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CSE/CEN 598
Hardware Security & Trust

Secure Computation Approaches: Security Protocols

Prof. Michel A. Kinsy

1

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Foundations of Secure Computing

- Security protocols
  - Multi-party computation, zero-knowledge, oblivious transfer, security models, etc.
- Homomorphic encryption (HE)
  - Hardware and software implementations
- Design and implementation of trusted platform modules (TPMs)
  - TPM-based anonymous authentication, signature, encryption, identity management, etc.
- Trusted execution environments (TEEs)
  - TEE-based security and privacy techniques, vulnerability and countermeasures of TEE, distributed TEE, decentralized TEE, etc.

2

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3

Threshold Secret Sharing Scheme

- Select
  - *p* a large prime number and
  - S as the secret value
  - $s_1,\ldots,s_{k-1}$ a set of randomly numbers from [0, p-1]
- A (k, n) threshold polynomial can be written by
  $s(x) \equiv S+s_1x+s_2x^2+\ldots+s_{k-1}x^{k-1} \pmod p$
- Send $(x_i,s(x_i))$ to the *i*-th participant
- Secret sharing in distributed systems provides
  - Fault-tolerant
  - Multi-factor authentication
  - Multi-party authorization

4

Threshold Secret Sharing Scheme

- Secret Reconstruction
  - To reconstruct the secret S, one needs to collect at least k partial secrets
  - The secret can then be reconstructed using Lagrange interpolation

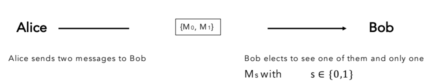
$$s(x) \equiv \sum_{j=1}^{k}\left[s(x_j)\prod_{i=1, i\neq j}^{k}\frac{x-x_i}{x_j-x_i}\right] \bmod p$$

- The scheme can be extended to support share renewal and share recovery

5

Oblivious Transfer

- Oblivious Transfer refers to the technique of transferring a specific piece of data based on the receiver's selection



  - Alice does not know which one of the two Bob has selected
  - Bob is also oblivious to the content of the non-selected message

6

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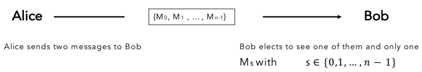

  - Alice does not know which one of the *n* Bob has selected
  - Bob is also oblivious to the content of the non-selected message

7

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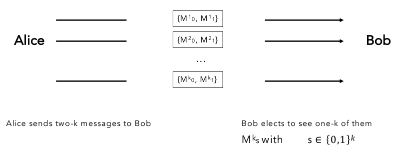

  - There are algorithms for optimizing these straightforward implementations

8

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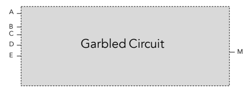
Oblivious Transfer

- Oblivious transfer is the necessary and sufficient condition for multiparty computation
- How can one practically perform this oblivious transfer?
  - For that let us introduce garbled circuits
    - Garbling is a process by means of which the Boolean gate truth table is obfuscated



9

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Garbled Circuit

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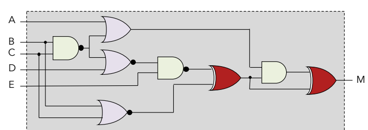
Garbled Circuit



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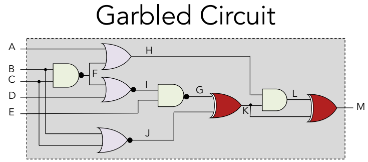
Garbled Circuit



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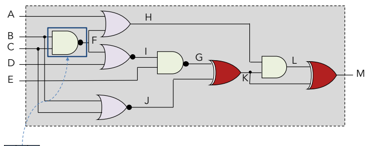
Garbled Circuit



B	C	F
0	0	1
0	1	1
1	0	1
1	1	0

13

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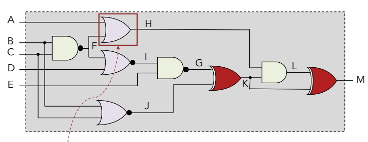
Garbled Circuit



B	C	F
0	0	1
0	1	1
1	0	1
1	1	0

A	F	H
0	0	0
0	1	1
1	0	1
1	1	1

14

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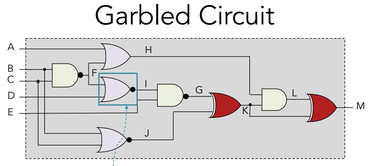

