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Northrop Grumman Cybersecurity Research Consortium (NGCRC)

Fall 2014 Symposium

Crypsis: Efficient Confidentiality Preserving Big Data Analysis in Untrusted Clouds

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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)
  - Increased use of cloud can increase the probability of a $20 million breach by as much as 3x
  - 36 percent of business-critical applications are housed in the cloud
  - 30 percent of business information is stored in the cloud
- Challenges
  - How safe is it to trust a third party cloud provider?
  - How can banking, finance and insurance sectors leverage this potential?

Preserving Confidentiality

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- *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
  - E.g.,
    - 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 (<)
- Conjecture
  - Partition programs according to attributes and use a different cryptosystem for each
  - We can use multiple PHE cryptosystems in parallel
  - Reencryption between PHE systems may be faster than FHE

Background

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- Map Reduce [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 - High level data flow language for expressing data analysis programs
  - Pig - runtime environment, generates Map Reduce programs
  - Pig version 0.11.1
- Example Pig Latin script

```
A = LOAD "file1" AS (a0, a1);
B = FILTER A BY a0 > 10;
C = GROUP B BY a1;
D = FOREACH C GENERATE group AS b0, SUM(C.a0) AS b1;
STORE D INTO "output";
```

Crypsis Intuition

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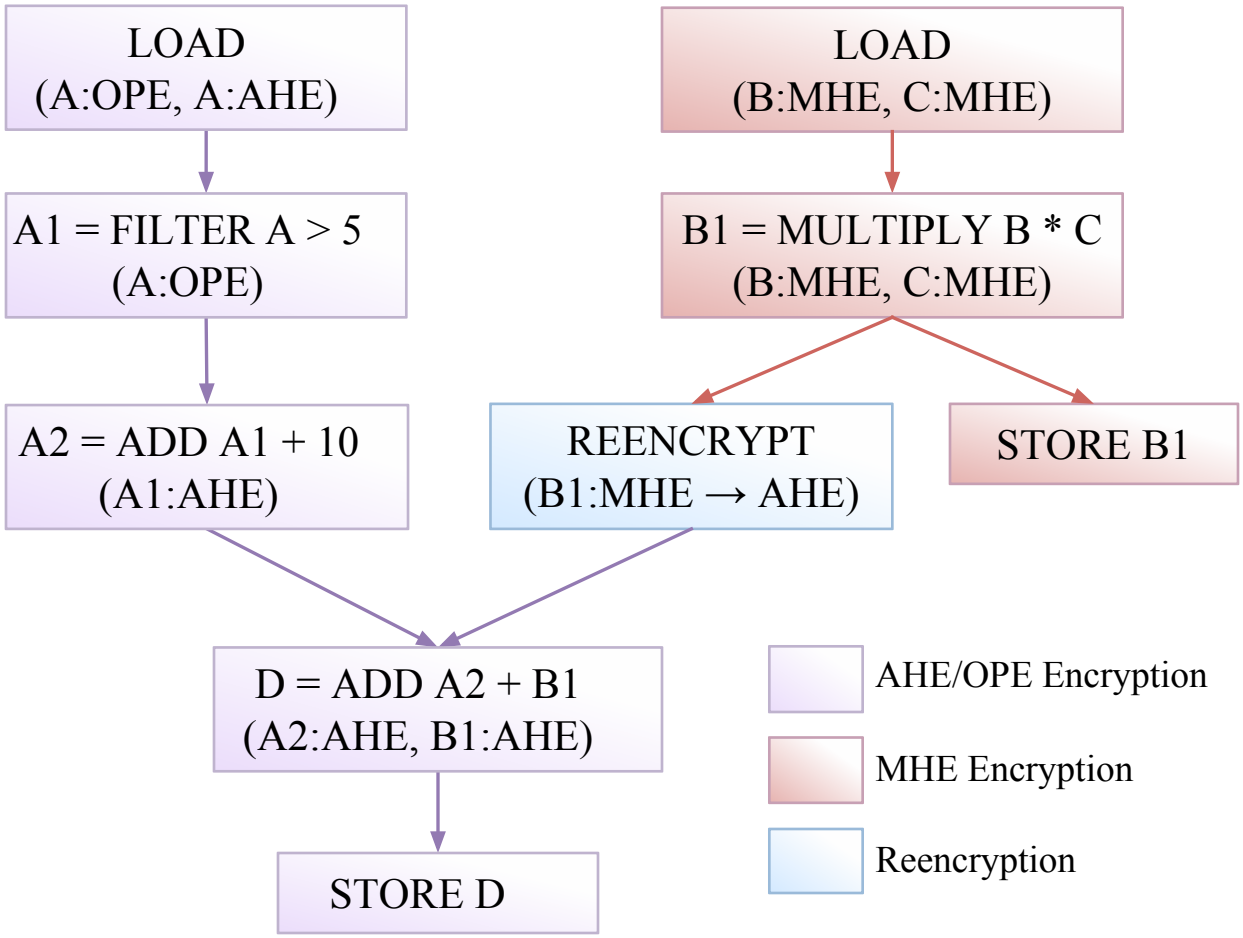
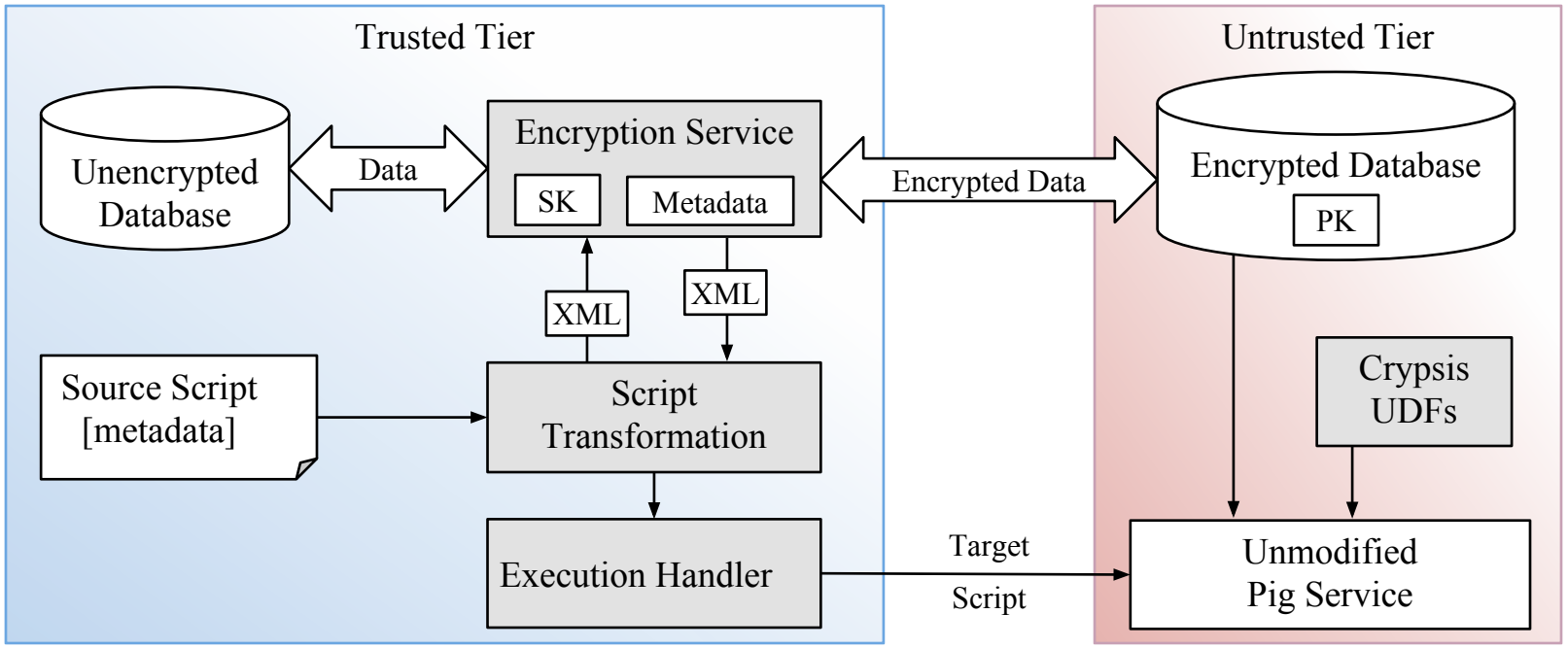


