Chap3#3: Privacy Preservation in Machine Learning #3

February 27, 2023

भारतीय प्रौद्योगिकी
संस्थान जम्मू
INDIAN INSTITUTE OF
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Chap 2: ML Applications in Security: Topics to study

- Privacy Preservation, What is Privacy? Data Privacy. Machine Learning in Privacy Preservation: Four Main stakes to Privacy preservation in ML. Two principle approaches: (a) Augmenting the ML techniques with the conventional approaches in the domain of privacy preservation to achieve privacy viz. Homomorphic Encryption(HE Algorithms and the associated mathematics), Secret Multi-party Computations, Zero Knowledge Proofs, Perturbation techniques (e.g. differential privacy), Anonymization techniques (e.g.)k-Anonymity, l-Diversity) (b) ML-specific approaches like Federated Learning OR Ensemble Learning. Ethical issues and Law for data / process privacy : GDPR, Alexa, other relevant applications [6 hours]

Reviewing the theme of ML Paradigms for Privacy Preservation

Four Main stakes to Privacy preservation

There are four main stakes to privacy preservation in general:

- Privacy of the input data, input queries , web search queries
- Privacy of the computations
- Privacy of the output data, web search query results
- Data Privacy General Regulations, Data protection strategies, processes and principles

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We examine one of these viz. Privacy of Computations in greater detail shortly hereafter seeing main stakes to Privacy preservation in ML

Four Main stakes to Privacy preservation in ML

There are four main stakes to privacy preservation in general:

- Privacy of the input data
  - the assurance that other parties, including the model developer, will not be able to see a user's input data
- Privacy of the output data
  - the assurance that the output of a model is only accessible to the client whose data is being inferred upon.
- Privacy of the model
  - rhe assurance that a hostile party will not be able to steal the model
- Data privacy in training
  - the assurance that a malicious party will not reverse-engineer the training data - although gathering information about training data and model is more difficult than that for the data.

Privacy Preserving Machine Learning: How to achieve?

The goal of privacy-preserving machine learning is

- to bridge the gap between privacy while receiving the benefits of machine learning.

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  - anonymization techniques like k-Anonymity and l-Diversity
  - ML-specific approaches like Federated Learning OR Ensemble Learning - the Privacy-Preserving Techniques - modifying the conventional ML training methods to keep user data private.

Augmenting ML for Privacy Preservation: Zero Knowledge Proofs

Zero Knowledge Proofs

Zero Knowledge Proof

- is a way of proving the validity of a statement without revealing the statement itself.

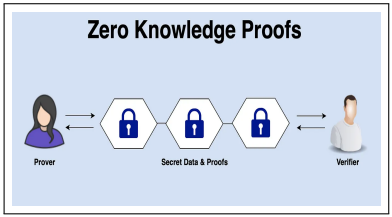

Figure: Eliminate the need to reveal information shared

Src: https://towardsdatascience.com/what-are-zero-knowledge-proofs-7ef6aab955fc

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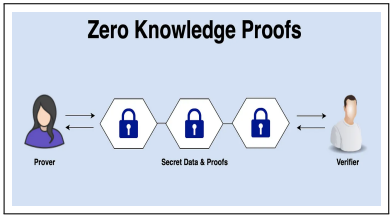

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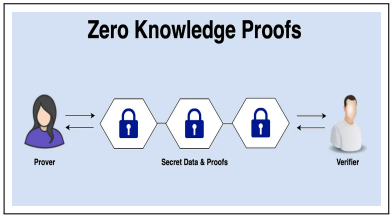

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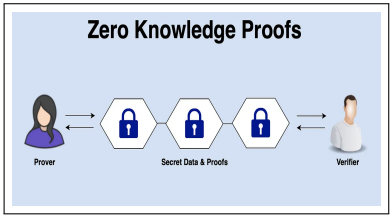

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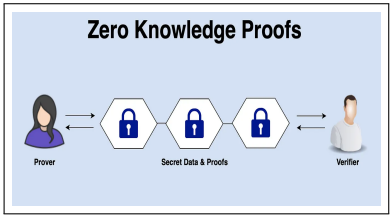

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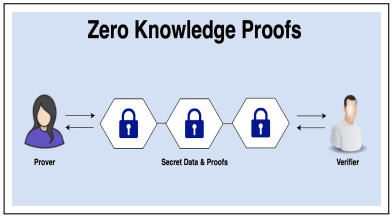

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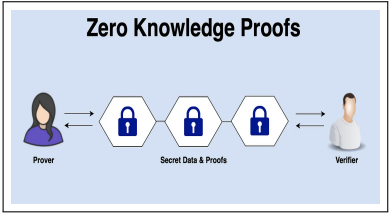

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ZKP Research Evolution Timeline

