Non-Interactive Secure Computation Based on Cut-and-Choose

Arash Afshar, Payman Mohassel, Benny Pinkas, and Ben Riva

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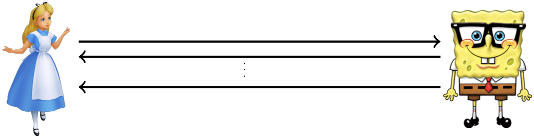
The Big Picture

- Secure Two Party Computation (2PC)
  - In presence of *malicious/active* adversaries.



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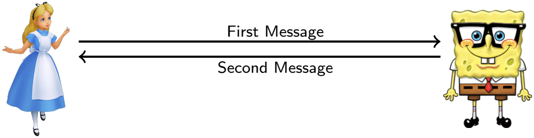

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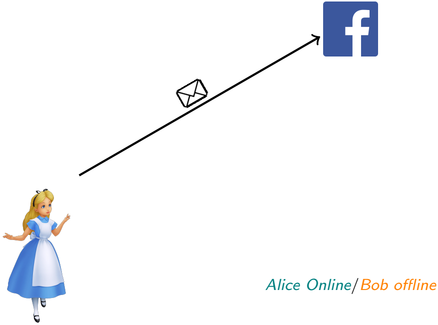
  - In presence of *malicious/active* adversaries.
- Non-interactive computation
  - A *single* message is sent and a *single* message received.
- Practical
  - $\sim$ 6.4 seconds for AES circuit evaluation on a common laptop.

Motivation



- General private computation.
- Asynchronous communications (i.e. email).
- Example usecases:
    - Private Set Intersection
    - DNA ancestry computation
    - ...

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Alice offline/*Bob online*

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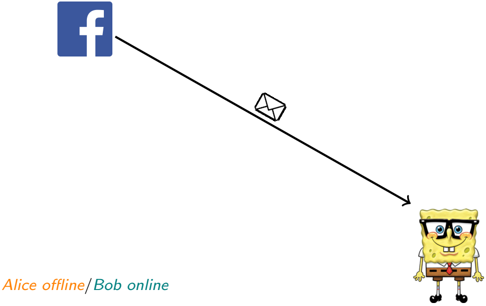

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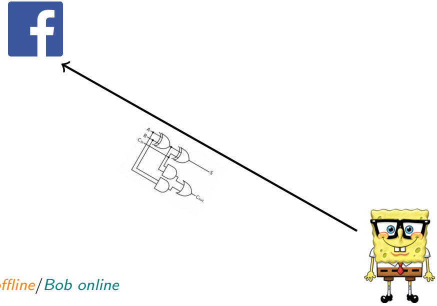

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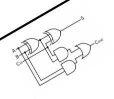

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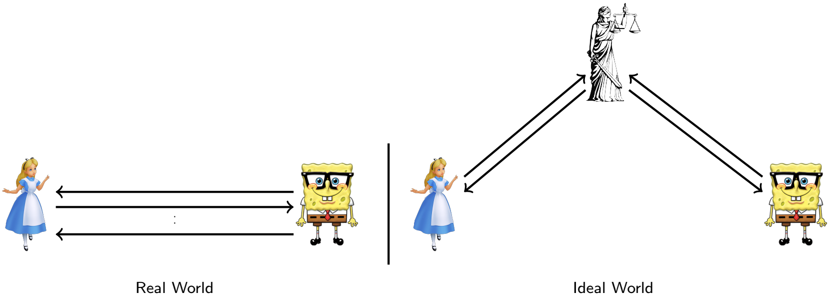
Outline

Security of 2PC

- Malicious adversary: might deviate from the protocol
- Computationally bounded adversary.
- Security is proved by simulation in Real/Ideal-world paradigm.
  - If an attack can be launched in Real-world,
  - then, Ideal-world will be compromised.



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- Semi-honest setting.
- *Easy to change* to *NISC*.

