# Efficient Leakage Resilient Circuit Compilers

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# Theory

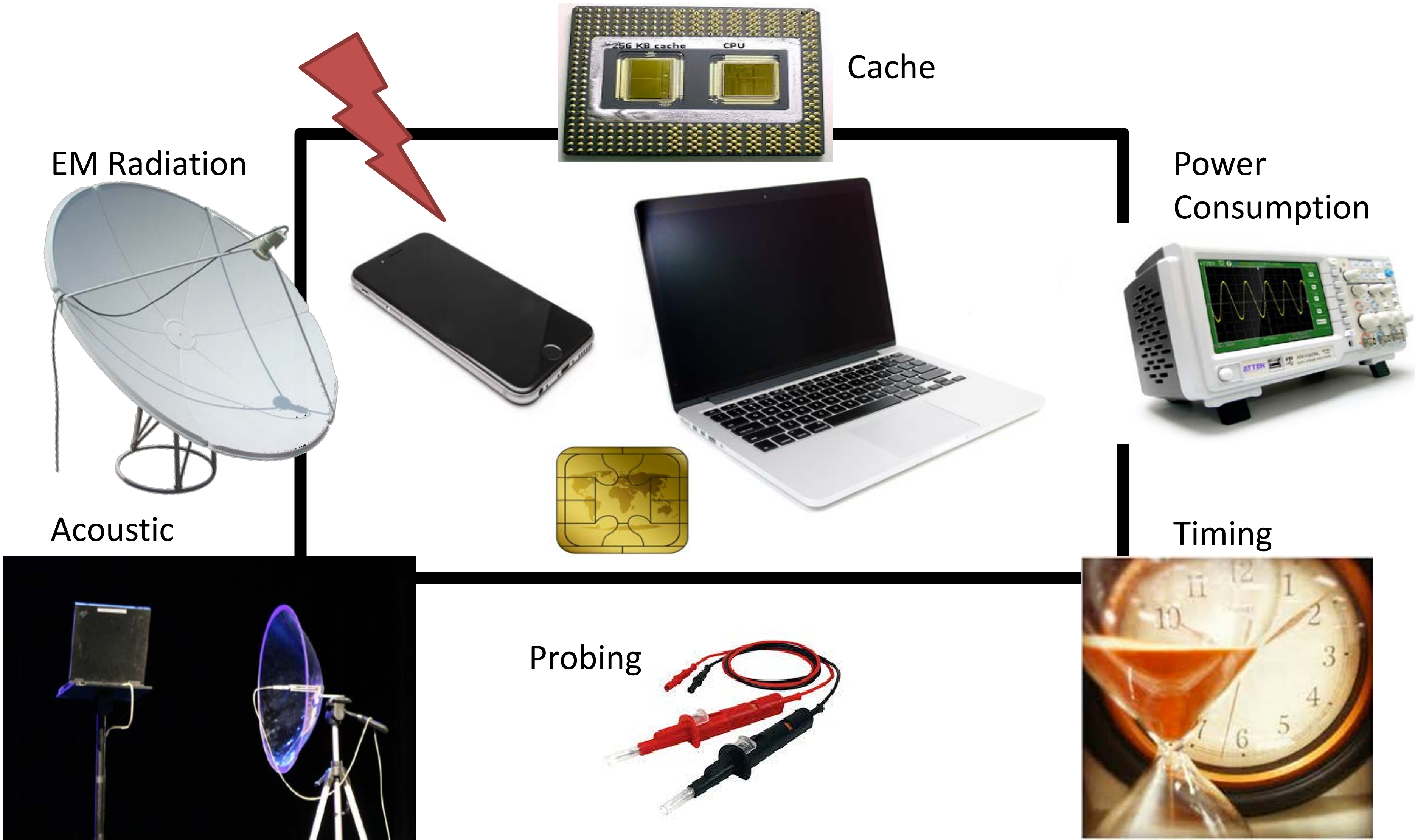
Cryptographic algorithms are often modeled as 'black boxes'

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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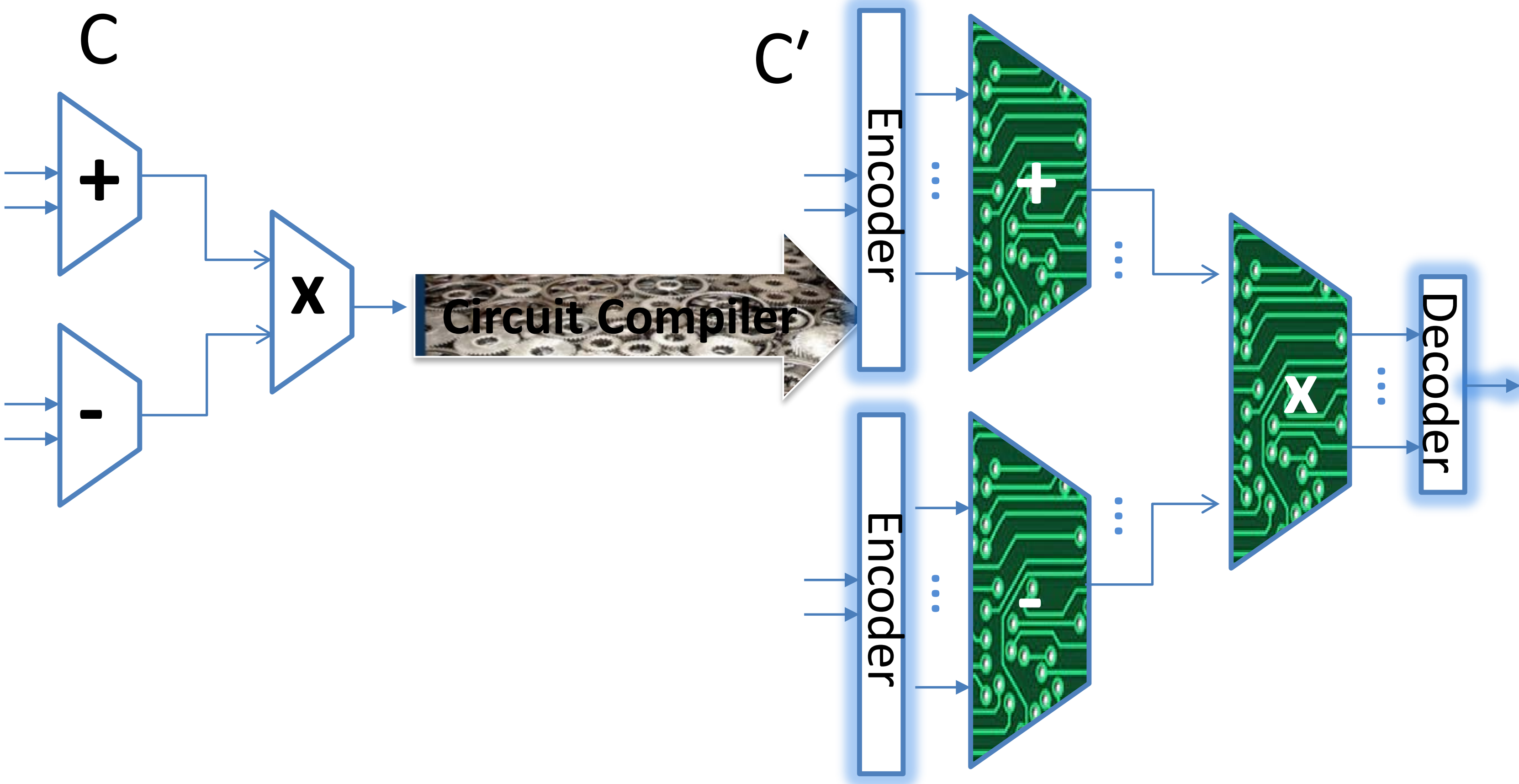

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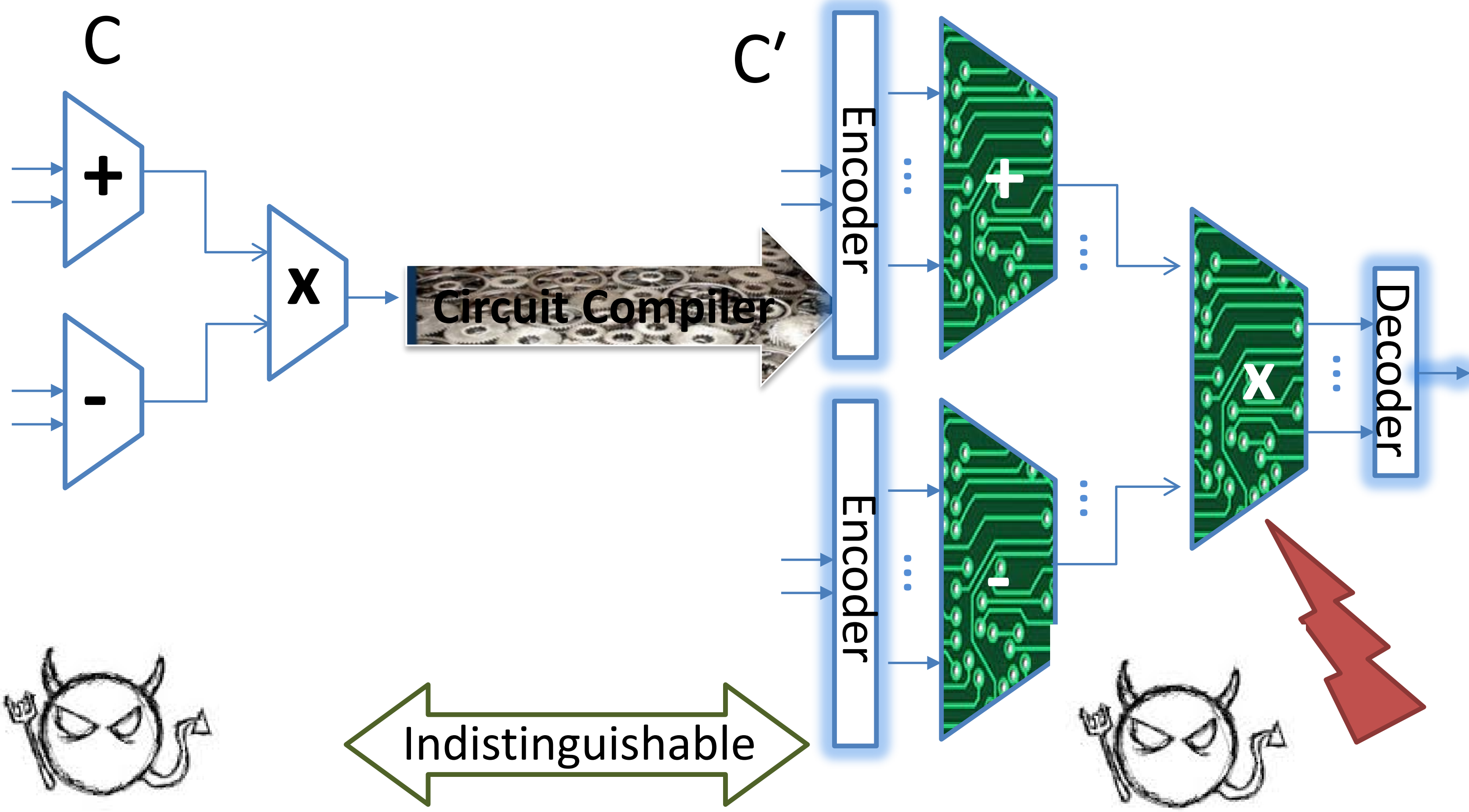