B	C	F
0	0	1
0	1	1
1	0	1
1	1	0

A	F	H
0	0	0
0	1	1
1	0	1
1	1	1

F	D	I
0	0	1
0	1	0
1	0	0
1	1	0

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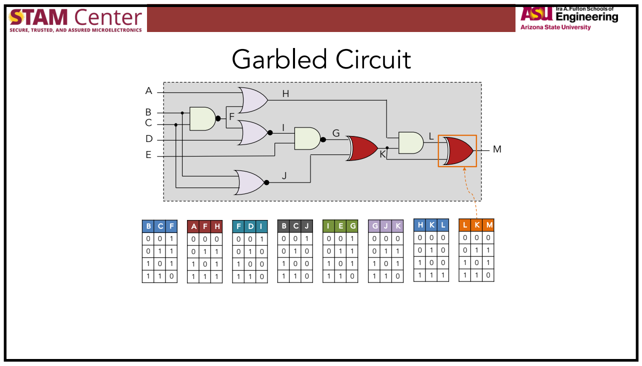
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Garbled Circuit
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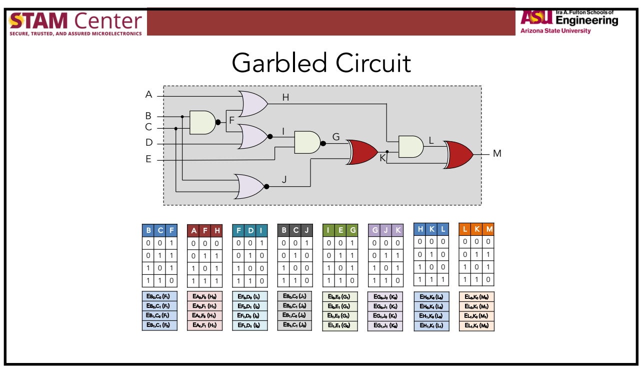
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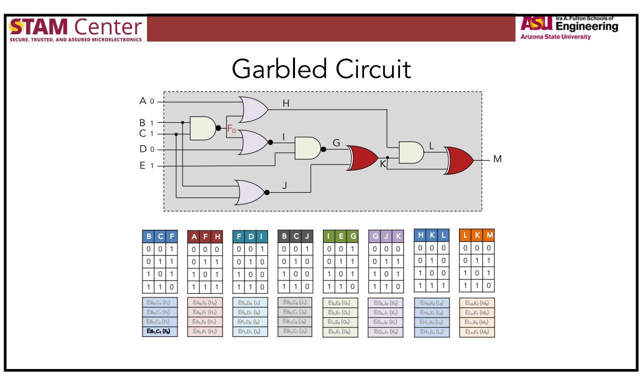
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Garbled Circuit
A 0
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D 0
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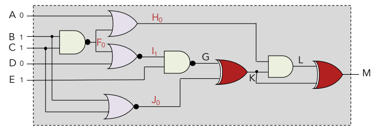
Garbled Circuit



B	C	F	A	F	H	F	D	I	B	C	J	I	E	G	G	J	K	H	K	L	L	K	M
0	0	1	0	0	0	0	0	1	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0
0	1	1	0	1	1	0	1	0	0	1	0	0	1	1	0	1	1	0	1	0	0	1	1
1	0	1	1	0	1	1	0	0	1	0	0	1	0	1	1	0	1	1	0	0	1	0	1
1	1	0	1	1	1	1	1	0	1	1	0	1	1	0	1	1	0	1	1	1	1	1	0

$E_{B_0,C_0}(F_1)$	$E_{A_0,F_0}(H_0)$	$E_{F_0,D_0}(I_1)$	$E_{B_0,C_0}(J_1)$	$E_{I_0,E_0}(G_1)$	$E_{G_0,J_0}(K_0)$	$E_{H_0,K_0}(L_0)$	$E_{L_0,K_0}(M_0)$
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19

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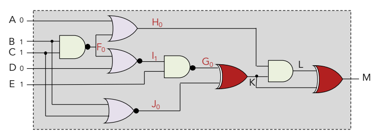

