Danger of using fully homomorphic encryption, a look at Microsoft SEAL

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360 INTERNET SECURITY CENTER

Who we are

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Research areas:

- Software security
- Applied cryptography
- Threat hunting

About the topic

Introduction to homomorphic encryption

Introduction to SEAL

Security pitfalls of SEAL

- CCA attack on BFV
- Data recovery against FPSI
- Circuit privacy of SEAL
- Information leakage
- Countermeasures

Other issues

Conclusion

Computing on encrypted data

Data leakage become more serious nowadays

Data security, privacy become a public concern

It will be nice to be able to….

Encrypt my data before send to the cloud

While still allowing the cloud to search/sort/edit the data on my behalf

Keep the data in cloud in encrypted form

Computing on encrypted data

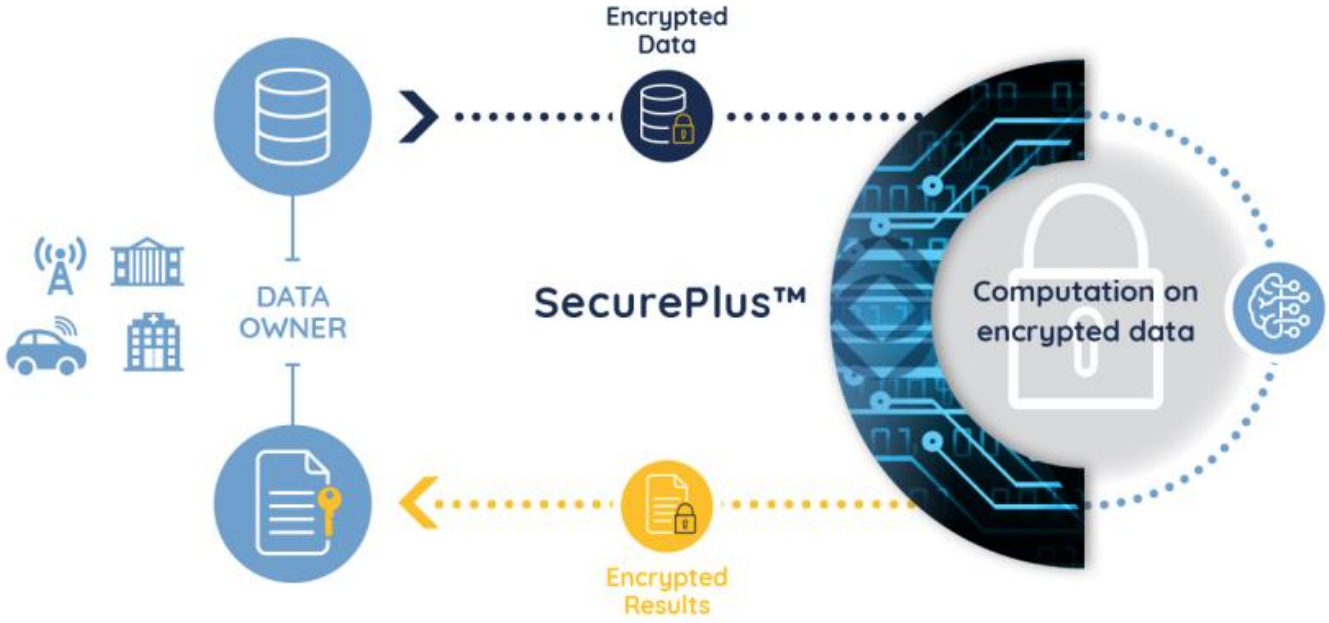
It will be nice to be able to….