Architecture Overview



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

Script Transformation

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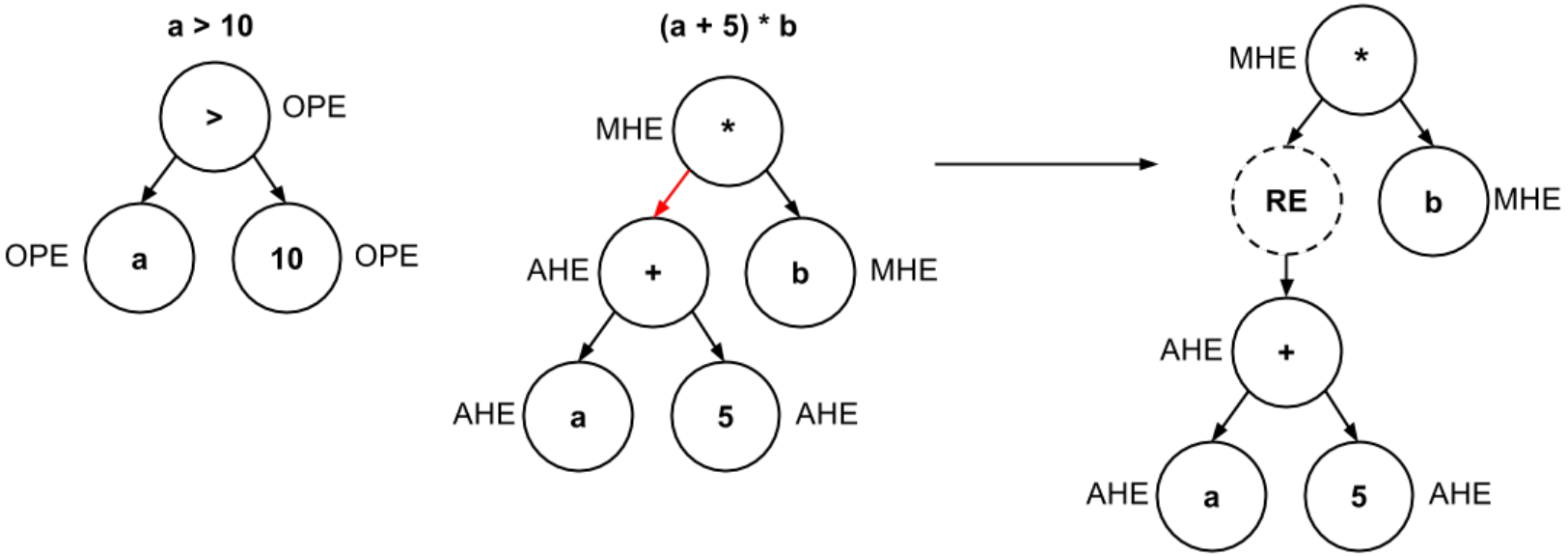
- Script analysis
  - Generate Data Flow Graph (DFG)
  - Nodes are relations (LOAD, FOREACH, etc…)
  - Edges are data flow between operators
- Generate Map of Expression Trees (MET)
  - Contains all expressions of the script
  - Keys are used to assign expressions to DFG
- Generate Set of Annotated Fields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



- Reencryption required when:
  - Required encryption not available
  - Incompatible operations e.g. addition followed by a multiplication
  - Reencryption is conceptual (can continue computation on client)