Even given leakage,
execution “looks like”
black-box access to C(·)

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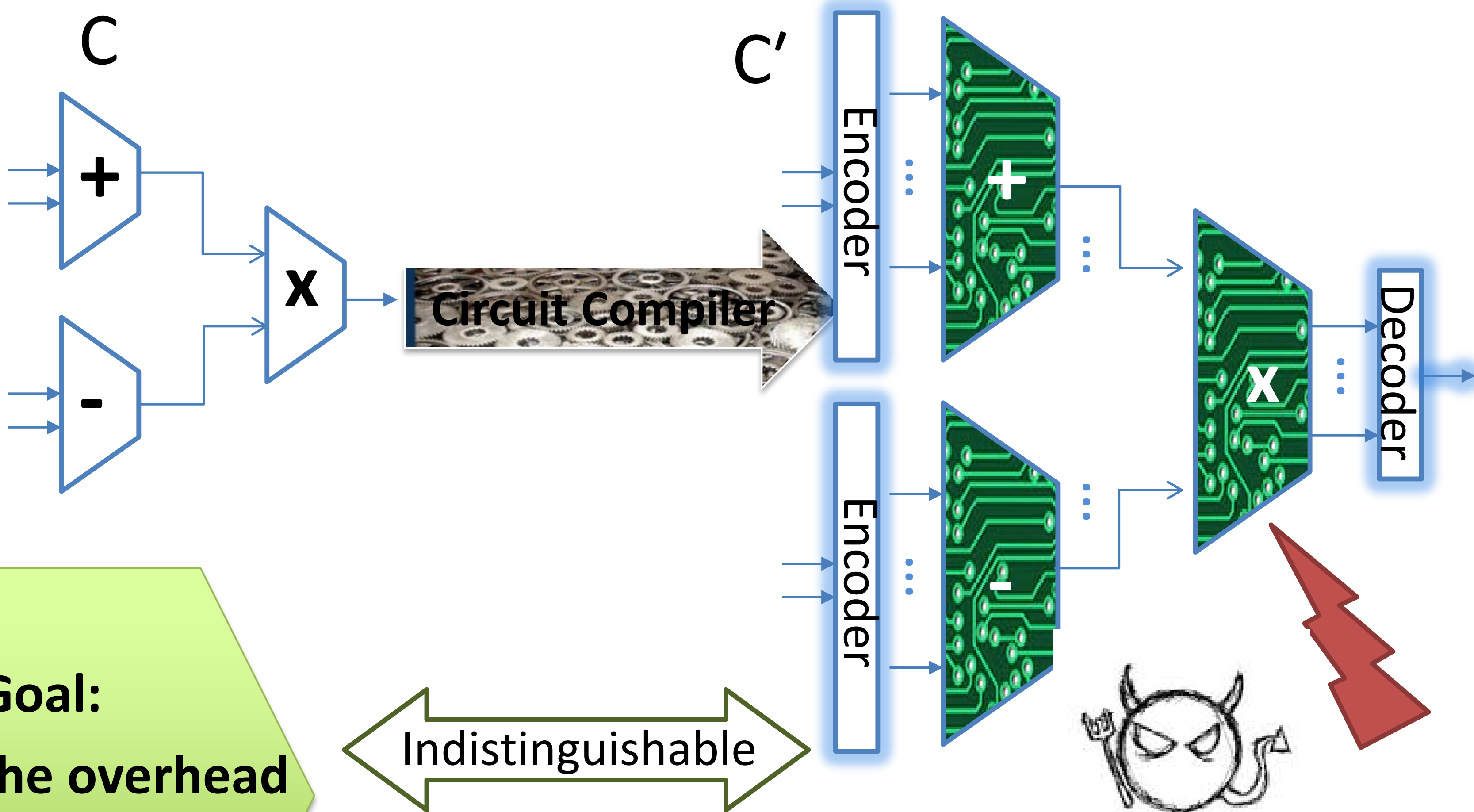


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**Goal:**
**Reduce the overhead induced by the compiler**

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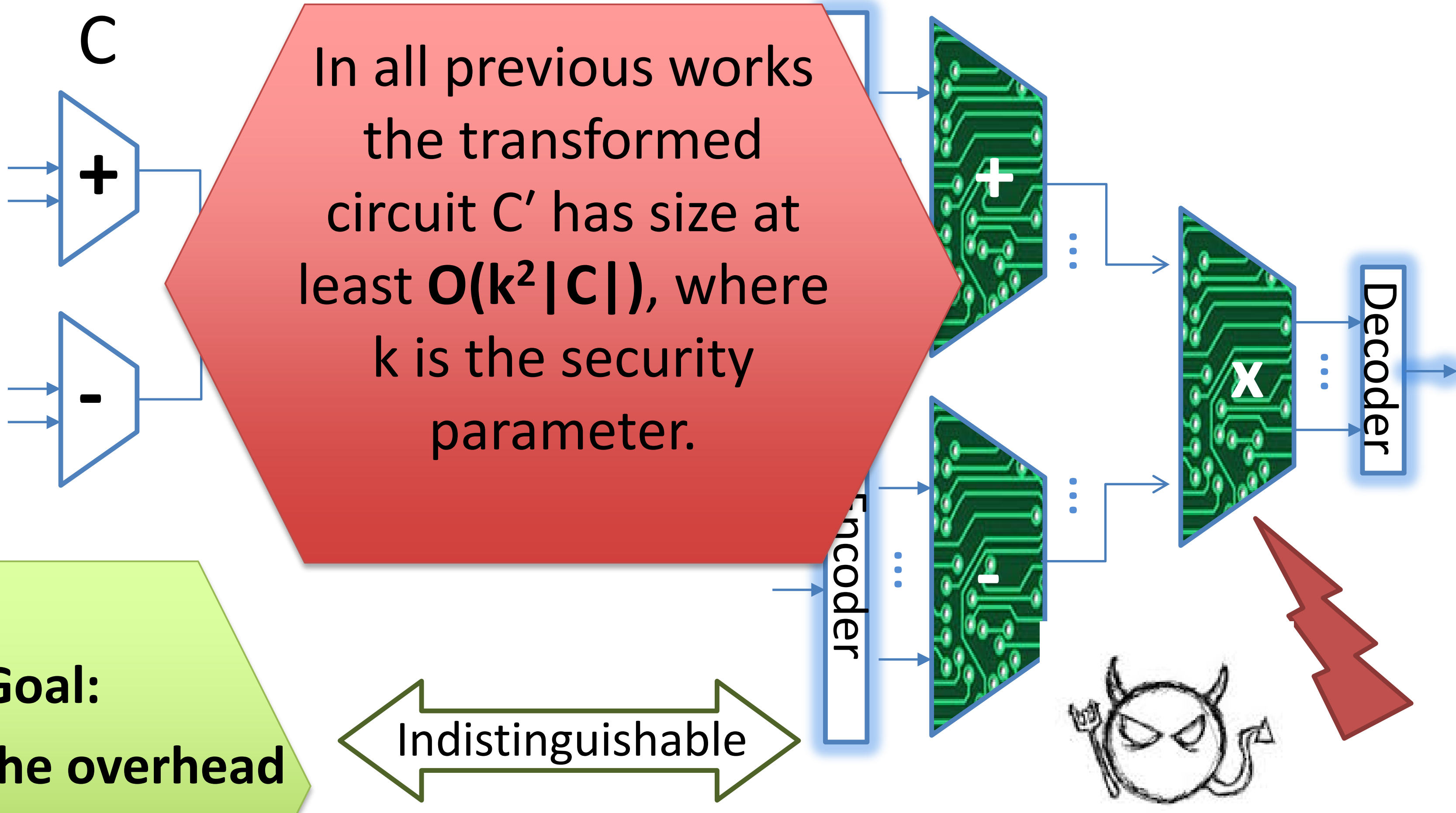



In all previous works the transformed circuit C′ has size at least **$O(k^2|C|)$**, where k is the security parameter.

**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

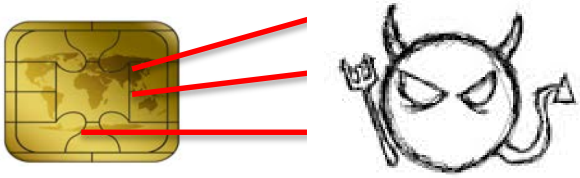
Is it possible to construct leakage resilient compilers with at most linear overhead?

- All previous works introduce at least quadratic overhead.

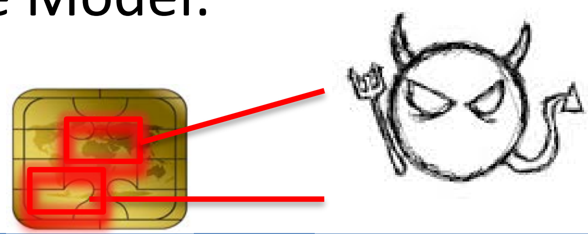
# Prior Work on General Compilers

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(polylog(k) ·|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·|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

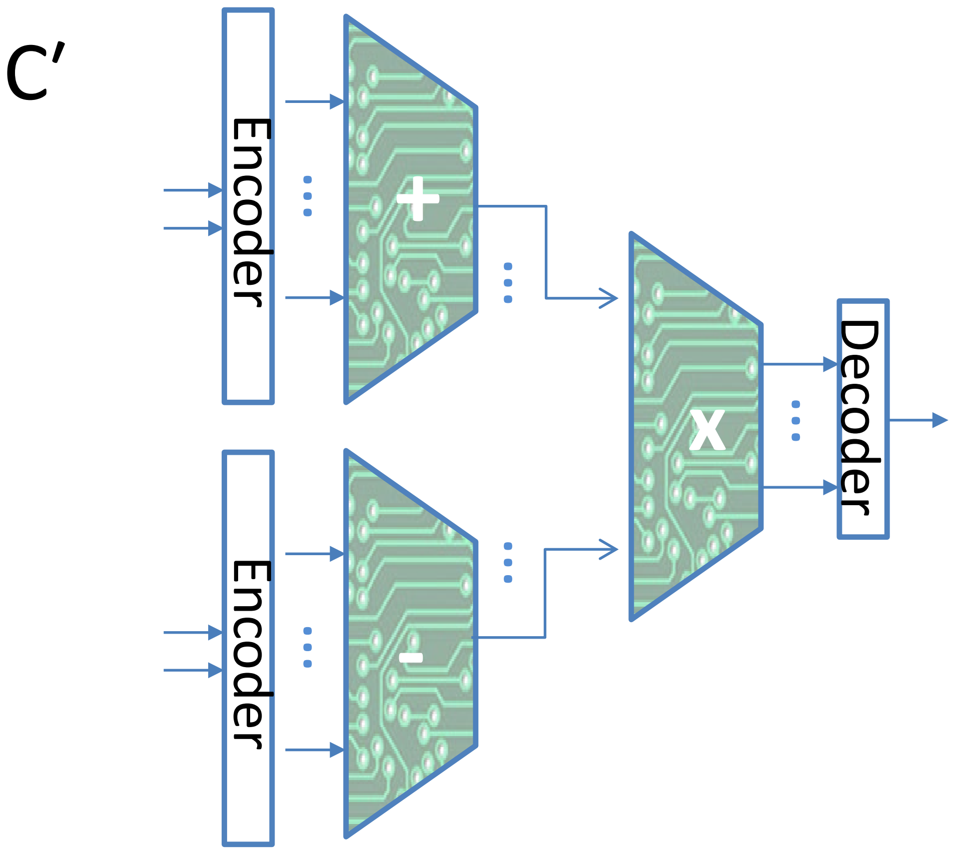
- **Informal Theorem :** A compiler that makes **any circuit** resilient to **computationally weak leakages**. The compiler increases the circuit size by a factor of **O(k)**.