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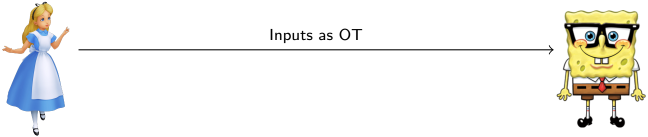

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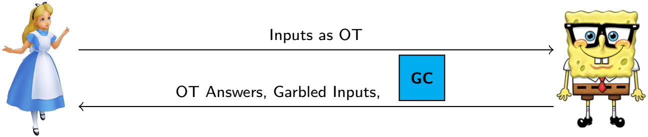
  - Sends OT answers corresponding to the Receiver's input.



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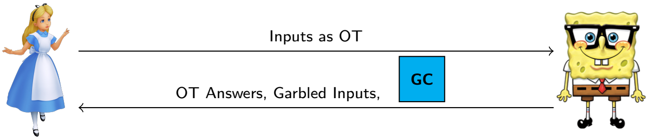
- Receiver
  - Evaluates the circuit.



Malicious 2PC Approaches (constant round approaches)

- *Not so easy!*

	Interactive	Non-interactive
Not Practical		
Asymptotically Efficient		
Highly Practical		

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Highly Practical	*Cut-and-Choose [Lin13]*	

Malicious 2PC Approaches (constant round approaches)

- *Not so easy!*
- A spectrum of approaches!
- Can we make *Cut-and-Choose 2PC non-interactive*?

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Asymptotically Efficient	MPC-in-the-head [IKO+11]	MPC-in-the-head [IKO+11]
Highly Practical	Cut-and-Choose [Lin13]	Our Approach!

Outline

Contributions

- Practical NISC with *small overhead* based on *Cut-and-Choose 2PC*
  - As efficient as the state of the art [Lin13].
- *First* implementation of NISC.

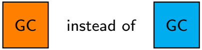
Making Cut-and-Choose Practical

- Cut-and-Choose Components
    - Checking circuits via Cut-and-Choose.
    - Input consistency.
    - Cheating Recovery.

Cut-and-Choose

Cut-and-Choose Construction

- Attack?
  - *Malicious Sender* garbles *different circuits*.



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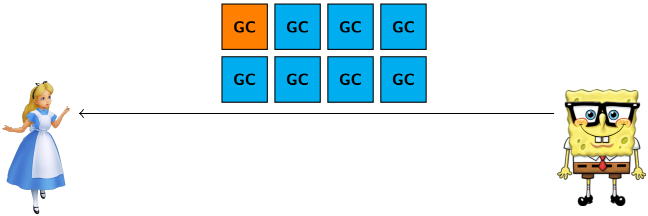
  - *Sender* garbles *many circuits* (i.e. around $\Omega(t)$ for 2^{-t} security).



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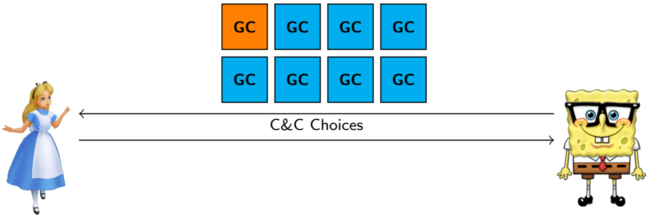

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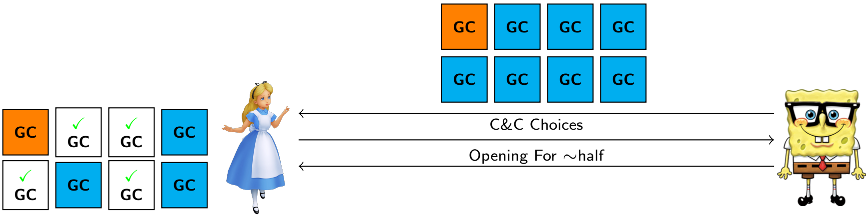

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  - Sender opens the selected circuits.
  - *Receiver evaluates* the other half and returns the majority result.

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- Cost?
  - Adds *an extra round* (2 messages).
  - At least, an overhead of $3t$ in computation and communication.