B	C	F	A	F	H	F	D	I	B	C	J	I	E	G	G	J	K	H	K	L	L	K	M
0	0	1	0	0	0	0	0	1	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0
0	1	1	0	1	1	0	1	0	0	1	0	0	1	1	0	1	1	0	1	0	0	1	1
1	0	1	1	0	1	1	0	0	1	0	0	1	0	1	1	0	1	1	0	0	1	0	1
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20

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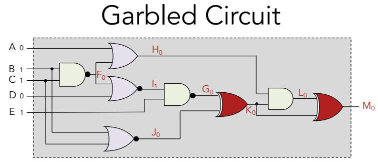

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0	0	1	0	0	0	0	0	1	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0
0	1	1	0	1	1	0	1	0	0	1	0	0	1	1	0	1	1	0	1	0	0	1	1
1	0	1	1	0	1	1	0	0	1	0	0	1	0	1	1	0	1	1	0	0	1	0	1
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21

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Secure Computation Approaches

Multi-Party Computation (MPC)

Pros
- Low compute requirements
- Easy to accelerate
- Provably secure
- Supports multiple threat models
- Easy to map existing algorithms

Cons
- High communication costs
- High latency
- Information theoretic proofs are weaker than PKE ones

Fully Homomorphic Encryption (FHE)

Pros
- Very low communication costs
- Requires a single round of communications, i.e., "fire and forget"
- Useful when one side is limited in compute / memory / storage
- Provably secure – relies on strength of PKE

Cons
- Very high computational requirements
- Harder to accelerate
- Mapping existing algorithms to FHE may be difficult

Trusted Execution Environments (TEE)

Pros
- No communication required
- Trivial to accelerate
- Great support for existing software

Cons
- Weaker security guarantees
- Cannot stop determined adversaries
- Historically plagued by vulnerabilities and breaches
- Long term deployment is difficult – TEE's can 'run out' of entropy / CRP's, etc.

22

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Secure Multiparty Computation

- For the Two-party secure multiparty computation
- Assume
  - Alice has x, Bob has y, and they want to compute two functions $f_A(x,y)$ and $f_B(x,y)$
    - It could be the same function f(x,y)
  - The desired outcome is that at the end of the protocol
    - Alice learns the result of her function $f_A(x,y)$ and not Bob's input y
    - Bob learns the result of his function $f_B(x,y)$ and not Alice's input x

24

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    - It could be the same function f(x,y)
- Illustration
  - Alice represents the function f(x,y) as a garbled circuit
  - She then sends the circuit and values corresponding to her input bits to Bob
  - Bob evaluates the circuits using the sent Alice's bits and his own input bits
  - He then transfers the result to Alice

25

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Secure Multiparty Computation

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- Assume
  - Alice has x, Bob has y, and they want to compute two functions $f_A(x,y)$ and $f_B(x,y)$
    - It could be the same function
- The set up for the n-party secure multiparty computation makes the same assumptions
  - Here instead of just Alice and Bob, there are n parties
  - Each party with a private input
  - And they want to jointly compute the function
    $f_X=(x_1, \ldots, x_n)$

26

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Secure Multiparty Computation

- Validity
  - Secure function evaluation (SFE) system must be able to correctly computed
    - For example, result must be computed with inputs from at least all correct parties
- Privacy
  - P_1 and P_2 cannot know each others input ip_1, ip_2
- Agreement
  - Result must be same for all parties (P_1 and P_2)
- Termination
  - All active parties (P_1 and P_2) eventually receive final result
- Fairness
  - P_1 should not be able to learn the result while denying it to P_2

27

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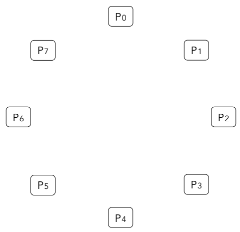
Secure Multiparty Computation

- Construction of the computation
  - Let us have 8 parties $P_1, \dots, P_7$ that want to perform a joint computation



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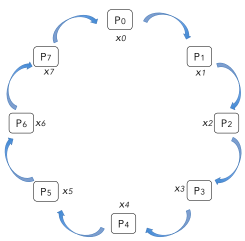
Secure Multiparty Computation

- Construction of the computation
  - Let us have 8 parties $P_0, \dots, P_7$ that want to perform a joint computation
  - Each party P_i with i ∈ [0..7], has private input x_i



