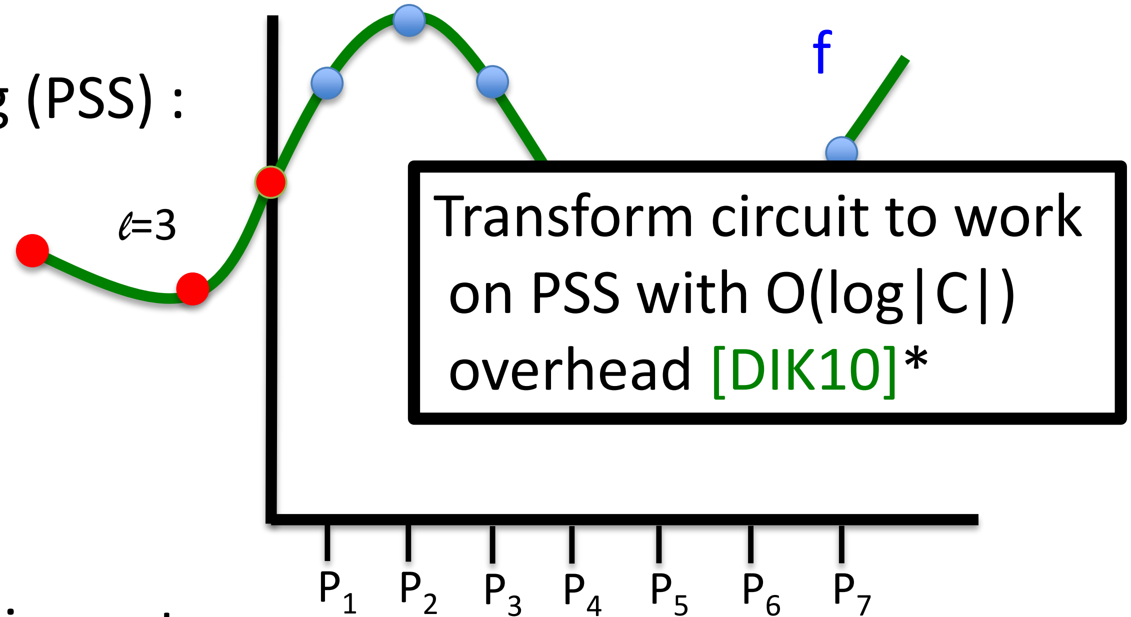
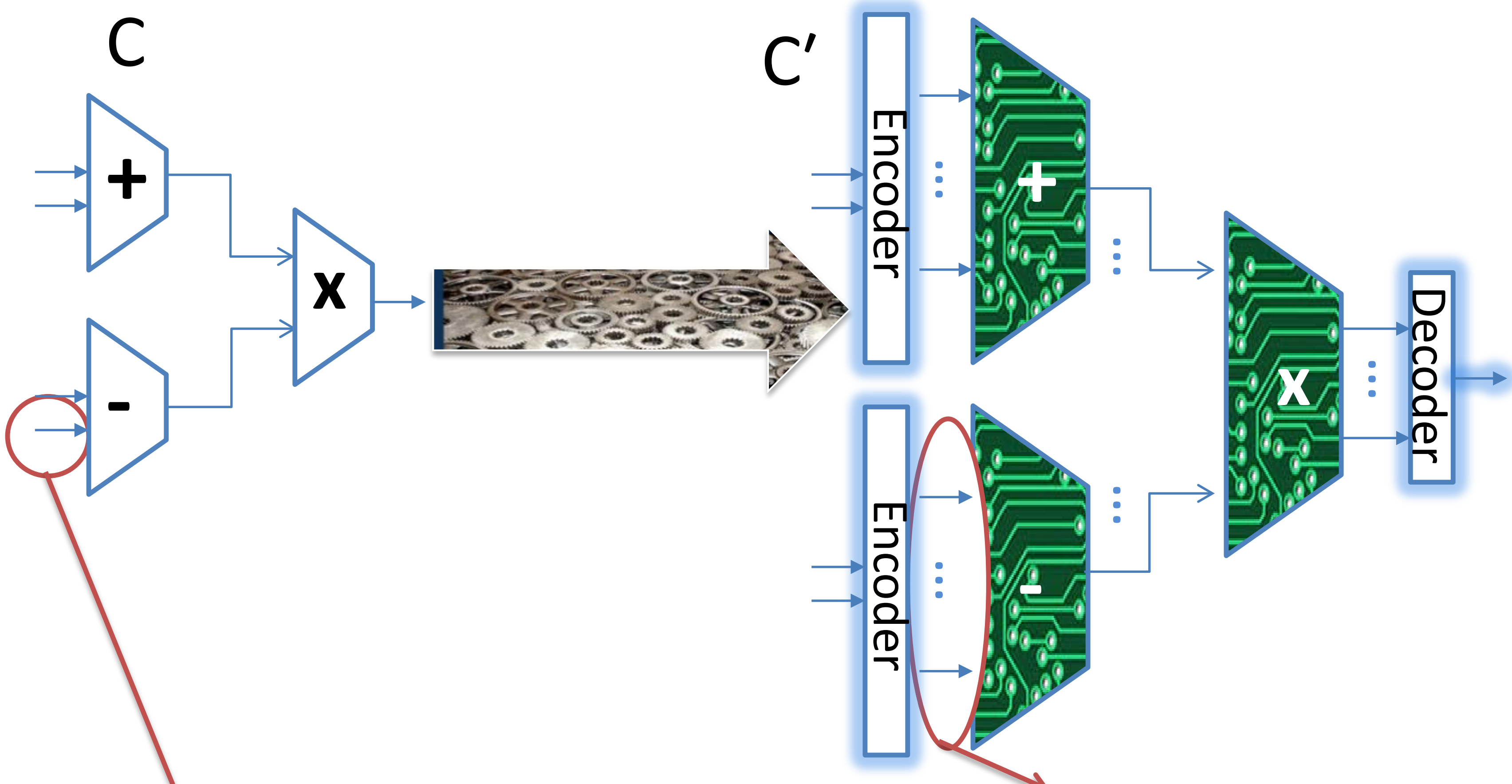
Packed Secret Sharing (PSS) :



Transform circuit to work on PSS with O(log|C|) overhead [DIK10]*

*Introduces Permutation gates.

- Every wire is encoded with PSS.
- Inputs are encoded; outputs are decoded.



Each wire w

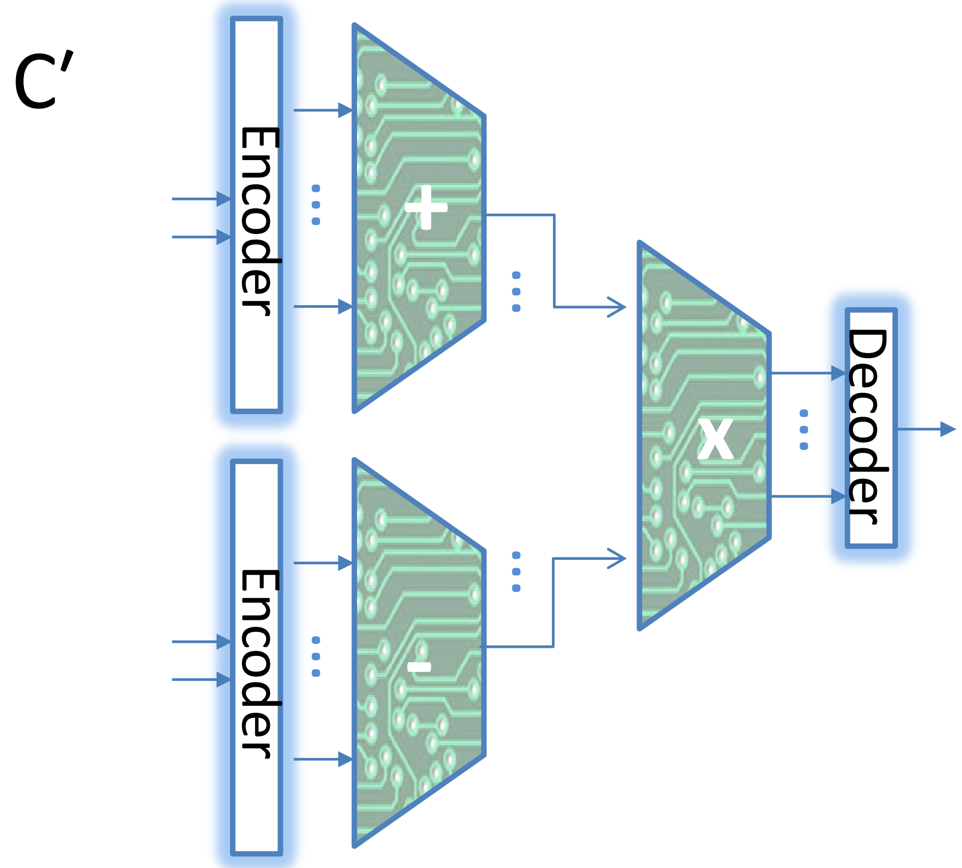
Wire bundle that carries the encoding of w, e.g. k shares of w. <u>Notation:</u> $(w_1,\ldots,w_k)=[w]_d$