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

Transformation Example

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Source Script

```
A = LOAD "file1" AS
    (a0, a1);
B = LOAD "file2" AS
    (x0);
C = FILTER A BY a0 > 10;
D = GROUP C BY a1;
E = FOREACH D GENERATE group AS
    b0, SUM(C.a0) AS b1;
F = JOIN E BY b0, B BY x0;
STORE F INTO "outfile";
```

Target Script

```
A = LOAD "enc_file1" AS
    (a0_ope, a0_ahe, a1_det);
B = LOAD "enc_file2" AS
    (x0_det);
C = FILTER A BY a0_ope > 918...234;
D = GROUP C BY a1_det;
E = FOREACH D GENERATE group AS
    b0, ENCSUM(C.a0_ahe) AS b1;
F = JOIN E BY b0, B BY x0_det;
STORE F INTO "enc_outfile";
```

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

Crypsis Implementation

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- Crypsis UDFs
  - Replace operations and aggregation functions with their encrypted version
  - Allows for an unmodified Pig service
- Secondary homomorphic property
  - AHE: $D(E(x1) \odot x2) = x1 * x2$
  - MHE: $D(E(x1) \odot x2) = x1 \wedge x2$
- Augmented expressiveness
  - $+, -, \sim, *, \wedge, ==, <, \leq, >, \geq$
  - Aggregation functions: SUM, MAX, MIN, DISTINCT, ORDERBY, AVG, MEDIAN, ABS
  - Negative numbers

Evaluation (PigMix)

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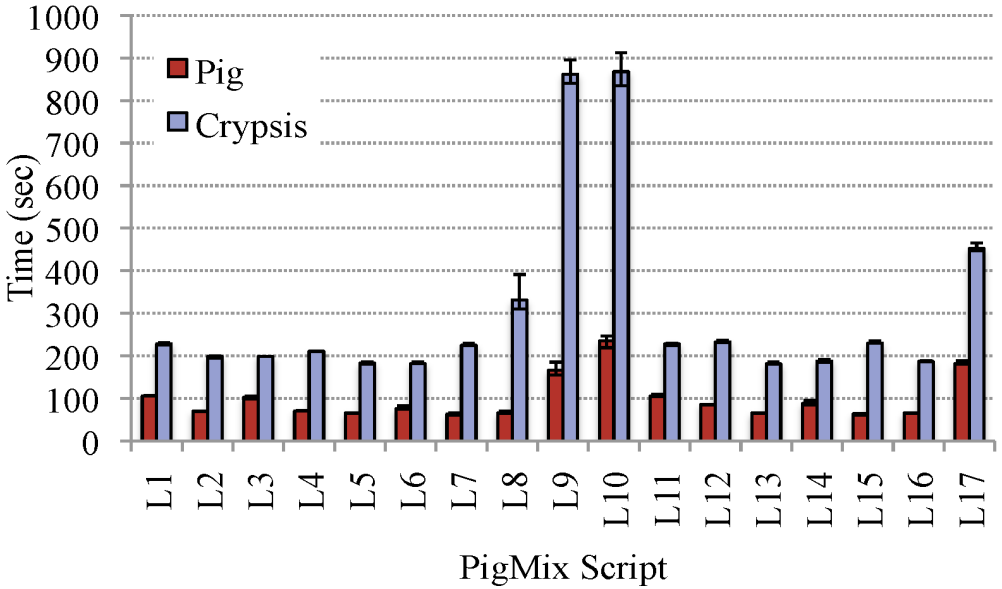

- 11 ec2 c3.large instances (2 vCPUs, 3.75GB ram)
- 5GB of data (over 3 million rows)
- An average of 3x overhead in terms of latency
- FHE can exhibit several 100 times overhead

Evaluation (CryptDB comparison)