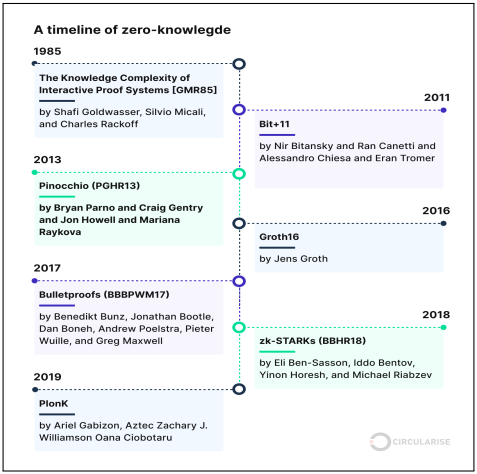
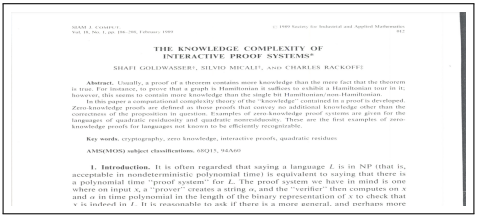


Figure: A timeline of the development of zero-knowledge proofs

Figure Src: https://www.circularise.com/blogs/zero-knowledge-proofs-explained-in-3-examples

ZKPs: First Definition



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THE KNOWLEDGE COMPLEXITY OF INTERACTIVE PROOF SYSTEMS*

SHAFI GOLDWASSER†, SILVIO MICALI‡, AND CHARLES RACKOFF‡

Abstract. Usually, a proof of a theorem contains more knowledge than the mere fact that the theorem is true. For instance, to prove that a graph is Hamiltonian it suffices to exhibit a Hamiltonian tour in it; however, this seems to contain more knowledge than the single bit Hamiltonian/non-Hamiltonian.

In this paper a computational complexity theory of the "knowledge" contained in a proof is developed. Zero-knowledge proofs are defined as those proofs that convey no additional knowledge other than the correctness of the proposition in question. Examples of zero-knowledge proof systems are given for the languages of quadratic residuosity and quadratic nonresiduosity. These are the first examples of zero-knowledge proofs for languages not known to be efficiently recognizable.

Key words. cryptography, zero knowledge, interactive proofs, quadratic residues

AMS(MOS) subject classifications. 68Q15, 94A60

1. Introduction. It is often regarded that saying a language L is in NP (that is, acceptable in nondeterministic polynomial time) is equivalent to saying that there is a polynomial time "proof system" for L. The proof system we have in mind is one where on input x, a "prover" creates a string σ, and the "verifier" then computes on x and σ in time polynomial in the length of the binary representation of x to check that x is indeed in L. It is reasonable to ask if there is a more general, and perhaps more

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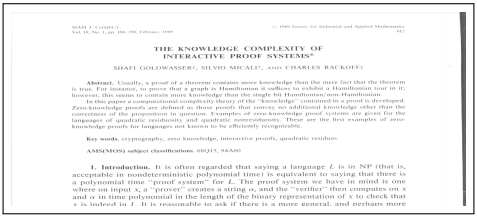

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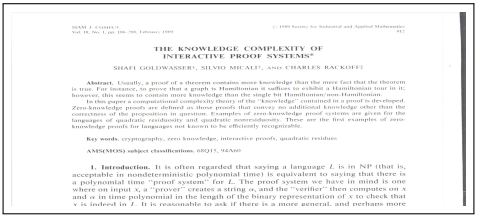

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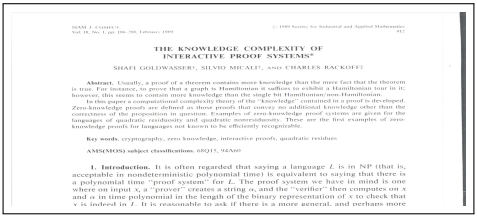

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First Definition of ZKP

A zero-knowledge protocol is a method by which one party (the prover) can prove to another party (the verifier) that something is true, without revealing any information apart from the fact that this specific statement is true.

S Goldwasser, S Micali, and C Rackoff. The knowledge complexity of interactive proof-systems. In Proc. of the 17th Annual ACM symposium on Theory of computing (STOC '85). 1985, ACM, NY, USA, 291–304.

Why do we need zero-knowledge proofs?

- There are many situations where we preserve the privacy and yet achieve the desired functionality. As for example.....

Figure: Proving the claim without revealing the knowledge

Fig Src: https://medium.com/@kotsbtechcdac/introduction-to-zero-knowledge-proof-the-protocol-of-next-generation-blockchain-305b2fc7f8e5

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- Identity theft becomes a critical issue, here

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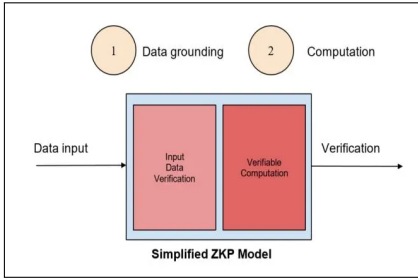

Figure: Eliminate the need to reveal information shared

Fig Src: https://www.newrealityblog.com/2019/02/20/an-introduction-to-zero-knowledge-proofs-and-three-ways-it-will-influence-our-world-part-1/

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- the authentication in IoT devices may be between machine to machine,

