The **Cryptographic** Lens: visions

Shafi Goldwasser
MIT
Weizmann

1983

FOREWORD

e 15th Annual
, April 25-27,
Computability

on January 5,
pers. The pa-
nticipated that

consideration,
nsoring organi-
contributed to

David Harel
Richard M. Karp
Nancy Lynch
Christos H. Papadin
Ronald L. Rivest
Walter L. Ruzzo
Joel Seiferas

1983-2013: A Remarkable Journey

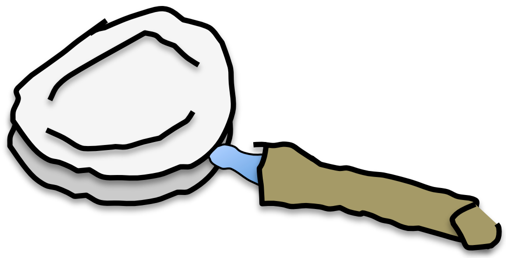
- Theoretical Computer Science

  Interaction, Randomization, Locality

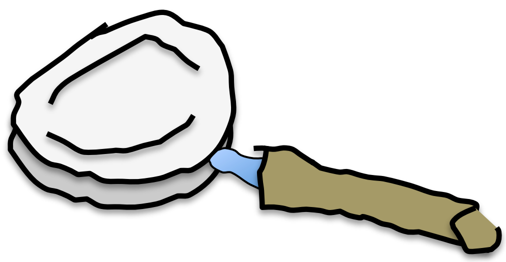
- Impact on Technology and Science

The Computational Lens

The Cryptographic Lens

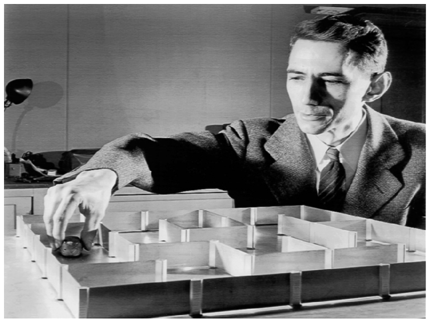


On Theoretical Computer Science



On Science and Technology

Historically



Shannon

“A Mathematical Theory of Communication”(1948)

“A Communication Theory of Secrecy Systems” (1945)

Turing

Inventor of the Universal computing machine

Theory and Practice: Breaking the enigma

War Time Research

Modern Cryptography
is not (just) about fighting the bad guys

- Enabler of `Surprising Abilities" which often seem paradoxical in the physical world
- Catalyst notions and techniques led to a series of `intellectual' leaps in TOC
- Future enable taking advantage of enormous data availability and global connectivity while keeping "civil liberties" and "economic stability" in check.

“Paradoxical” Abilities 1983-

- Exchanging Secret Messages without Ever Meeting
- Simultaneous Contract Signing Over the Phone
- Generating exponentially long pseudo random strings indistinguishable from random
- Proving a theorem without revealing the proof
- Playing any digital game without referees
- Private Information Retrieval
- Arbitrary Computations on Encrypted Data

Unifying Theme:
The Presence of the Adversary

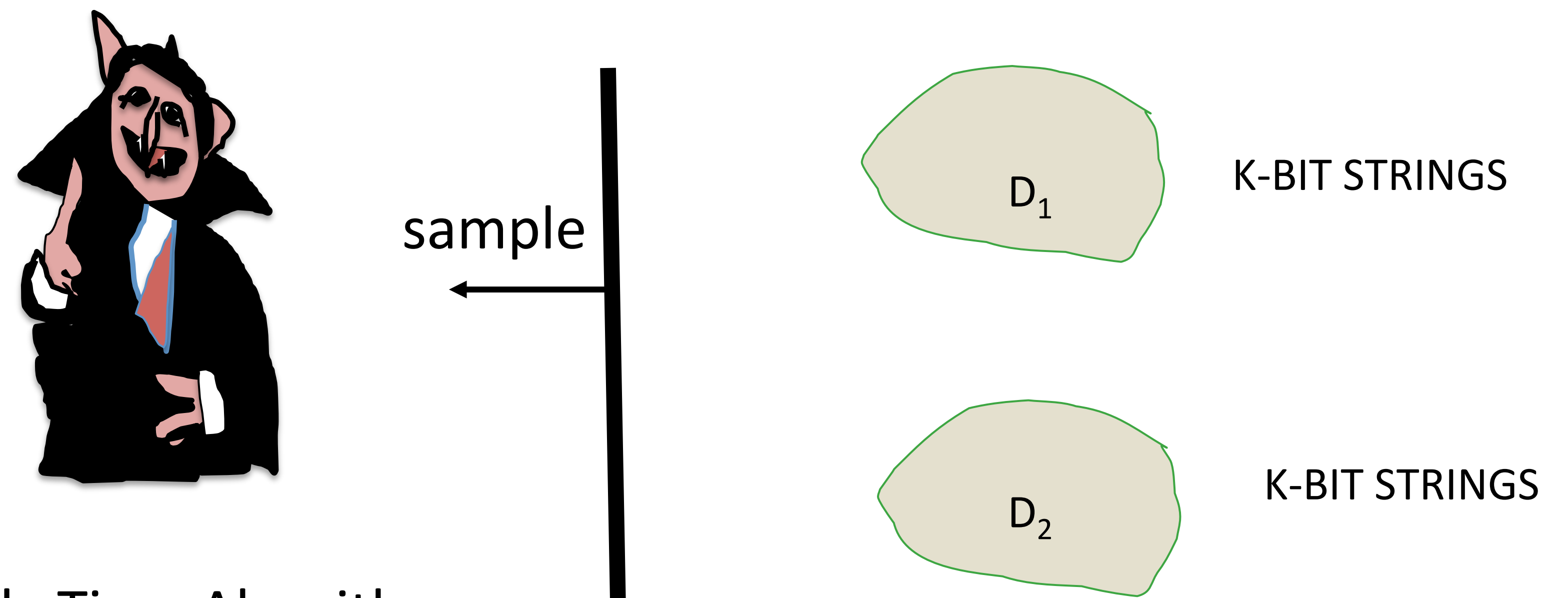
- Integral Part of the Definition of the Problem
- Determines the Quality of Acceptable Solutions
- The Key to Analysis of Complex Systems

The Power of the Adversary

- Make no assumptions on the Adversary strategy
- Worst Case: Do not assume Adversary is Random
- But will assume **Computationally Bounded**
  - Realistic
  - Great power: Enlarges the range of Application

"Axiom 1": Computationally Indistinguishablity

If the "Adversary" cannot tell apart two different probability distributions then they are the "same".