29

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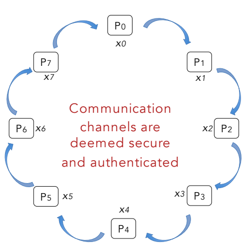

30

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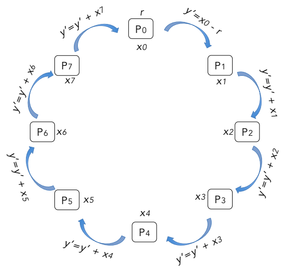
Secure Multiparty Computation

- Construction of the computation
  - r is a random number



31

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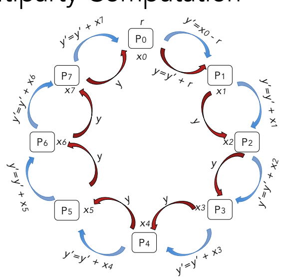

32

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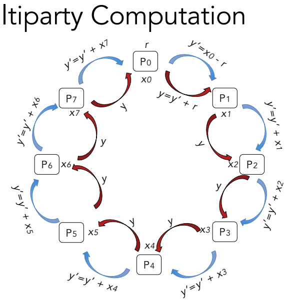
Secure Multiparty Computation

- Construction of the computation
  - r is a random number
  - If any P_i is semi-honest or malicious, then these messages may not be passed along properly or be modified in a way that break the protocol



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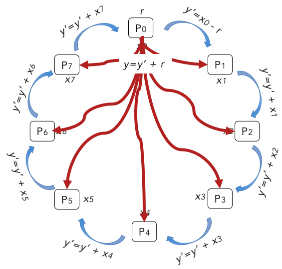
Secure Multiparty Computation

- Construction of the computation
  - Result distribution could be faster



34

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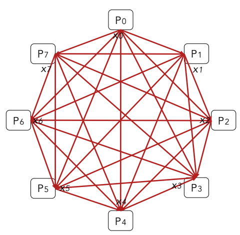
Secure Multiparty Computation

- Construction of the computation
  - Even fast compute



35

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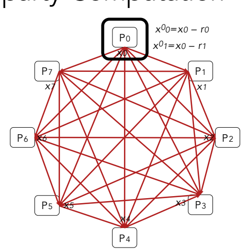
Secure Multiparty Computation

- Construction of the computation
  - *The parties can use a linear secret sharing scheme to create a distributed state of their inputs*
  - *For each party, the random variables r_i are different*

$x^0_2 = x_0 - r_2$ $x^0_3 = x_0 - r_3$
$x^0_4 = x_0 - r_4$ $x^0_5 = x_0 - r_5$
$x^0_6 = x_0 - r_6$ $x^0_7 = x_0 - r_7$



36

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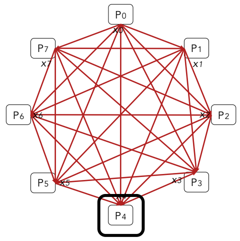
Secure Multiparty Computation

- Construction of the computation
  - *The parties can use a linear secret sharing scheme to create a distributed state of their inputs*
  - *For each party, the random variables r_i are different*

$x^4_0 = x_4 - r_0$ $x^4_3 = x_4 - r_3$
$x^4_1 = x_4 - r_1$ $x^4_4 = x_4 - r_4$
$x^4_2 = x_4 - r_2$ $x^4_5 = x_4 - r_5$
$x^4_6 = x_4 - r_6$ $x^4_7 = x_4 - r_7$



37

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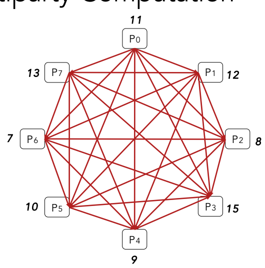
Secure Multiparty Computation

- Construction of the computation
  - Let us have 8 parties P_1, . . . , P_7 that want to perform a joint computation
  - Let us do summation



38

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Secure Multiparty Computation

Private Inputs		P0	P1	P2	P3	P4	P5	P6	
11	P0								
12	P1								
8	P2								
15	P3								
9	P4								
10	P5								
7	P6								
13	P7								
				Local Total					

39

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Secure Multiparty Computation