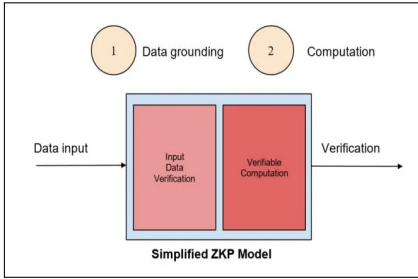

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Fig Src: https://www.newrealityblog.com/2019/02/20/an-introduction-to-zero-knowledge-proofs-and-three-ways-it-will-influence-our-world-part-1/

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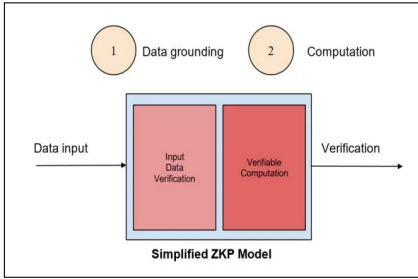

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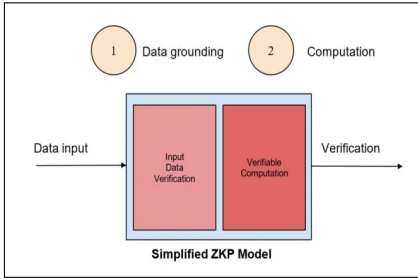

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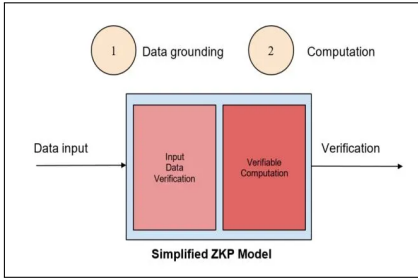

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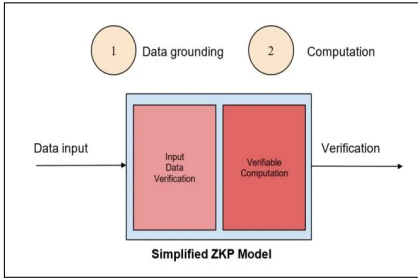
- The solution for these use-cases always has two parts, as shown in the figure, here.



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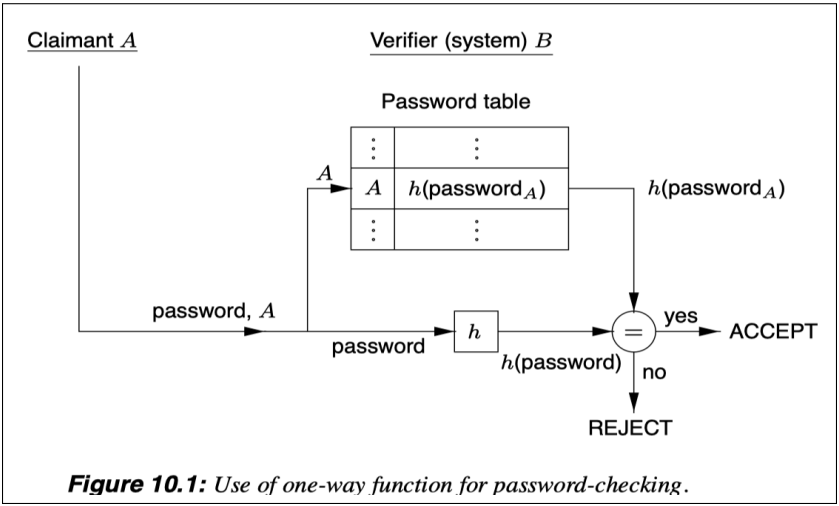

Figure 10.1: *Use of one-way function for password-checking.*

Figure: As above

Fig Src: Menezes, vanOorschot, Vanstone, Handbook of Applied Cryptography

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- Efficient multiparty computation can be used to construct efficient zero-knowledge proofs of knowledge.

Zero Knowledge Proofs USecases and Applications

ZKP: A Toy usecase

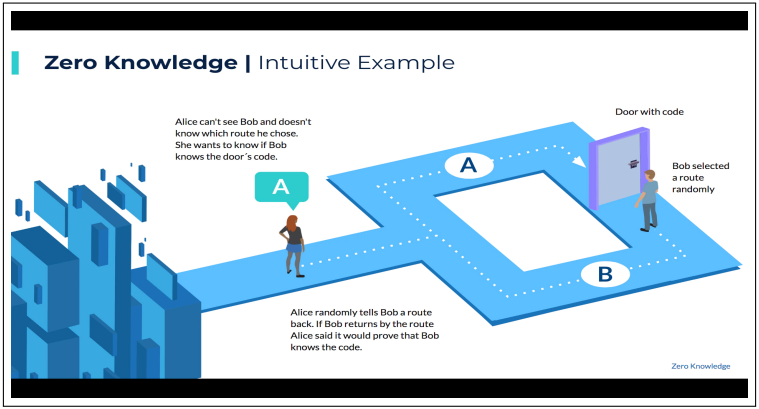

Figure: Alibaba Cave ZKP Usecase

• Bob (the 'prover') owns a code for a door inside cave and Alice (the 'verifier') wants to buy it, but first she wants to be sure that Bob is not lying. How can Bob show Alice that he has the code without revealing its contents?