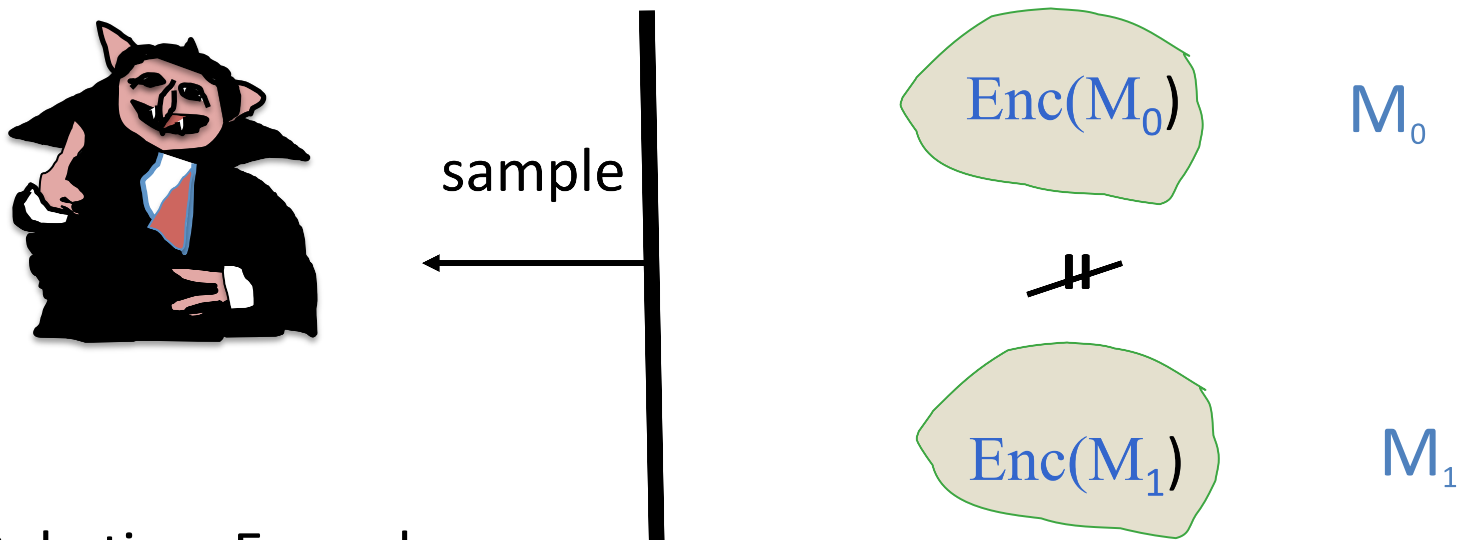


Any Poly Time Algorithm

Encryption, Pseudo Randomness, Simultaneity, Correctness

Computationally Indistinguishable Encryption

Probability distributions = encryptions of messages.

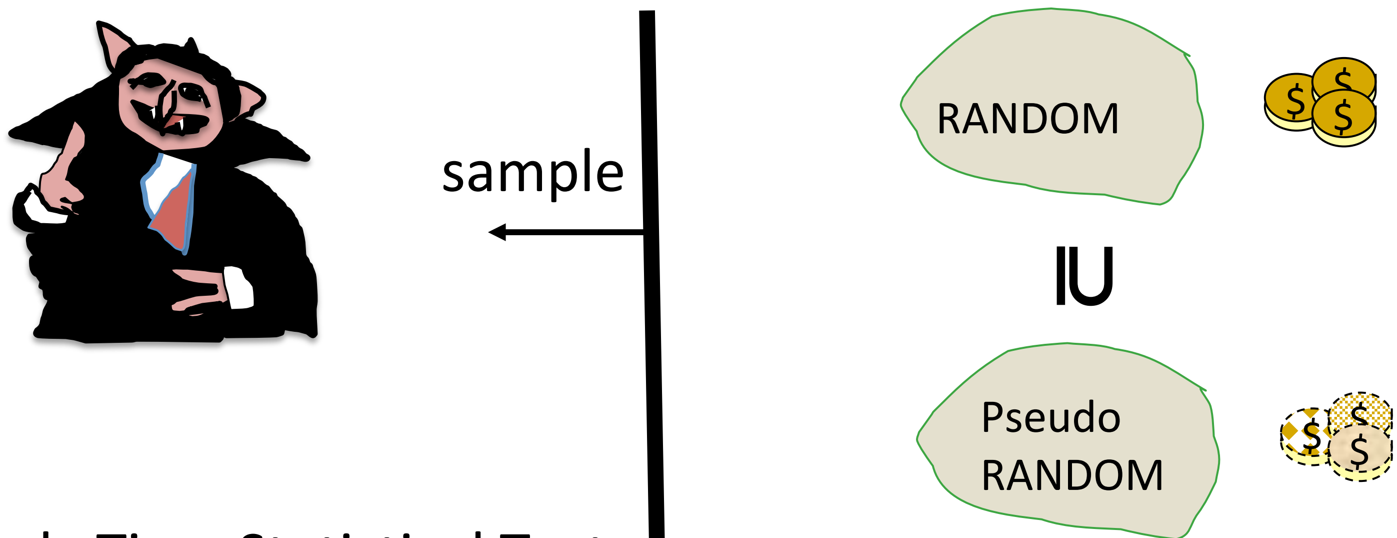


Any Poly-time Eavesdropper

Encryption Hiding All Partial Information is Possible [GM82]

Computationally Indistinguishable Randomness

Probability Distributions = exponentially long strings which adversary can randomly access

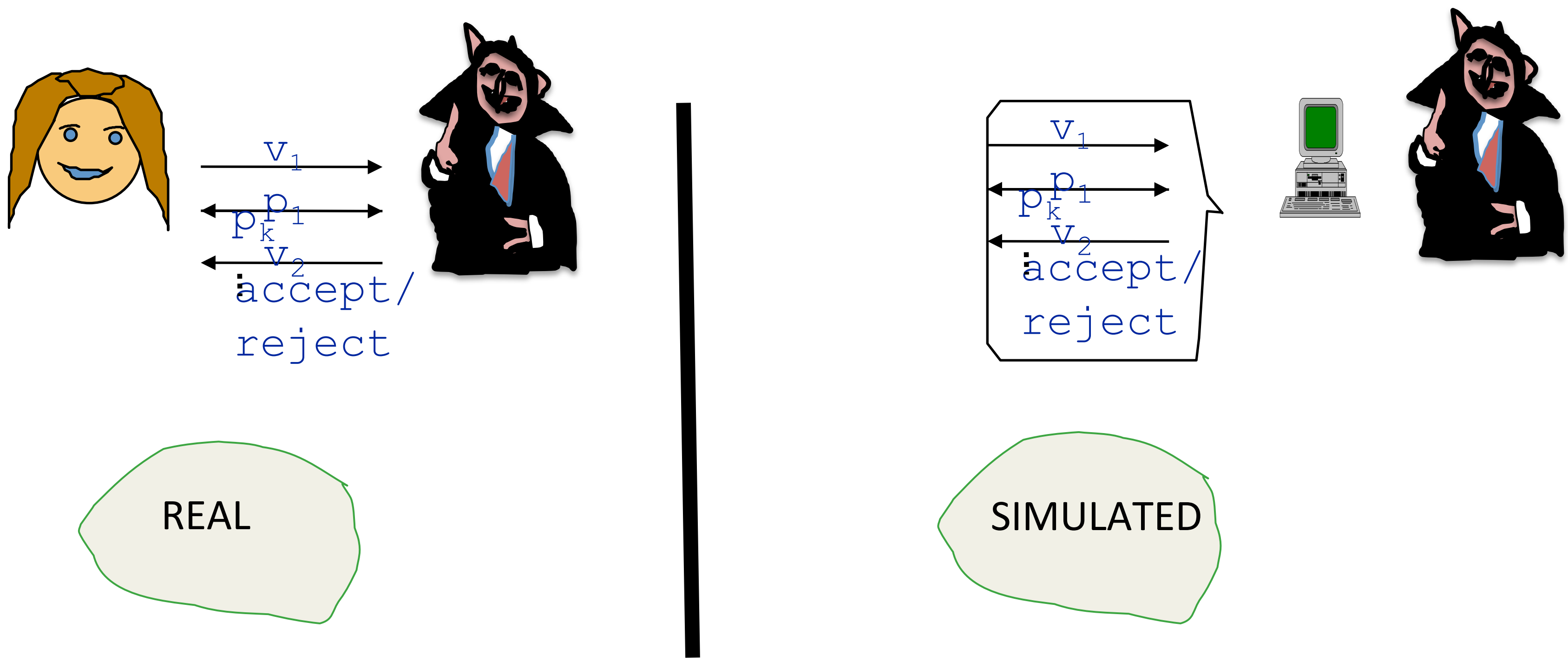


Any Poly Time Statistical Test

Pseudo Randomness Generation is Possible [BM82,Y82,GGM84]

“Axiom 2”: If you can simulate, might as well stay at home

The “insiders view” gives adversary zero knowledge if he can generate computationally indistinguishable “simulated view”



Catalytic Developments 1983-

Zero Knowledge Proofs

- Probabilistic Proof Systems
- *Hardness of Approximation*
- ***Delegating Computation to the Cloud***
- ***Quantum Interactive Experiments***

