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Department of Computer Science

Practical Confidentiality Preserving Big Data Analysis in Untrusted Clouds

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Julian Stephen, Savvas Savvides, Russell Seidel
and Patrick Eugster

Problem Statement

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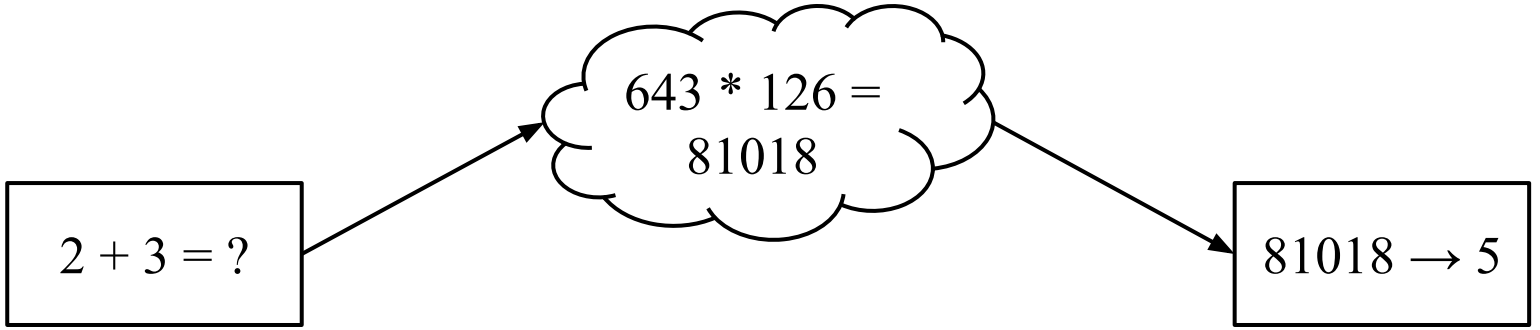
"Today, running your business on private servers is on the same level of odd behavior as carrying scuba tanks to provide a private air supply"
RIP Server, Peter Coffee, Mar 29, 2014

- 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: $D(E(x1) \oplus E(x2)) = x1 + x2$
  - ElGamal [ElGamal; ToIT'86] ► MHE: $D(E(x1) \oplus E(x2)) = x1 * x2$
  - DET (=), OPE (<)



Crypsis Intuition

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- 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