PSS is Secure Against AC^0 Leakages

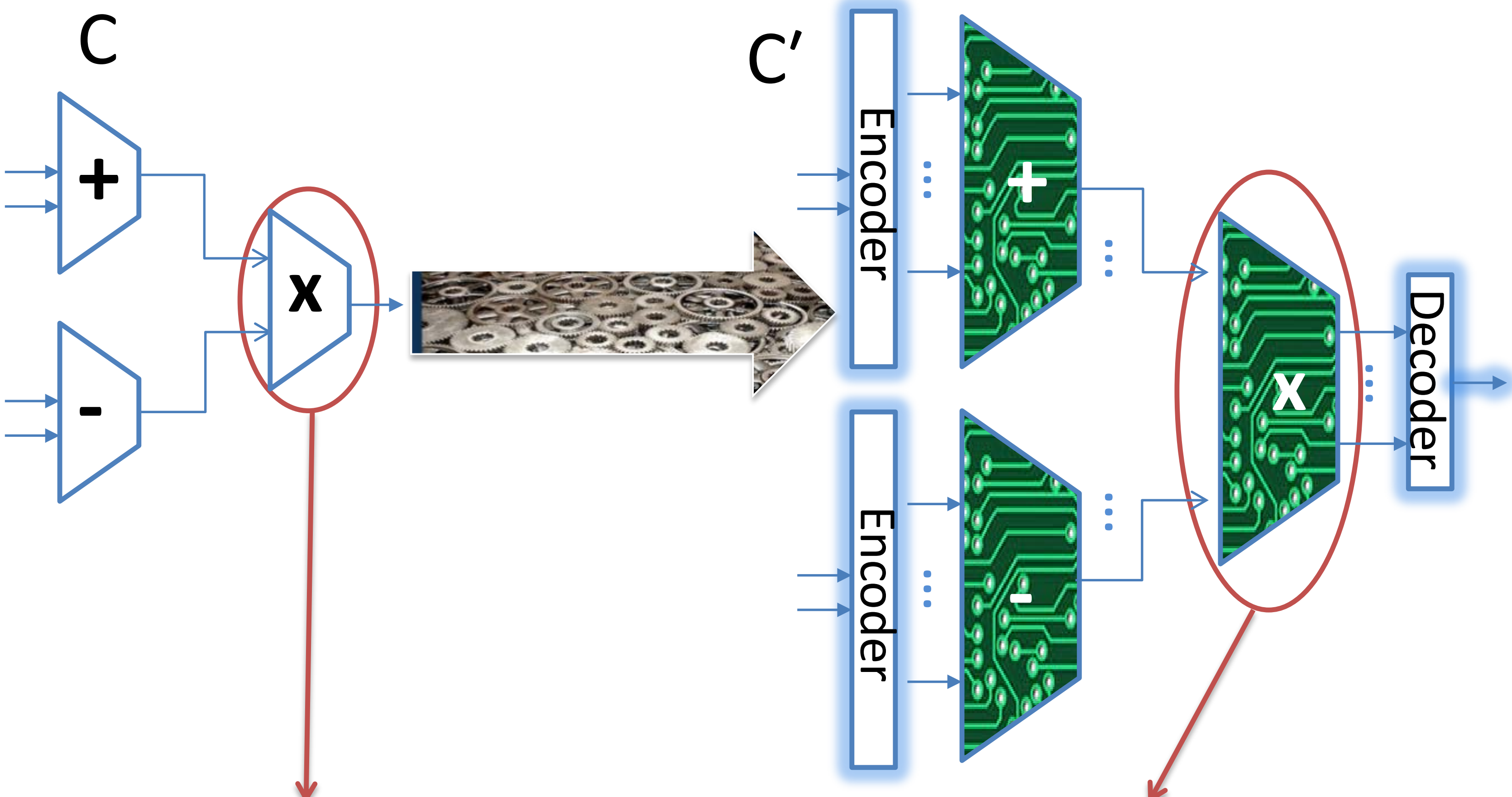
A function is in AC^0 if it can be computed by a poly-size $O(1)$ depth Boolean circuit with unbounded fan-in AND, OR (and NOT) gates.

- PSS Encoding is AC^0 indistinguishable, i.e. Inner product hard to compute in AC^0.

The Compiler:
From Gates to Gadgets



- Every gate is replaced by a gadget operating on encoded PSS bundles.



Gates

Gadgets: built from normal gates and opaque gates and operate on encodings.

Opaque Gates

[G89,GoldOstr95]…Leak-free processor: oblivious RAM

[MR04], [DP08], [GKR08], [DF12]…Leak-free memory: “only computation leaks”, one-time programs

[FRRTV10],… Opaque Gates

[GR12],[R13]… Ciphertext banks

Opaque Gates: simple gates that sample from a fixed distribution

e.g.: **securely draw strings with inner product 0**.

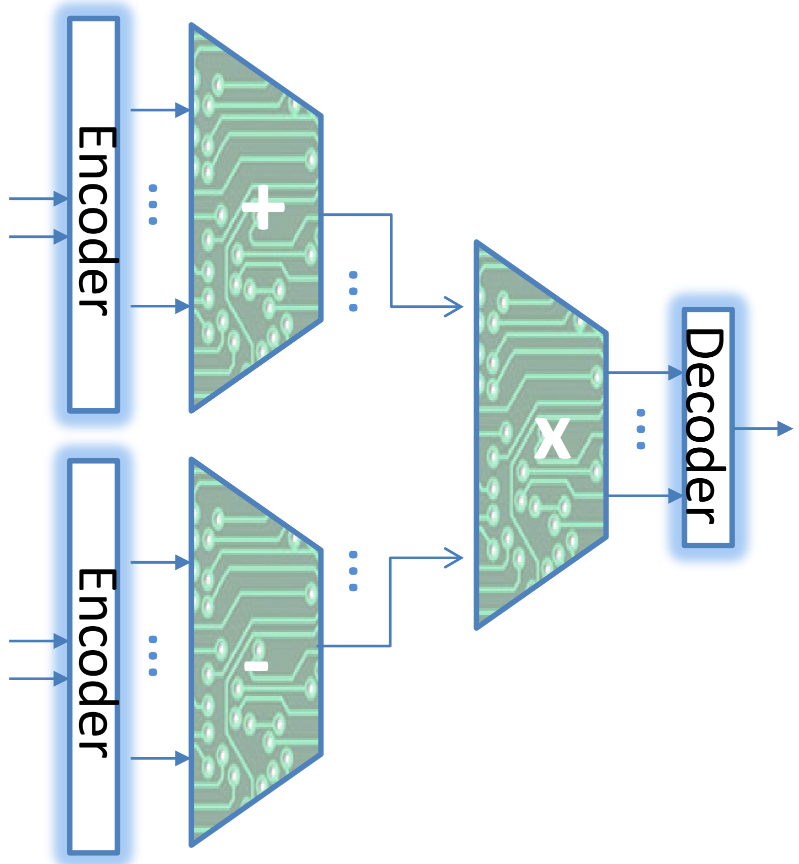
✓ Stateless: No secrets are stored

✓ Small and simple

✓ Computation independent: No inputs, so can be pre-computed

The Compiler:
Addition & Subtraction Gadgets

C′



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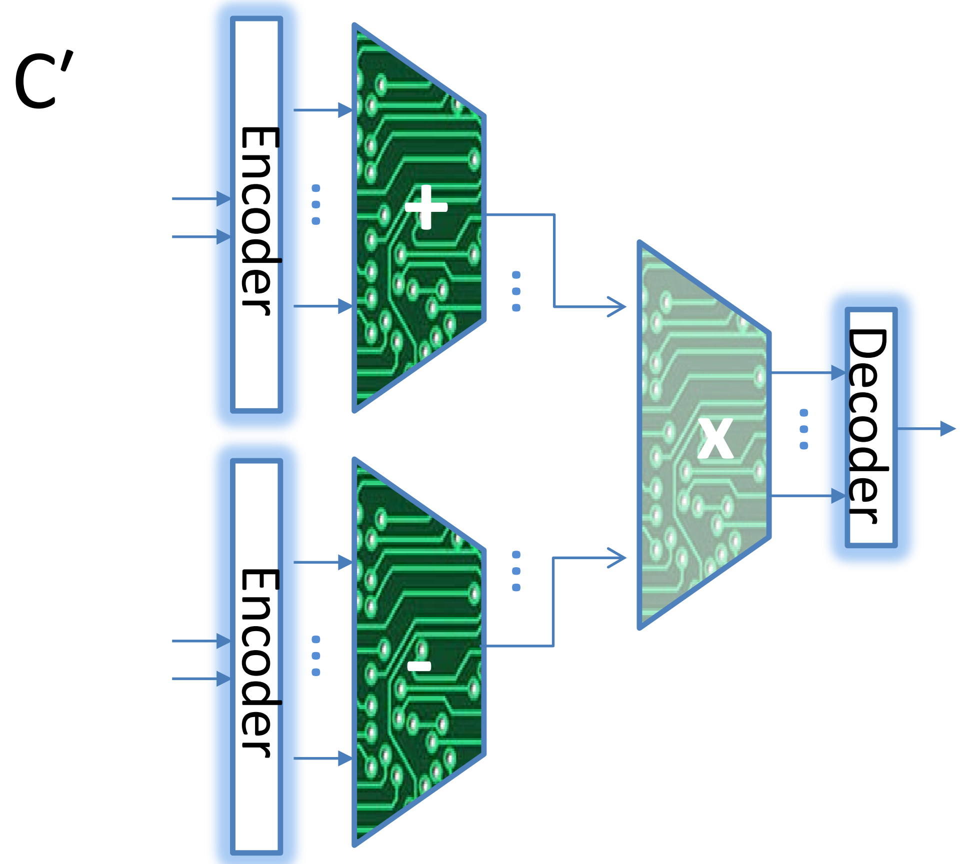