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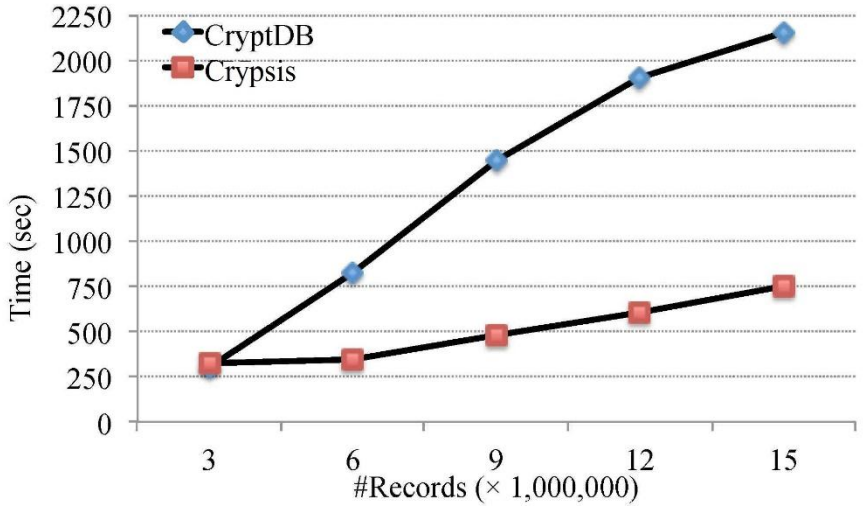
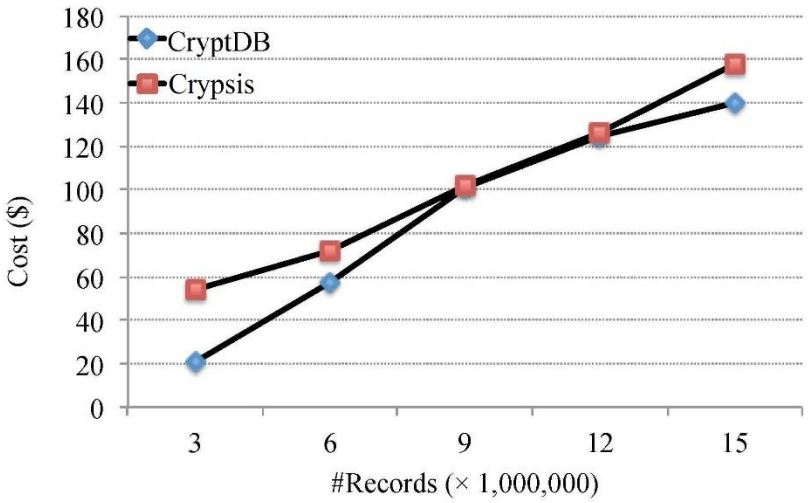


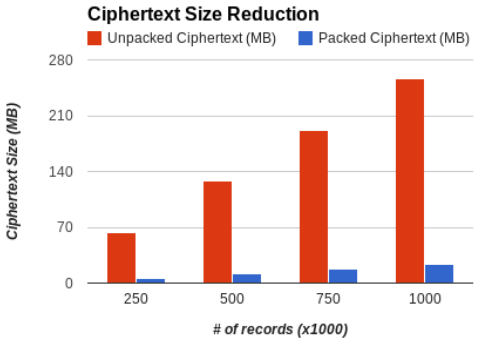


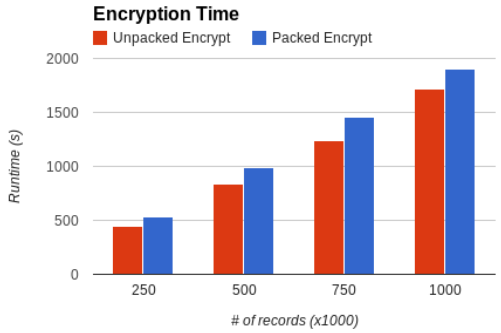
- 3 m3.medium instances (1 vCPUs, 3.75GB ram)
- ~ 3x faster for 15 million records
- Similar overall cost

