Secure Data Outsourcing with Adversarial Data Dependency Constraints

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Boxiang Dong Wendy Hui Wang Jie Yang

Department of Computer Science
Stevens Institute of Technology

School of Software Engineering
South China University of Technology

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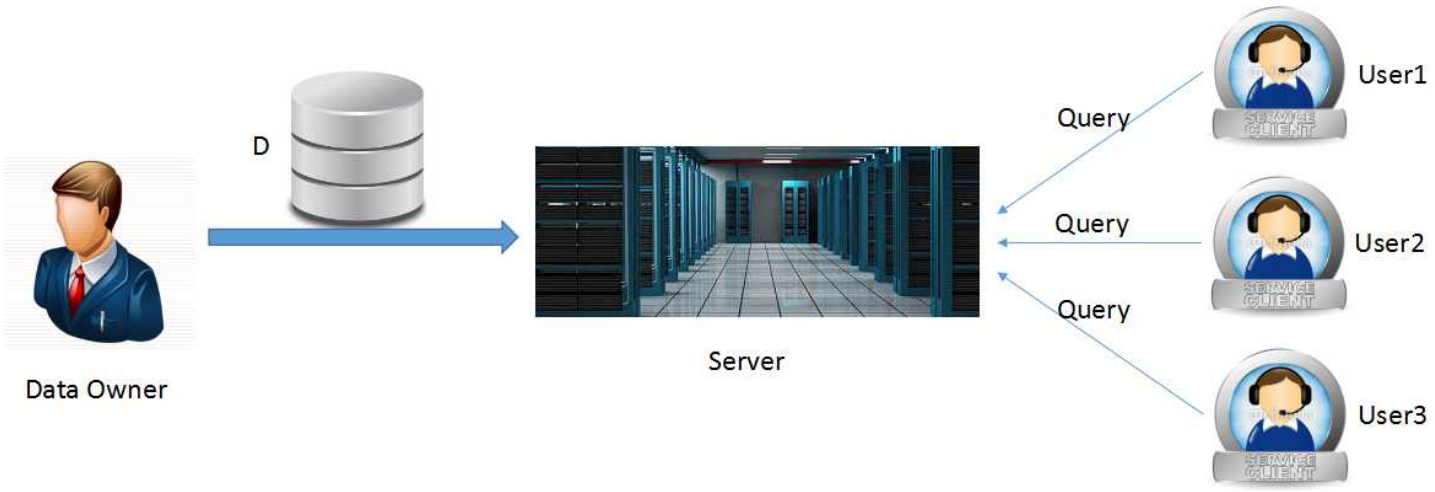
Database-as-a-Service (DaS)

Database as a Service:

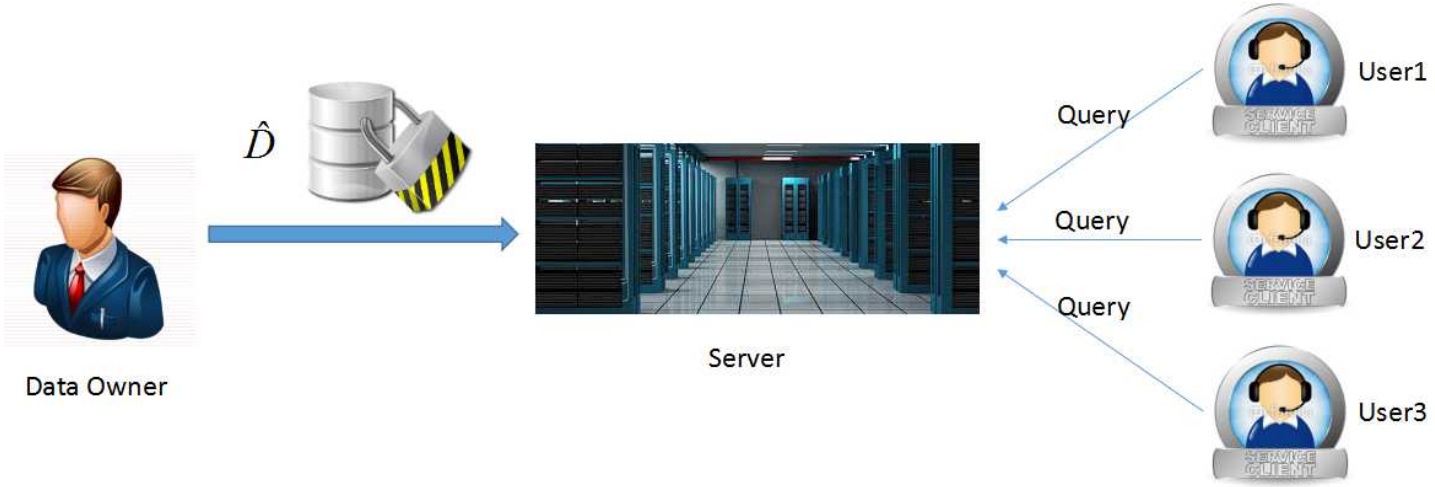


- Weak data owner
- Computationally powerful service provider (e.g. cloud)
- DaS enables the data owner to outsource the database services to a third party server.

Data Security Issue

Security The outsourced data may contain important and sensitive information.

Solution The data owner encrypts the data before outsourcing.



Security Constraint

Security constraint $\Pi_Y \sigma_C$

- Y is a set of attributes.
- C is a conjunction of equalities of $A = B$ or $A = a$.

Basic encryption $\bar{D}$ Encrypt the sensitive values specified by the security constraint.