Private Inputs		P_0	P_1	P_2	P_3	P_4	P_5	P_6	
11	P_0	-1	1	4	3	1	0	3	0
12	P_1								
8	P_2								
15	P_3								
9	P_4								
10	P_5								
7	P_6								
13	P_7								

Local Total

40

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Secure Multiparty Computation

Private Inputs		P_0	P_1	P_2	P_3	P_4	P_5	P_6	
11	P_0	-1	1	4	3	1	0	3	0
12	P_1	3	-5	1	2	4	0	2	5
8	P_2	1	0	0	0	2	3	1	1
15	P_3	4	3	1	-4	3	2	2	4
9	P_4	1	1	3	0	2	0	1	1
10	P_5	2	4	0	1	2	-2	3	0
7	P_6	1	0	5	2	0	1	-5	3
13	P_7	1	2	3	2	1	1	3	0

Local Total

41

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Secure Multiparty Computation

Private Inputs		P_0	P_1	P_2	P_3	P_4	P_5	P_6	
11	P_0	-1	1	4	3	1	0	3	0
12	P_1	3	-5	1	2	4	0	2	5
8	P_2	1	0	0	0	2	3	1	1
15	P_3	4	3	1	-4	3	2	2	4
9	P_4	1	1	3	0	2	0	1	1
10	P_5	2	4	0	1	2	-2	3	0
7	P_6	1	0	5	2	0	1	-5	3
13	P_7	1	2	3	2	1	1	3	0
85		**12**	**5**	**17**	**6**	**15**	**5**	**10**	**14**

Local Total

42

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Secure Multiparty Computation

- There are two major adversary models for secure computation
  - Semi-honest/passive model
    - Follows all required steps
    - Looks for all advantageous information leaked
    - Assumed to be selfish
  - Fully malicious/active model
    - Arbitrarily deviates from the protocol
    - Aborts the protocol at anytime
    - Takes any step that runs counter to the desirable outcome

43

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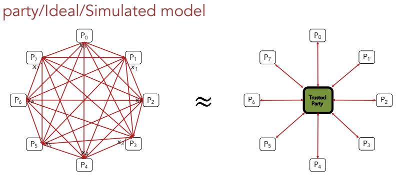
Secure Multiparty Computation

- The multiparty computation is secure if it emulates the trusted central party model to a negligible error range
  - If the two are shown to be indistinguishable
  - Trusted party/Ideal/Simulated model



44

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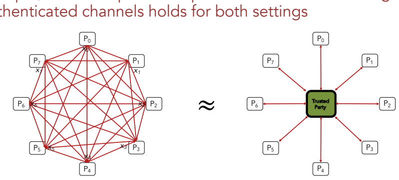
Secure Multiparty Computation

- The security multiparty computation protocol is also evaluated though the simulated model
  - For example, the assumption that parties communicate through secure and authenticated channels holds for both settings



45

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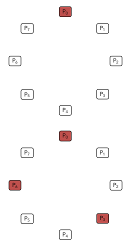
Secure Multiparty Computation

- Dealing with semi-honest and malicious

D. Chaum, C. Crépeau, and I. Damgard. Multiparty unconditionally secure protocols. In Proceedings of the twentieth annual ACM symposium on Theory of computing (STOC '88)

M. Ben-Or, S. Goldwasser, and A. Wigderson Completeness theorems for non-cryptographic fault-tolerant distributed computation. In Proceedings of the twentieth annual ACM symposium on Theory of computing (STOC '88)



46

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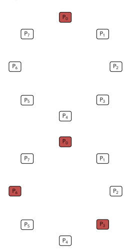
Secure Multiparty Computation

- Dealing with semi-honest and malicious
  - Any function $f(x_1, \ldots, x_n)$ can be securely computed in a semi-honest setting if the majority is honest
    - The passive adversary controls less than n/2 of the parties
  - Any function $f(x_1, \ldots, x_n)$ can be securely computed if the adversary actively controls less than n/3 of the parties



47

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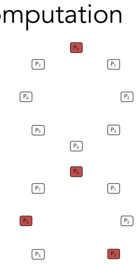
Secure Multiparty Computation

- It is a rich area of research
  - Secure multiparty computation over groups, fields, rings
  - Authentication of the communication channels
  - Synchronous versus asynchronous messaging
  - And many more sub-topics