Pseudo Random Generators & Functions

- *De-randomization of randomized complexity classes*
- *Simple Concepts are un learnable*
- *Impossibility of Lower Bounds by Natural Proofs*

Hard Core Bit Proofs

- *List Decoding of Hadamard Codes*
- Efficient List Decoding for Reed-Solomon codes
- Explicit Codes which achieve the list decoding bound

Oblivious Transfer

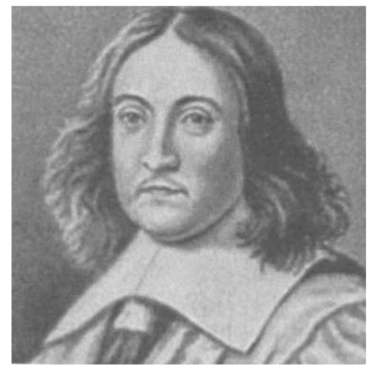
- Private Information Retrieval
- *Locally Decodable Codes*
- *Linear rate codes with sub-linear decoding*

Techniques for Average Case Hardness

- Random Self Reducibility
- Algorithms for Self/Testing
- ***Property Testing***

Classical Proofs

...



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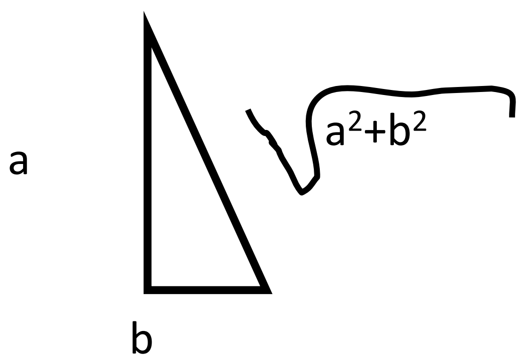

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Axiom 1
Axiom 2
Axiom 1⇒A
A⇒B
QED

...

Prime-Number Thm

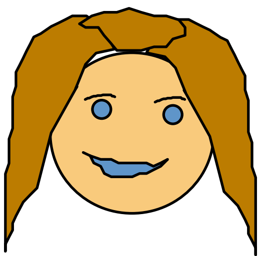
Example: EQ(x_1,…,x_n) is solvable

Efficiently Verifiable Proofs

Prover

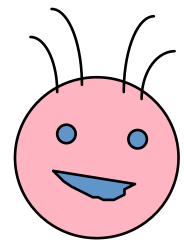
Claim

Verifier



Solution x_1,…,x_n

proof



Checks proof

Accept if satisfiable

Hard Working

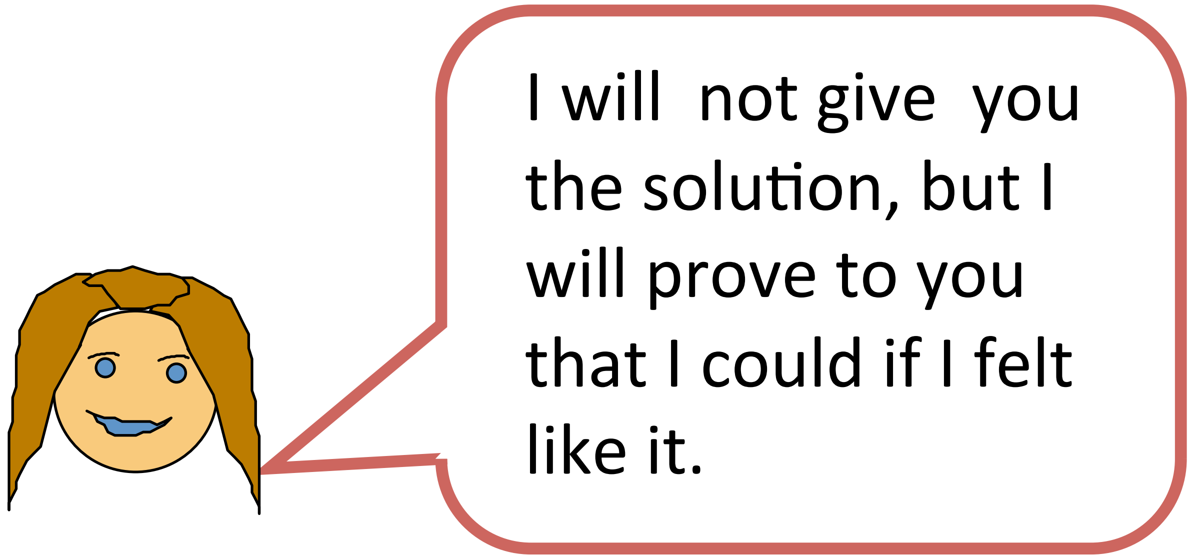
Polynomial Time in claim size

After interaction, Verifier knows:

1) Equation is solvable

2) A particular solution

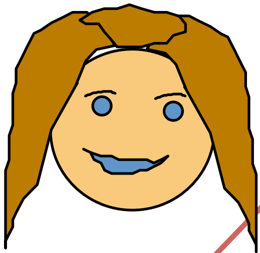
Is there any other way?



Randomness 

Interaction

Claim: $y = x^2 \bmod N$ is solvable



r= 

Consider the two equations

(1) $z=r^2 \bmod n$

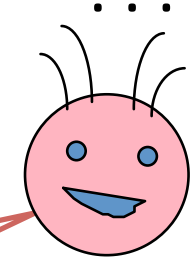
(2) $zy=r^2y \bmod n$

If I solved both for you, you would be 100% certain that the claim is true since $\frac{\sqrt{zy}}{\sqrt{z}} = \sqrt{y}$

So, I will only give you a solution to one of the equations.

You choose which!

???



Chooses at random  which solution to see

$\text{Prob}_{\text{coins}}(\text{Verifier catches mistake}) \geqq 1-(1/2)^k$

Accepts claim
he gets the
ight solutions

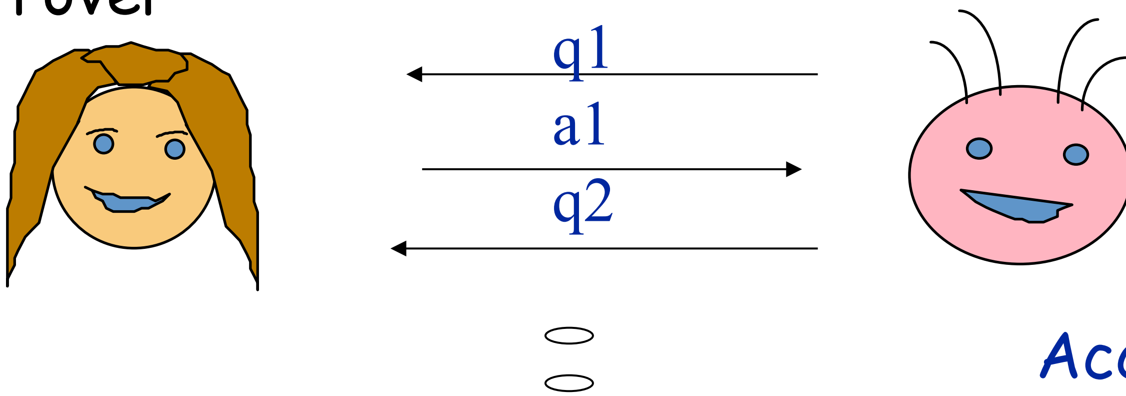
Zero Knowledge Interactive Proofs (ZK-IP)

[GMR85]

"x in L?"

Prover

Verifier



Randomized Polynomial time

Accepts or Rejects claim

COMPLETENESS: if $x \in L$, Bob will always accept

This is what a proof ultimately is!

ZERO KNOWLEDGE

Many Uses of Zero Knowledge

Lots of Applications to cryptography..