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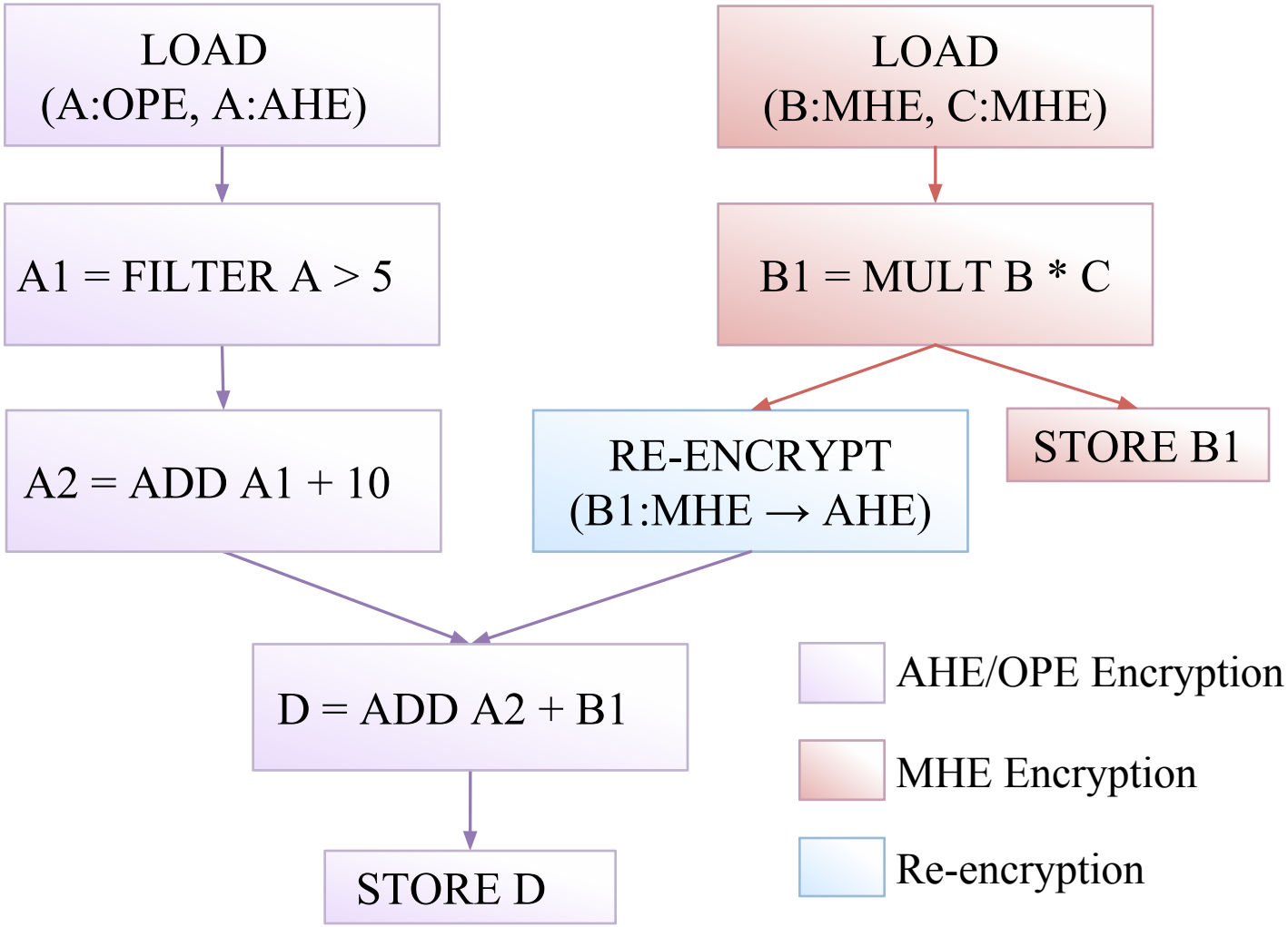
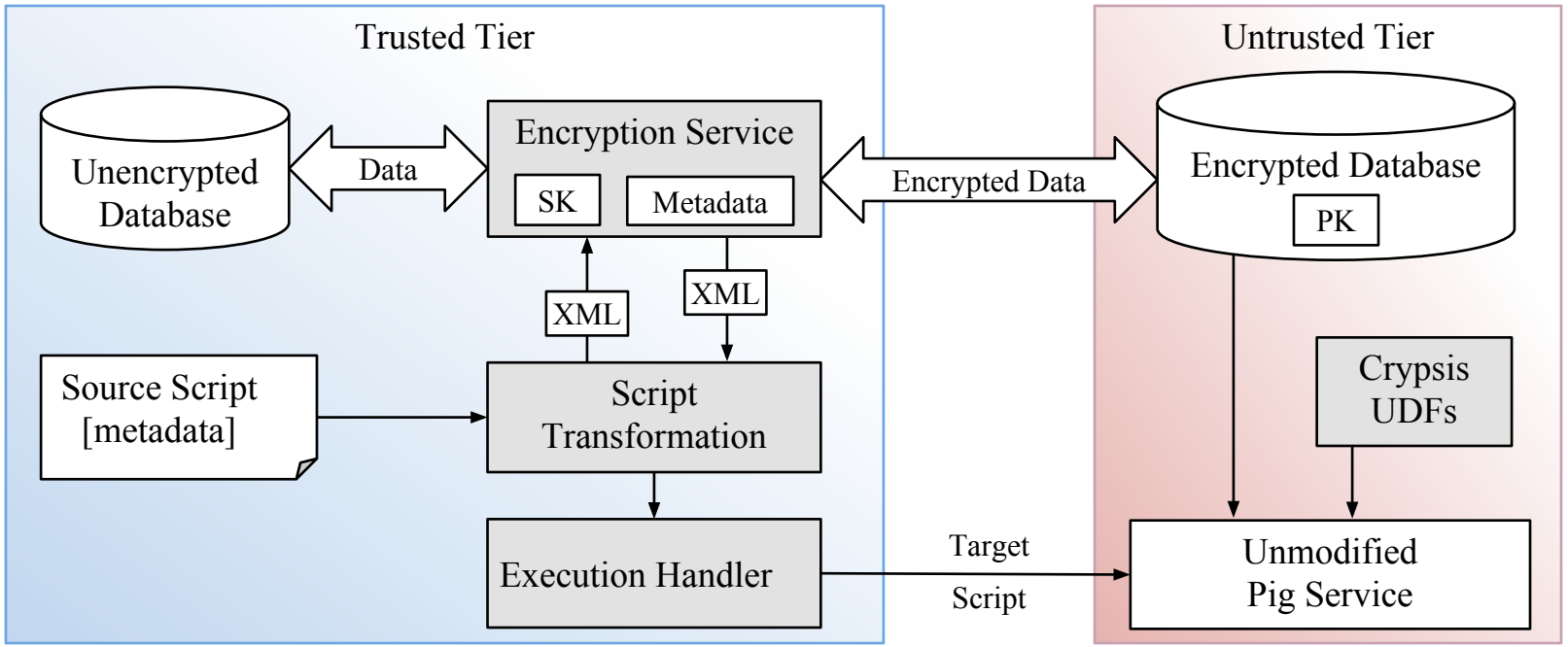
- Mapreduce [Dean&Ghemawat; OSDI'04]
  - Parallel execution (map and reduce functions)
  - Hadoop version 1.2.1
- Pig and Pig Latin [Gates et.al; VLDB'09]
  - Pig Latin - Data flow language for expressing data analysis programs
  - Pig - runtime environment, generates Mapreduce programs
- Example Pig 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)
LOAD
(B:MHE, C:MHE)
A1 = FILTER A > 5
B1 = MULT B * C
A2 = ADD A1 + 10
RE-ENCRYPT
(B1:MHE → AHE)
STORE B1
D = ADD A2 + B1
STORE D
AHE/OPE Encryption
MHE Encryption
Re-encryption