Src: https://www.bbva.com/en/zero-knowledge-proof-how-to-maintain-privacy-in-a-data-based-world/

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ZKP in Bitcoin and Ethereum: Public verification of transactions

- Enhancing privacy in cryptocurrencies: Cryptocurrencies Zcash, Monero (https://www.getmonero.org/, use ZKPs to provide anonymous transactions when sending and receiving money over its network.

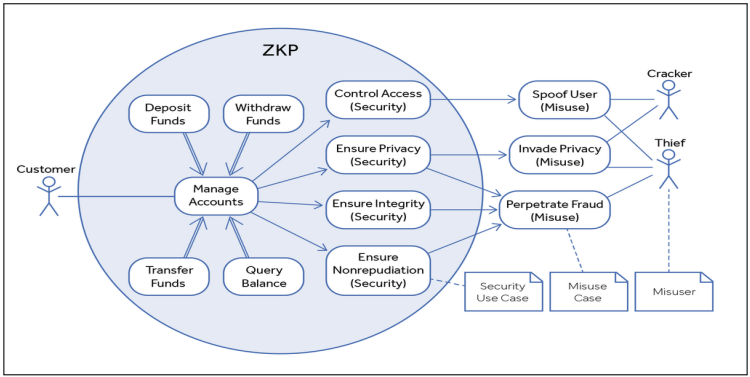

Figure: One of the ZKP Usecase

Src: https://www.privid.co/usecases

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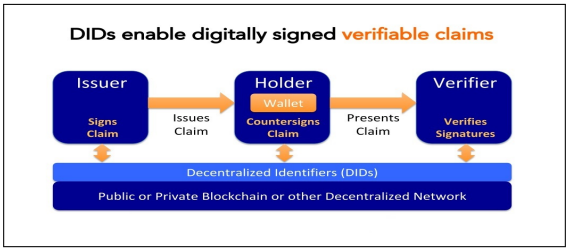

Figure: Decentralized identifiers enable digitally-signed verifiable claims

Figure Src: wiki

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  - Three such example projects are cryptocurrency Zcash, the Ethereum blockchain iand ZK-Rollup.

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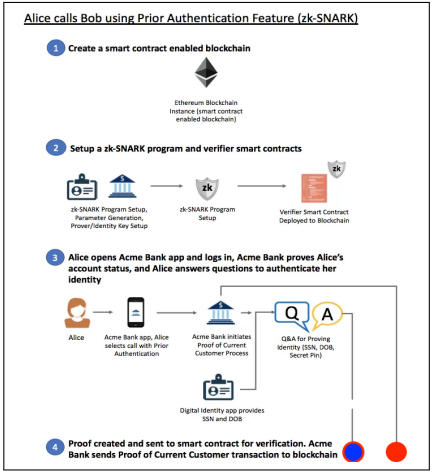

Figure: Alice calls Bob using prior authentication based on ZK-snark

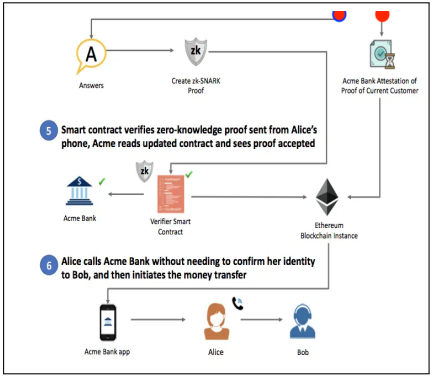

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Figure Src: https://medium.com/coinmonks/zk-snarks-a-realistic-zero-knowledge-example-and-deep-dive-c5e6eaa7131c

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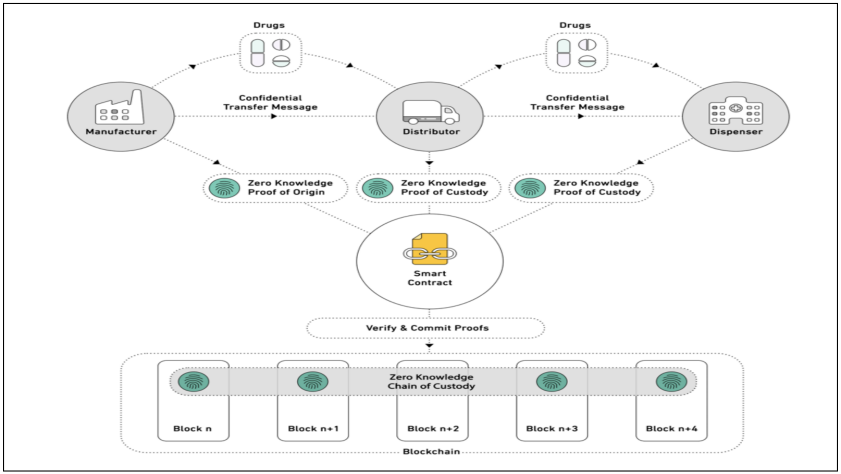

Figure: ZK-Snark for pharmaceutical industry

Figure Src: https://fisher.wharton.upenn.edu/wp-content/uploads/2020/09/Thesis_Terrence-Jo.pdf

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Zero-knowledge rollups (ZK-rollups)