Encrypt my query to the cloud

While still allowing the cloud the process them

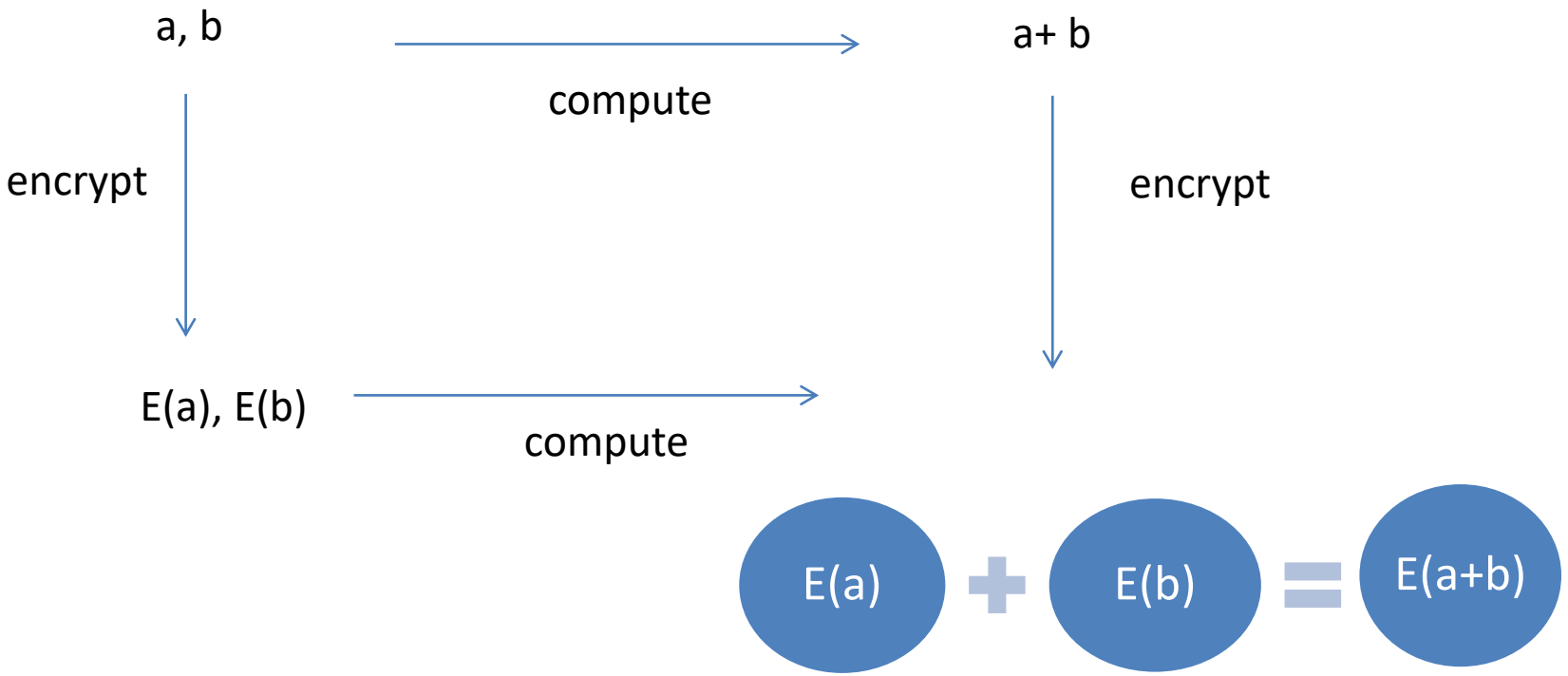
Cloud returns encrypted answers

that I can decrypt



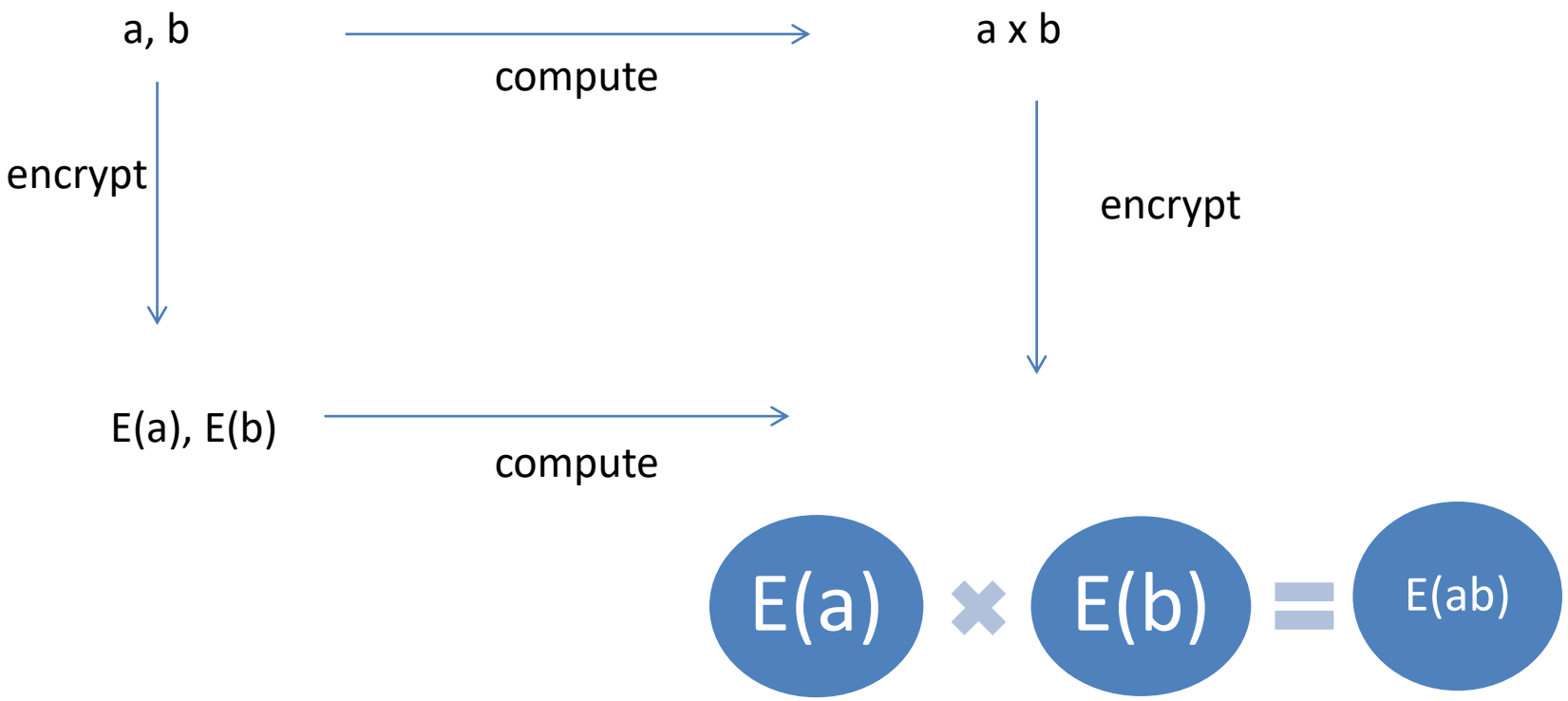
This picture is from duality.cloud

Homomorphic addition



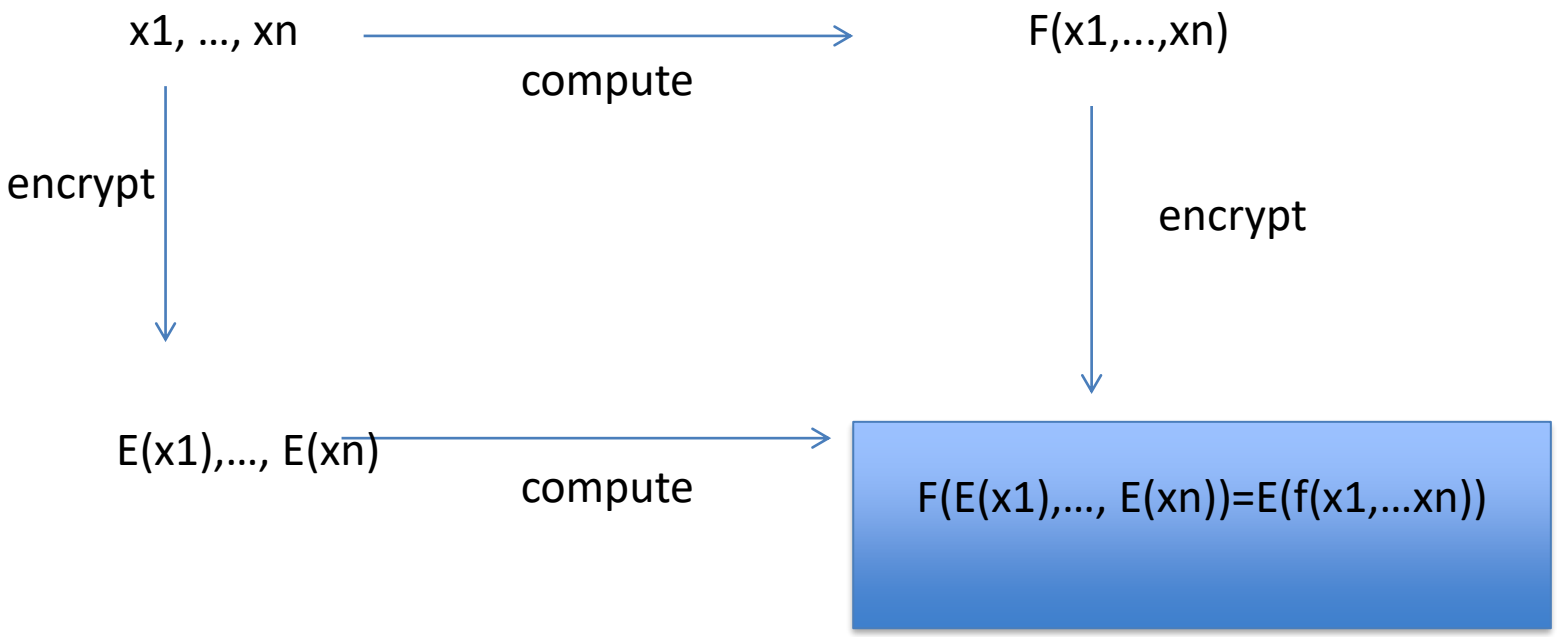
Pure RSA support homomorphic addition!

Homomorphic multiplication



Pure Elgamal support homomorphic multiplication!

Fully homomorphic encryption



Craig Gentry proposed the first fully homomorphic encryption in 2009

Protecting Data via Encryption
A famous metaphor

1. Put your gold in the locked box
2. Keep your key
3. Let the worker work on it through a glove box
4. Unlock the box and get the jeweler