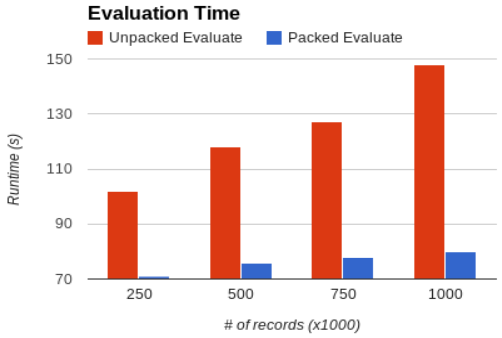
Packing Optimization

- Minimize ciphertext overhead
  - Pack multiple values in a single plaintext before encrypting
  - Must handle overflows

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







Selective Encryption

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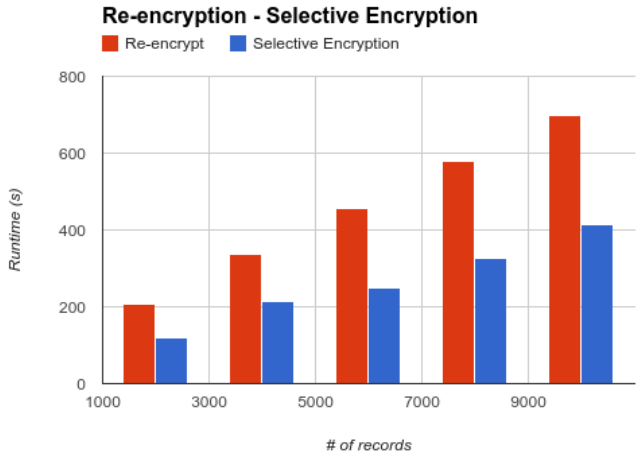
- Often only parts of input data need to be encrypted: selectively encrypt
  - Reduce overall size of data
  - Reduce required re-encryptions e.g. (a + b) * c

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

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



Limitations

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- Iterations – recursion
  - Pig Latin is a query based language
  - No support for iterations or recursion
  - Use of UDFs for more complex operations
  - Iterations over encrypted data can be very expensive (reencryptions)
- User Defined Functions (UDFs)
  - Many big data analysis languages propose UDFs vs. built-in/pre-defined operators and functions
  - Black-boxes from perspective of program analysis (Cannot support transformation)
  - Can analyze byte-code on Java UDFs

Opportunities for Reducing Reencryption

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- Statement re-ordering, e.g.,

```
a1 < 0   (OPE)
...          (CS1 != OPE)
a1 > 20 (OPE)
```

```
a1 < 0  (OPE)
a1 > 20 (OPE)
...          (CS1 != OPE)
```

- Computation re-writing, e.g.,

```
t1 = t2 * (t3 + t4)
...
t5 = t1 + t6
```

```
t1 = t2 * t3
t7 = t2 * t4
...
t5 = t1 + t7 + t6
```

- Condition re-writing, e.g.,

```
(x1 + x2 > 0)
```

```
(x1 > 0 AND x2 > 0)
```

Related Work

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- CryptDB [Popa et al.;SOSP'11]
  - Encrypted database for MySQL (subset)
  - No Parallelism
  - No reencryption; client-side query completion
- MrCrypt [Lesani et al.;OOPSLA'13]
  - Program analysis for individual MapReduce tasks
  - No reencryption
- Monomi [Tu et al; VLDB'13]
  - Uses techniques to improve performance of complex queries on encrypted data
  - Built on top of Postgres, Centralized Design

Conclusions and Future Work

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"Big data absolutely has the potential to change the way governments, organizations, and academic institutions conduct business and make discoveries, and its likely to change how everyone lives their day-to-day lives" - Susan Hauser, corporate vice president, Microsoft'

- Cloud computing
  - On demand computation infrastructure has great potential but inherent confidentiality concerns
- Crypsis
  - Addresses these confidentiality concerns. Efficient big data analysis over encrypted data
- Future work
  - More fine-grained encryption system
  - Identify more opportunities to reduce re-encryptions
- NSF Secure and Trustworthy Cyberspace grant
  - "Practical Assured Big Data Analysis in the Cloud"

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