Architecture Overview



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

Script Transformation

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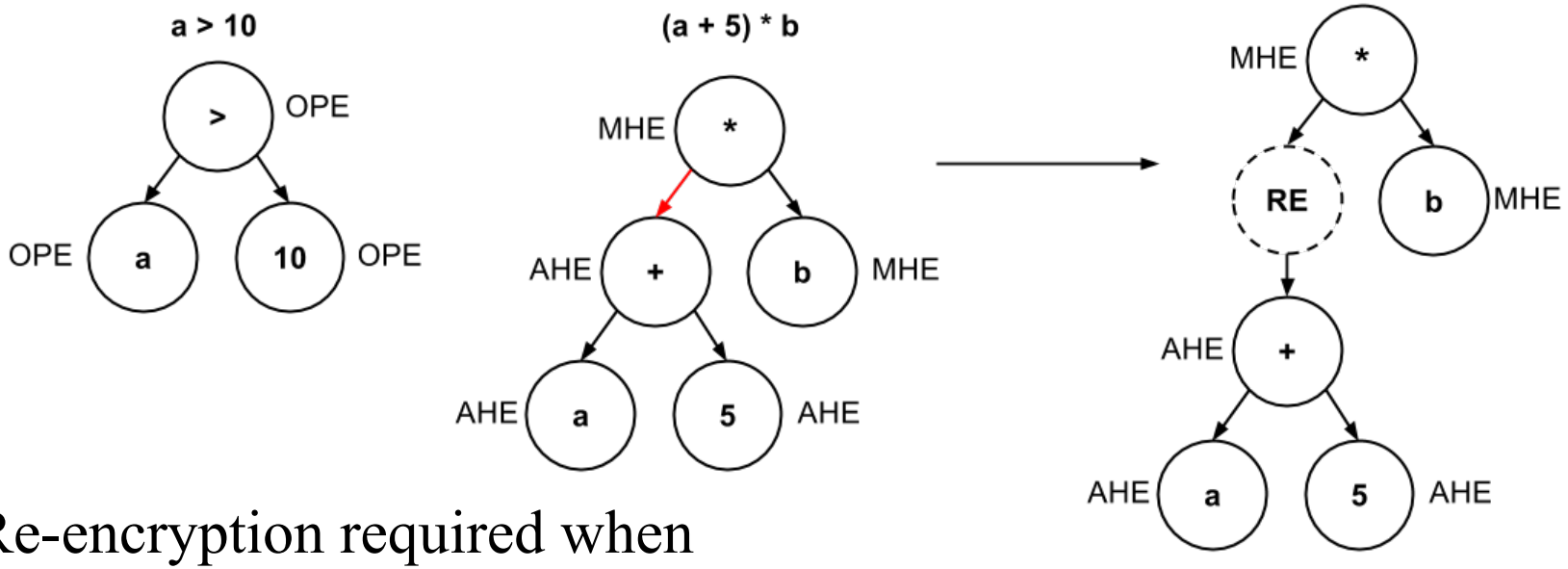
- Script analysis
  - Generate Data Flow Graph (DFG)
  - Nodes are relational operations (LOAD, FOREACH, etc…)
  - Edges are data flow between relational operations
- Generate Map of Expression Trees (MET)
  - Contains all expressions of the script
  - Keys are used to assign expressions to DFG
- Generate 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