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

However we must assume something [MR04]:

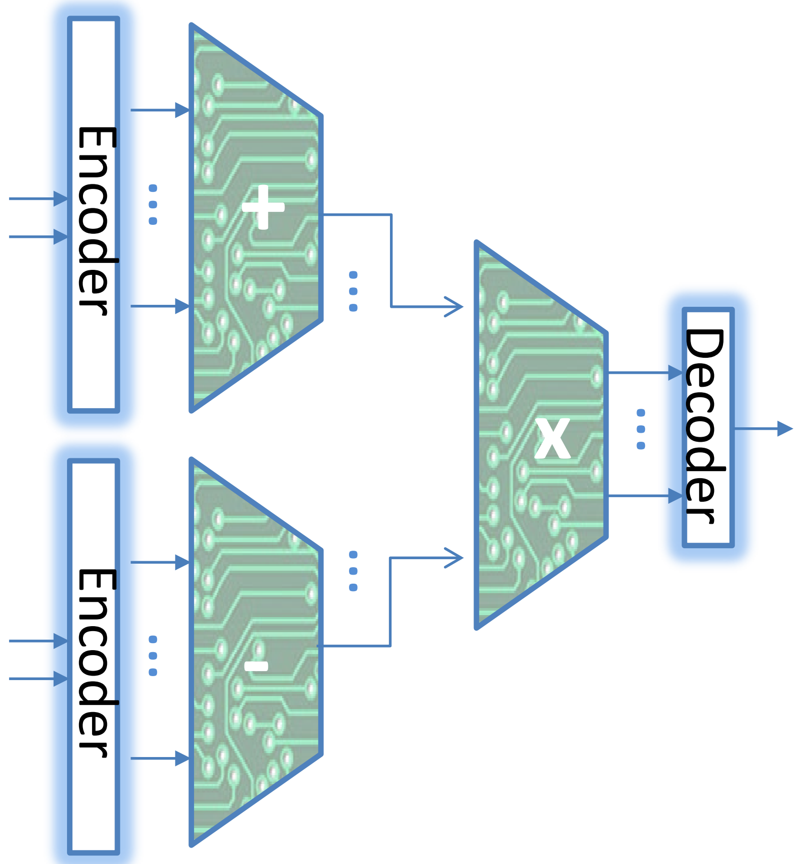
- **Leakage function is computationally weak.**
- **Simple opaque gates.**

# The Compiler



# The Compiler:
# From Wires to Wire Bundles

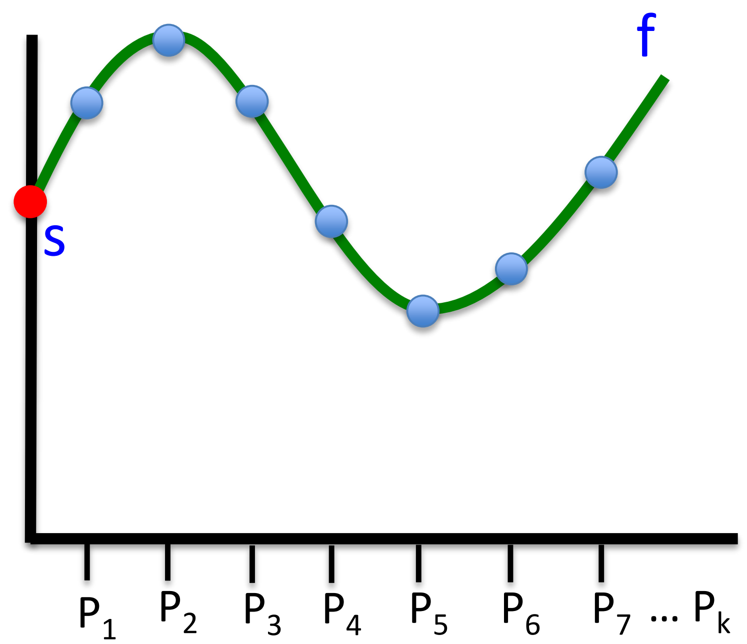
C′



# 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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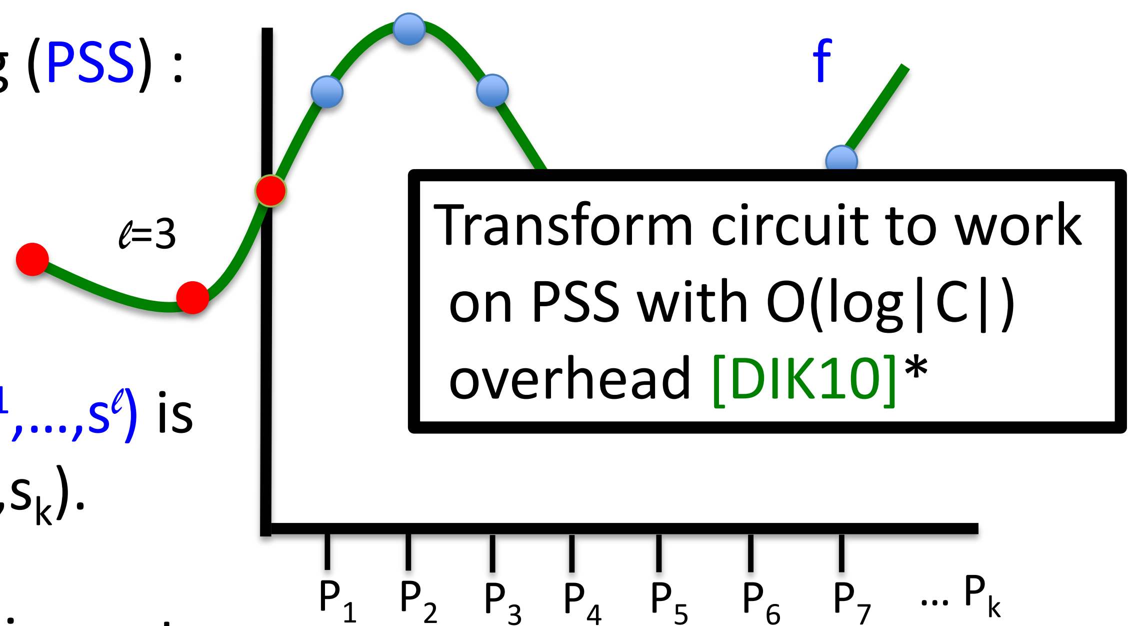
Packed Secret Sharing (PSS) :



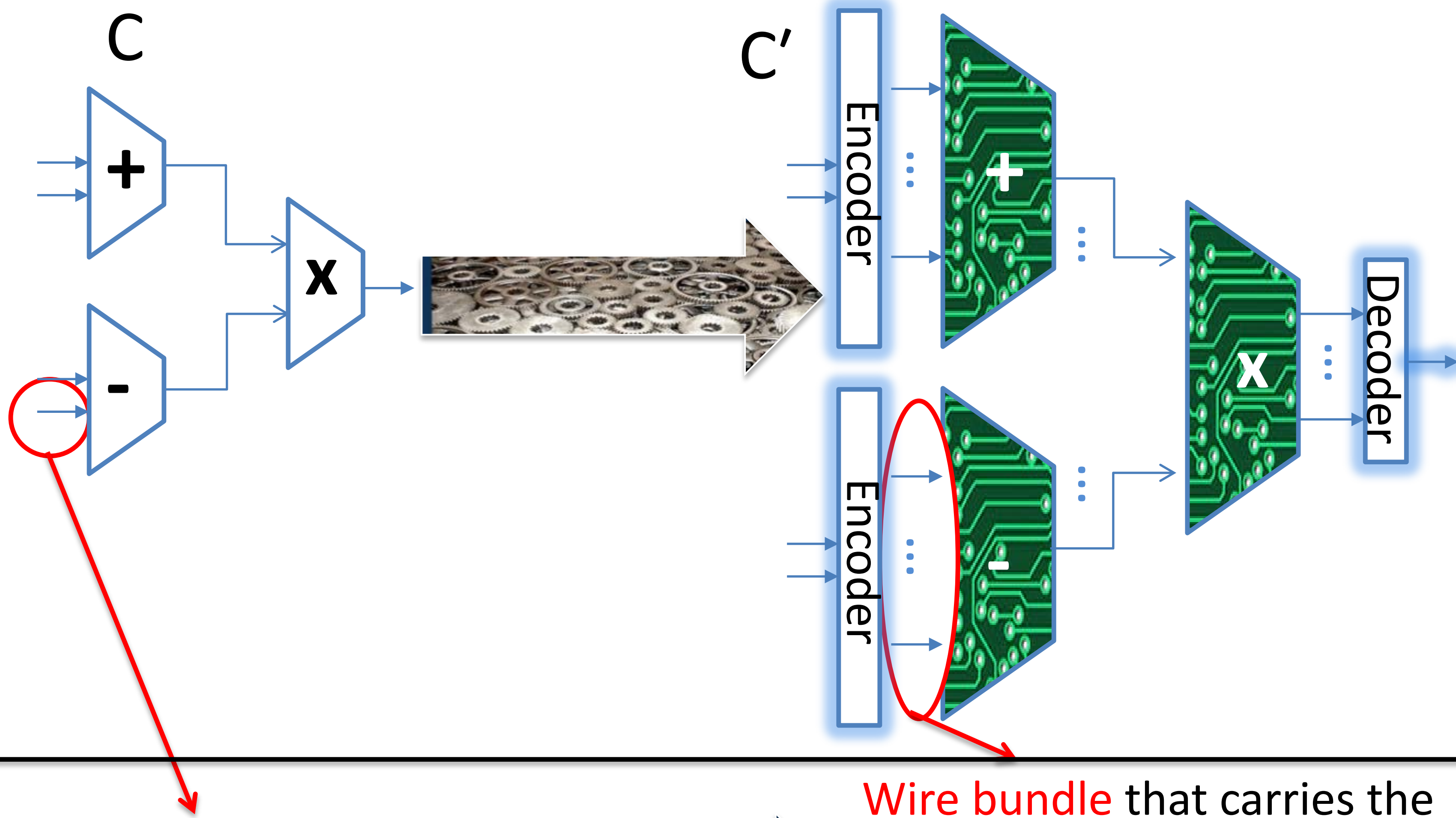

Transform circuit to work on PSS with O(log|C|) overhead [DIK10]*

Notation:

Secret sharing of **s**=($s^1$,…,$s^\ell$) is denoted by $[s]_d$=($s_1$,…,$s_k$).

*Introduces Permutation gates.