Due to generality

Theorem[GoldreichMicaliWigderson86]:

If One Way Functions exist,

Any NP statement has a ZK interactive proof

Zero Knowledge and Nuclear Disarmament [BarakGlasserGoldstone11]

Catalyst

Decoupled "Correctness" from "Knowledge of the proof"

Ask new questions about nature of proof

Questions have been asked and answered in last 25+ years leading up to current research on cloud computing

Classically: Can Efficiently Verify

		$EQ(x_1,\ldots,x_n)$
NP	✓	$\exists$ solution
Co-NP	?	0 solutions
#P	?	2^{100} -13 solutions
PSPACE	?	$\forall\ \exists\ \forall \ldots \exists$

Can you prove more via interactive proofs?

Interactively Provable= IP

[FortnowKarloffLundNissan89, Shamir89]

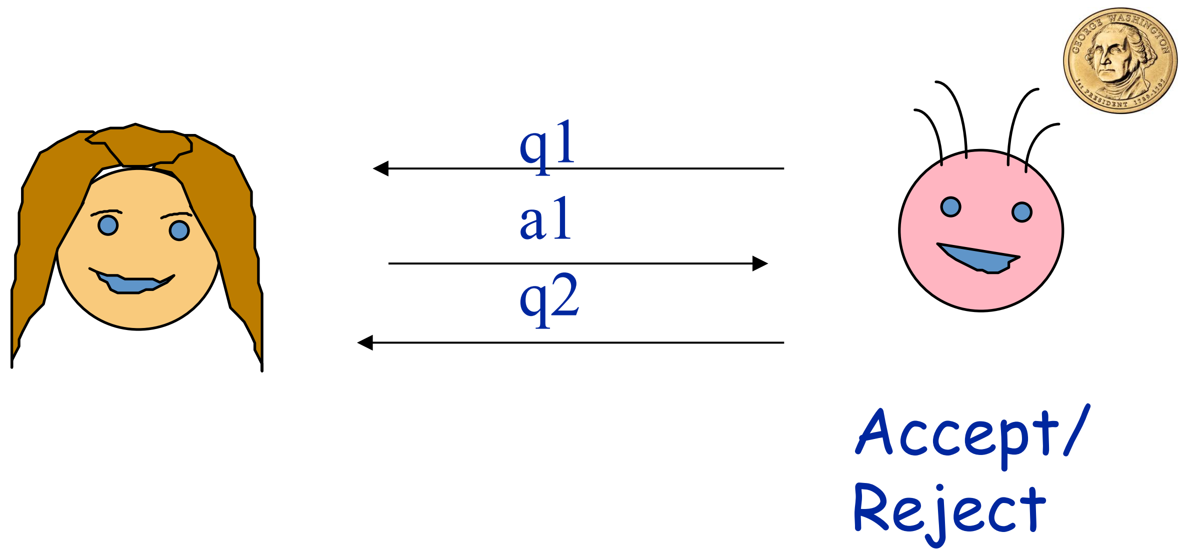
NP

Co-NP

#P

PSPACE

=IP



Other Ways to define probabilistic proof systems?

The Arrival of the Second Prover (MIP)

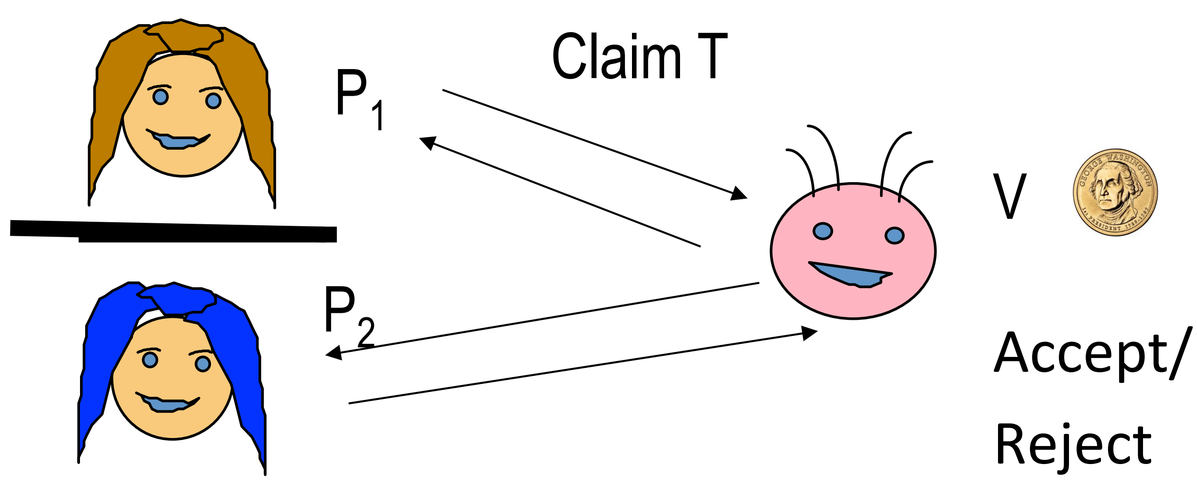
[BenorGoldwasserKilianWigderson88]

NP ✓

Co-NP ✓

#P ✓

PSPACE ✓



Why would two be better than one?

Can check **consistency**,
provers get caught if deviate

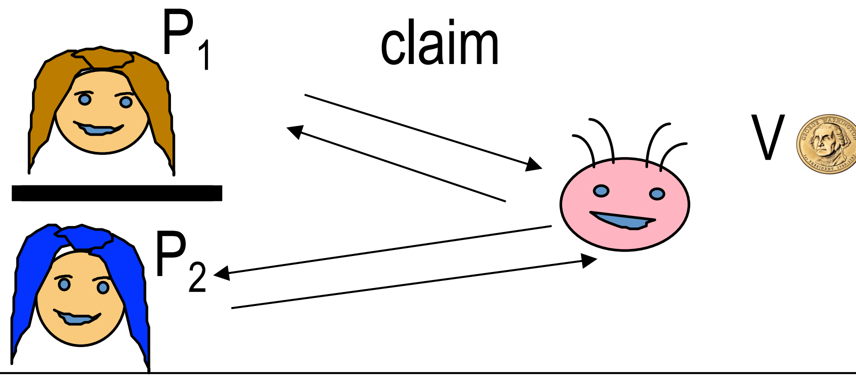
Theorem:

MIP has Zero Knowledge Proofs
For NP **unconditionally**

The Power of the Second Prover (MIP)

- NP ✓
- Co-NP ✓
- #P ✓
- PSPACE ✓
- NEXPTIME ✓

[BabaiFortnow Lund90]



claim: ∃ solution for > 99% of the equations

$x_1+x_2+x_3=1$ $\quad$ $x_1+x_4+x_7=0$

$x_4+x_5+x_6=1$ $\quad$ $x_1+x_4+x_7=0$

$x_7+x_8+x_9=1$ $\quad$ $x_3+x_6+x_9=0$

V chooses a random equation

Requests from P1: Solution to equation, i.e x_1,x_4,x_7

Requests from P2: Value of variable in equation

Much less communication !

Led to PCP theorem: NP statements can be verified by reading a constant number of bits

Far Reaching Consequences to showing Hardness of approximation.