Applications of HE

Outsourcing computation

Machine learning on encrypted data

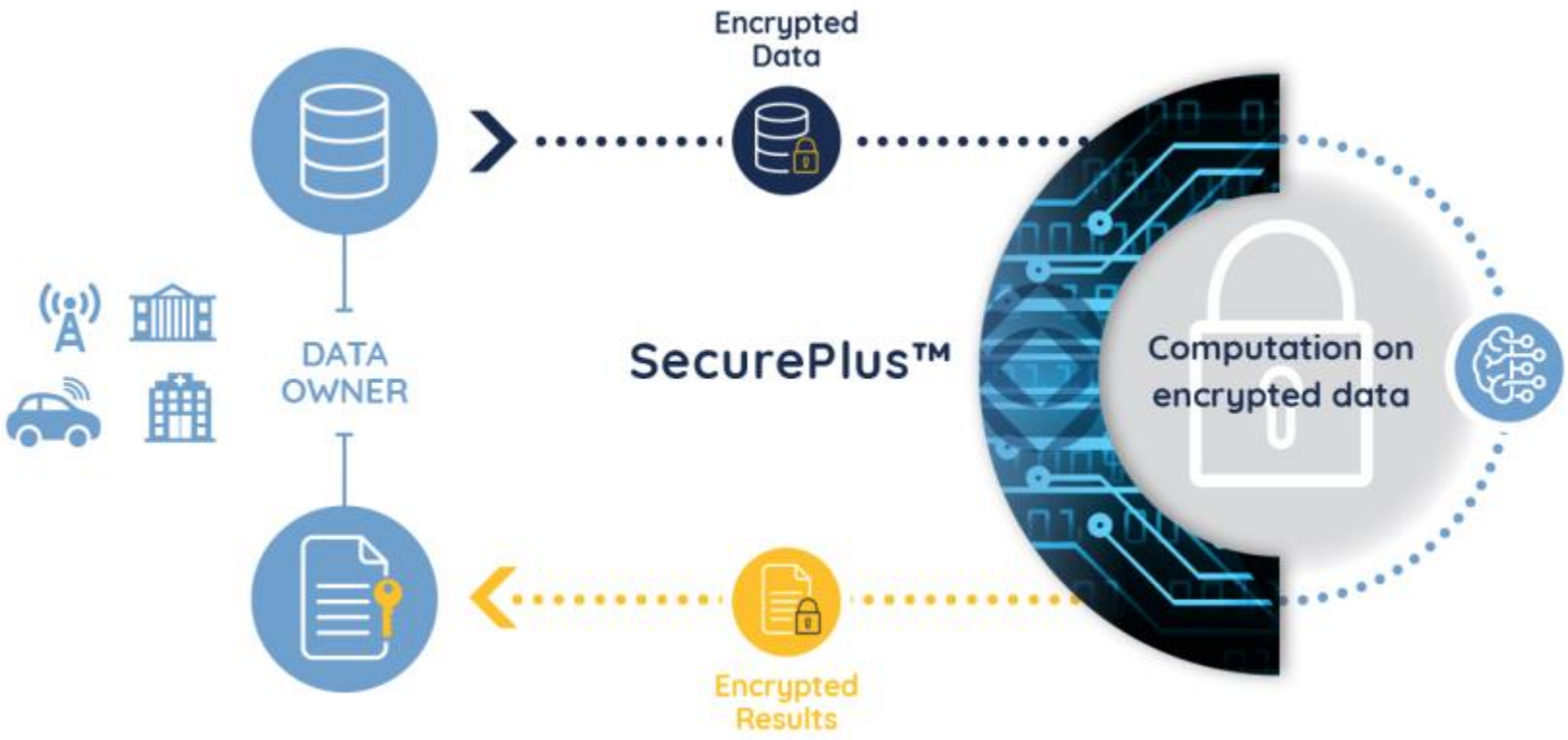
Cloud service without knowing clients' privacy

There are two kinds of applications:

private data , public function

private data , private function

Private data , Public function

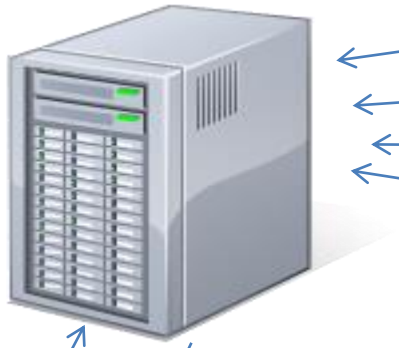


This picture is from duality.cloud

Data should be keep secret.

The function f can be public.

Disease prediction



Genomic data

Health monitor

Health record

Lab results

private data , public function

- All data uploaded to the server encrypted under patient's public or private key
- Cloud operates on encrypted data and returns encrypted predictive results

Private data , Private function

This picture is from duality.cloud

Both data and the model should be keep secret.

Circuit privacy:

An additional requirement in many FHE applications is that the evaluated ciphertext should also hide the function f.

SEAL

Simple Encrypted Arithmetic Library

Quick Background

Homomorphic Encryption library from Microsoft Research

First version released in 2015; SEAL 3.1 just released

Developed in standard C++

Implements BFV and CKKS schemes

Simple and easy to use

Comes with detailed examples

Performance of SEAL

CryptoNets:

- **MIST handwritten digital picture recognition**
- **60,000 predictions per hour**
- **99% correct rate**
- **16 encrypted pictures per second**

Our experiment:

- **logistic regression prediction**
- **10,000 pieces of data in 5 minutes**
- **300 times slower than using sklearn directly on plaintext**

Seems reasonable

HOW DOES IT WORK

Ring-LWE problem

Ring $R=Z_q[x]/(x^n+1)$

Given:

To make it simply to understand

You can think all elements here are integer

- $a_1, b_1=a_1 \cdot s+e_1$
- $a_2, b_2=a_2 \cdot s+e_2$
- …
- $a_k, b_k=a_k \cdot s+e_k$

Find: s

s is random in R

e_i are "small" (distribution symmetric around 0)

Decision Ring-LWE problem

Ring $R=Z_q[x]/(x^n+1)$

Given:

- **a_1, b_1**
- **a_2, b_2**
- **…**
- **a_k, b_k**

Question: Does there exist an s and "small"

- **$e_1, \dots, e_k$ such that $b_i=a_i \cdot s+e_i$**
- **or are all b_i uniformly random in R?**

BFV key pair

SecretKeyGen():

sample secret key $s \in \chi$

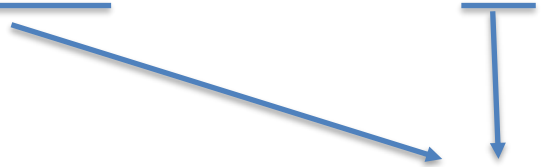
Over simplified!

