Practical Confidentiality Preserving Big Data Analysis in Untrusted Clouds

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Problem Statement

"Today, running your business on private servers is on the same level of odd behavior as carrying scuba tanks to provide a private air supply"

RIP Server, Peter Coffee, Mar 29, 2014

● Data breach: “The Cloud Multiplier Effect” (Ponemon Institute)
  ○ 36 percent of business-critical applications are housed in the cloud
  ○ 30 percent of business information is stored in the cloud
  ○ Increased use of cloud can increase the probability of a $20 million breach by 3x

● Challenges
  ○ How safe is it to trust a third party cloud provider?
  ○ How can banking, finance and insurance sectors leverage this potential?
Preserving Confidentiality

- **Fully** homomorphic encryption (FHE)
  - Prohibitive overhead, getting more practical
  - Limited expressiveness

- **Partially** homomorphic encryption (PHE)
  - Allows for certain operations to be performed in encrypted form
  - Paillier [Paillier; EuroCrypt’99]  
    - AHE: \( D(E(x_1) \oplus E(x_2)) = x_1 + x_2 \)
  - ElGamal [ElGamal; ToIT’86]  
    - MHE: \( D(E(x_1) \oplus E(x_2)) = x_1 \times x_2 \)
  - DET (=), OPE (<)

\[
643 \times 126 = 81018
\]

\[
81018 \rightarrow 5
\]

\[
2 + 3 = ?
\]
Crypsis Intuition

- Avoid using FHE, use more practical PHE cryptosystems instead
- Partition programs according to attributes and use a different PHE cryptosystem for each
- We can use multiple PHE cryptosystems of the same column in parallel
- Use re-encryption when PHE alone would fail
  - Use trusted base to decrypt and encrypt under desired cryptosystem
  - May be faster than FHE
Background

- Mapreduce [Dean & Ghemawat; OSDI'04]
  - Parallel execution (map and reduce functions)
  - Hadoop version 1.2.1

- Pig and Pig Latin [Gates et al.; VLDB’09]
  - Pig Latin - Data flow language for expressing data analysis programs
  - Pig - runtime environment, generates Mapreduce programs

- Example Pig Latin script
  A = LOAD "infile" AS (a0, a1);
  B = FILTER A BY a0 > 10;
  C = GROUP B BY a1;
  D = FOREACH C GENERATE SUM(C.a0) AS b1;
  STORE D INTO "outfile";
Example

LOAD (A:OPE, A:AHE)

A1 = FILTER A > 5

A2 = ADD A1 + 10

LOAD (B:MHE, C:MHE)

B1 = MULT B * C

RE-ENCRYPT (B1:MHE → AHE)

D = ADD A2 + B1

STORE D

STORE B1

AHE/OPE Encryption

MHE Encryption

Re-encryption
Architecture Overview

Practical Confidentiality Preserving Big Data Analysis
[J. Stephen et al; USENIX HotCloud14]
Script Transformation

- Script analysis
  - Generate Data Flow Graph (DFG)
  - Nodes are relational operations (LOAD, FOREACH, etc…)
  - Edges are data flow between relational operations

- Generate Map of Expression Trees (MET)
  - Contains all expressions of the script
  - Keys are used to assign expressions to DFG

- Generate Set of Annotated Fields (SAF)
  - One entry for each <relation, field> of the script
  - <relation, field>, parent, available encryptions, required encryptions
  - Get available encryptions from lineage of field (parent)
  - Get required encryptions using MET
Identifying re-encryptions

- Re-encryption required when
  - Required encryption not available
  - Incompatible operations e.g. addition followed by a multiplication

- 17 PigMix2 benchmarks (PigMix1 + 5)
  - Only script 8 requires re-encryption (averaging)
  - 1 additional script requires same attribute available in 2 encryptions
Transformation Example

Source Script

EMP = LOAD "employees" AS ( salary, department);
HIGH_PD = FILTER EMP BY salary > 80000;
HP_DEP = GROUP HIGH_PD BY department;
TOTAL = FOREACH HP_DEP GENERATE group AS department,
SUM(HIGH_PD.salary) AS total;
STORE TOTAL INTO "salary_per_dep";

Target Script

EMP = LOAD "employees_enc" AS ( salary_ope, salary_ahe, department_det);
HIGH_PD = FILTER EMP BY ENCGT(salary_ope, 98...24);
HP_DEP = GROUP HIGH_PD BY department_det;
TOTAL = FOREACH HP_DEP GENERATE group AS department_det,
ENCSUM(HIGH_PD.salary_ahe) AS t;
STORE F INTO "salary_per_dep_enc";

Program Analysis for Secure Big Data Processing
[J. Stephen et al; IEEE/ACM ASE2014]
Name Obfuscation

Target Script

EMP = LOAD "employees_enc" AS (salary_ope, salary_ahe, department_det);

HIGH_PD = FILTER EMP BY ENCGT(salary_ope, 98...24);

HP_DEP = GROUP HIGH_PD BY department_det;

TOTAL = FOREACH HP_DEP GENERATE group AS department_det, ENCSUM(HIGH_PD.salary_ahe) AS total;

STORE F INTO "salary_per_dep_enc";

Obfuscated Target Script

A = LOAD "input" AS (a1, a2, a3);

B = FILTER A BY f1(a1, 98...24);

C = GROUP B BY a3;

D = FOREACH C GENERATE group AS d1, f2(B.a2) AS d2;

STORE F INTO "output";
Crypsis Implementation

- **Compiler**
  - Performs script transformation
  - Identifies and applies optimizations

- **Crypsis UDFs**
  - Replace operations and aggregation functions with their encrypted version
  - Allows for an unmodified Pig service