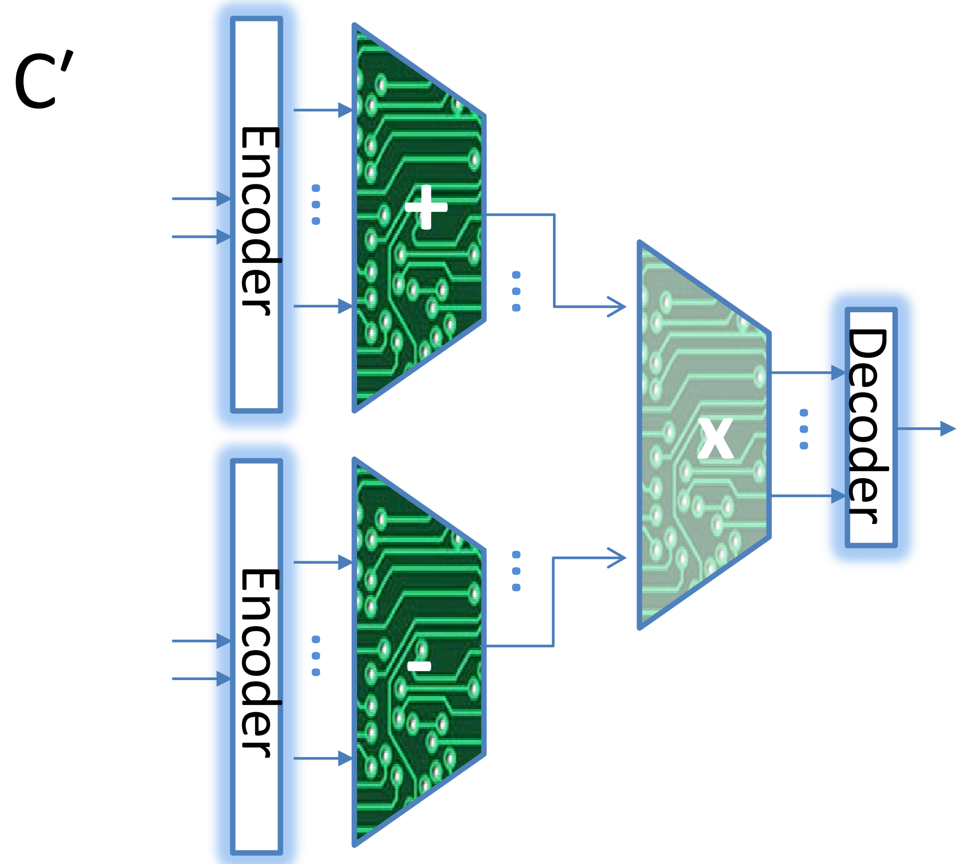
The Compiler: Addition & Subtraction Gadgets

Goal : $c=a+b \Rightarrow [a+b]_d \leftarrow [a]_d + [b]_d$

$[0]_d \leftarrow$ Opaque gate

1. $[a+b]_d = [a]_d+[b]_d+[0]_d$ OR $[a-b]_d = [a]_d-[b]_d+[0]_d$

The Compiler:
Multiplication Gadgets



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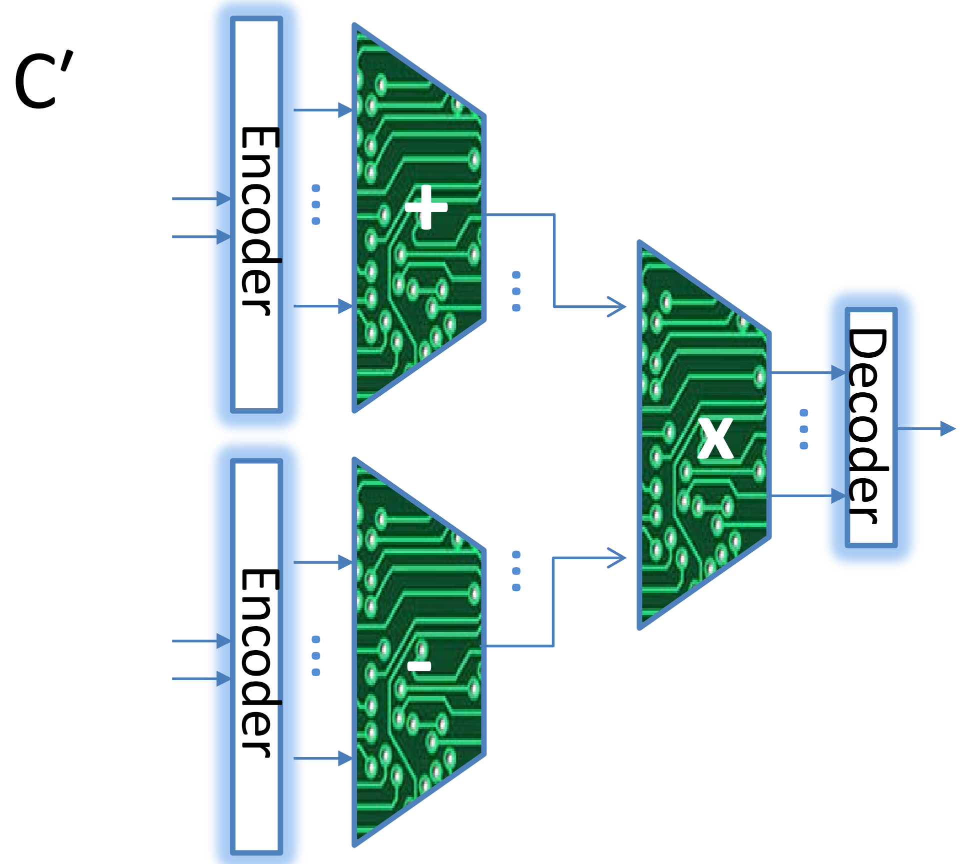

The Compiler: Multiplication Gadgets

Goal: $c = ab \Rightarrow [ab]_d \leftarrow [a]_d[b]_d$

$[r]_d, [r]_{2d} \leftarrow$ Opaque gate

1. $[ab]_{2d} = [a]_d[b]_d$
2. $[ab + r]_{2d} = [ab]_{2d} + [r]_{2d}$
3. $(\mathbf{ab+r}) \leftarrow$ Decode$([ab+r]_{2d})$
4. $[ab+r]_d \leftarrow$ Encode $(\mathbf{ab+r})$
5. $[ab]_d = [ab+r]_d - [r]_d$

Permutation gadget follows in the same fashion.

Compiler: High-Level

- Circuit topology is preserved.
- Every wire is encoded yielding a wire bundle; Inputs are encoded; outputs are decoded.
- PSS Encoding is AC^0 indistinguishable
- Every gate is converted into a gadget operating on encodings.

Security of the Compiled Circuit

Prove security via ‘*shallow*’ Reconstructors per gadget (technique introduced in [FRRTV10])

- Reconstructor: on input the inputs and the outputs of a gadget is able to simulate its internals in a way that looks indistinguishable for leakages from AC^0.

Conclusion

Three efficient circuit compilers ….

- ✓ compile any circuit
- ✓ ‘Local’ Wire-Probing
- ✓ ‘Local’ OC Leakage
- ✓ ‘Global’ Computational weak Leakage

Question

Connection to Obfuscation

Thank you!

Optimally Efficient Multi-Party Fair Exchange and Fair Secure Multi-Party Computation

Handan Kılınç [1]   Alptekin Küpçü [2]

[1]EPFL, Koç University
[2]Koç University

CT-RSA, 2015

Outline

1. Introduction
   - Multi-Party Fair Exchange
   - Definitions
2. Our New Protocols
   - MFE Protocol
     - Resolve Protocols
   - Fair and Secure MPC
3. Conclusion
   - Security and Fairness
   - Comparison with Previous Works
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MFE

Exchange Protocol

Two or more parties exchange their items with the other parties.