You can think all these are integer

PublicKeyGen(s):

sample $a \in R_q$, $e \in \chi$

$pk_0 = -(a \cdot s + e)$ $pk_1 = a$



Ring-LWE pair

s cannot be recovered

BFV encryption

Encrypt(m): sample $u \in R_q$, e_1 $e_2 \in \chi$

$c_0 = pk_0 \cdot u + e_1 + \Delta \cdot m$, $c_1 = pk_1 \cdot u + e_2$

Replace pk with $(-(a \cdot s + e), a)$

$c_0 = -(a \cdot s + e) \cdot u + e_1 + \Delta \cdot m$, $c_1 = a \cdot u + e_2$

$c_0 = -w \cdot s + e_1 + e \cdot u + \Delta \cdot m$, $c_1 = w + e_2$

Decision Ring-LWE pair (cannot be distinguished with random value)
Message m is encrypted with a random pad

Ciphertext can be consider as a polynomial:

$f(x) = c_0 + c_1 * x$

BFV decryption

Decrypt(c):

$f(x)=c_0+c_1 \cdot x$

$f(s)=c_0+c_1 \cdot s$

substitute x with s

Replace c with $=([-w \cdot s + e_1 + e \cdot u + \Delta \cdot m]_q, [w + e_2]_q)$

$f(s)=-w \cdot s + e_1 + e \cdot u + \Delta \cdot m + (w + e_2) \cdot s$

$=e_1 + e \cdot u + e_2 \cdot s + \Delta \cdot m$

Much smaller than Δ

Then we can recover m

We can think that:

$f(s)= v + \Delta \cdot m$

where v is much smaller than Δ

Homomorphic addition

Homomorphic addition:

Ciphertext1: $f_1(x)$

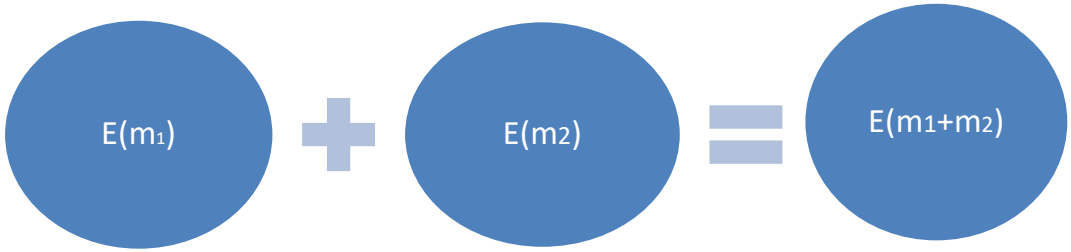
Ciphertext2: $f_2(x)$

Compute: $f_3(x)=f_1(x)+f_2(x)$

We have:

$f_1(s)=v_1+\Delta \cdot m_1$

$f_2(s)=v_2+\Delta \cdot m_2$



Then decrypt $f_3(x)$:

$f_3(s)=f_1(s)+f_2(s)=v_1+v_2+\Delta \cdot (m_1+m_2)$

$=v_3+\Delta \cdot (m_1+m_2)$

Homomorphic multiplication

Homomorphic multiplication:

Ciphertext1: $f_1(x)$

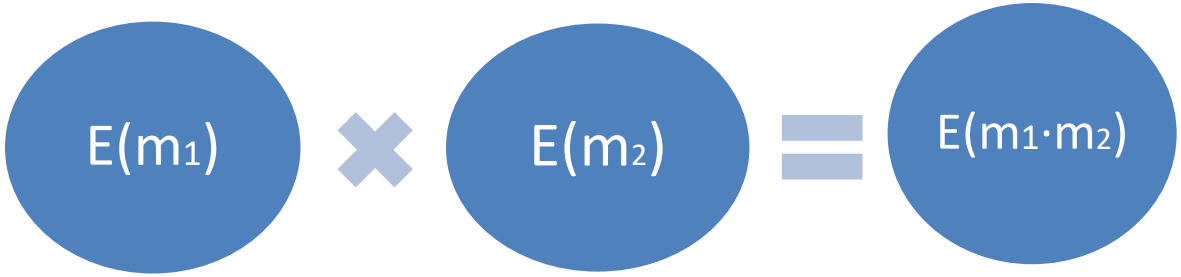
Ciphertext2: $f_2(x)$

Compute: $f_3(x)=f_1(x)*f_2(x)$

We have:

$f_1(s)=v_1+\Delta \cdot m_1$

$f_2(s)=v_2+\Delta \cdot m_2$



Then decrypt f3(x):

$f_3(s)=f_1(s)*f_2(s)=v_1 \cdot v_2+\Delta \cdot (v_1 \cdot m_2+ v_2 \cdot m_1)+\Delta \cdot m_1 \cdot m_2$

Divide by Δ , we can get:

$f_3(s)/\Delta= v_3+\Delta \cdot (m_1 \cdot m_2)$

Security of BFV schemes

Encrypt message m to an polynomial f(x)

Decrypt by substitute x with s

get $f(s)=v+\Delta \cdot m$, can recover m easily

Message is "blind" by Ring-LWE pair + noise

Distinguish ciphertext → distinguish Ring-LWE pair

Provable security: IND-CPA → Ring-LWE

Chosen plaintext attack

If someone break IND-CPA, he can break Ring-LWE

Ring-LWE is suppose to be a hard math problem

IND-CCA?