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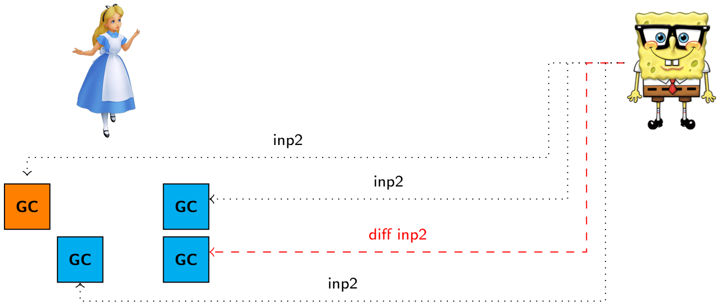
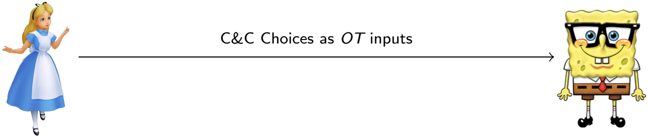
- Problem: Sender's Input Consistency
  - Malicious Sender may send *different inputs* to *different circuits*.



Non-interactive Cut-and-Choose

- Receiver's Message: Same as before



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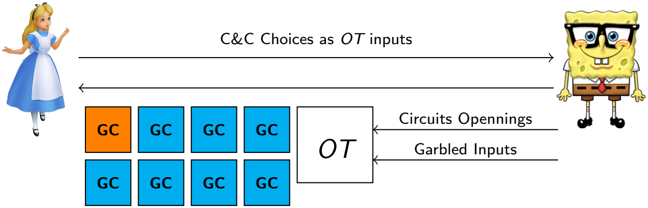

Non-interactive Cut-and-Choose

- Receiver's Message: Same as before
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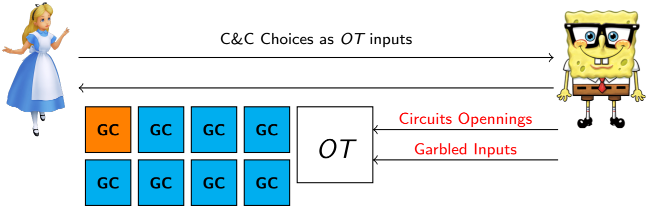
- Receiver's Computation: *For each circuit*
  - Receives *either* the opening
  - *or* the keys for evaluation



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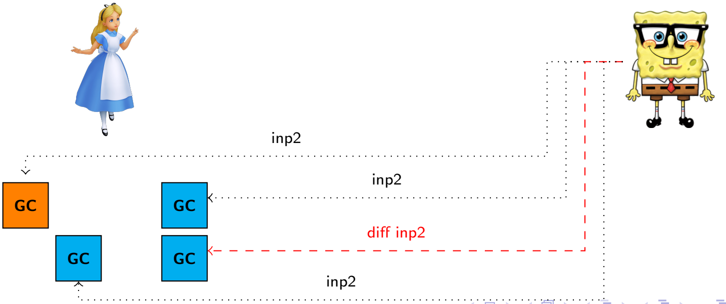

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  - Defense: Modified ideas of [LP11] and [SS11].
- *Sender's* input consistency:
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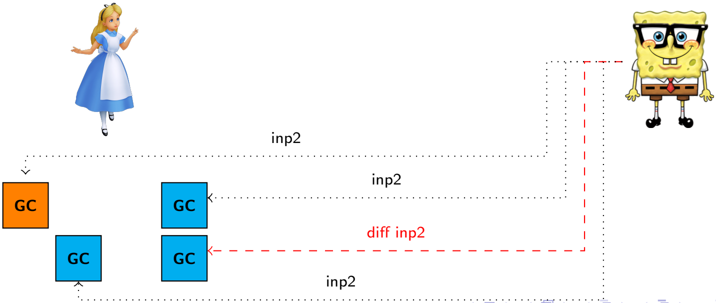
  - *Interactive Defense*: Different solutions with different costs!
  - *State of the art*: [MR13] and [sS13]



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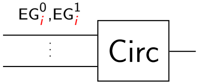
- Commits to original values.