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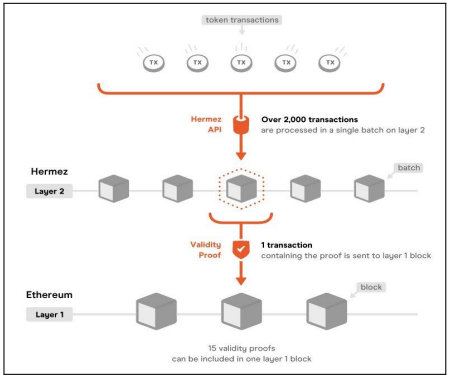

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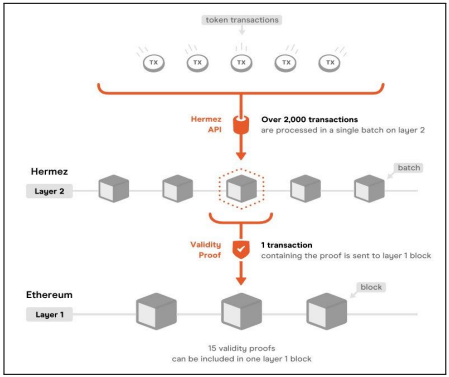

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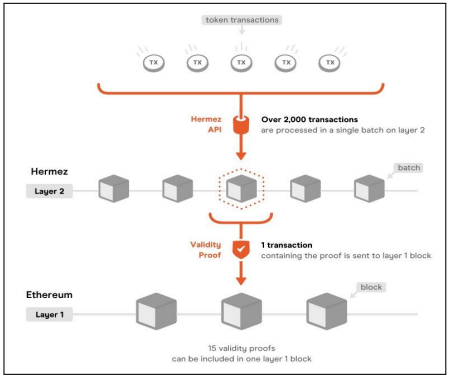

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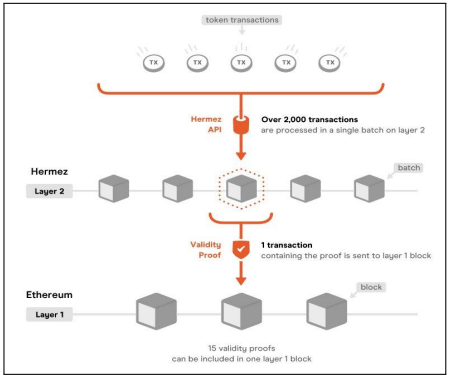

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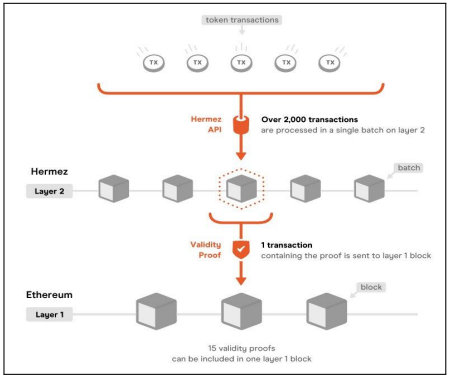

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Zero Knowledge Proofs Requirements and Constituents

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• The components described are those of the early zero-knowledge protocols - ones that used interactive zero-knowledge proof - ....

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  - the workflow of an NIZK proof resembles a digital signature:

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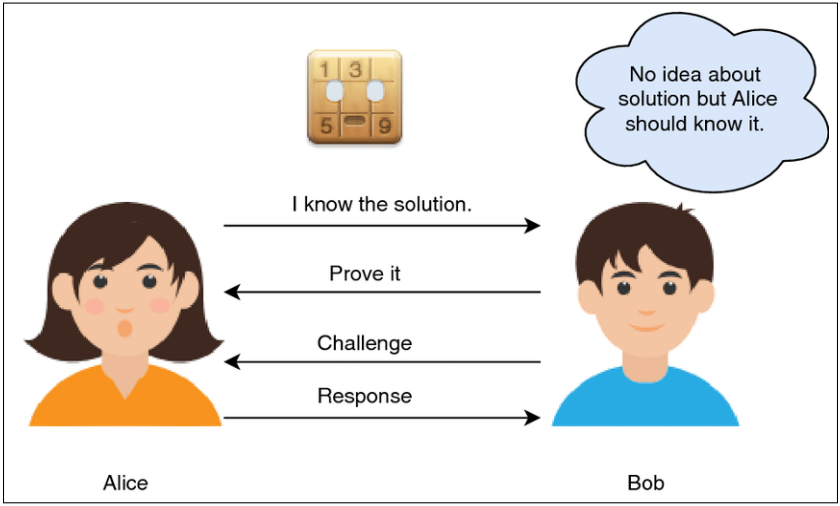
Interactive ZKP: Basic Operation