Fair Exchange Protocol

The exchange protocol is fair if in the end of

- All parties receive their desired items or,
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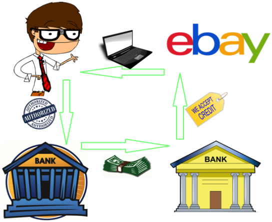

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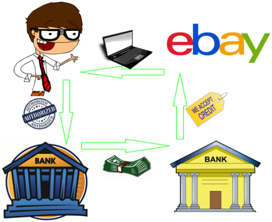
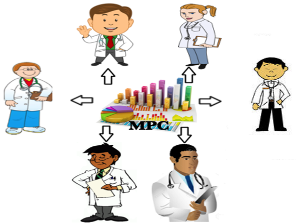
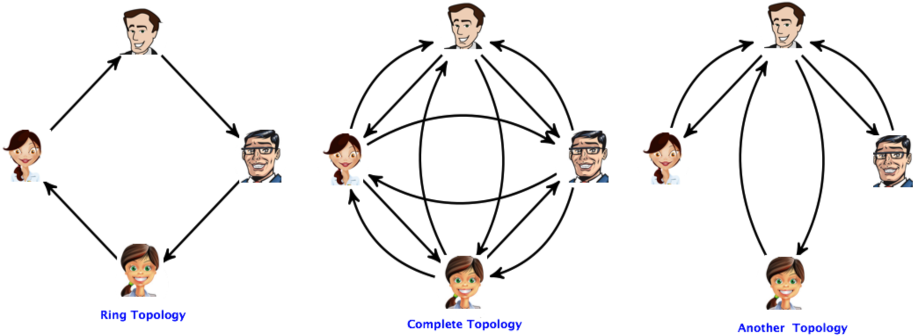




MFE Topologies



Optimistic MFE

- ☹Fairness is not possible without trusted third party (TTP).
- ☹There is a lack of TTP. So the efficiency is important.

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Multi-Party Computation

MPC

A group of parties ($P_1, P_2, ..., P_n$) with their private inputs w_i desires to compute a function ϕ.

- This computation is secure when the parties do not learn anything beyond what is revealed by the output of the computation.
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MFE is MPC

Multi-party fair exchange is multi-party computation.

- Each party P_i has item f_i.
- They need the compute the functionality ϕ where

$$\phi(f_1, f_2, ..., f_n) = (\phi_1, \phi_2, ..., \phi_n)$$

MFE id MPC

- For the complete topology:

$$\phi_i(f_1, ..., f_n) = (f_1, ..., f_{i-1}, f_{i+1}, ..., f_n)$$

- For the ring topology:
  if $i = 1$

$$\phi_i(f_1, ..., f_n) = f_n$$

  else

$$\phi_i(f_1, ..., f_n) = f_{i-1}$$

Ideal World for Fair and Secure MPC

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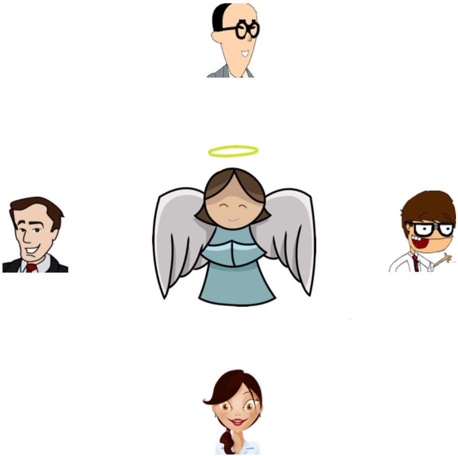

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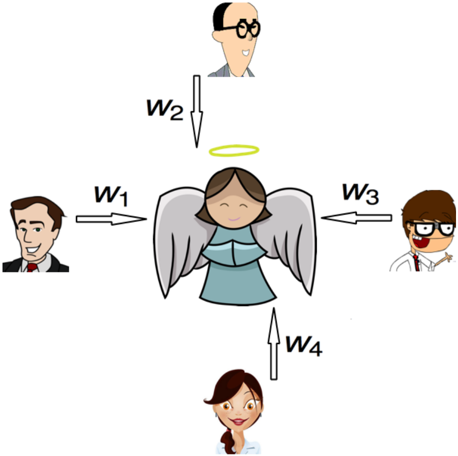

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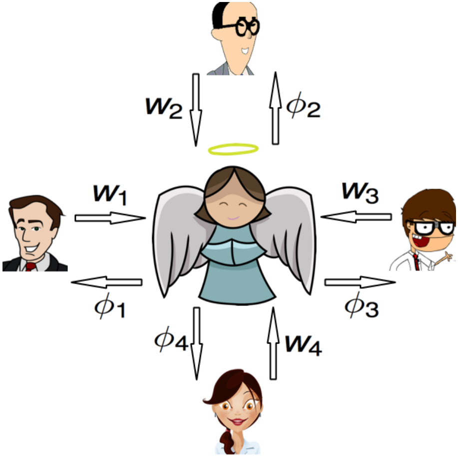
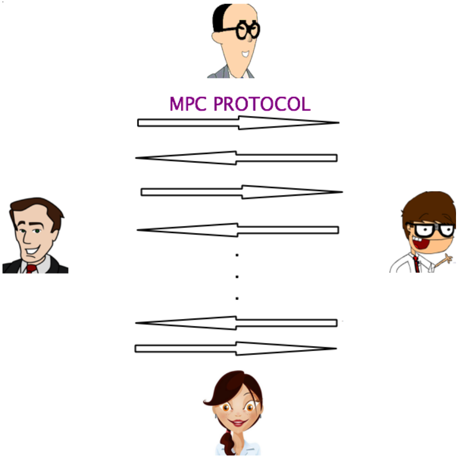
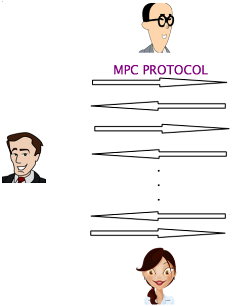


Real World for MPC



Secure and Fair MPC



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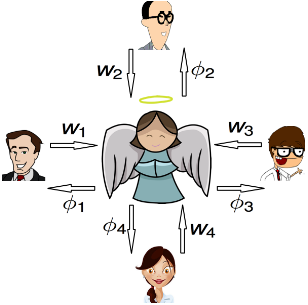

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Overview of MFE protocol

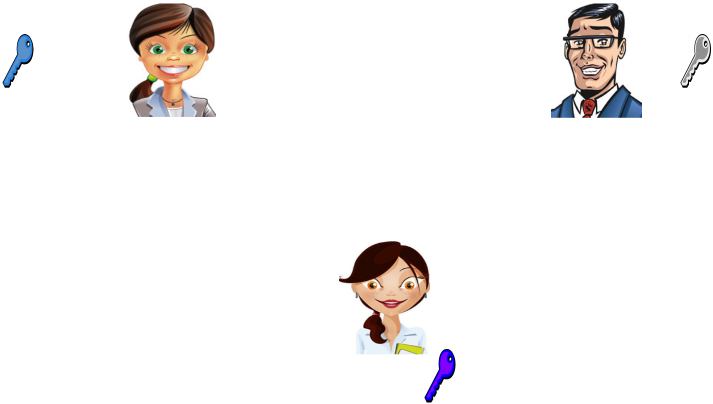
The parties are $P_1, P_2, ..., P_n$ and each party P_i has item f_i. They want the items of all parties (complete topology).
The TTP and his public key pk is known by all parties.

- Phase 1: Setup
- Phase 2: Encrypted Item Exchange
- Phase 3: Decryption Share Exchange

Phase 1: Setup Phase

They agree on two timeouts t_1 and t_2 and know TTP's public key

Phase 1: Setup Phase



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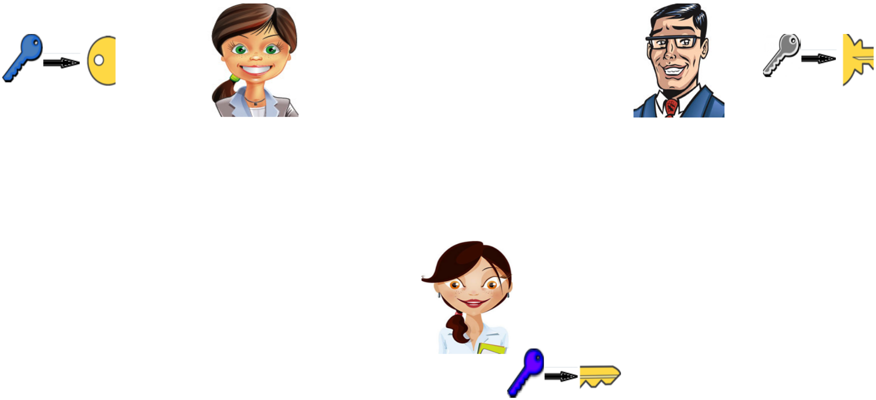

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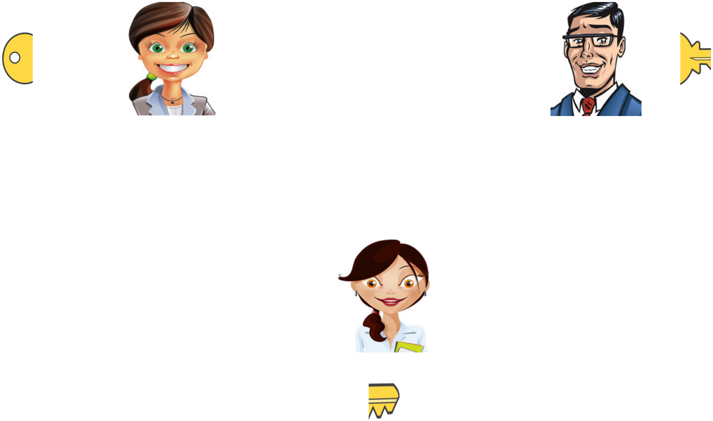