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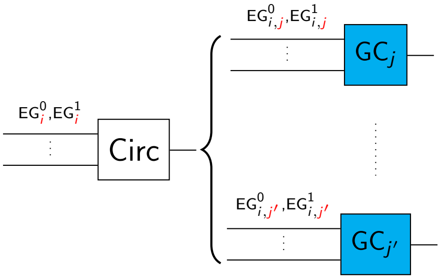

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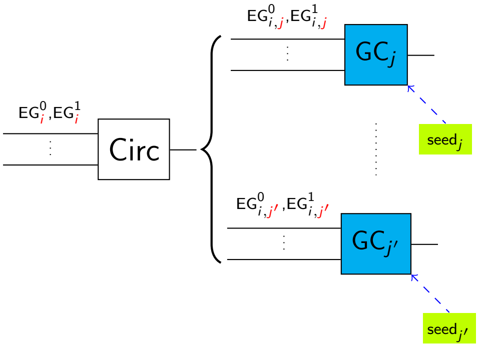

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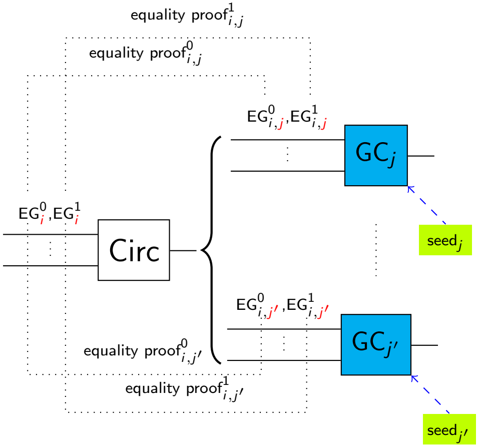

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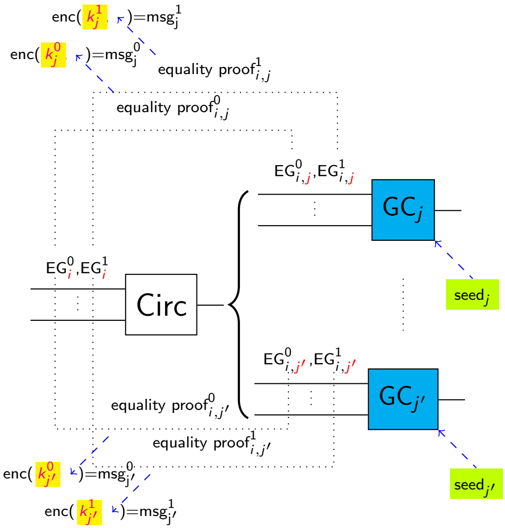

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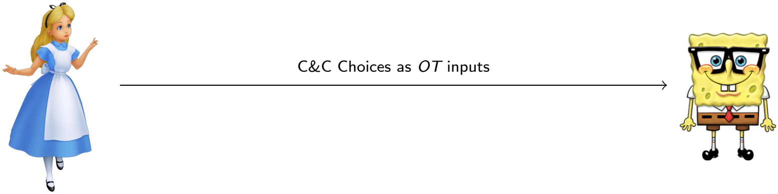

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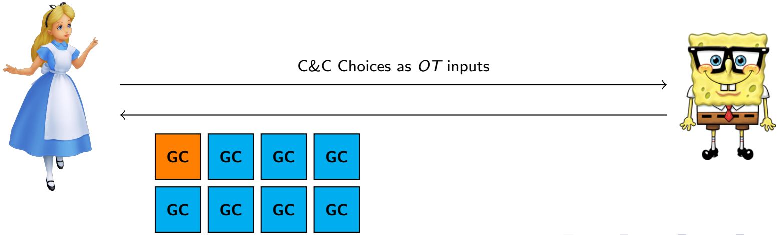

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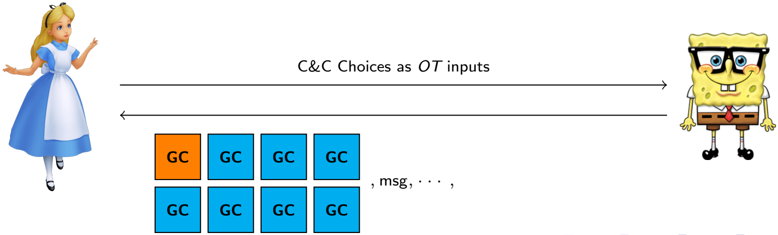