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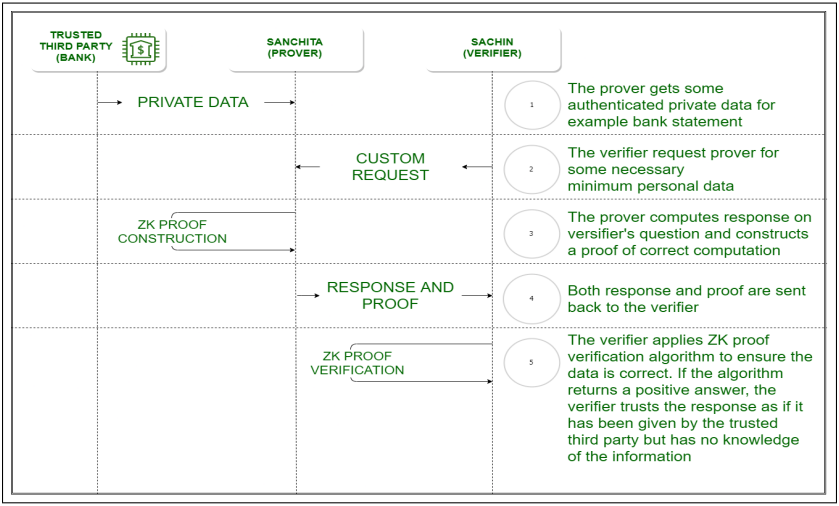
Interactive ZKP: A Usecase for Data Exchange in an Auction



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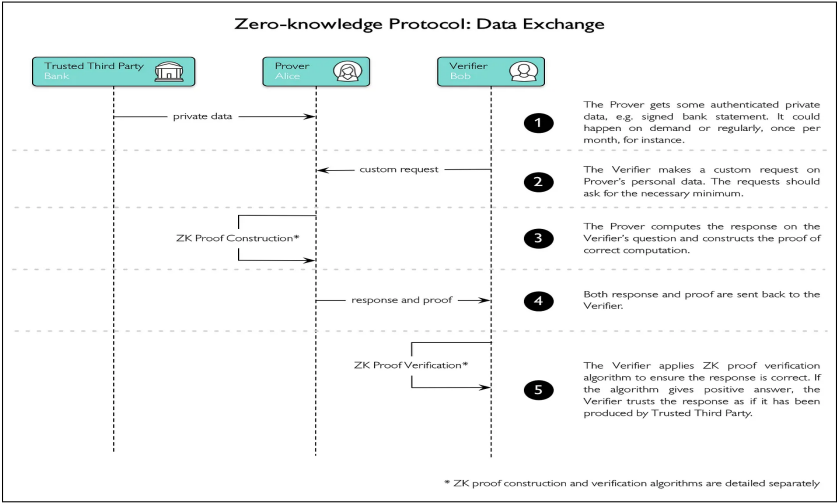

Figure: Interactive ZKP

Src: https://medium.com/@kotsbtechcdac/introduction-to-zero-knowledge-proof-the-protocol-of-next-generation-blockchain-305b2fc7f8e5

Interactive Zero Knowledge Proofs Protocols

Discrete Logarithm & Discrete Logarithm Problem

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- given three integers a, b and m, finding an integer k such that $a^k \equiv b \pmod{m}$ where a and m are relatively prime. If it is not possible for any k to satisfy this relation, print -1.

```
Input: 2 3 5
Output: 3
Explanation:
a = 2, b = 3, m = 5
The value which satisfies the above equation
is 3, because
=> 2^3 = 2 * 2 * 2 = 8
=> 2^3 (mod 5) = 8 (mod 5)
=> 3
which is equal to b i.e., 3.

Input: 3 7 11
Output: -1
```

Figure: Discrete Logarithm

Discrete Logarithm Problem

- Given a cyclic group $\mathbb{G}$ of order m, a group element h, a generator g of the group, (i.e. $h^g \bmod \mathbb{G} \equiv 1 \bmod \mathbb{G}$) the problem is to find an integer k such that $g^k \equiv h \pmod{\ } \mathbb{G}$

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- this is the same as saying that given a group $\mathbb{G}$, a generator g of the group $\mathbb{G}$ and an element h of $\mathbb{G}$, to find the discrete logarithm to the base g of h in the group $\mathbb{G}$ i.e. to find log_g^h mod $\mathbb{G}$

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- e.g. consider the following parameters: $\mathbb{Z}_5$, generator $g = 2$, element h=1, then the discrete logarithm of 1 is 4 because 2^4 mod $5 \equiv 1$ mod 5.

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- Now let us look at the Schnorr's protocol.....

Objective: With it, a Prover i.e. Alice can convince the Verifier i.e. Bob that she knows the discrete logarithm x of some value $h = g^x$ without revealing x

Public input: cyclic group $\mathbb{G}$ of prime order q, a generator g of $\mathbb{G}$ and an $h \in \mathbb{G}$
Private input: Prover knows secret $x \in {\mathbb{Z}^*}_q$ such that $h = g^x$

- Alice chooses a number r uniformly at random from ${\mathbb{Z}^*}_q$ i.e. from $[0, q-1]$ and computes $u = g^r \bmod q$.

Interactive ZKP: Schnorr's Protocol: Proof of Knowledge of Discrete Log

Objective: With it, a Prover i.e. Alice can convince the Verifier i.e. Bob that she knows the discrete logarithm x of some value $h = g^x$ without revealing x

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- Alice chooses a number r uniformly at random from $\mathbb{Z}^*_q$ i.e. from $[0, q-1]$ and computes $u = g^r \bmod q$.
- Alice sends u to Bob.
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- Bob sends c to Alice.
- Alice computes $z = r + x * c \bmod q$
- Alice sends it to Bob. item Bob computes g^z mod q and checks whether $g^z \stackrel{?}{=} u.h^c \bmod q$.