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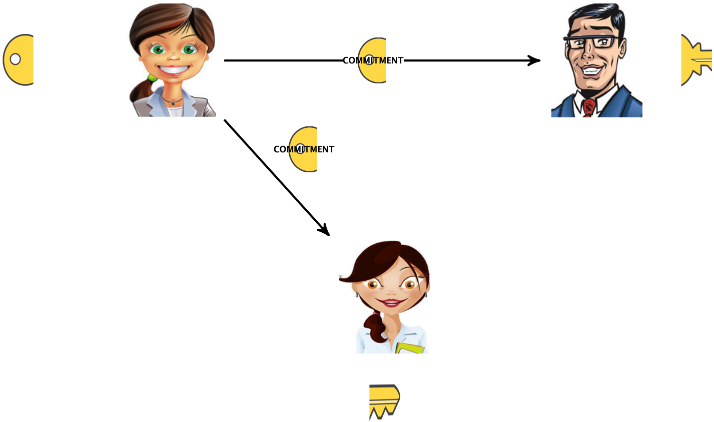

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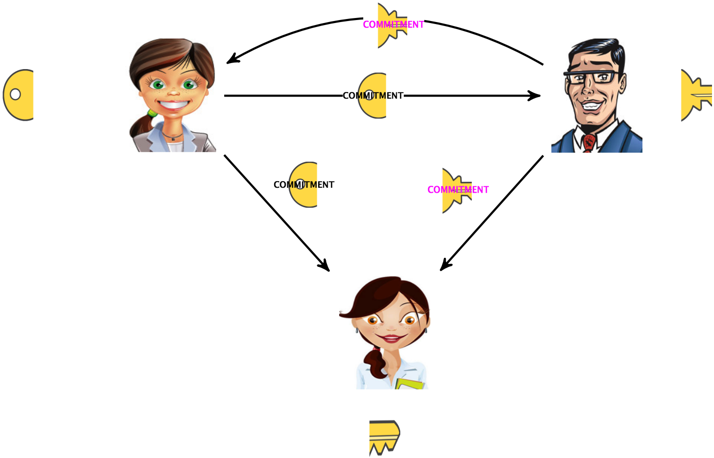

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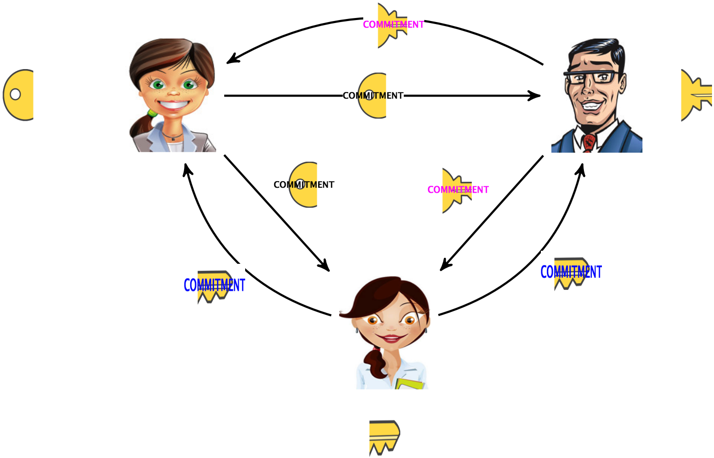

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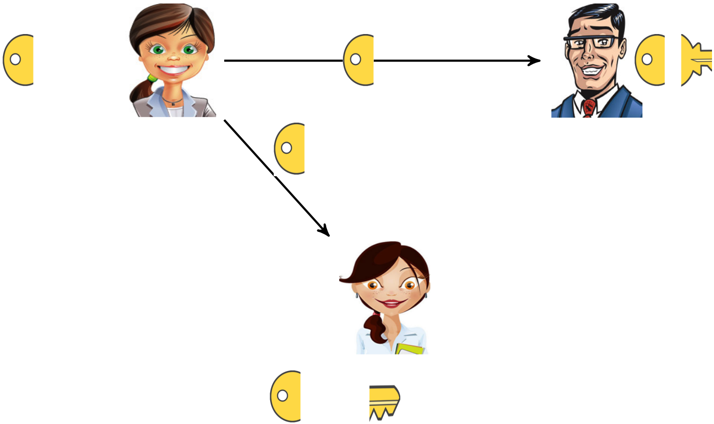

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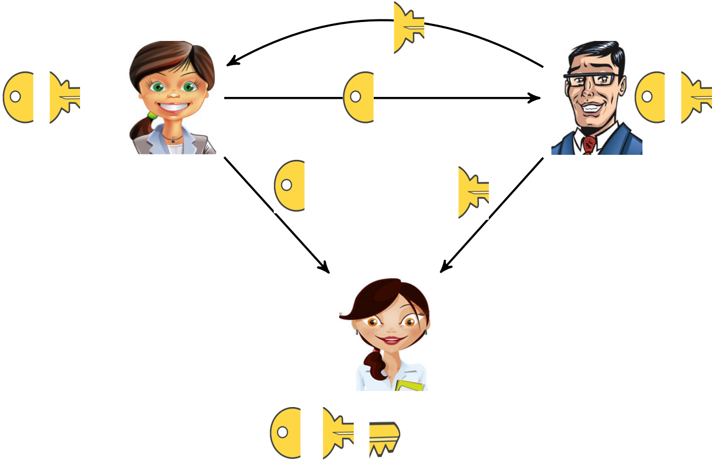

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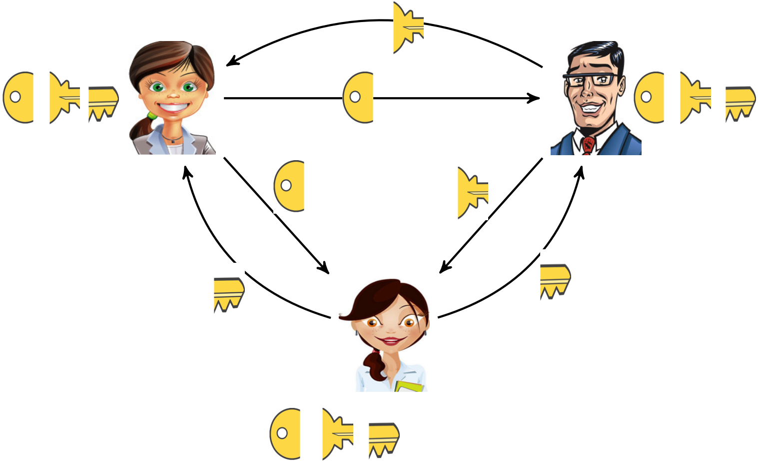

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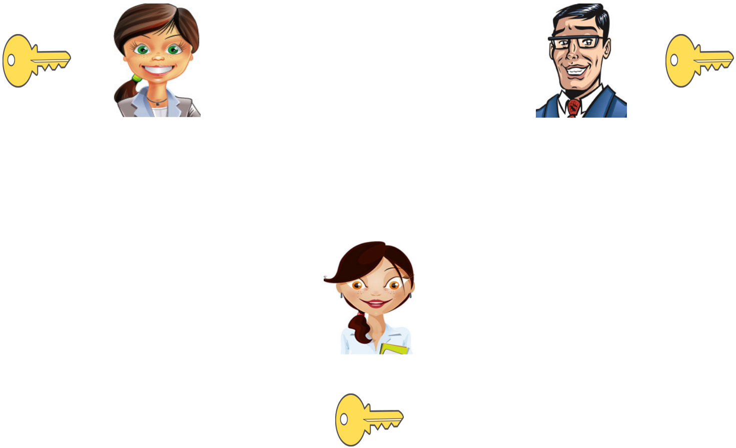
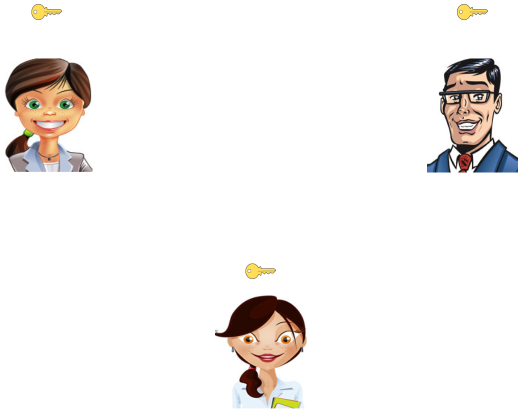


Phase 2: Verifiable Encryption of Items



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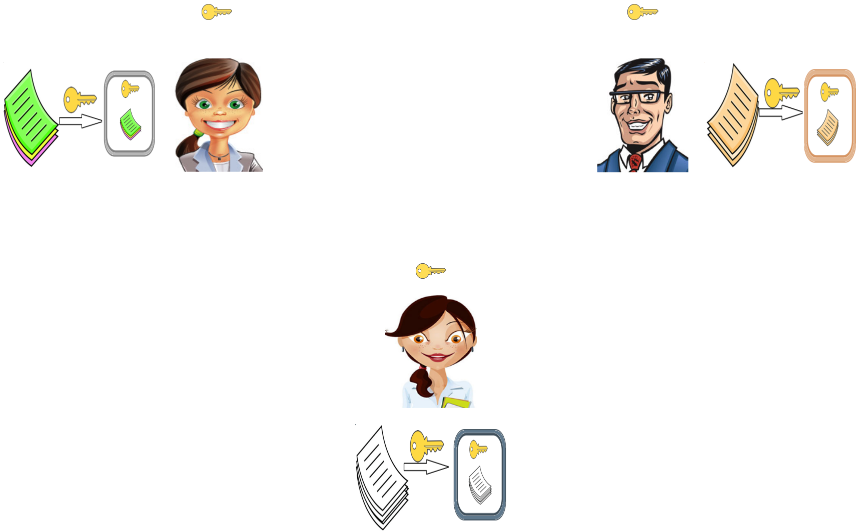