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




Each wire w

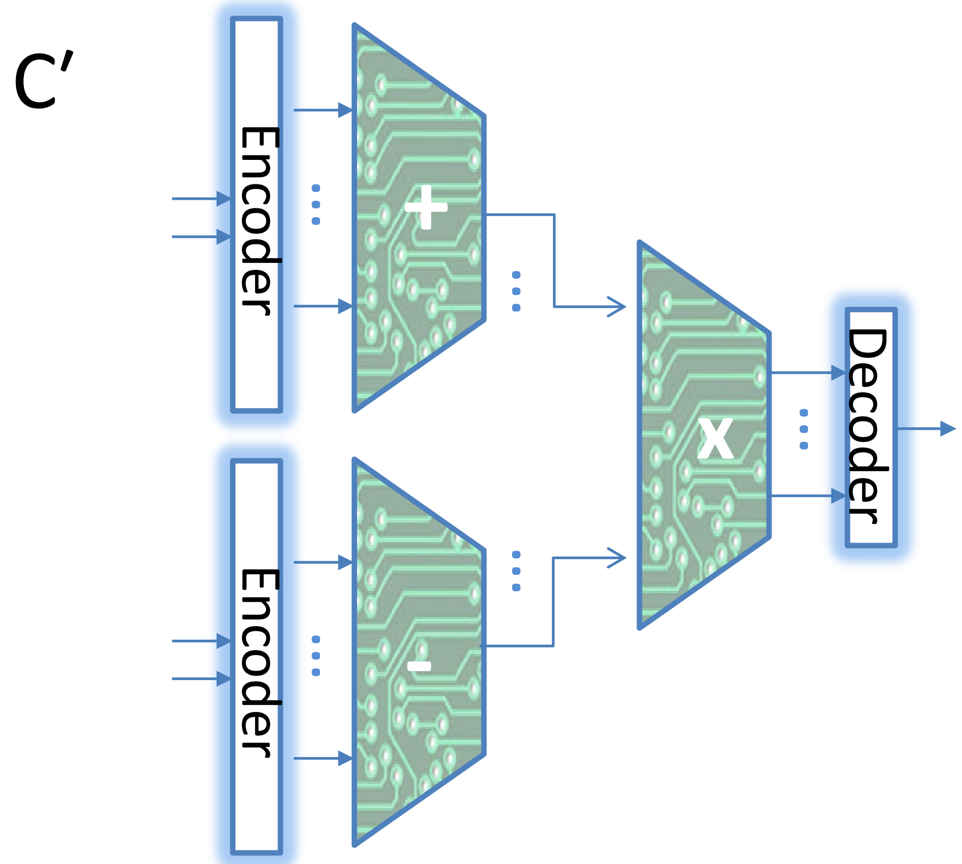
Wire bundle that carries the encoding of w denoted by $[w]_d = (w_1,\ldots,w_k)$.

# PSS is Secure Against $AC^0$ Leakages

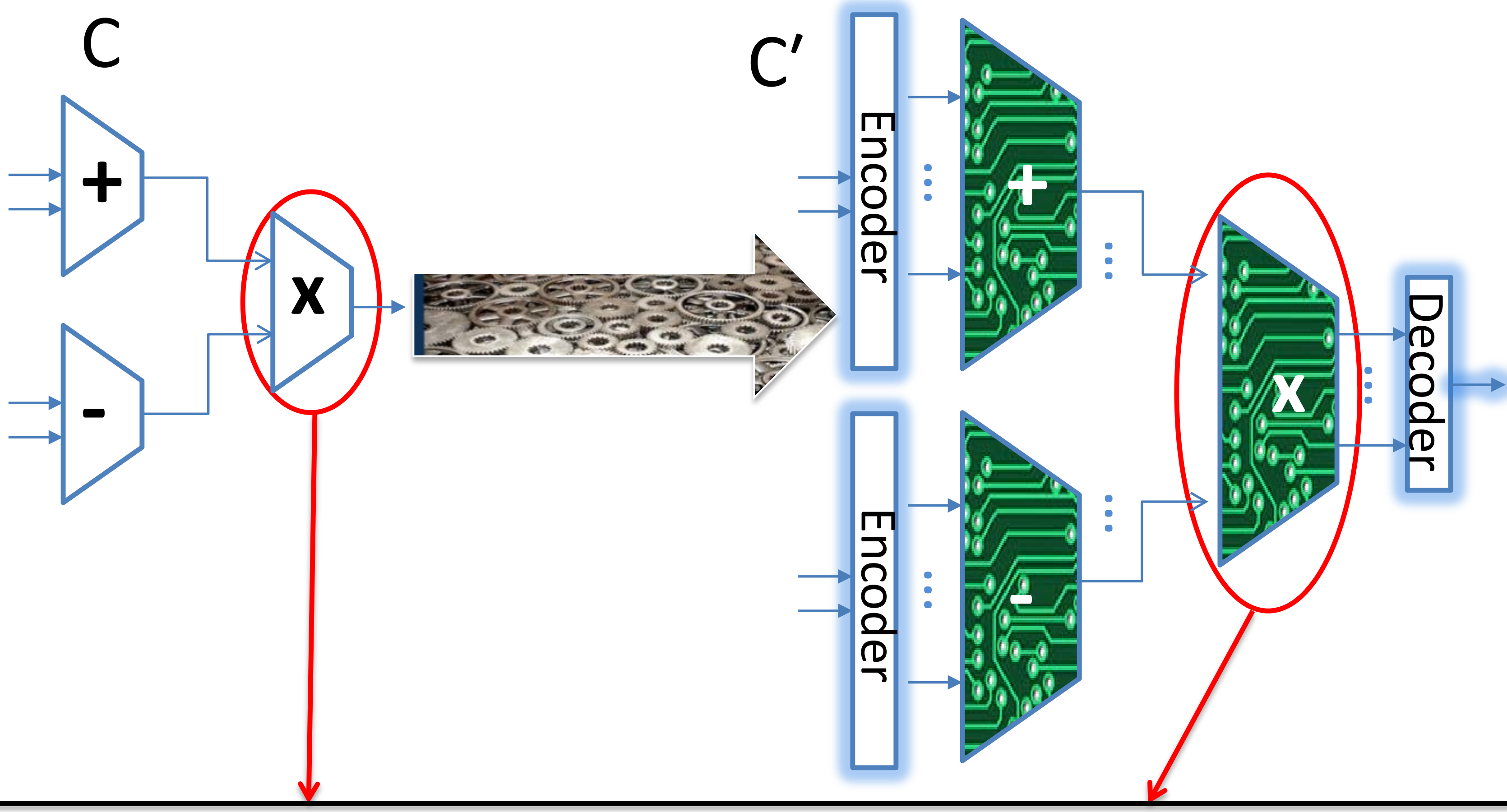
A function is in $AC^0$ if it can be computed by a poly-size O(1) depth Boolean circuit with unbounded fan-in AND, OR (and NOT) gates.

- 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

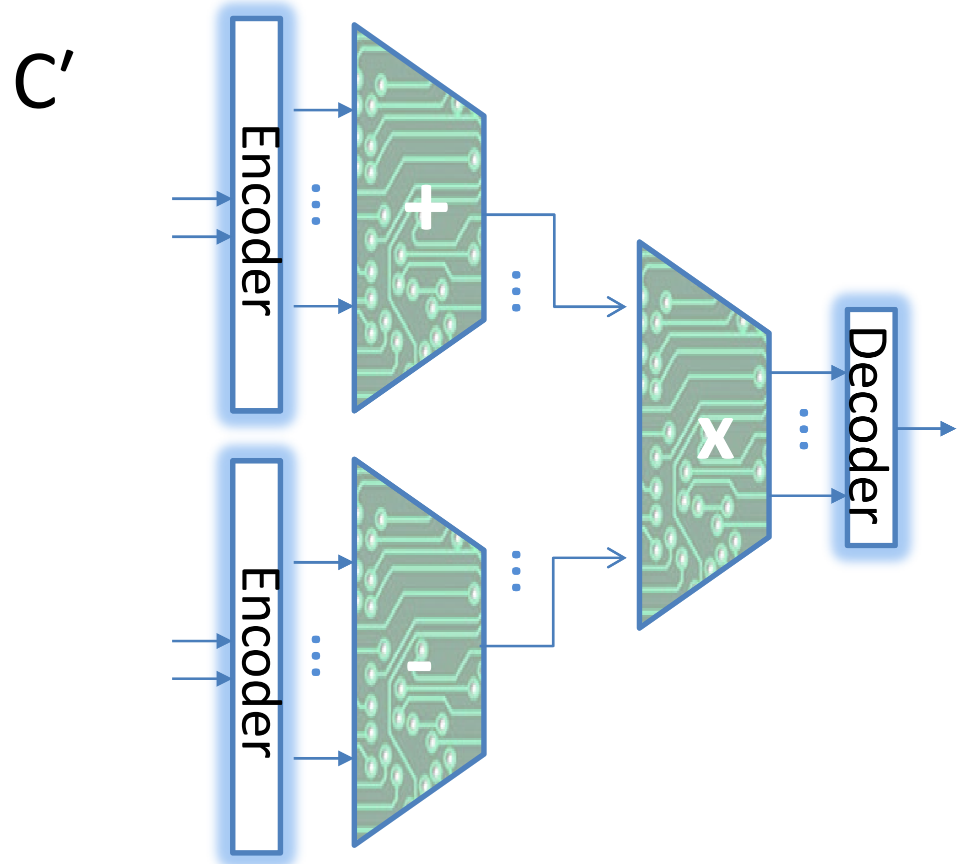
e.g.: **securely draw strings with inner product 0**.

✓ Stateless: No secrets are stored

✓ Small and simple

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

# The Compiler:
# Addition & Subtraction Gadgets



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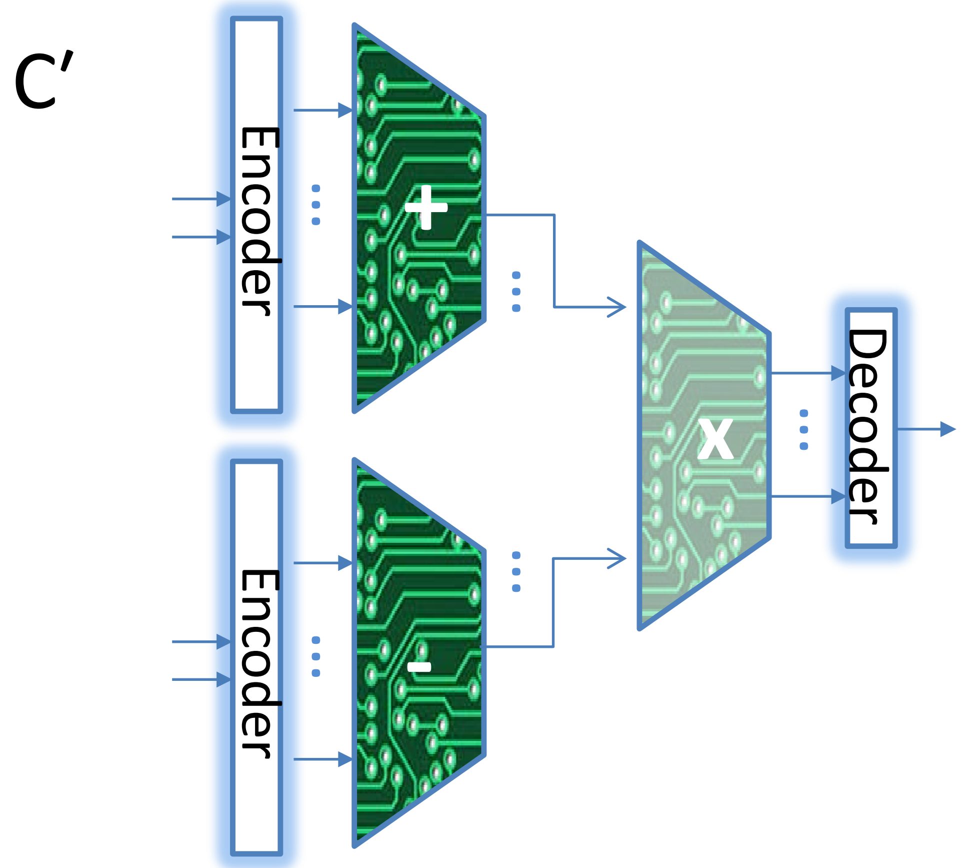