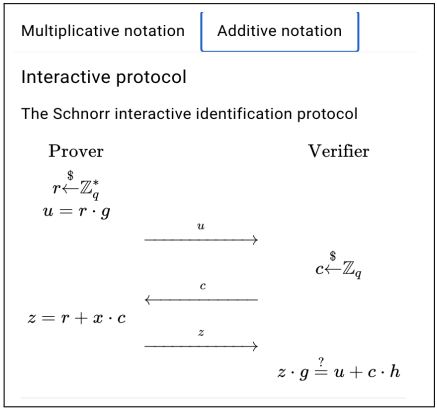

Figure: Interactive ZKP: Schnorr's Protocol: Additive

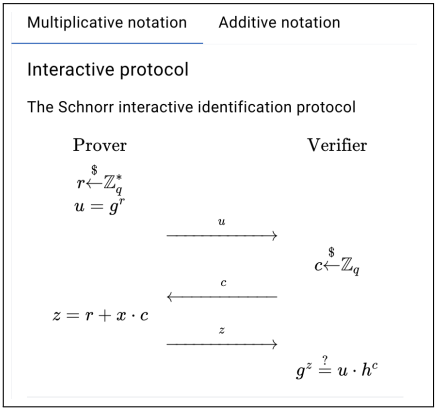

Figure: Interactive ZKP: Schnorr's Protocol: Multiplicative

Src: https://www.zkdocs.com/docs/zkdocs/zero-knowledge-protocols/schnorr/

Interactive ZKP: Schnorr's Protocol: Proof of Knowledge of Discrete Log

- Suppose, a prover wants to prove it knows the discrete logarithm x of some group element $h = g^x \in \mathbb{G}$, where $\mathbb{G}$ is a group of prime order q.

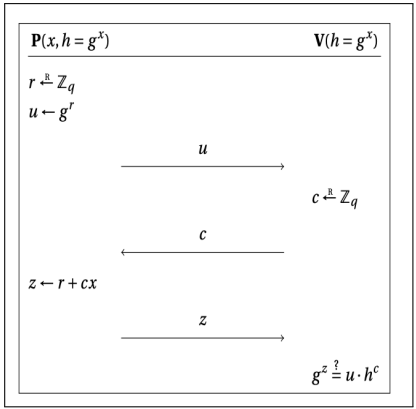

Figure: Interactive ZKP: Schnorr's Protocol

Src: https://www.researchgate.net/figure/Interactive-zero-knowledge-proof_fig3_354455915

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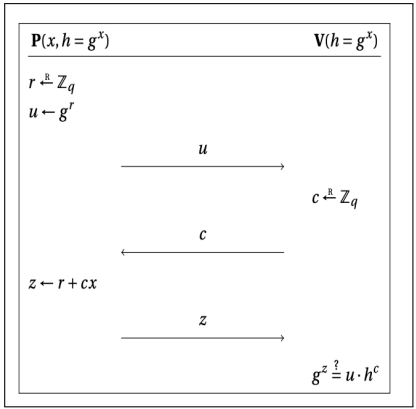

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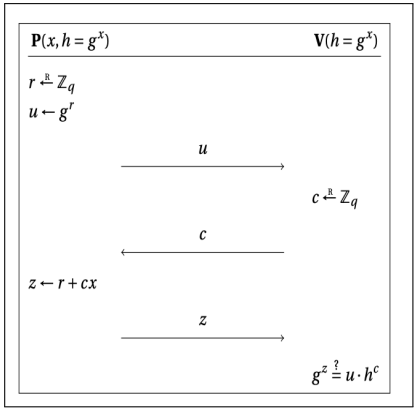

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Interactive ZKP: Goldwasser Micali Rackoff QR ZKP

Objective: Assuming that QR $= \{(x, y|\ y$ is a quadratic residue mod $x)\}$ and QNR $= \{(x, y|\ y$ is a quadratic nonresidue mod $x)\}$, the goal for the verifier Bob is to verify x is a quadratic residue modulo a number or not.

Shared values: x, the number Alice is trying to prove to Bob that it is quadratic residue and n the modulus being used Private input: As in the code below

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- How does this equivalence convince Bob that the claim of Alice that x is QR of u is indeed true ?

Interactive ZKP: Fiat-Shamir Simple Identification Protocol

- Objective: Alice to identify herself to verifier Bob by proving knowledge of a secret s (associated with Alice through authentic public data), without revealing any information about InReds not known or computable by B prior to execution of the protocol.

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- then the protocol execution is as shown further....

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Objective: Alice proves knowledge of s to Bob in t executions of a 3-pass protocol.
One-time setup :

- A trusted center T selects and publishes an RSA-like modulus $n/;= /; pq$. The primes p and q are kept secret.

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- $A \rightarrow B$: $y = r * s^e mod\ n$ .....(3)

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Then the protocol actions follow as shown further.