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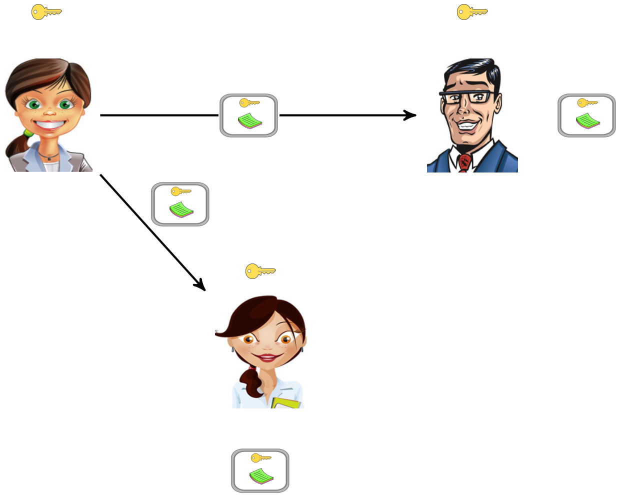

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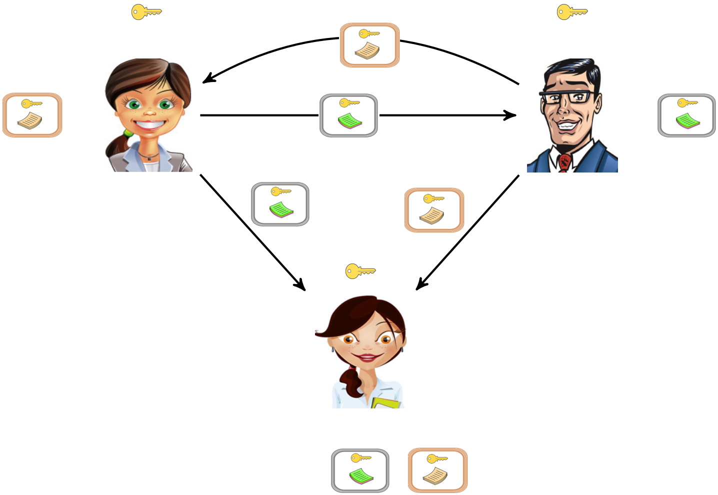

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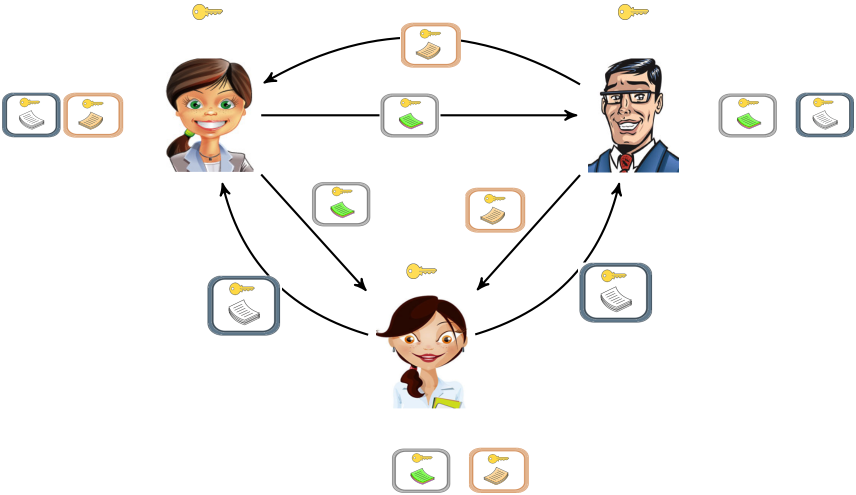

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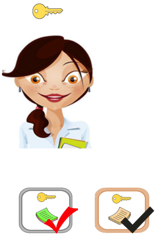
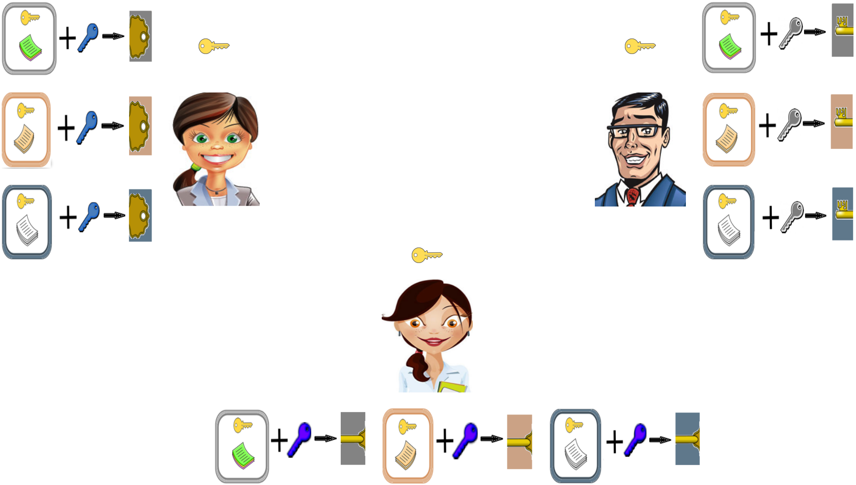
If any party does not receive verifiable encryption, (s)he aborts.



Phase 2: Decryption Share Encryption



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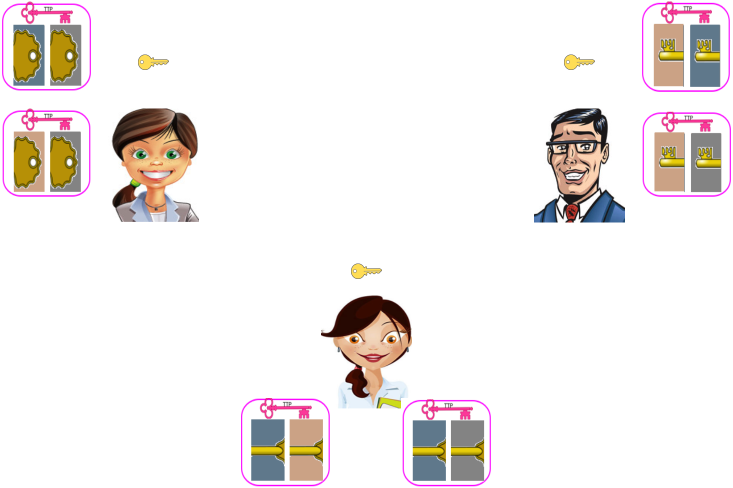

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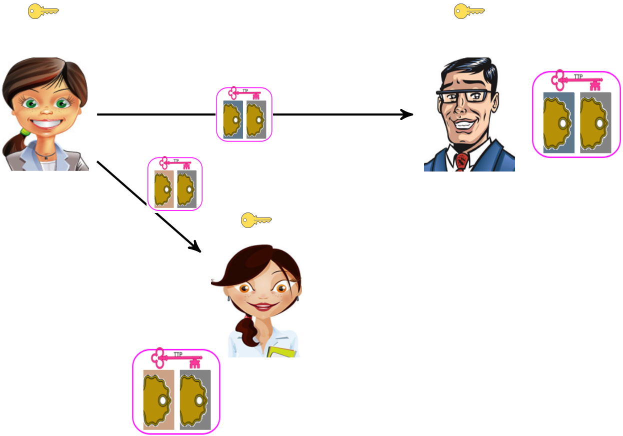

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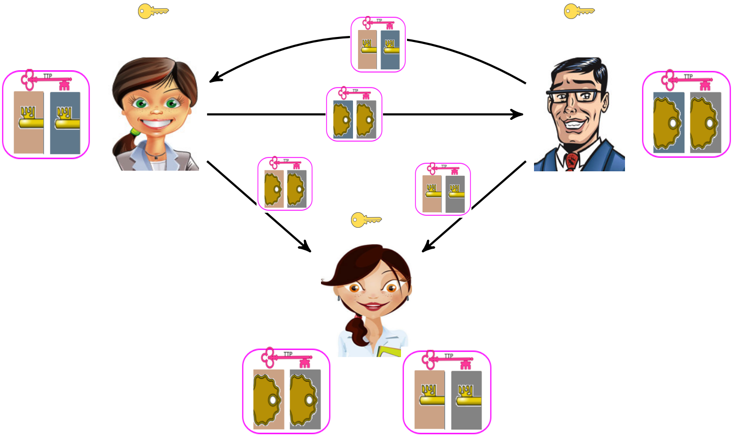