# The Compiler:
# Addition & Subtraction Gadgets

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

$[0]_d \leftarrow$ Opaque gate

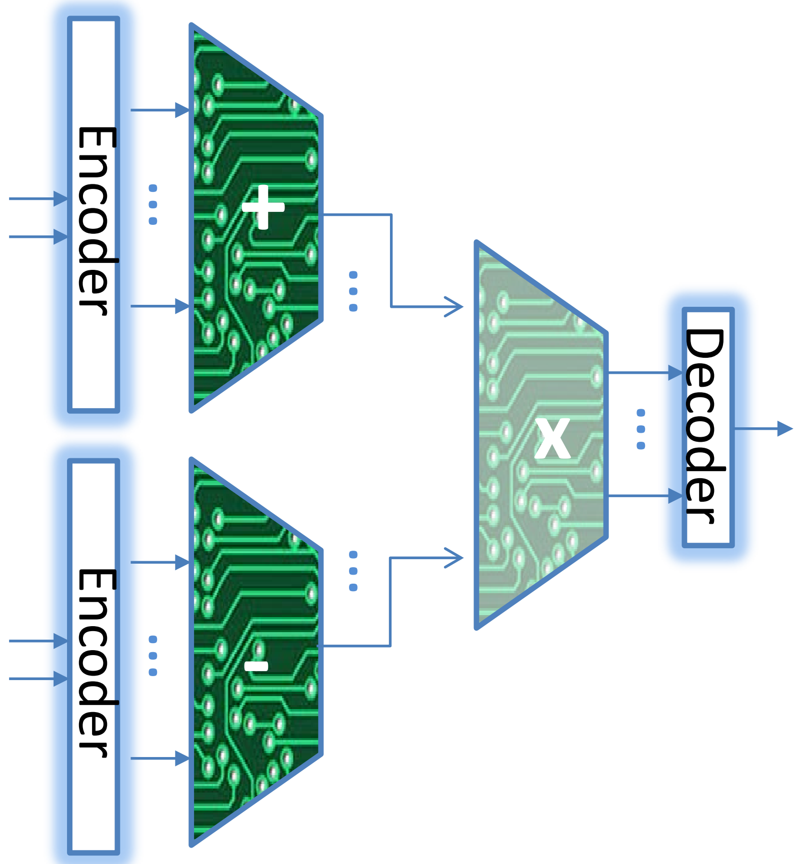
$[a+b]_d = [a]_d + [b]_d + [0]_d$

OR

$[a-b]_d = [a]_d - [b]_d + [0]_d$

# The Compiler:
# Multiplication Gadgets

C′



# The Compiler: Multiplication Gadgets

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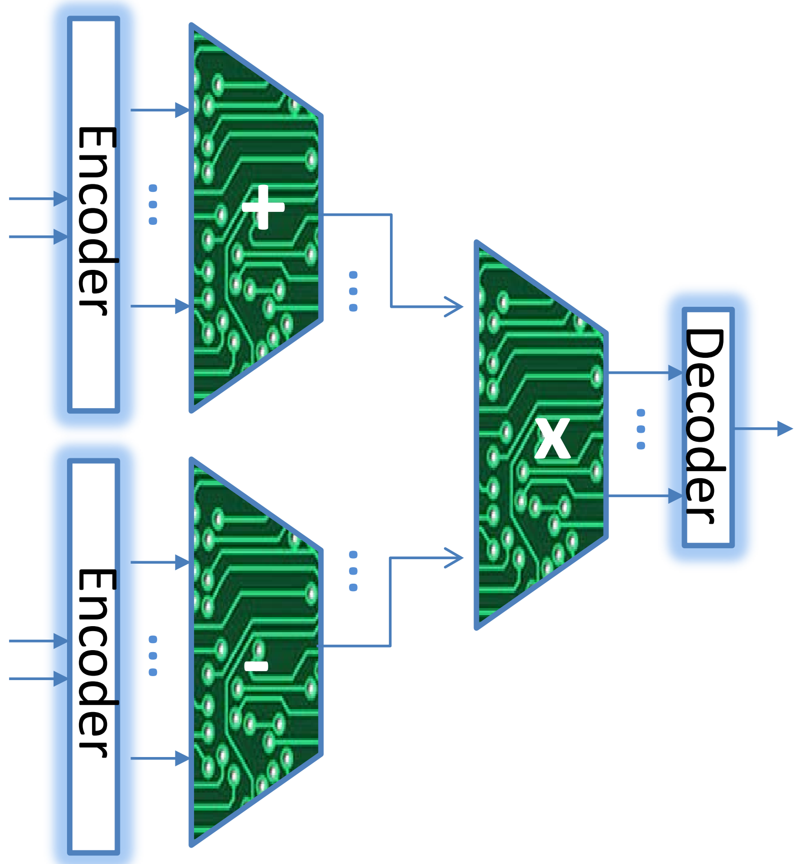

# The Compiler:
# Multiplication Gadgets

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

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

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

Permutation gadgets follow in a similar way.

# 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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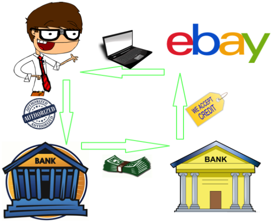


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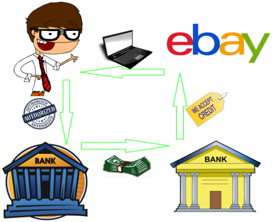
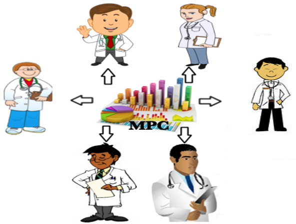
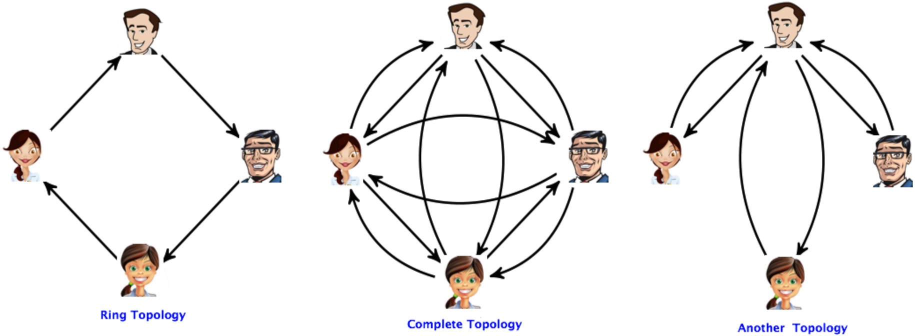


# MFE Topologies



# Optimistic MFE

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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 $\phi$.

- This computation is secure when the parties do not learn anything beyond what is revealed by the output of the computation.
- This computation is fair if either all of the parties learn their corresponding output in the end of computation, or none of them learns.

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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 $\phi$ 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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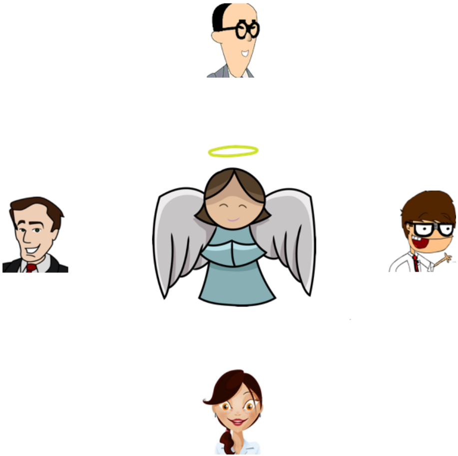

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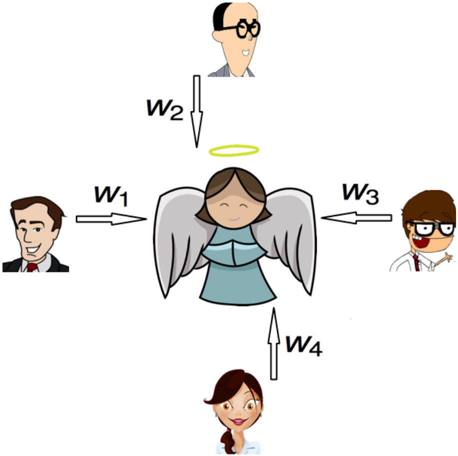

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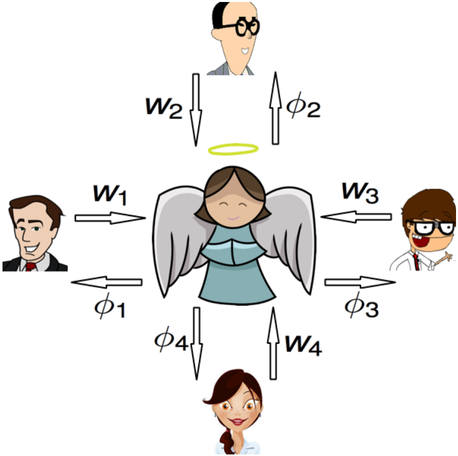
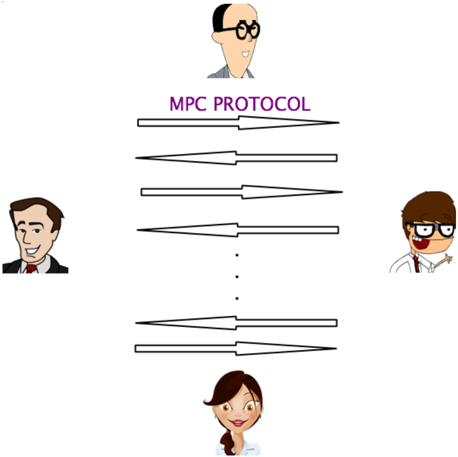
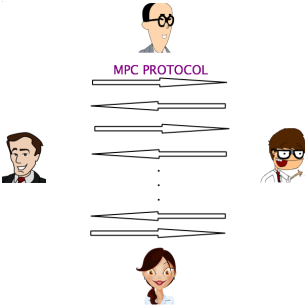


# Real World for MPC



# Secure and Fair MPC

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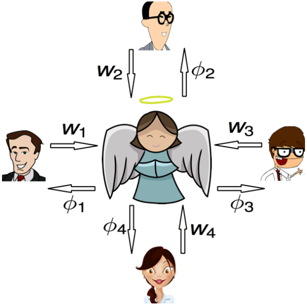

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# Overview of MFE protocol

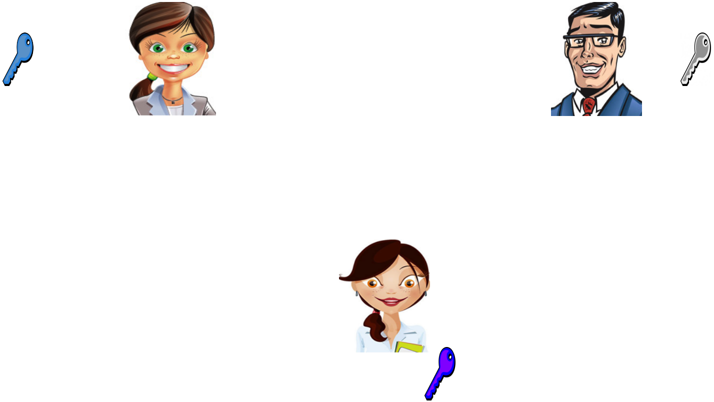
The parties are $P_1, P_2, ..., P_n$ and each party $P_i$ has item $f_i$. They want the items of all parties (complete topology).
The TTP and his public key $pk$ is known by all parties.