- **Expressiveness**
  - $+, -, \sim, *, ^, ==, <, \leq, >, \geq$
  - Aggregation functions: SUM, MAX, MIN, DISTINCT, ORDERBY, AVG, MEDIAN, ABS
  - Negative numbers
  - Floating point numbers (limited)
Optimizations

● Minimize number of re-encryptions
  ○ Expression rewriting
  ○ Operation reordering
  ○ Selective encryption

● Avoid redundant computations
  ○ Repeated sub-expressions

● Reduce amount of data computed on
  ○ Filter reordering
  ○ Packing
Expression Rewriting / Operation Reordering

**Before**

A = LOAD "infile" AS (col);
B = FOREACH A GENERATE
   col * 2 AS x,
   col * 3 AS y;
C = FOREACH B GENERATE
   (x + y) * 2 AS result;
STORE C INTO "outfile";

**After**

A = LOAD "infile" AS (col);
B = FOREACH A GENERATE
   col * 2 AS x,
   col * 3 AS y;
C = FOREACH B GENERATE
   x * 2 + y * 2 AS result;
STORE C INTO "outfile";

**Before**

A = LOAD "infile" AS (col);
B = FOREACH A GENERATE
   col + 10 AS x;
C = ORDER B BY x;
STORE C INTO "outfile";

**After**

A = LOAD "infile" AS (col);
B = ORDER A BY col;
C = FOREACH B GENERATE
   col + 10 AS x;
STORE C INTO "outfile";
Selective Encryption

- Often only parts of the input data hold sensitive information
  - Selectively encrypt
  - Reduce overall size of data
  - Reduce required re-encryptions e.g. \((a + b) * c\)

- Secondary homomorphic property
  - AHE: \(D(E(x1) \odot x2) = x1 * x2\)
  - MHE: \(D(E(x1) \odot x2) = x1 ^ x2\)

\[
\begin{align*}
X &= \text{ENC_ADD}(a_{ahe}, b_{ahe}) \\
Y &= \text{REENCRYPT}(X, \text{ahe->mhe}) \\
Z &= \text{ENC_MULT}(Y, c_{mhe}) \\
X &= \text{ENC_ADD}(a_{ahe}, b_{ahe}) \\
Y &= \text{ENC_PMULT}(X, c_{plain})
\end{align*}
\]
Repeated Sub-expressions

Before

ITEMS = \textbf{LOAD} "infile" \textbf{AS} (price, discount, tax);
PRICES = \textbf{FOREACH} ITEMS \textbf{GENERATE}
    \texttt{price} * (1 - discount) \textbf{AS} disc\_price,
    \texttt{price} * (1 - discount) * (1 + tax) \textbf{AS} charge;
\textbf{STORE} C \textbf{INTO} "outfile";

After

ITEMS = \textbf{LOAD} "infile" \textbf{AS} (price, discount, tax);
\textbf{DISCOUNT} = \textbf{FOREACH} ITEMS \textbf{GENERATE}
    \texttt{price} * (1 - discount) \textbf{AS} disc\_price, tax;
\textbf{PRICES} = \textbf{FOREACH} \textbf{DISCOUNT} \textbf{GENERATE}
    disc\_price,
    disc\_price * (1 + tax) \textbf{AS} charge;
\textbf{STORE} C \textbf{INTO} "outfile";
Filter Reordering

Before

A = LOAD "infile" AS ( 
    salary, 
    rating); 
B = FOREACH A GENERATE 
    salary + 100 AS bonus, 
    rating; 
C = FILTER B BY 
    rating > 8; 
STORE C INTO "outfile";

After

A = LOAD "infile" AS ( 
    salary, 
    rating); 
B = FILTER A BY 
    rating > 8; 
C = FOREACH B GENERATE 
    salary + 100 AS bonus, 
    rating; 
STORE C INTO "outfile";
Packing

- Ciphertext space is much larger than plaintext space
- Pack multiple values in a single plaintext before encrypting
- Must handle overflows
- Can be applied on AHE and MHE (limited)

\[\begin{array}{cc}
\text{Padding n} & x_n \\
\text{Padding n} & y_n \\
\end{array} \quad \begin{array}{c}
\ldots \\
\ldots \\
\end{array} \quad \begin{array}{cc}
\text{Padding 1} & x_1 \\
\text{Padding 1} & y_1 \\
\end{array} \]

\[=\]

\[\begin{array}{c}
x_n + y_n \\
x_1 + y_1 \\
\end{array}\]
Evaluation (PigMix)

- 11 ec2 c3.large instances (2 vCPUs, 3.75GB RAM)
- 5GB of data (over 3 million rows)
- An average of 3x overhead in terms of latency
- FHE can exhibit several 100 times overhead
Evaluation (CryptDB Comparison)

- 3 m3.medium instances (1 vCPUs, 3.75GB RAM)
- ~3x faster for 15 million records (7GB)
- Similar overall cost
Related Work

- **CryptDB [Popa et al.; SOSP’11]**
  - Encrypted database for MySQL (subset)
  - No Parallelism
  - No re-encryption; client-side query completion

- **Monomi [Tu et al.; VLDB’13]**
  - Uses techniques to improve performance of complex queries on encrypted data
  - Built on top of PostgreSQL, Centralized Design

- **MrCrypt [Lesani et al.; OOPSLA’13]**
  - Program analysis for individual MapReduce tasks
  - No re-encryption
Conclusions and Future Work

● Cloud computing
  ○ On demand computation infrastructure has great potential
  ○ Inherent confidentiality concerns

● Crypsis
  ○ Addresses confidentiality concerns.
  ○ Efficient big data analysis over encrypted data

● Future work
  ○ More fine-grained encryption system (annotations)
  ○ Identify more opportunities to reduce re-encryptions
Thank you!

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