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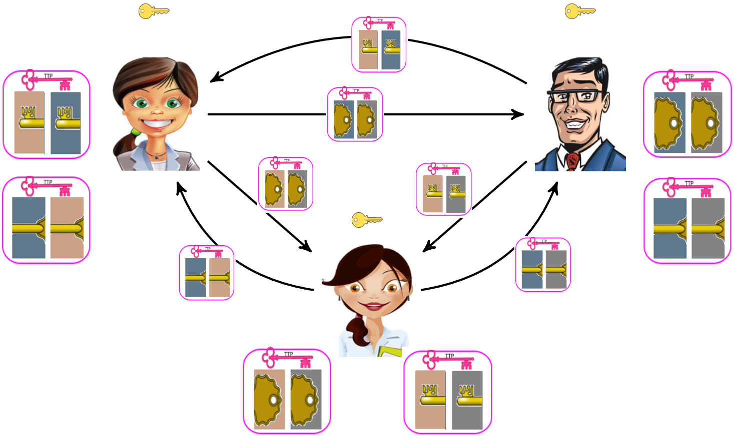

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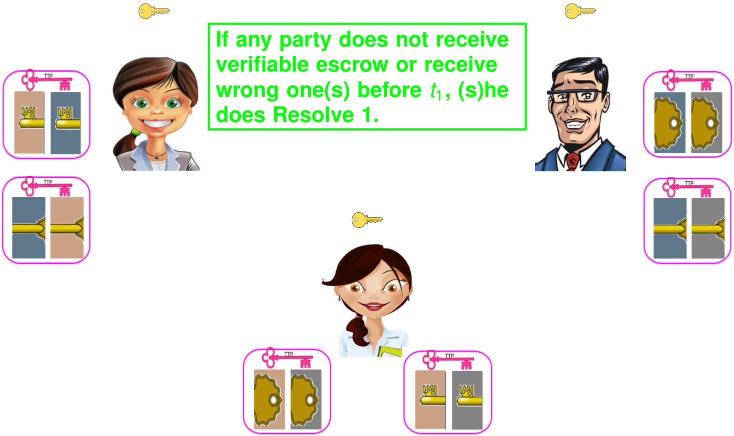
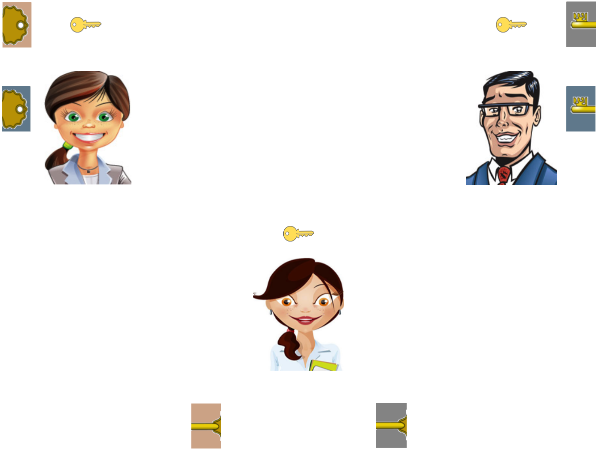


If any party does not receive verifiable escrow or receive wrong one(s) before t_1, (s)he does Resolve 1.

Phase 3: Decryption Share Exchange



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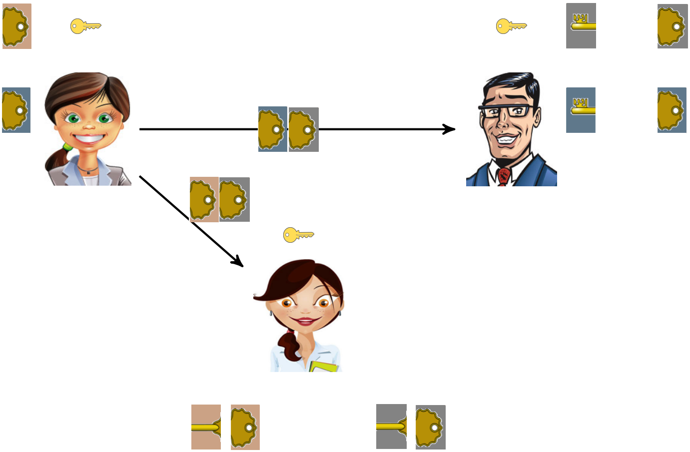

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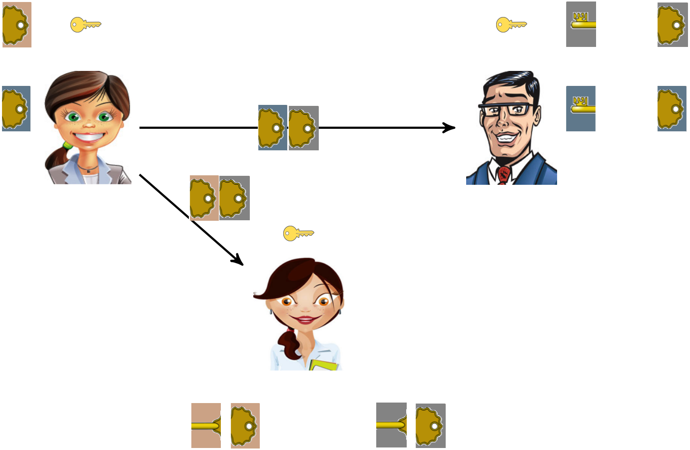

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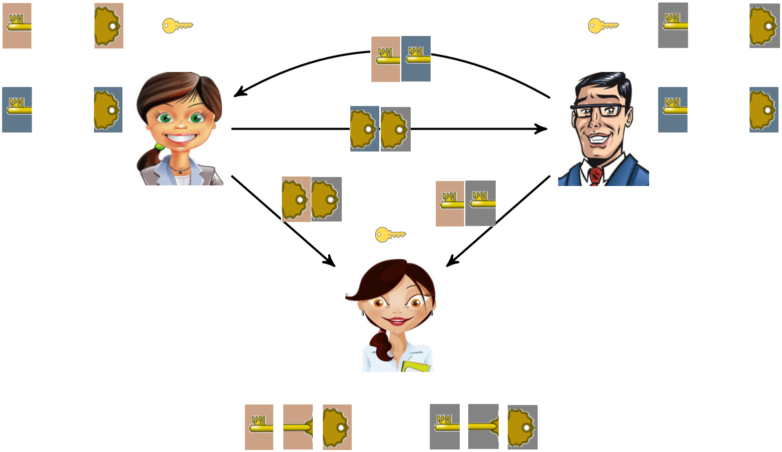

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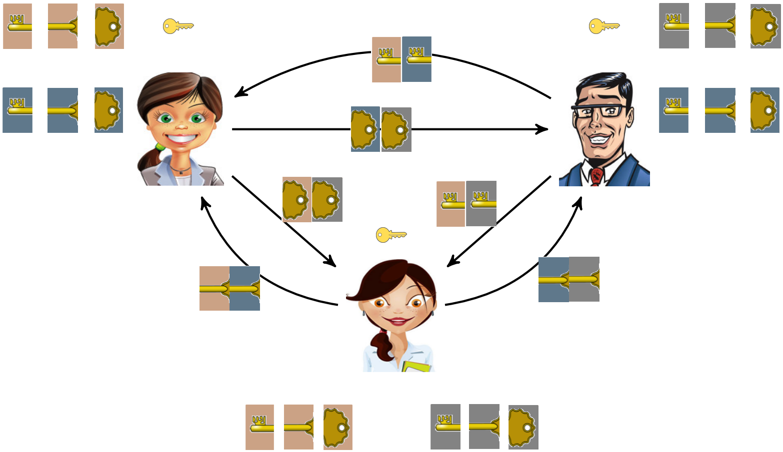

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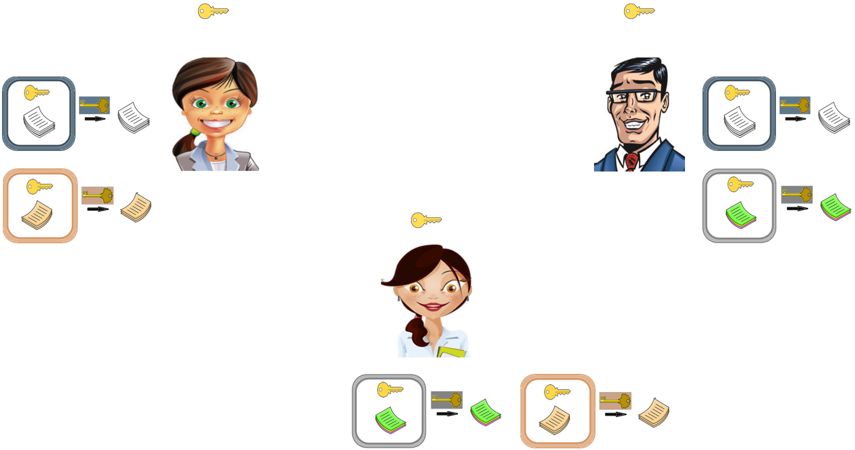

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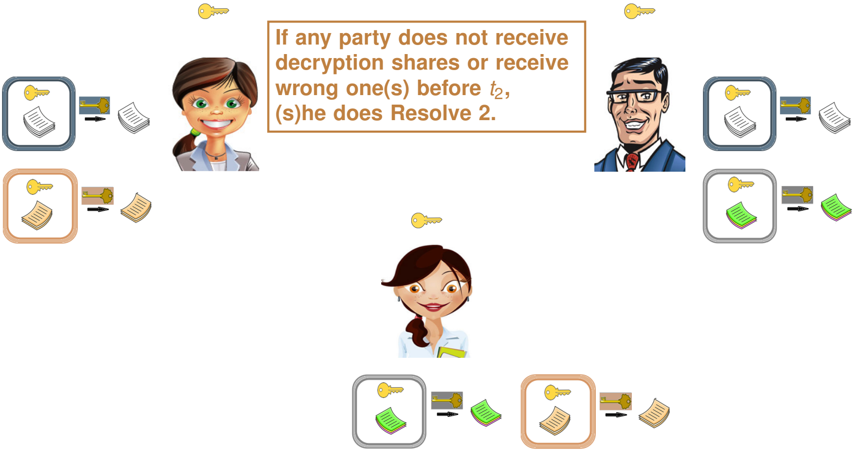

If any party does not receive decryption shares or receive wrong one(s) before t_2, (s)he does Resolve 2.