In a Parallel Universe

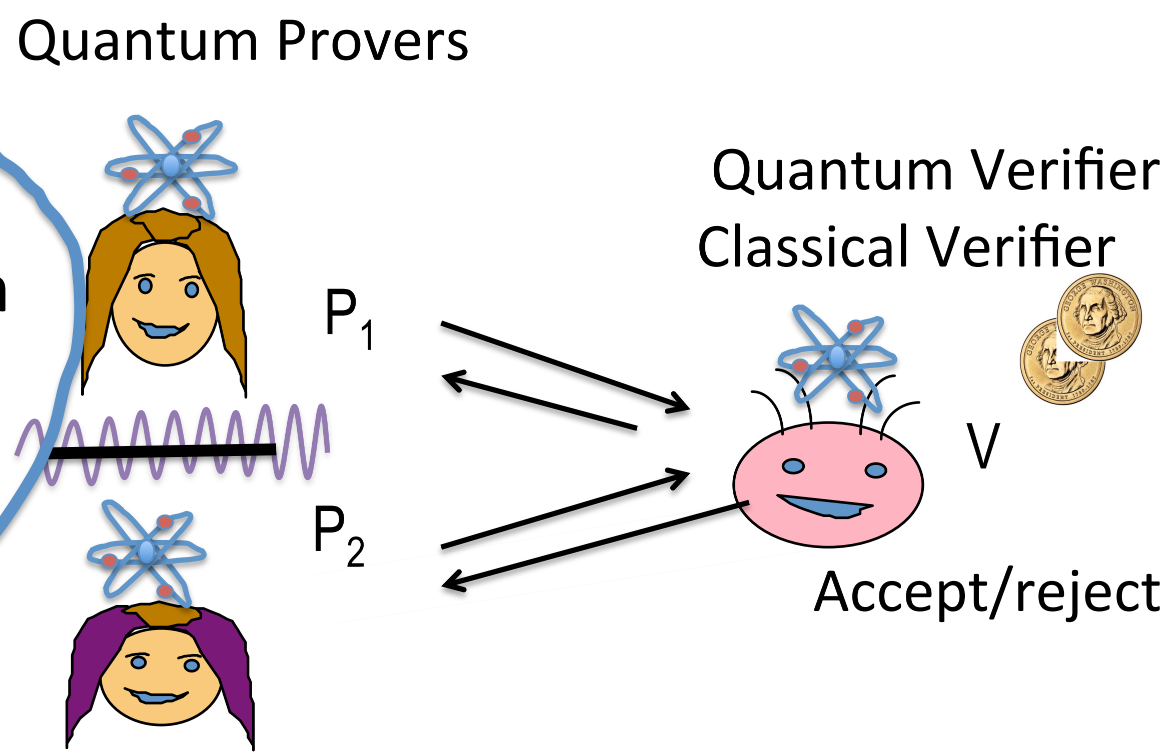
Q: Can the correctness of a QBP computation be even checked by a Classical verifier?

[AharonovBenorEban10]

PSPACE=QIP

NEXPTIME=QMIP

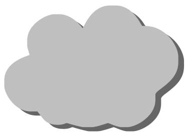
[JJUN10,KMY03]



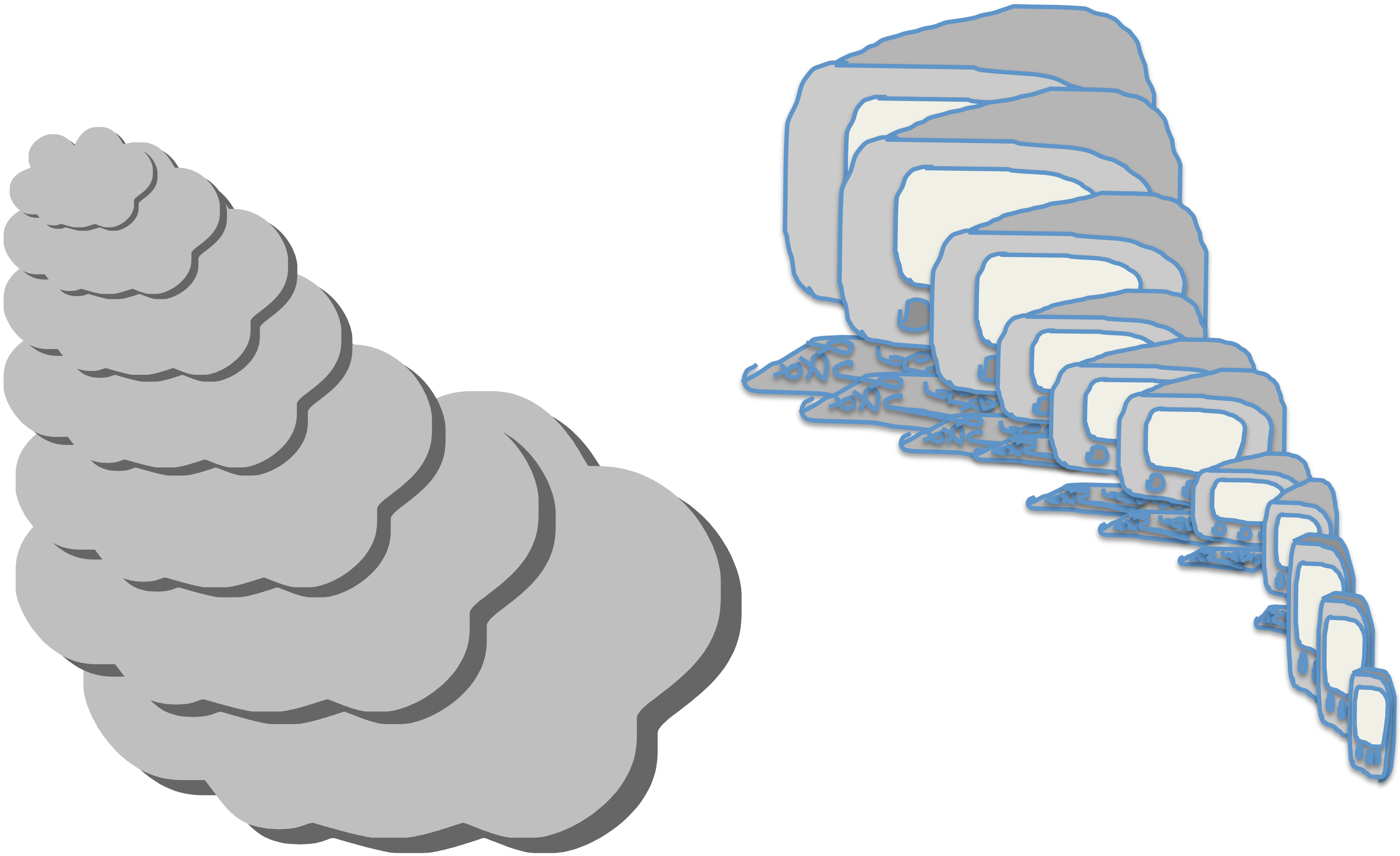
Theoerm[ReichardtUngerVazirani13]:

A Classical Verifier Can Verify the Computation of Two Entangled but Non-Communicating BQP Algorithms