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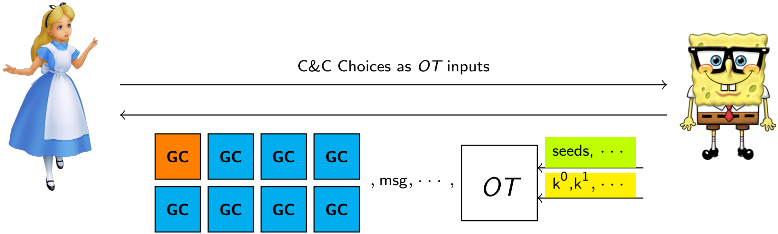

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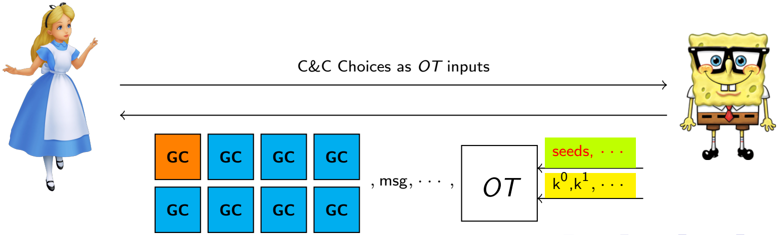

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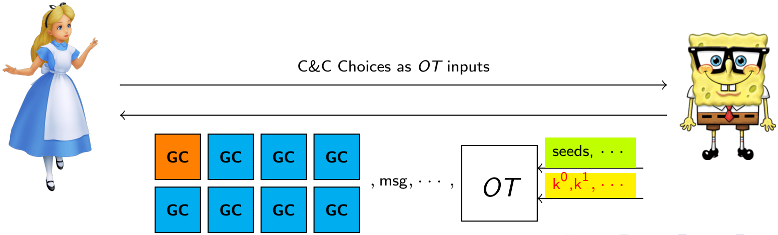
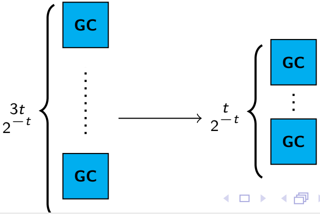


Cheating Recovery

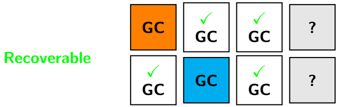
Cheating Recovery

- Goal
  - Reducing the $3t$ circuit overhead to t for security of 2^{-t}.
  - *No majority* checking.
  - At least *one correct* circuit.



Cheating Recovery

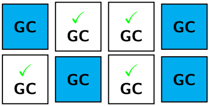
- The idea: Recover Sender's input
  - *two different* output wire values.



Cheating Recovery

- With t circuits, input *cannot* be recovered if
  - all evaluating are *the same* and *correct*.
    - Won't punish honest Sender.

Not Recoverable
Desirable!



Cheating Recovery

- With t circuits, input *cannot* be recovered if
- all evaluating are *the same* and *incorrect*.
    - 2^{-t} failure probability.

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Cheating Recovery (cont.)

- How?
  - Use extra malicious 2PC [Lin13],
  - on a small circuit.

Cheating Recovery (cont.)

- How?
  - Use extra malicious 2PC [Lin13],
  - on a small circuit.
- cost?
  - *Extra rounds* for the extra 2PC.
  - Small computation and communication overhead for the extra 2PC.

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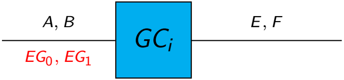
    - *Change* input labels to ElGamal commitments.