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  - This is so because, depending on e, $y^2 = x$ or $y^2 = x * v \bmod n$ since $v = s^2 \ mod \ n$. Note that checking for y = 0 precludes the case r = 0

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p=101, q=103, n=10403	p=101, q=103, n=10403
secret s=23, r=21	secret s=23, r=21
$v=s^2 \bmod n = 23^2 \bmod 10403$	$v=s^2 \bmod n = 23^2 \bmod 10403$
$x = r^2 \bmod n$ i.e. $21^2 \bmod 10403$, sends x	r=21, $x = r^2 \bmod n$ i.e. $21^2 \bmod 10403$, sends x
e=0	e=1
Alice sends: y=r i.e. y=21	Alice sends $y=r*s \bmod n$ i.e. y=21*23 mod 10403
y != 0 so Bank does not reject the proof	y != 0 so Bank does not reject the proof
Bank accepts if : $y^2 \equiv x * v^e \bmod n$ i.e. $21^2 \equiv (21^2 \bmod 10403) * 1 \bmod 10403 \equiv 21^2 \bmod 10403$	Bank accepts if : $y^2 \equiv x * v^e \bmod n$ i.e. $y^2 \equiv x * v \bmod n$ i.e. $21^2*23^2 \bmod 10403 \equiv 21^2 \bmod 10403 * (23^2 \bmod 10403) \bmod 10403 \equiv 21^2*23^2 \bmod 10403$

Figure: Interactive ZKP: Fiat-Shamir's Protocol

Non-Interactive Zero Knowledge Proofs

Types of ZKP: Non-Interactive ZKPs

Non-Interactive zero-knowledge proofs:

- a general structure consists of just a single action between participants Prover and Verifier

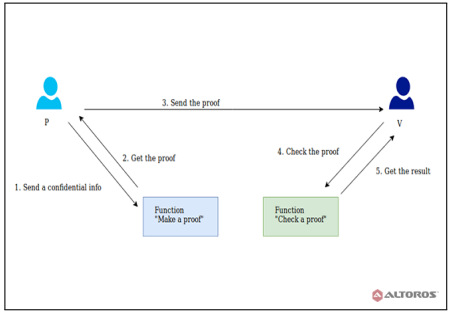

Figure: Non-Interactive ZKP

Figure Src: https://www.altoros.com/blog/zero-knowledge-proof-improving-privacy-for-a-blockchain/

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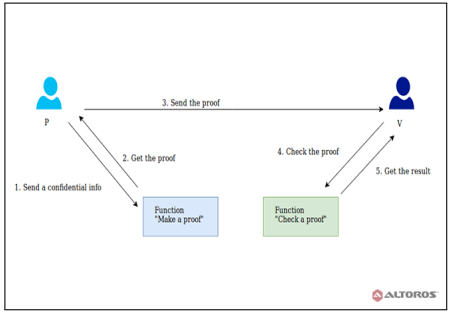

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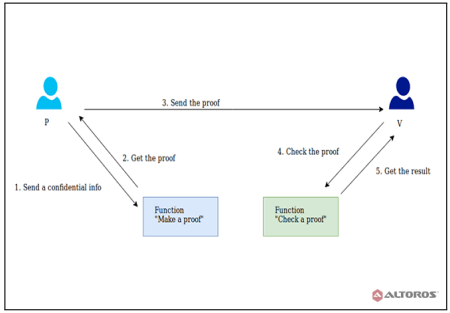

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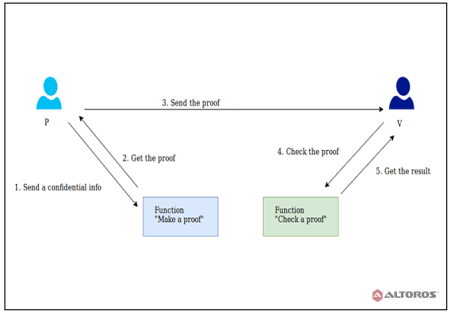

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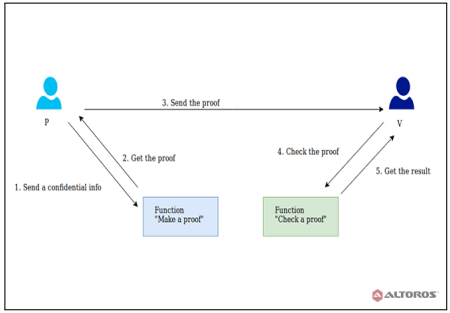

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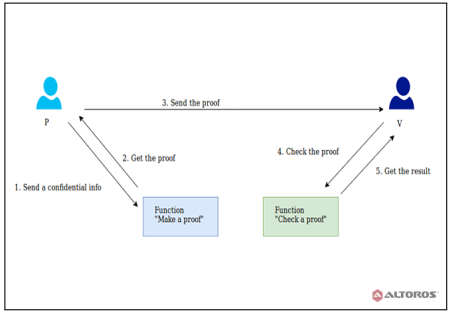
- V then checks if P knows the secret information using the "proof" and another special function—"check a proof."



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Non-Interactive ZKPs: General Applications

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  - since zero-knowledge proof has the potential to encrypt data in portions, it enables providing access to a particular user while limiting access for others

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