48

Secure Multiparty Computation

- Commitment
  - Let p and q be two large prime numbers such that q divides p-1
  - Generator g of the order-q subgroup of Zp*
  - A secret s from Zp such that $y=g^s$ mod p
  - Where the values p,q,g, and y are public
  - There is only one secret s in the system residing with Bob

Alice —— {M} ——→ **Bob**

M = $g^x y^r$ mod p

Alice commits to some x∈Zq
Then selects a random r ∈Zq

Bob now has M

49

Secure Multiparty Computation

- Commitment
  - Let p and q be two large prime numbers such that q divides p-1
  - Generator g of the order-q subgroup of Zp*
  - A secret s from Zp such that $y=g^s$ mod p
  - Where the values p,q,g, and y are public
  - There is only one secret s in the system residing with Bob

Alice —— {M} ——→ **Bob**

M = $g^x y^r$ mod p

Alice commits to some x∈Zq
Then selects a random r ∈Zq

Bob now has M

—— **{ x, r }** ——→ Bob can verify that $M= g^x(g^s)^r=g^{x+sr}$ mod p

Alice reveals x and r

50

Secure Multiparty Computation

- Zero-Knowledge
  - Let p and q be two large prime numbers such that q divides p-1
  - Generator g of the order-q subgroup of Zp*

Alice —— {U= **g^r mod p** } ——→ **Bob**

Alice knows a number s such that **M = g^s mod p**
and wants to prove it to Bob

r is random number ∈ [1..q]

Bob also know M

51

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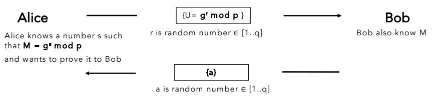
Secure Multiparty Computation

- Zero-Knowledge
  - Let p and q be two large prime numbers such that q divides p-1
  - Generator g of the order-q subgroup of Zp*



52

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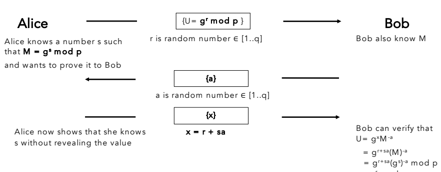
Secure Multiparty Computation

- Zero-Knowledge
  - Let p and q be two large prime numbers such that q divides p-1
  - Generator g of the order-q subgroup of Zp*



53

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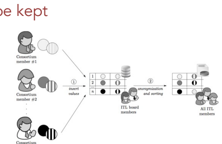
Secure Multiparty Computation

- Use Case
  - In order to analyze the economic situation of an industrial sector, a secure system is needed for jointly collecting and analyzing sensitive financial data
  - The financial data should be kept
    - Confidential
    - Anonymous



Deploying secure multi-party computation for financial data analysis
D. Bogdanov, R. Talviste and J. Willemson

54

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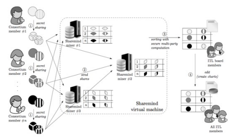
Secure Multiparty Computation

- Use Case
  - Improved version
    - Data stored/sorted separately on three servers
    - No single party has access to original data
    - Anonymous to the board members



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Secure Computation Approaches

Multi-Party Computation (MPC)

Pros
- Low compute requirements
- Easy to accelerate
- Provably secure
- Supports multiple threat models
- Easy to map existing algorithms

Cons
- High communication costs
- High latency
- Information theoretic proofs are weaker than PKE ones

Fully Homomorphic Encryption (FHE)

Pros
- Very low communication costs
- Requires a single round of communications, i.e., "fire and forget"
- Useful when one side is limited in compute / memory / storage
- Provably secure – relies on strength of PKE

Cons
- Very high computational requirements
- Harder to accelerate
- Mapping existing algorithms to FHE may be difficult

Trusted Execution Environments (TEE)

Pros
- No communication required
- Trivial to accelerate
- Great support for existing software

Cons
- Weaker security guarantees
- Cannot stop determined adversaries
- Historically plagued by vulnerabilities and breaches
- Long term deployment is difficult – TEE's can 'run out' of entropy / CRP's, etc.

56

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Upcoming Lectures

- Secure Computation Approaches
  - Trusted Execution Environment (TEE)
  - Homomorphic Encryption

57