Resolve 1

- Parties do *not* learn any decryption shares here.
- They can just complain about other parties to the TTP.
- The TTP creates a fresh *complaintList* for the protocol with parameters id, t_1, t_2.

Resolve 2

- The party P_i, who comes for Resolve 2 **between $\mathbf{t_1}$ and $\mathbf{t_2}$**, gives all verifiable escrows that he has already received from the other parties and his own verifiable escrow to the TTP.
- The TTP uses these verifiable escrows to save the decryption shares required to solve the complaints in the *complaintList*.
  - If the *complaintList* is not empty in the end, P_i comes after t_2 for **Resolve 3**.
  - Otherwise, TTP decrypts the verifiable escrow and gives decryption shares.

Resolve 3

- If the *complaintList* still has parties, even after t_2, the TTP answers each resolving party saying that the protocol is **aborted**, which means nobody is able to learn any item.
- If the *complaintList* is *empty*, the TTP decrypts any verifiable escrow that is given to him.

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   - Multi-Party Fair Exchange
   - Definitions
2. Our New Protocols
   - MFE Protocol
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Making SMPC Fair with MFE

SMPC

Parties are able to compute the following function in a secure way by using SMPC protocol.

$$\phi(w_1, ..., w_n) = (\phi_1(w_1, ..., w_n), ..., \phi_n(w_1, ..., w_n))$$

Making SMPC Fair with MFE

Fair SMPC

- Change input of the each P_i as $z_i = (w_i, x_i)$.
- Compute the following functionality with SMPC.

$$\psi_i(z_1, z_2, ..., z_n) = (E_i(\phi_i(w_1, ..., w_n)), \{g^{x_j}\}_{1 \leq j \leq n})$$

where

$$E_i(\phi_i(w_1, ..., w_n)) = (g^{r_i}, \phi_i h^{r_i})$$

- Execute Phase 3 of MFE protocol.

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Why MFE is fair?

- Parties do not learn anything without any missing decryption share.
  ⇒ All parties depend each other. So even though $n-1$ malicious party exist, they can not exclude an honest party.
- If an honest party does not receive verifiable escrow, (s)he does not continue.
  ⇒ This obliges malicious party to send his verifiable escrow to the honest party, otherwise malicious one cannot learn anything.
- TTP does not decrypt verifiable escrow and send any decryption share until it is sure that he has all missing verifiable escrows.
  ⇒ Resolve protocols preserve fairness.

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Privacy in MFE and MPC

Privacy

The **privacy against the TTP is preserved.** He just learns some decryption shares, but he cannot decrypt the encryption of exchanged items, since he never gets the encrypted items.

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Previous works in Complete Topology

	Solution	Topology	Round Complexity	Number of Messages	Broad-cast
Garay & MacKenzie	MPCS	Complete	$O(n^2)$	$O(n^3)$	Yes
Baum & Waidner	MPCS	Complete	$O(tn)$	$O(tn^2)$	Yes
Mukhamedov & Ryan	MPCS	Complete	$O(n)$	$O(n^3)$	Yes
Mauw et al.	MPCS	Complete	$O(n)$	$O(n^2)$ ✓	Yes
Asokan et al.	MFE ✓	Any ✓	$O(1)$ ✓	$O(n^3)$	Yes
Ours	MFE ✓	Any ✓	$O(1)$ ✓	$O(n^2)$ ✓	No ✓

Previous works in Ring Topology

	Number Messages	**All or None**	**TTP-Party Dependency**	**TTP Privacy**
Bao et al.	$O(n)$	No	Yes	Not Private
González & Markowitch	$O(n^2)$	No	Yes	Not Private
Liu & Hu	$O(n)$	No	Yes	Not Private
Ours	$O(n^2)$	Yes ✓	No ✓	Private ✓

Previous works in fair SMPC

	Technique	**TTP**	**Number of Rounds**	**Proof Technique**
Garay et al.	Gradual Release	No	$O(\lambda)$	NFS
Bentov & Kumaresan	Bitcoin	Yes	Constant ✓	NFS
Andrychowicz et al.	Bitcoin	Yes	Constant ✓	NFS
Ours	MFE	Yes	Constant ✓	FS ✓

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Our Contributions

MFE

- ✓ We design a MFE protocol requires only $\mathbf{O}(\mathbf{n^2})$ messages and **constant** number of rounds for n parties.
- ✓ Our MFE **optimally** (in complete topology) guarantees fairness (for honest parties) even when $n-1$ out of n parties are malicious and colluding.
- ✓ We show how to employ our MFE protocol for **any exchange topology**, with the performance improving as the topology gets sparser.
- ✓ We formulate MFE as a secure multi-party computation protocol. We then **prove** security and fairness **via ideal-real world simulation** [9].

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Authors

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Phase 1: Setup Phase

All participants agree on the prime p-order subgroup of $\mathcal{Z}_q^*$, where q is a large prime, and a generator g of this subgroup. Then each P_i does

$\underline{P_i}$	**Phase 1**	$\underline{P_j}$
pick x_i		pick x_j
compute $h_i = g^{x_i}$		compute $h_j = g^{x_j}$
$C_i = Com(h_i, r_i)$	$\xrightarrow{C_i}$	$C_j = Com(h_j, r_j)$
	$\xleftarrow{C_j}$	
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pick r_i		pick r_j
$E_i = (a_i, b_i) = (g^{r_i}, f_i h^{r_i})$	$\xrightarrow{VE_i = V(E_i, h; \emptyset)\{(v_i, f_i) \in R_{item}\}}$	$E_j = (a_j, b_j) = (g^{r_j}, f_j h^{r_j})$
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If VE is not received from at least one of the parties

Abort

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Note that $\mathbf{a_k} = \mathbf{g^{r_k}}$ (First part of the k^{th} item's encryption).
The relation R_s is $\mathbf{\log_g h_i} = \mathbf{\log_{a_k} a_k^{x_i}}$ for each k.

$\underline{P_i}$	**Phase 3**	$\underline{P_j}$
compute $\{d_k^i = a_k^{x_i}\}_{k=1}^n$	$\xrightarrow{VS_i = V(E_i^t, pk; t_1, t_2, id, P_i)\{(h_i, \{d_k^i\}) \in R_s\}}$	compute $\{d_k^j = a_k^{x_j}\}_{k=1}^n$
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If VS is not received from at least one of the parties before time t_1

Resolve 1

$$\xrightarrow{\{d_k^i\} j, PK(h_i, \{a_k\})\{(h_i, \{d_k^i\}) \in R_s\}}$$

$$\xleftarrow{\{d_k^j\}, PK(h_j, \{a_k\})\{(h_j, \{d_k^j\}) \in R_s\}}$$

If d_k^j are not received before t_2

Resolve 2

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compute $\{d_k^i = a_k^{x_i}\}_{k=1}^n$ $\xrightarrow{VS_i = V(E_i^t, pk; t_1, t_2, id, P_i)\{(h_i, \{d_k^i\}) \in R_s\}}$ compute $\{d_k^j = a_k^{x_j}\}_{k=1}^n$

$E_i^t = Enc_{pk}(\{d_k^i\}_{k=1}^n)$ $\xleftarrow{VS_j = V(E_j^t, pk; t_1, t_2, id, P_j)\{(h_j, \{d_k^j\}) \in R_s\}}$ $E_j^t = Enc_{pk}(\{d_k^j\}_{k=1}^n)$

If VS is not received from at least one of the parties before time t_1

Resolve 1

$\xrightarrow{\{d_k^i\}j, PK(h_i, \{a_k\})\{(h_i, \{d_k^i\}) \in R_s\}}$

$\xleftarrow{\{d_k^j\}, PK(h_j, \{a_k\})\{(h_j, \{d_k^j\}) \in R_s\}}$

If d_k^i are not received before t_2

Resolve 2

Phase 3

Note that $\mathbf{a_k} = \mathbf{g^{r_k}}$ (First part of the k^{th} item's encryption).
The relation R_s is $\mathbf{\log_g h_i} = \mathbf{\log_{a_k} a_k^{x_i}}$ for each k.

P_i | **Phase 3** | P_j

compute $\{d_k^i = a_k^{x_i}\}_{k=1}^n$ | $\xrightarrow{VS_i = V(E_i^t, pk; t_1, t_2, id, P_i)\{(h_i, \{d_k^i\}) \in R_s\}}$ | compute $\{d_k^j = a_k^{x_j}\}_{k=1}^n$

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