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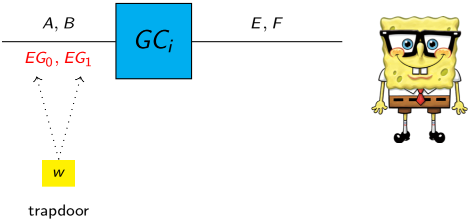

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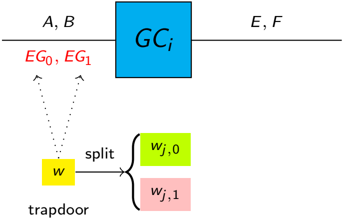

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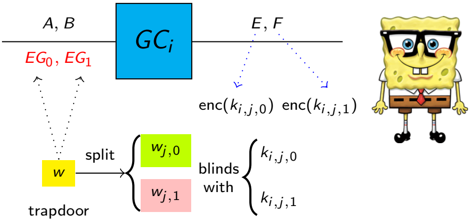

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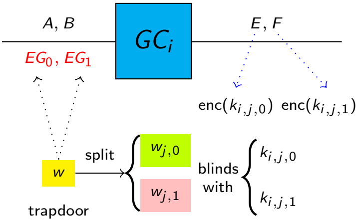

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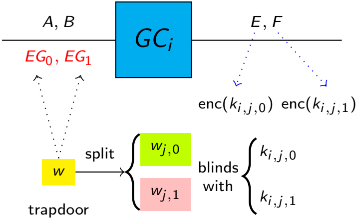
  - Cheating → learn *both* $w_{j,b}$.



Implementation

Results

- Experimented on a Linux VM on a laptop
  - 64bit, i7-4650U, CPU @ 1.70GHz and 5.4GB of RAM.
  - Used only one core.
  - Enabled AES-NI instructions set.
- AES circuit (with 8,492 non-XOR and 25,124 XOR gates).
  - $\sim$ 6.4 seconds
- Libraries used:
  - JustGarble [BHKR13], OpenSSL, RELIC-toolkit.

Observations

Module or part name	**Time**(sec.)	**Time**(sec.)
	AES circuit	*SHA256* circuit
First message	0.03	0.03
Second message	3.55	7.59
Receiver's computation	2.79	5.10
Cheating recovery	< 0.01	< 0.01
Total time	6.39	12.74
I/O time	0.53	4.89

Figure : For $t = 40$

- *Very small*
  - Garbling time.
  - Cheating recovery time.
- *Bottlenecks*
  - Exponentiations (Elliptic curve multiplication)
  - IO (used file for communications)

Observations

Module or part name	Time(sec.)	Time(sec.)
	AES circuit	*SHA256* circuit
Total time	6.39	12.74
I/O time	0.53	4.89
Non-I/O time	5.86	7.85

Figure : For $t = 40$

- *SHA256* garbled circuit size is $\sim$ *10 times larger*.
- Same input size, different output size
- Resulting in
  - Large increase in IO.
  - Small increase in non-IO.

Thank You!

References

Mihir Bellare, Viet Tung Hoang, Sriram Keelveedhi, and Phillip Rogaway.
Efficient garbling from a fixed-key blockcipher.
In *IEEE S&P*, 2013.

Yuval Ishai, Eyal Kushilevitz, Rafail Ostrovsky, Manoj Prabhakaran, and Amit Sahai.
Efficient non-interactive secure computation.
In *EUROCRYPT*, pages 406–425. Springer-Verlag, 2011.

Yehuda Lindell.
Fast cut-and-choose based protocols for malicious and covert adversaries.
In *CRYPTO*, pages 1–17, 2013.

Yehuda Lindell and Benny Pinkas.
Secure two-party computation via cut-and-choose oblivious transfer.
In *TCC*, pages 329–346. Springer, 2011.

Payman Mohassel and Ben Riva.
Garbled circuits checking garbled circuits: More efficient and secure two-party computation.
In *CRYPTO*, pages 36–53, 2013.

Chris Peikert, Vinod Vaikuntanathan, and Brent Waters.
A framework for efficient and composable oblivious transfer.
In *CRYPTO*, 2008.

Abhi Shelat and Chih-Hao Shen.
Two-output secure computation with malicious adversaries.
In *EUROCRYPT*, pages 386–405. Springer, 2011.

abhi shelat and Chih-hao Shen.
Fast two-party secure computation with minimal assumptions.
In *CCS*, pages 523–534. ACM, 2013.

resources...

- SHA256 circuit (with 194,083 non-XOR gates and 42,029 XOR gates).
- AES circuit (with 8,492 non-XOR and 25,124 XOR gates).