- 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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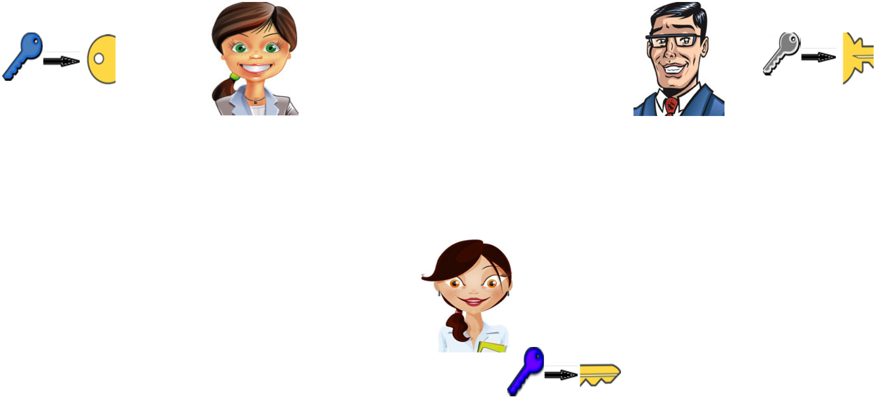

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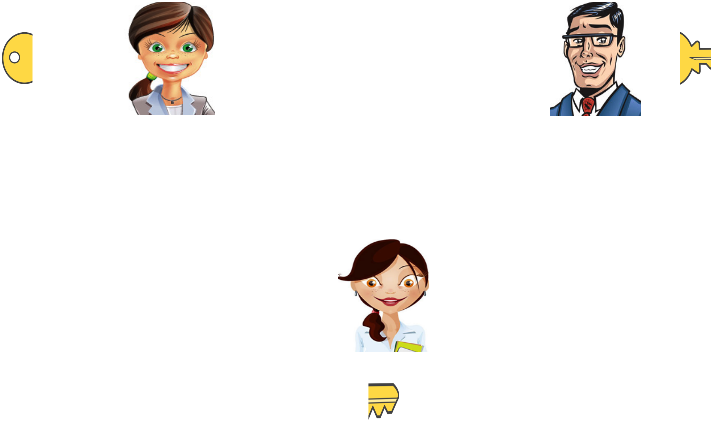

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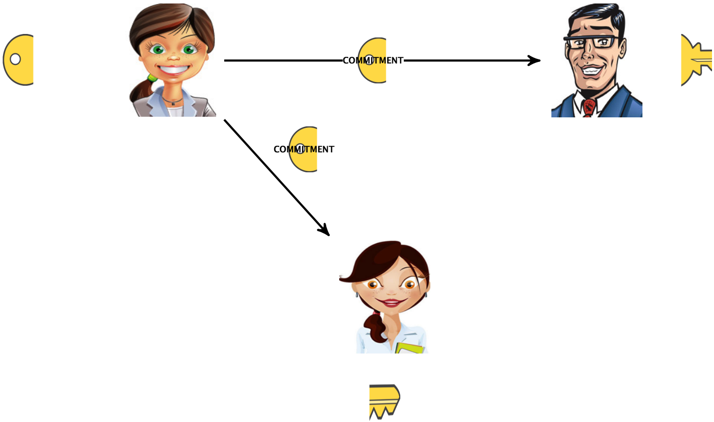

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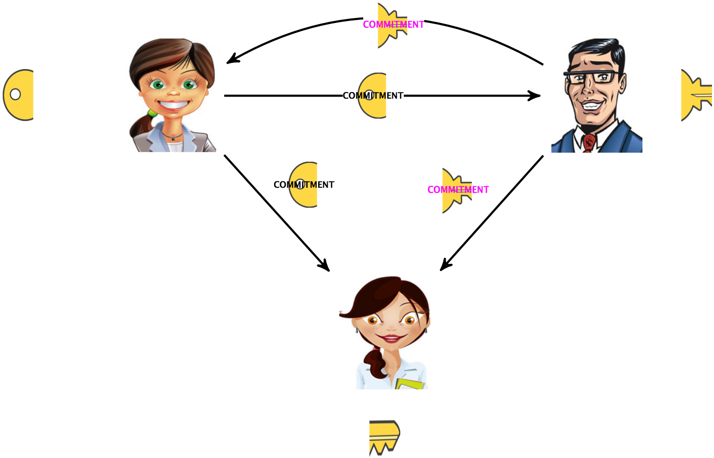

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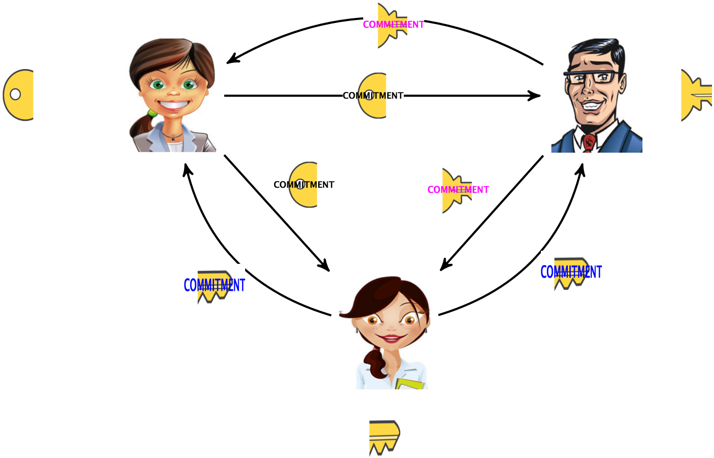

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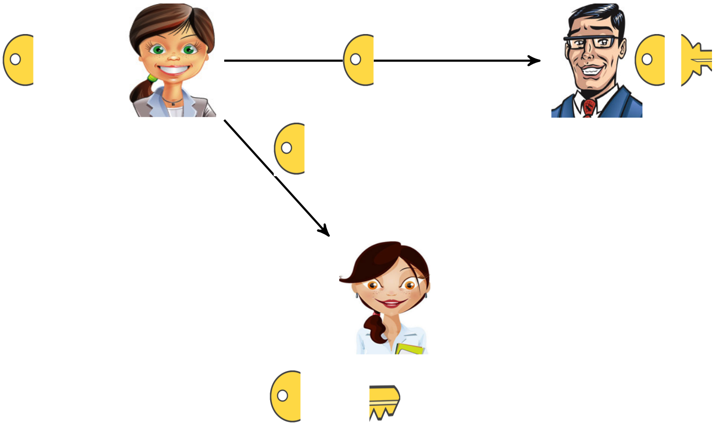

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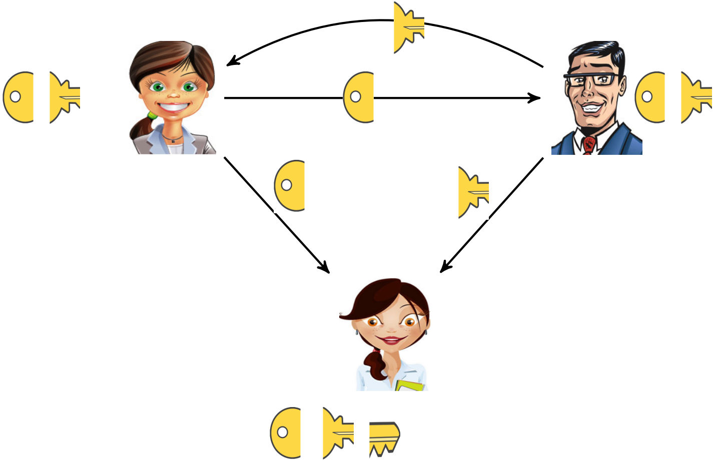

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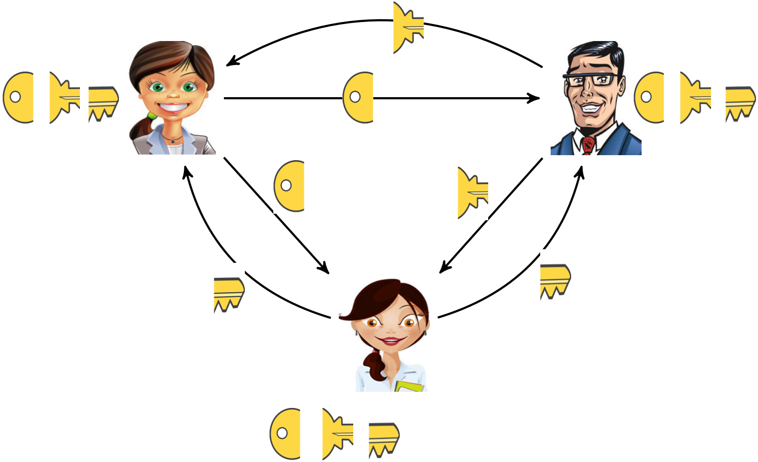

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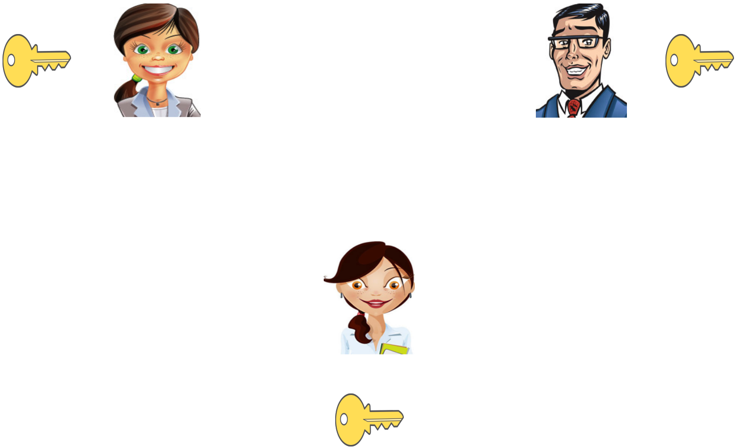
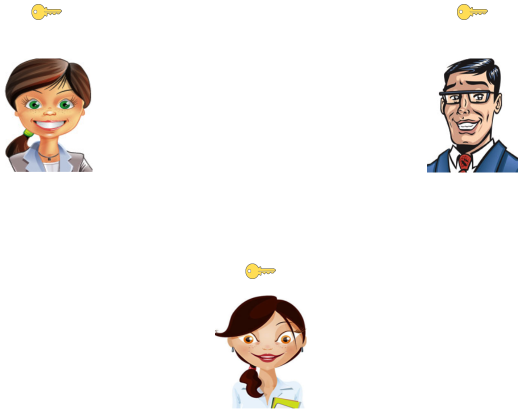