chosen ciphertext attack

attacker is given access to a *decryption oracle*

BFV doesn't have IND-CCA security

All practical FHE cannot guarantee IND-CCA

homomorphic property seem conflict with CCA

Theoretical research on CCA FHE

Chosen-Ciphertext Secure Fully Homomorphic Encryption

All FHE implementation cannot guarantee security in the IND-CCA scenario

IND-CCA Scenario

Why need IND-CCA

attacker can always ask for a decryption in real scenario

IND-CCA is a standard requirement for encryption scheme

Scenarios that require HE often require IND-CCA

rich data flows between data-owner and cloud

multi-party's cooperation and data exchange

If certain decrypted data is leaked to the cloud

break the CPA model, need CCA security

One query attack

Suppose attacker can query decryption oracle 1 time

Realistic in many scenarios

Ask to decrypt a malicious ciphertext f(x)

$f(x)=c_0+c_1x$ with $c_0=0$, $c_1=\Delta$

Decryption subsisuttte x with s

We have : $f(s)=\Delta s$

then the decrypted message equal to s (private key)

Recover private key with only one query

extremely dangerous

other FHE face the same problem

Countermeasures

Do not use HE in any scenario that decrypted result may leak to evaluator.

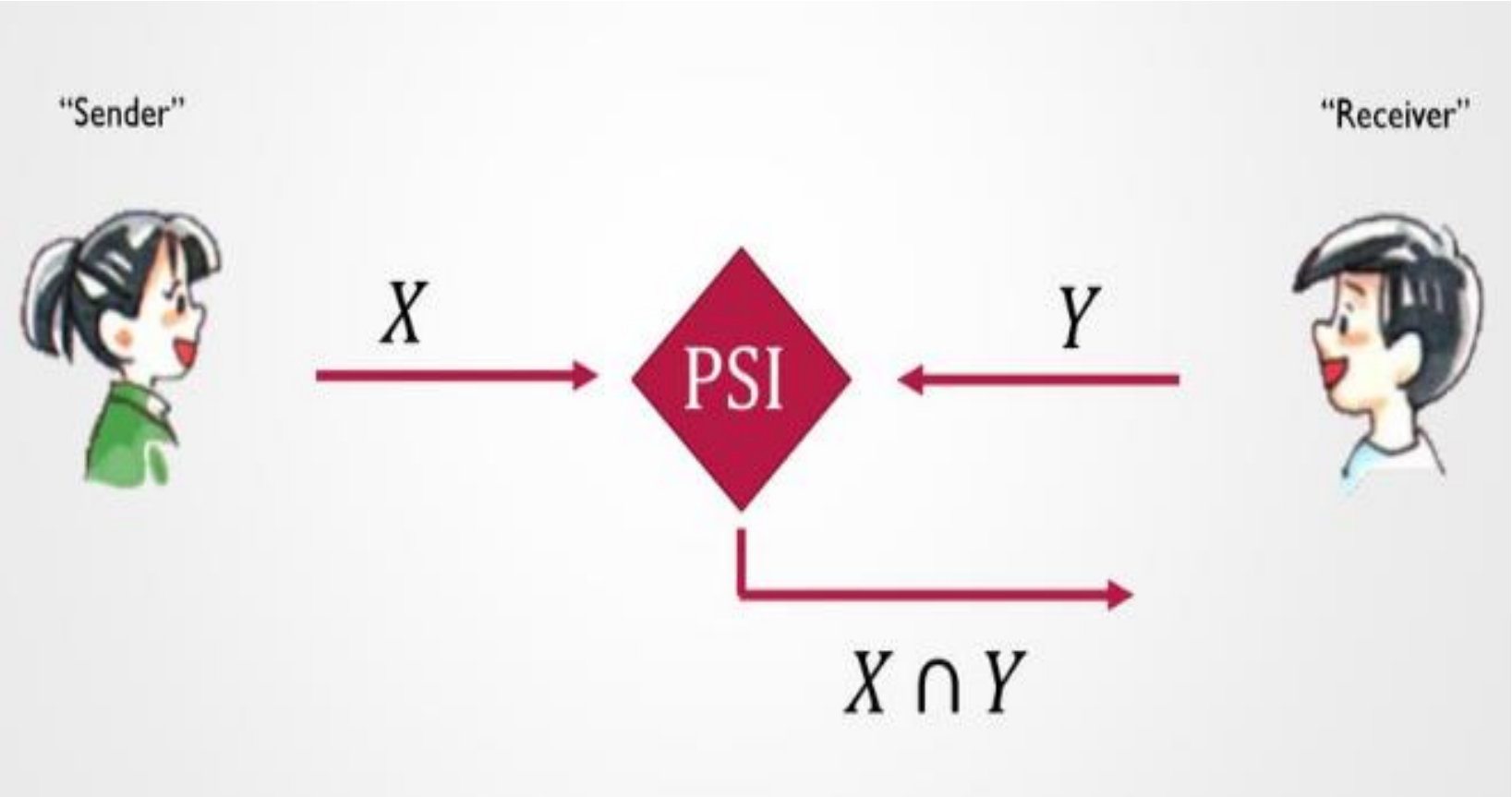
Otherwise, there is no encryption at all.