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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

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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

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- 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
  - +, -, ~, *, ^, ==, <, ≤, >, ≥
  - Aggregation functions: SUM, MAX, MIN, DISTINCT, ORDERBY, AVG, MEDIAN, ABS
  - Negative numbers
  - Floating point numbers (limited)

Optimizations

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- 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

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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) ⊙ x2) = x1 * x2
  - MHE: D(E(x1) ⊙ x2) = x1 ^ x2

```
X = ENC_ADD(a_ahe, b_ahe)
Y = REENCRYPT(X, ahe->mhe)
Z = ENC_MULT(Y, c_mhe)
```

```
X = ENC_ADD(a_ahe, b_ahe)
Y = ENC_PMULT(X, c_plain)
```

Repeated Sub-expressions

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Before

```
ITEMS = LOAD "infile" AS (price, discount, tax);
PRICES = FOREACH ITEMS GENERATE
   price * (1 - discount) AS disc_price,
   price * (1 - discount) * (1 + tax) AS charge;
STORE C INTO "outfile";
```

After

```
ITEMS = LOAD "infile" AS (price, discount, tax);
DISCOUNT = FOREACH ITEMS GENERATE
   price * (1 - discount) AS disc_price, tax;
PRICES = FOREACH DISCOUNT GENERATE
   disc_price,
   disc_price * (1 + tax) AS charge;
STORE C INTO "outfile";
```

Filter Reordering

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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

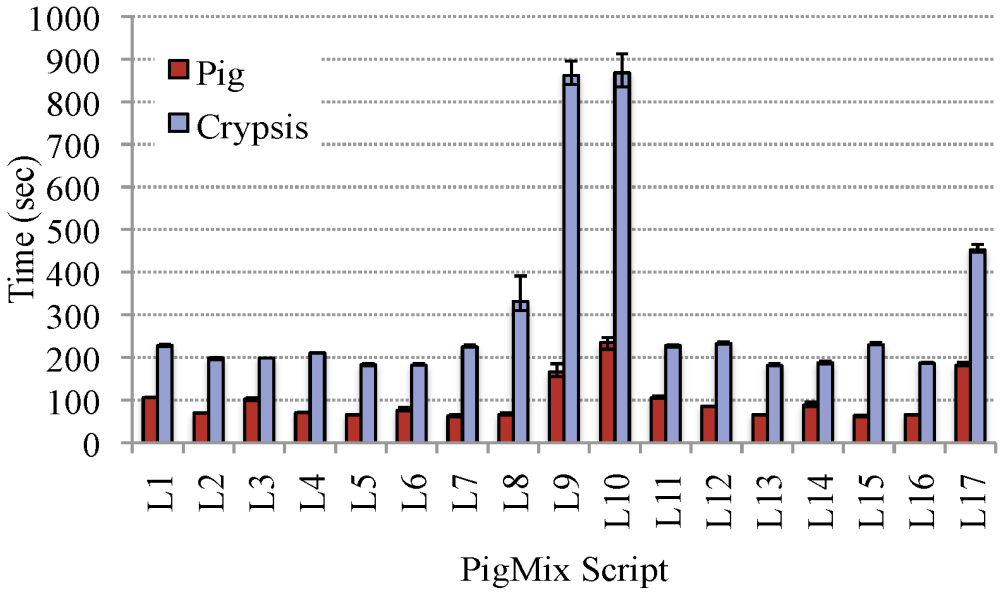
```
A = LOAD "infile" AS (
    salary,
    rating);
B = FILTER A BY
    rating > 8;
C = FOREACH B GENERATE
    salary + 100 AS bonus,
    rating;
STORE C INTO "outfile";
```