# Phase 2: Verifiable Encryption of Items



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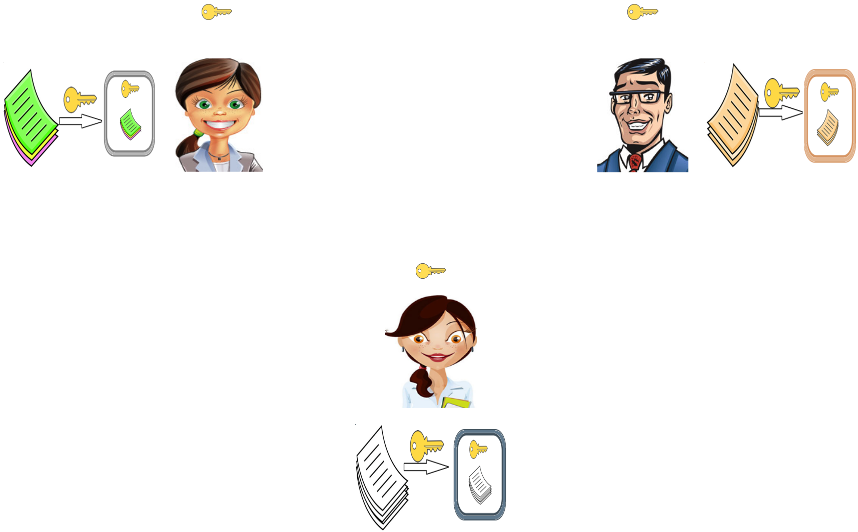

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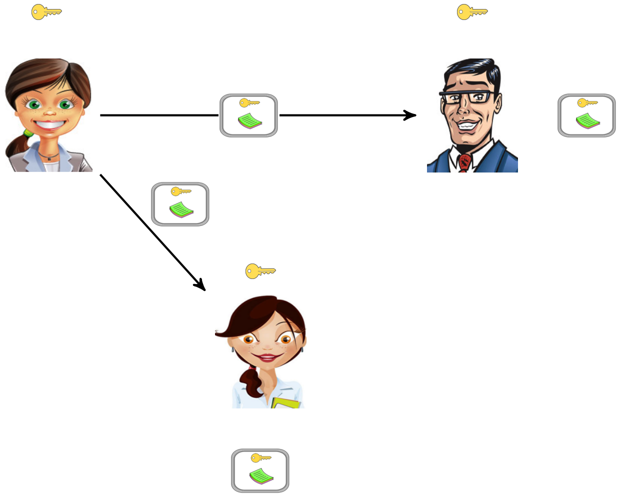

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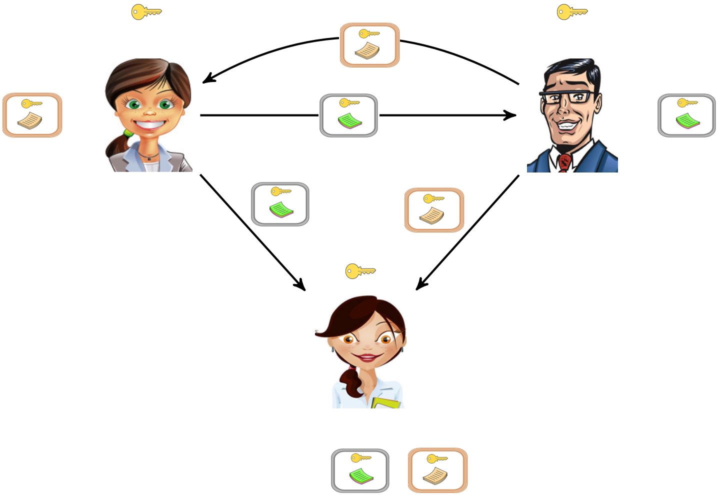

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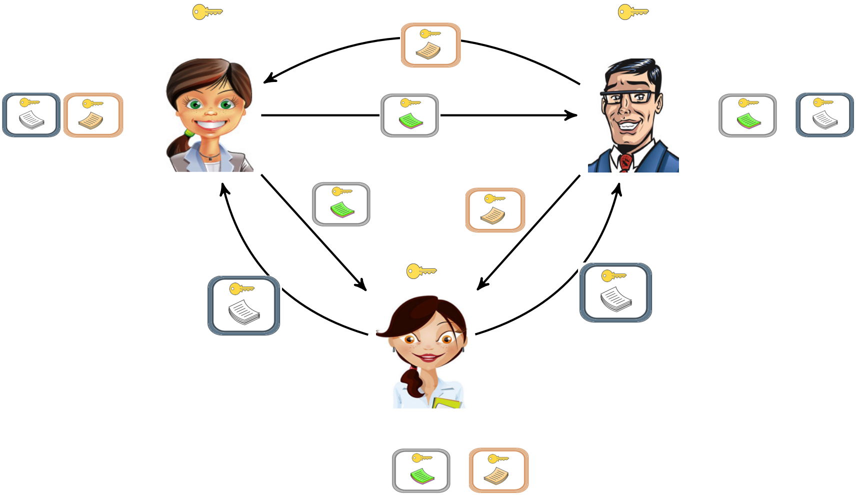

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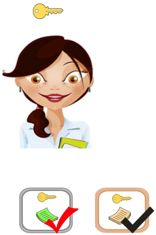
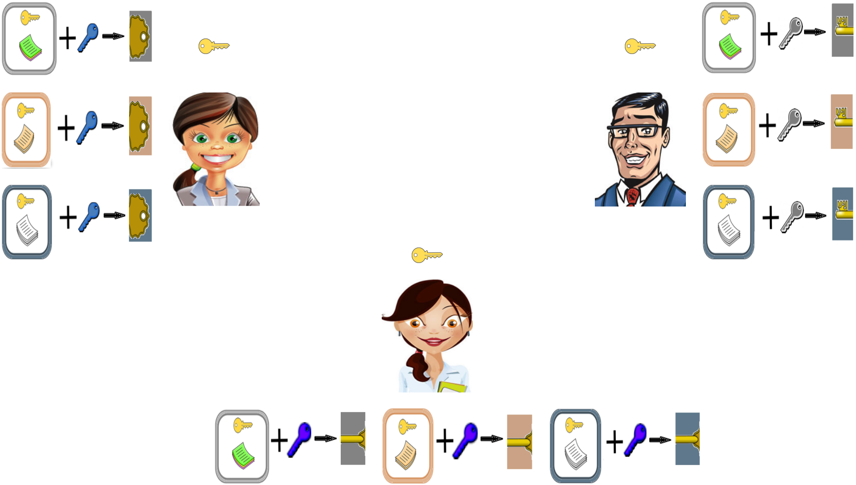
**If any party does not receive verifiable encryption, (s)he aborts.**



# Phase 2: Decryption Share Encryption



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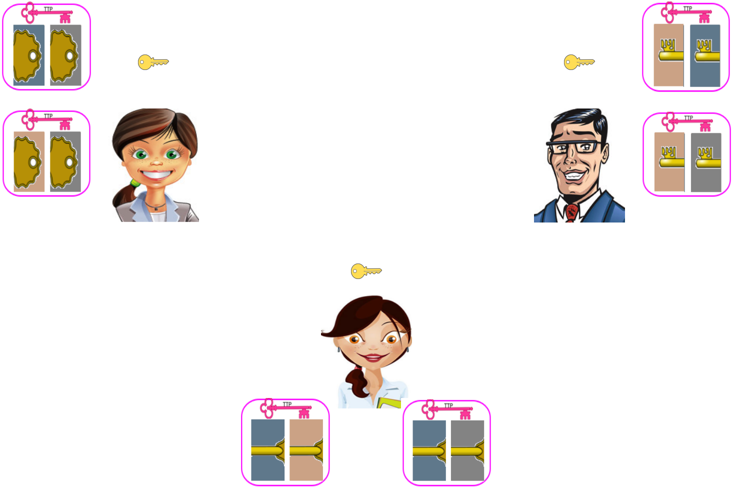

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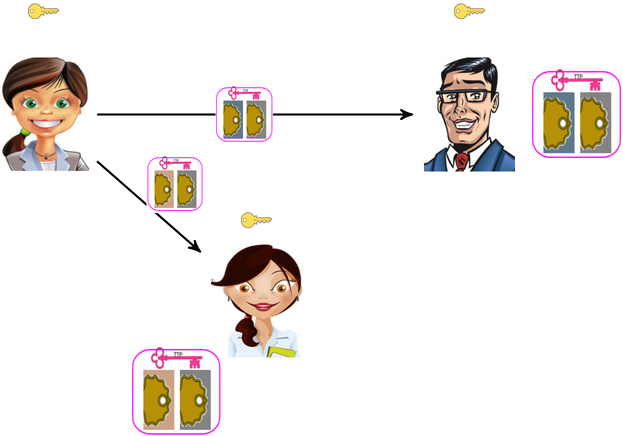

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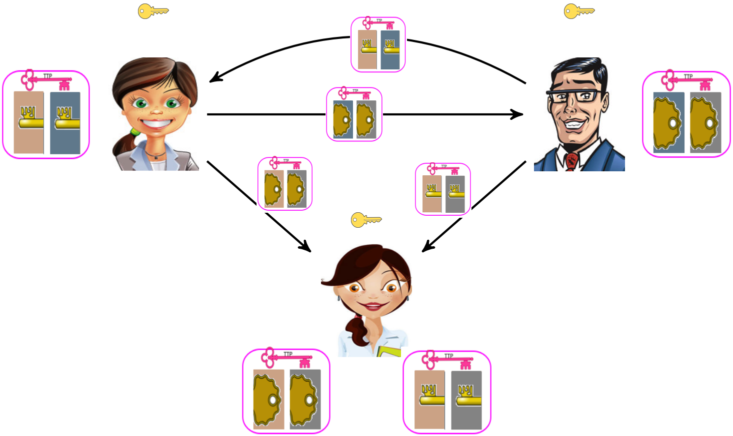

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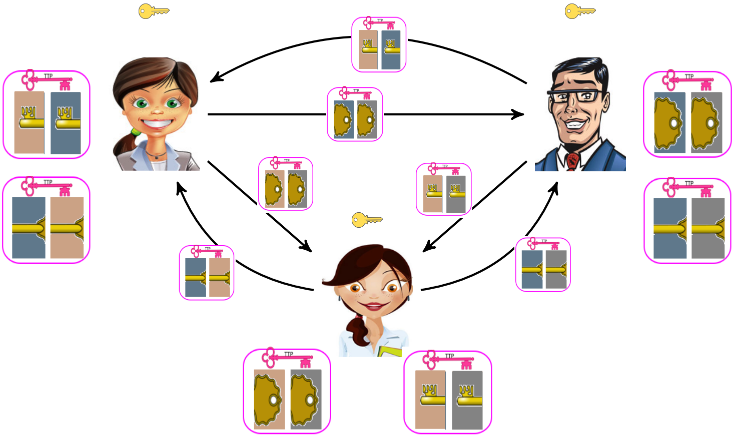