The decrypted result may leak to evaluator in many scenarios, with or without being noticed.

But how can We make sure there is no leakage?

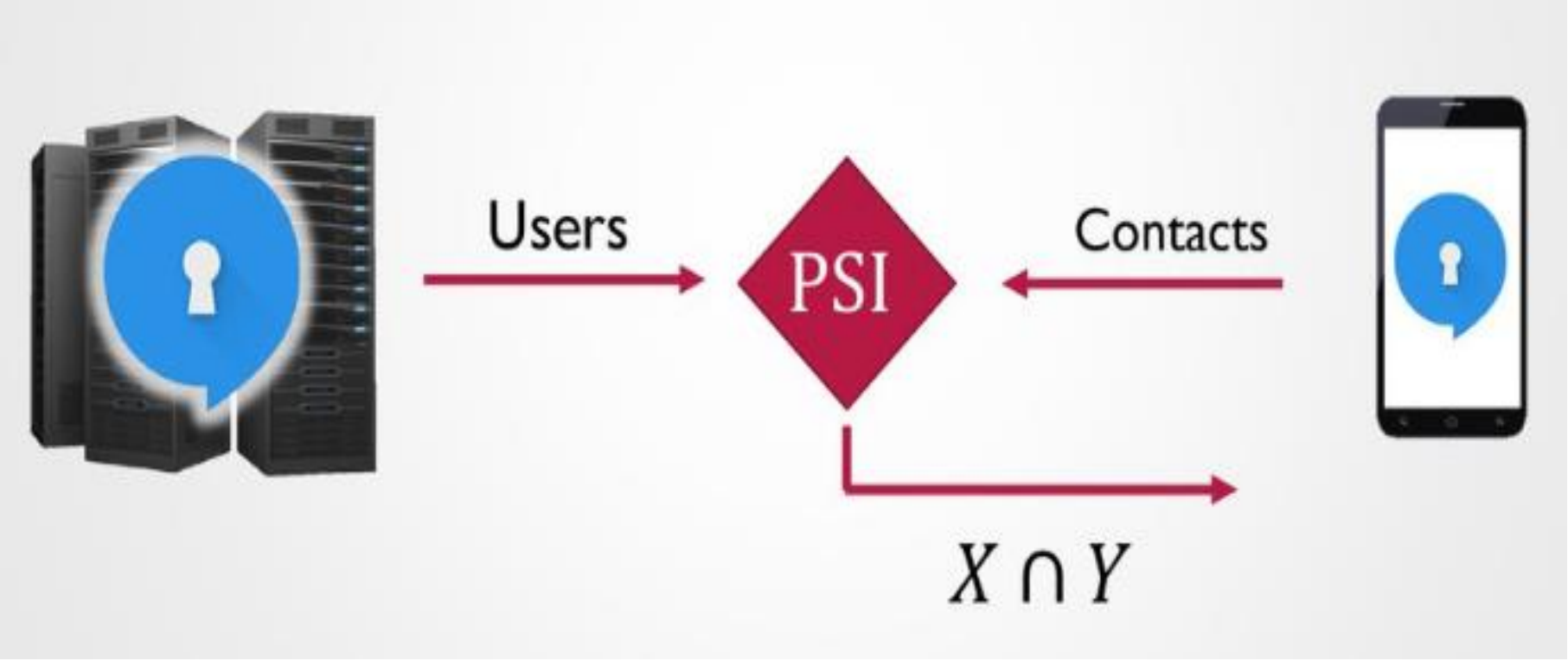
Currently, SEAL team is working on building mitigations on this problem. To detect malicious ciphertext before decrypt it.

Private Set Intersection (PSI)



Without leaking anything else

App: Contact discovery



private contact discovery on E2EE IM (signal…)

Using HE to build PSI
FPSI in CCS17 (oversimplified)

local database Y

Encrypt(X) with HE

Send Encrypted X to Server

Compute with local database Y,
get the encrypted X∩Y

Send Encrypted X∩Y to Client

Decrypt the result,
Get the X∩Y

CCA attack on this scenario

After client get X∩Y.
He found out that X∩Y are also using signal.
Then he add them as friends

X∩Y in plaintext

Information leakage
To server.
Server can launch CCA attack!

Lesson learned:

There are always unexpected data flows between data-owner and cloud.

Be extremely careful when using homomorphic encryption.

Another attack

local database Y

Encrypt(X) with HE

Send Encrypted X to Server

Compute with local database Y,
get the encrypted X∩Y .
But most of the HE have no circuit privacy.
Other information except X∩Y may also leak.

Send Encrypted X∩Y to Client

Client decrypt the result,
Get the X∩Y
Also get other information on Y

More details can be found on our whitepaper

Circuit Privacy of SEAL

SEAL doesn't provide circuit privacy on default

Addressed in SEAL handbook

Best practice is "noise flooding"

adding an encrypted 0 to the final result, with "enough" noise

But there is no standard interface of "noise flooding" in SEAL

normal software developer definitely can't play with the magic

Hardness of providing "noise flooding"

Need to know how much noise is needed, this is also some kind of information we need to protect. :(

All practical FHE lib seems have the circuit privacy problem

The crypto community need to solve this

Countermeasures

An improved PSI protocol is published in CCS18

https://eprint.iacr.org/2018/787

Secure against malicious party

As for circuit privacy of SEAL and HE

You need an crypto expert to review your implementation

You need professional knowledge on lattice-based crypto

SEAL team is working on provide a standard interface to this problem

Info leakage of Encoder

HE is working on a polynomial ring based on finite field

plaintext is integer, float or string

we need convert them to the ring

IntegerEncoder of SEAL

encode an integer to a polynomial

many to one mapping

Information leakage!