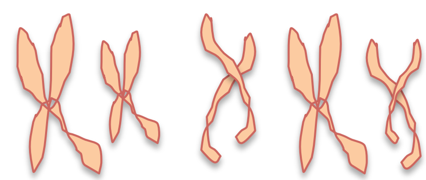
The Evolution of Computing



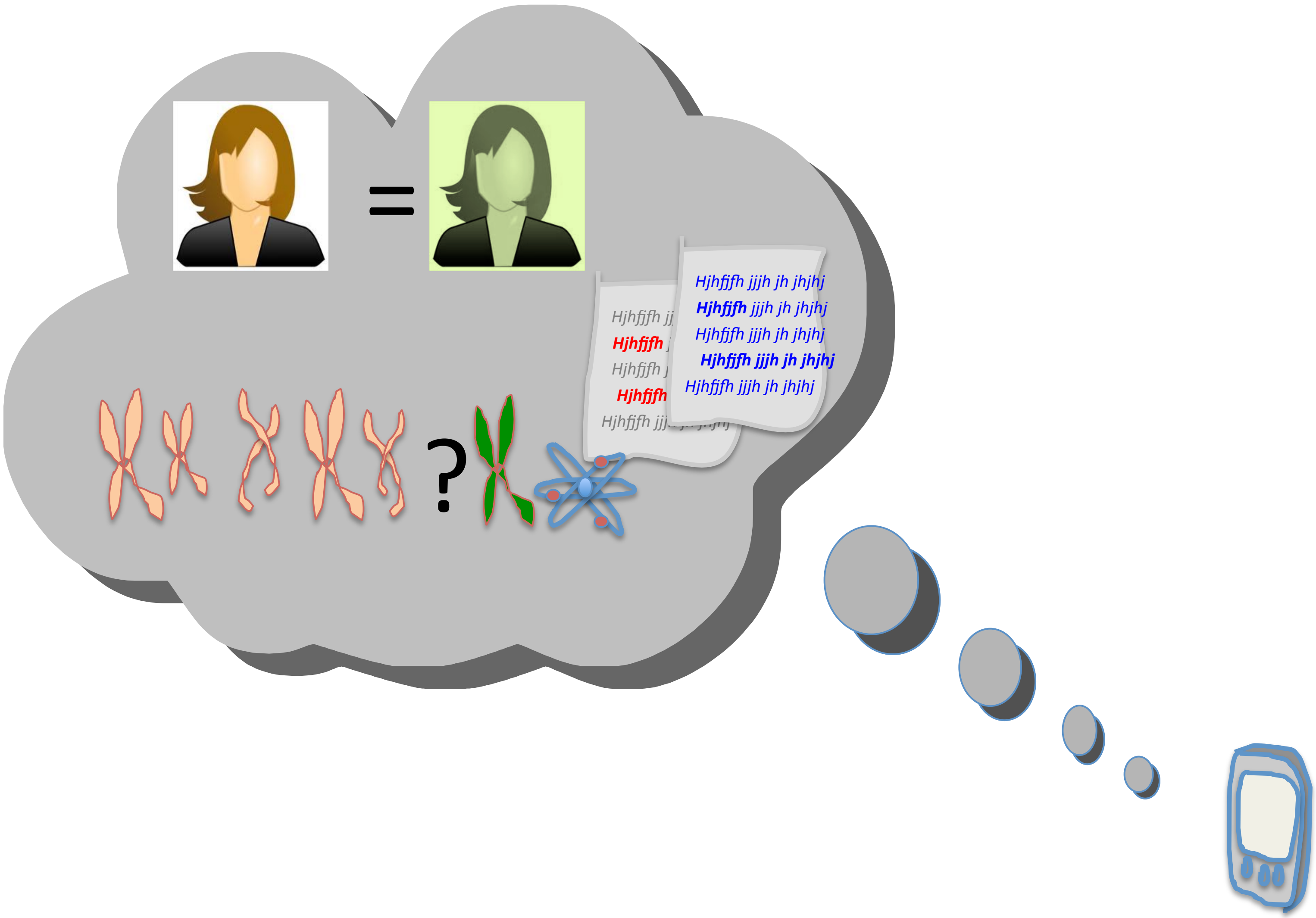
The Evolution of Computing



A Migration of Data

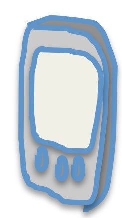


A Migration of Computation



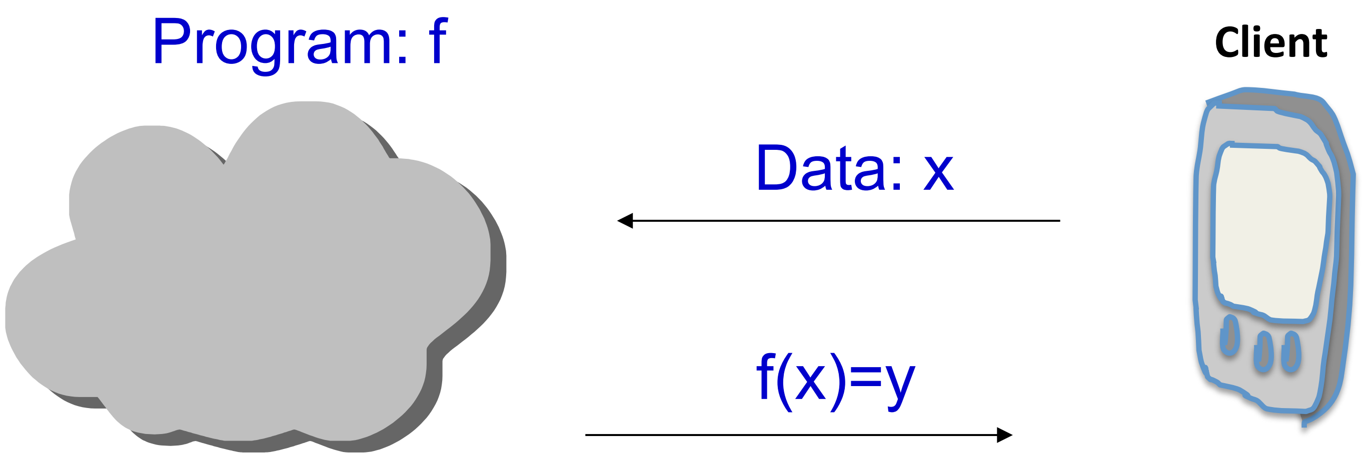
Brave New World…Enormous Potential in Globalization of Knowledge

Can we do it all
Without relinquish of control



Challenge 1:

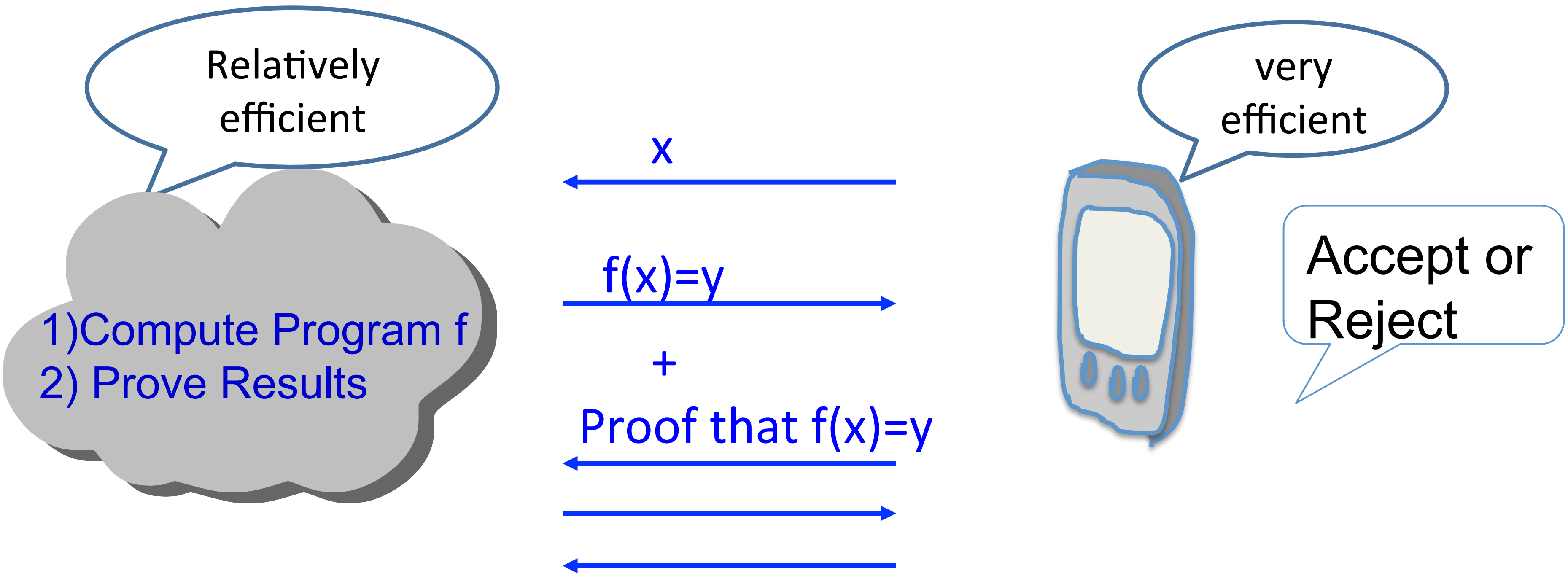
Verify correctness of remote storage/computation



Why trust the server?