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)

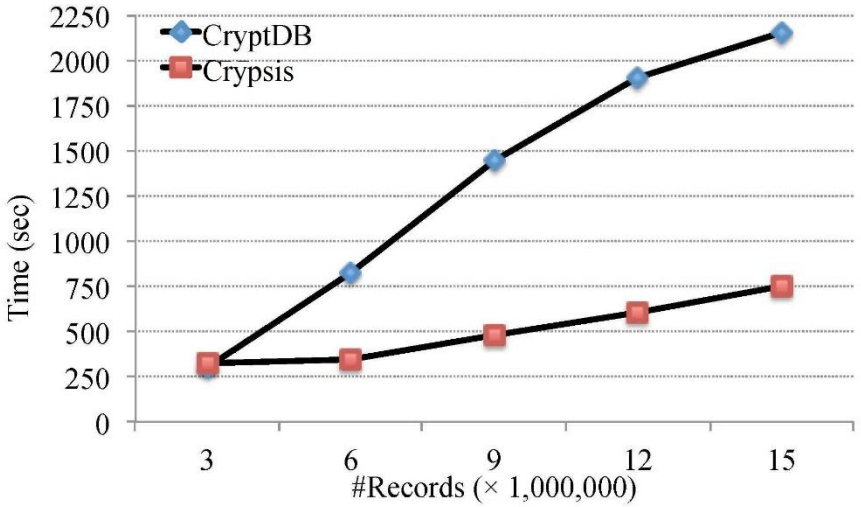
Padding n	x_n	...	Padding 1	x_1
		+		
Padding n	y_n	...	Padding 1	y_1
		=		
$x_n + y_n$			$x_1 + y_1$	

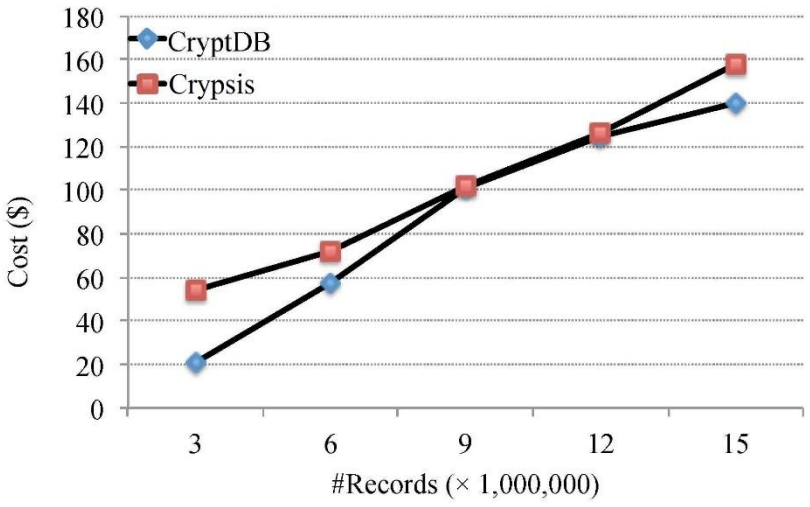
Evaluation (PigMix)



- 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

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- 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 Postgres, Centralized Design
- MrCrypt [Lesani et al.;OOPSLA'13]
  - Program analysis for individual MapReduce tasks
  - No re-encryption

Conclusions and Future Work

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- 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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