More details can be found on our whitepaper.

I think you don’t want the mathematical formula here.

Countermeasures

Coding problem may also happen in other HE libs

- Be careful when using encode functionality provided by HE lib
- The crypto part have a security proof, but the encoding may not

Don’t use IntegerEncoder, FloatEncoder in SEAL

- They should considered primarily as a demonstrative tool
- BatchEncoder is safe in SEAL

Other security issues

HE does not provide the security features as the commonly known encryption algorithms

HE is not an Authenticated Encryption

cannot guarantee the integrity of the data

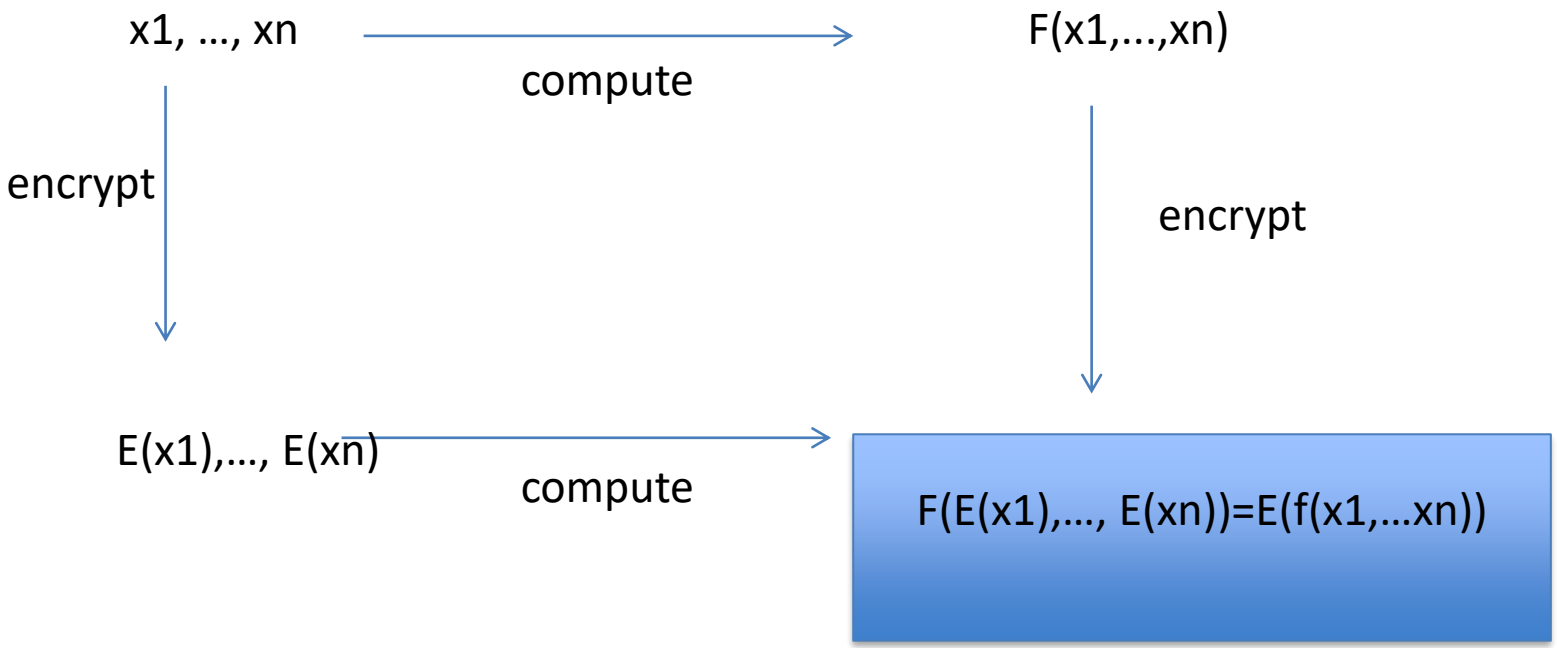
attacker can use the homomorphic nature of HE to modify the ciphertext

don’t use HE for storage and data transmission directly

We need a standard documentation for HE

Microsoft is currently leading the development of standard for HE

Is FHE really can compute arbitrary function?



Arbitrary function in FHE means arbitrary addition and multiplication here.

Arbitrary addition and multiplication does not mean you can run arbitrary program

You can’t do comparison directly

(if branch is not support here)

Update the famous metaphor

1.Put your gold in the locked box

2.Keep your key

3.Let the worker work on it through a glove box with eyeshade

4.Unlock the box and get the jeweler

This box should be opaque!

Conclusion

HE is a useful in many scenario

Its performance is improving and acceptable

HE is not omnipotent

It can not really run arbitrary program

HE has many security pitfalls

It’s extremely dangerous to use HE without an crypto expert for now

Still need a long way to go

Acknowledgments

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For their valuable comments and suggestions to the talk

Thanks