Challenge: to delegate P time computation so that Prover's task not much harder than computing

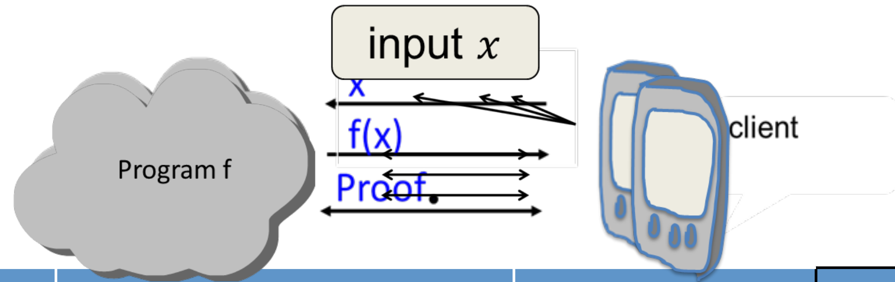
on



Interactive Proof for $L_f=\{(x,y) \text{ s.t. } f(x)=y\}$

IP=PSPACE $\Rightarrow$ any space S algorithm, can be "delegated" to $2^{poly(S)}$ time prover and verified by poly(S) time verifier

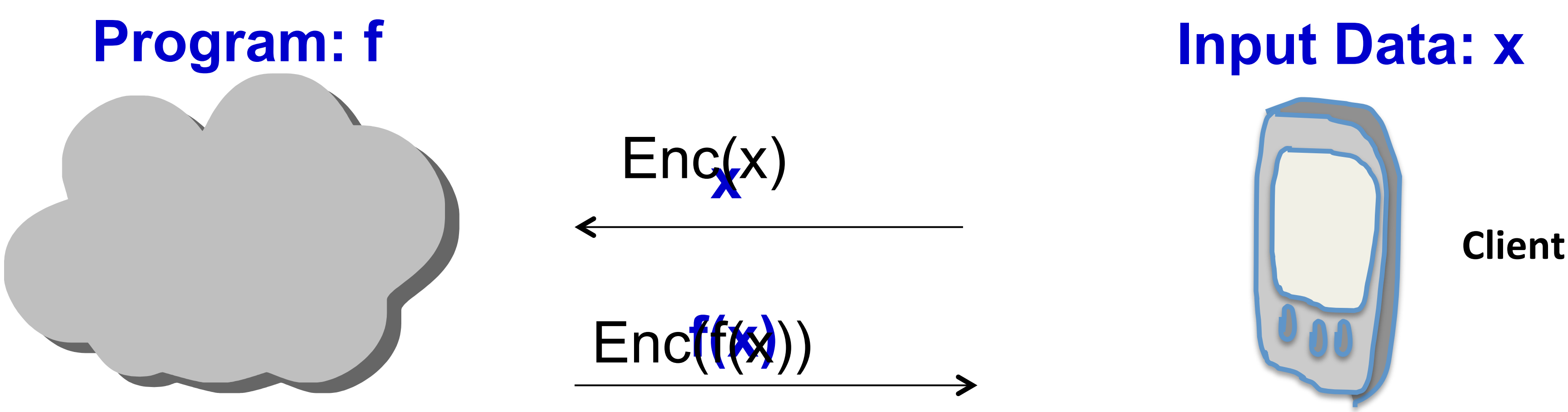
Active Research Area



Model	Computation	Prover Time	Verifier Time
Interactive Proof [GoldwasserKalaiRothlum08]	CKT SIZE S, depth D	poly(S)	Quasi |x|+ D D ROUNDS
Computational Soundness.Assume FHE. [KalaiRazRothblum13]	TIME(T) Turing Machine	Poly(T,k)	Quasi |x|+poly((log T),k) 1 ROUND Public Key model
Computational Soundness. Stronger Ass. [BitanksiCanettiCiessaTrom13]	NTIME(T) RAM	Poly(T,k)	Quasi |x| +poly((log T,k) 1 ROUND Public Key Model
Interactive Proof For ε-proximity [RothbVadanWigderson13]	CKT SIZE S, depth D	Poly(ε^{-1}, S)	Sublinear |x| + ε^{-1} D rounds

[BCCGTV13] RAM model analogues
⇒Implementations for C-programs delegation

Challenge 2:
Compute on Encrypted Data



Privacy ✚ Functionality?

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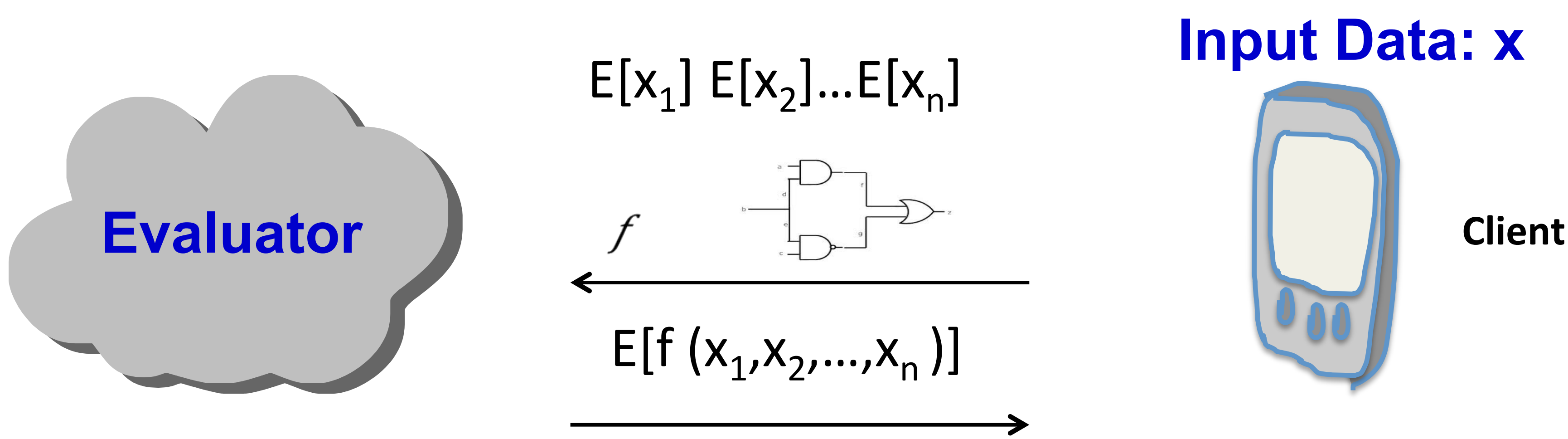
Fully Homomorphic Encryption (FHE)

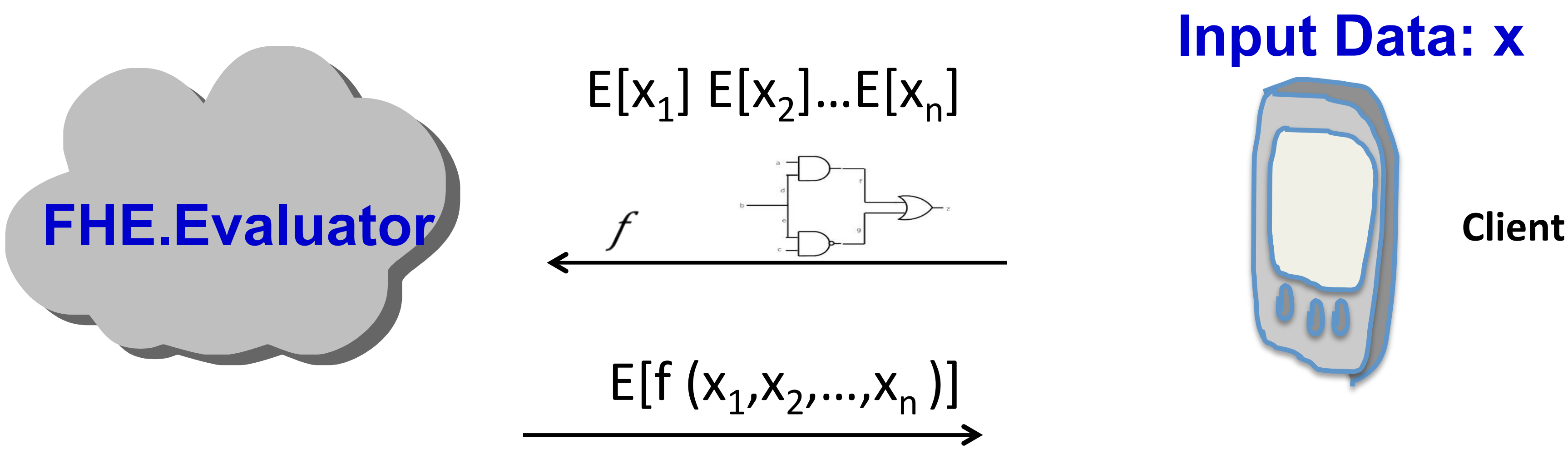
[RivestAdelmanDertuzous78, **Gentry09**, BrakerskiVaikuntanathan11]



Hailed tool for computing on encrypted data

But, is it enough?