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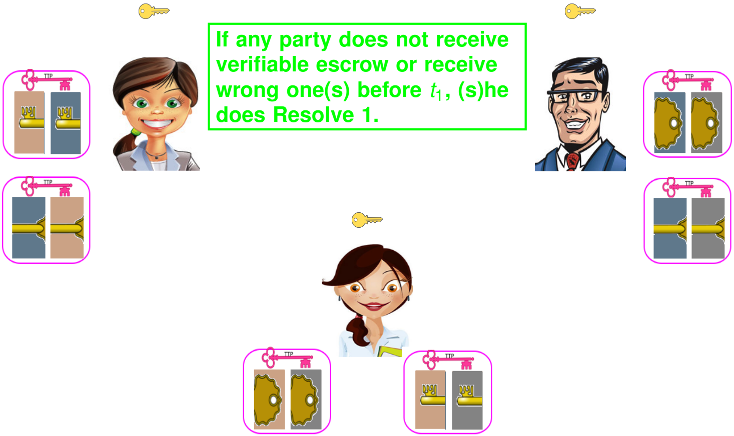
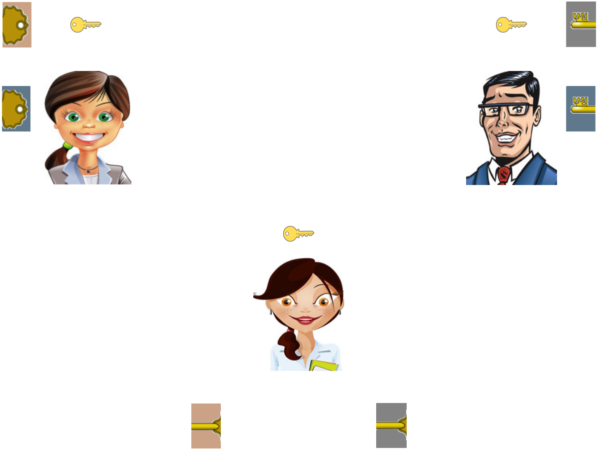


# Phase 3: Decryption Share Exchange



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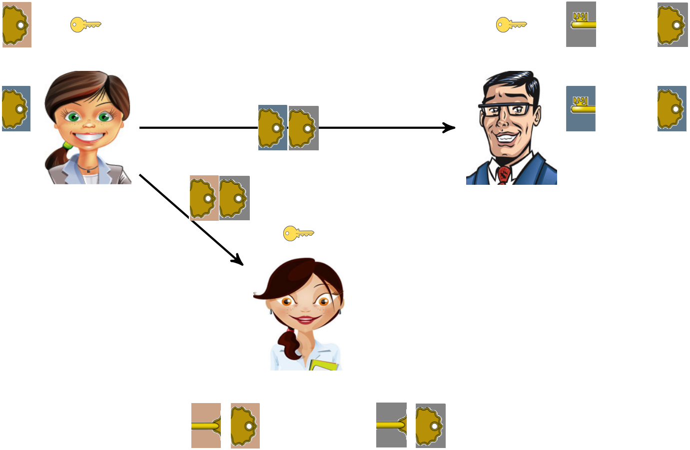

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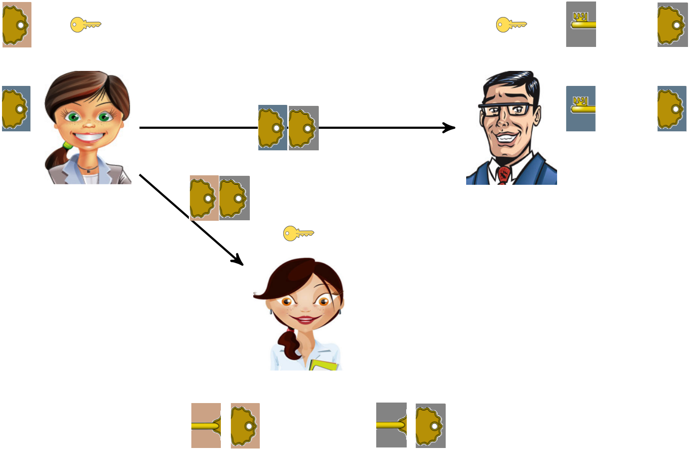

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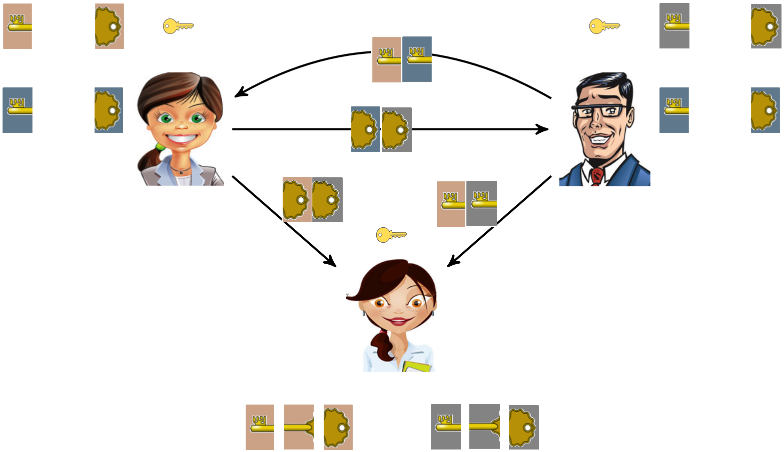

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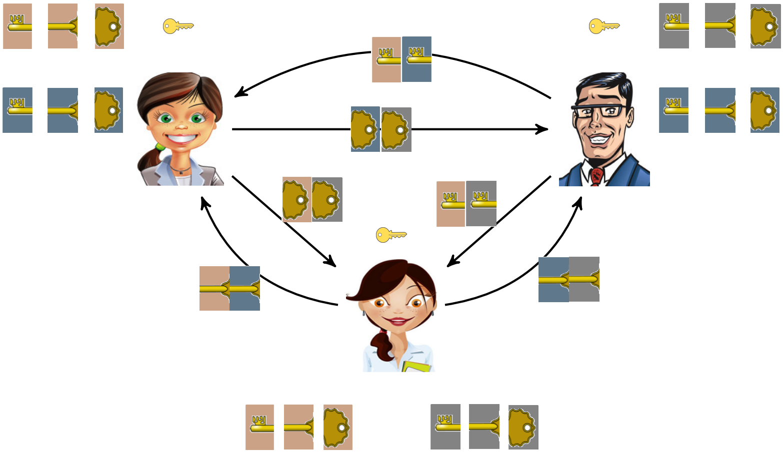

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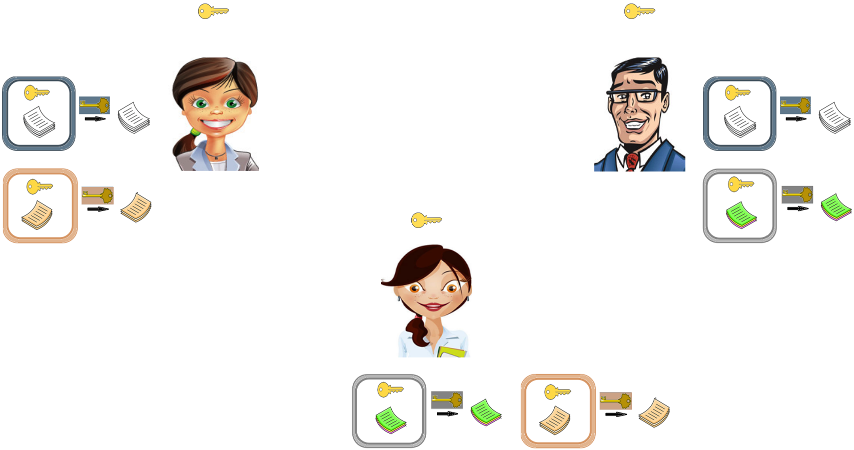
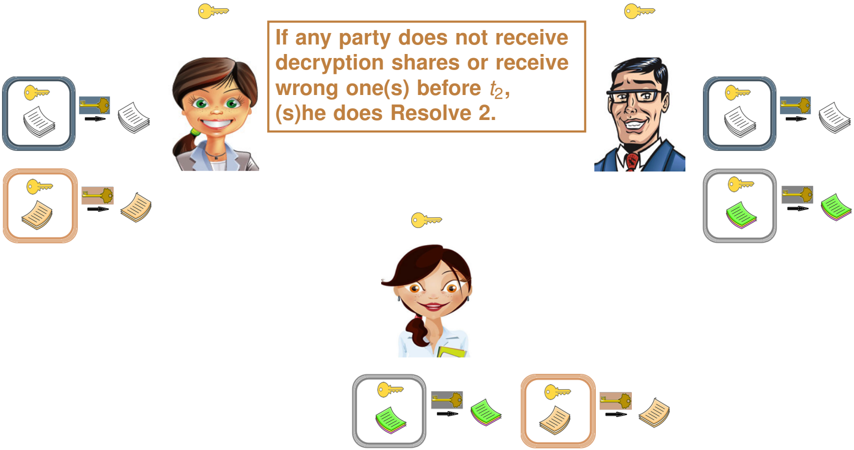


# Phase 3: Decryption Share Exchange

**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.

# Outline

1 Introduction
- Multi-Party Fair Exchange
- Definitions

2 Our New Protocols
- MFE Protocol
  - Resolve Protocols
- Fair and Secure MPC

3 Conclusion
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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.
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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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## TTP Usage

- ✓ The TTP for fairness in our MFE is in the *optimistic* model The TTP has a very low workload.
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# Authors

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*Inf. Comput.*, pages 272–290, 2008.

# 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 $h_j = g^{x_j}$ |
| $C_i = Com(h_i, r_i)$ | $\xrightarrow{C_i}$ | $C_j = Com(h_j, r_j)$ |
| | $\xleftarrow{C_j}$ | |
| | $\xrightarrow{h_i}$ | |
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# Phase 2

| $\underline{P_i}$ | **Phase 2** | $\underline{P_j}$ |
|---|---|---|
| compute $h = \prod_{k=0}^{n} h_k$ | | compute $h = \prod_{k=0}^{n} h_k$ |
| pick $r_i$ | | pick $r_j$ |
| $E_i = (a_i, b_i) = (g^{r_i}, f_i h^{r_i})$ | $\xrightarrow{VE_i = V(E_i, h; \emptyset)\{(v_i, f_i) \in R_{item}\}}$ <br> $\xleftarrow{VE_j = V(E_j, h; \emptyset)\{(v_j, f_j) \in R_{item}\}}$ | $E_j = (a_j, b_j) = (g^{r_j}, f_j h^{r_j})$ |

*If VE is not received from at least one of the parties*

Abort

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*If VE is not received from at least one of the parties*

Abort

# 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 $k$.

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

*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 $d_k^j$ are not received before $t_2$*

Resolve 2

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The relation $R_s$ is $\mathbf{\log_g h_i} = \mathbf{\log_{a_k} a_k^{x_i}}$ for each $k$.

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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 $\{d_k^j = a_k^{x_j}\}_{k=1}^n$ |
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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 $d_k^i$ 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 $k$.

**Phase 3**

$\underline{P_i}$ | | $\underline{P_j}$

compute $\{d_k^i = a_k^{x_i}\}_{k=1}^n$

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$\xrightarrow{VS_i = V(E_i^t, pk; t_1, t_2, id, P_i)\{(h_i, \{d_k^i\}) \in R_s\}}$

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*If $d_k^i$ are not received before $t_2$*

Resolve 2