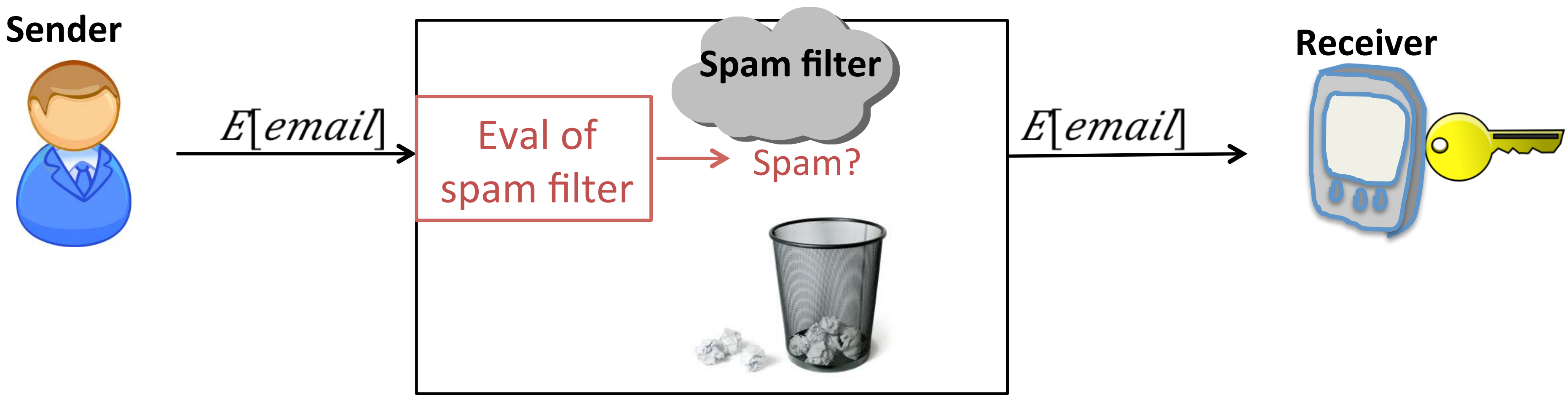
How FHE works:



FHE is not enough when the evaluator needs to decrypt the computation results.

When would we want to do that?

Example 1: Decrypt for Classification



Need to decrypt "spam filter" result but nothing else!

Example 2: Decrypt for Maintaining both our Civil Liberties & Safety

Snap

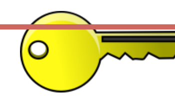
E(photo)

Suspect Data Base

Eval of comparison to suspect face

yes, suspect is in photo

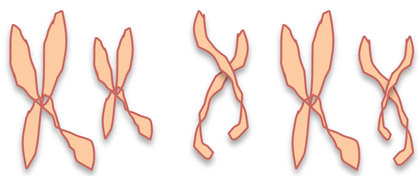
Law and Order



Need to know if suspect appears in the scene but nothing else!

Example 3: Conduct Medical study on Confidential Medical Information

Laboratory



E(medical file)

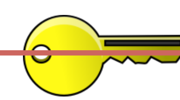
Drug Company

Eval of algorithm checking for gene presence

Yes

Tally positive

Make new gene therapy

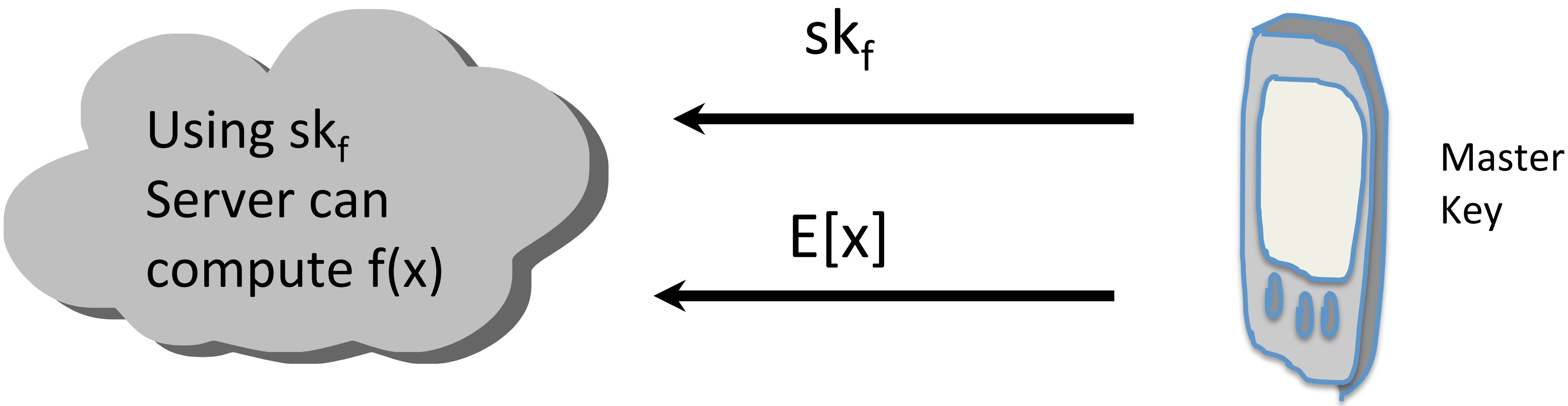


Need to know if result of the blood test are positive for X, not entire profile !

Filterable Decryption = Functional Encryption

[…BonehSahaiWaters11, O'Neill11]

Allow server *to compute partial information f(x) from E(x) but nothing else*:



Security def: can simulate server's view given f(x) even without seeing E[x]

Is this possible?

For inner product functions [KSW'08, SSW09];

More generally if you allow a ciphertext E[x] size which as large as f's circuit size [GVW12]

Succinct Filterable Decryption [GoldwasserKalaiPopaVinodZeldovich13]

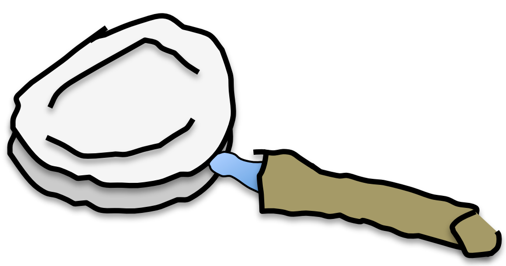
Theorem:
Succinct Filterable Decryption that supports any polynomial time functions assuming the Sub-Exponential Hardness of Learning with Errors

Succinct:
F is circuit of **depth d** $\Longrightarrow$ ciphertexts growing in **d**

Corollary: can address all of the aforementioned examples and …much more
Corollary: Add function privacy & get ``obfuscation variant''

The Cryptographic Lens

Our Physical world intuition should not constrain out expectation for what is possible for "Digital Privacy "



How can today's Cryptographic methods and fine control of information affect complexity theory of tomorrow?