NM	SEX	AGE	DC	DS
Alice	F	53	CPD5	HIV
Carol	F	30	VPI8	Cancer
Ela	F	24	VPI8	Cancer

(a) The original dataset D

$S_1 : \Pi_{DS} \sigma_{NM='Alice'}$

$S_2 : \Pi_{DS} \sigma_{NM='Ela'}$

NM	SEX	AGE	DC	DS
Alice	F	53	CPD5	α
Carol	F	30	VPI8	Cancer
Ela	F	24	VPI8	γ

(b) The basic encryption $\bar{D}$

: sensitive data

FD Attack

Functional dependency (FD) $X \rightarrow Y$ if $r_1[X] = r_2[X]$, then $r_1[Y] = r_2[Y]$.

FD attack Infer the encrypted sensitive value based on the FD.

NM	SEX	AGE	DC	DS
Alice	F	53	CPD5	HIV
Carol	F	30	VPI8	Cancer
Ela	F	24	VPI8	Cancer

(a) The original dataset D

$FD : DC \rightarrow DS$

$S_1 : \Pi_{DS}\sigma_{NM='Alice'}$

$S_2 : \Pi_{DS}\sigma_{NM='Ela'}$

NM	SEX	AGE	DC	DS
Alice	F	53	CPD5	α
Carol	F	30	VPI8	Cancer
Ela	F	24	VPI8	γ

(b) The unsafe basic encryption $\bar{D}$

: sensitive data

: inference channel

Naive Solutions

1. Encrypt all the data values.

NM	SEX	AGE	DC	DS
β	δ	ϵ	ζ	α
η	δ	θ	ι	γ
λ	δ	μ	ι	γ

(encryption overhead: 13)

2. Encrypt all values of the attributes that involve a FD.

NM	SEX	AGE	DC	DS
Alice	F	53	ζ	α
Carol	F	30	ι	γ
Ela	F	24	ι	γ

(encryption overhead: 4)

: sensitive data
: additional encrypted data

Encryption Overhead Amount of encrypted non-sensitive values.

Drawbacks Large encryption overhead.

- Incur high encryption cost.
- Reduce the data useability.

Related Work

Encryption in DaS model

- Searchable encryption [SWP00]: can not defend against FD attack.
- Homomorphic encryption [SV10]: inefficient.

Inference attack in Multi-level Security Database

- Database-design time [CHKP07, SO91]: over-encrypt the data.
- Query-time [BFJ00]: not applicable to our scenario.

K-anonymity

- Suppression and generalization [Swe02, WL11]: can not defend against FD attack.

Goal

Design a scheme.

- Robust against FD attack
- Efficiency
- Low encryption overhead

NM	SEX	AGE	DC	DS
Alice	F	53	CPD5	α
Carol	F	30	ι	Cancer
Ela	F	24	VPI8	γ

(encryption overhead: 1)

: sensitive data
: additional encrypted data

Sensitive/Evidence Records

$FD : X \rightarrow Y$.

For all records with the same (x, y) values,

Sensitive record $S(x, y)$

- $r[Y]$ is sensitive.
- $r[X]$ is not sensitive.

Evidence record $E(x, y)$

- $r[Y]$ is not sensitive.
- $r[X]$ is not sensitive.

RID	NM	SEX	AGE	DC	DS
r_1	Alex	M	36	VPI8	Cancer
r_2	Bob	M	53	VPI8	Cancer
r_3	Carol	F	30	VPI8	Cancer
r_4	Ela	F	24	VPI8	γ
r_5	Amy	F	20	VPI8	γ

$S : \Pi_{DS}\sigma_{AGE<30}$

$S(VPI8, Cancer) = \{r_4, r_5\}$

$E(VPI8, Cancer) = \{r_1, r_2, r_3\}$

: sensitive data

: sensitive records

: evidence records

Encryption for One Single SC

Pick the scheme which has smaller encryption overhead.

Scheme 1 Pick $A \in X$, encrypt $r[A]$ for $r \in S(x, y)$.

Scheme 2 Pick $A \in X \cup Y$, encrypt $r[A]$ for $r \in E(x, y)$.

RID	NM	SEX	AGE	DC	DS
r_1	Alex	M	36	VPI8	Cancer
r_2	Bob	M	53	VPI8	Cancer
r_3	Carol	F	30	VPI8	Cancer
r_4	Ela	F	24	ι	γ
r_5	Amy	F	20	ι	γ

(Scheme 1: *overhead* $= 2$)

RID	NM	SEX	AGE	DC	DS
r_1	Alex	M	36	ι	Cance
r_2	Bob	M	53	ι	Cance
r_3	Carol	F	30	ι	Cance
r_4	Ela	F	24	VPI8	γ
r_5	Amy	F	20	VPI8	γ

(Scheme 2: *overhead* $= 3$)

: sensitive data
: additional encrypted data

Encryption for Multiple SCs

Theorem (NP-Completeness)

Given a dataset D and $k > 1$ SCs $\mathcal{S}$, the problem of finding the optimal robust scheme that enforces $\mathcal{S}$ on D against the FD attack is NP-complete.

RID	NM	SEX	AGE	DC	DS
r_1	Joe	M	28	CPD5	α
r_2	Alice	F	24	CPD5	α
r_3	Maggy	F	33	CPD5	HIV
r_4	Phil	M	43	CPD5	HIV
r_5	Peter	M	39	CPD5	HIV
r_6	Ray	M	52	CPD5	HIV
r_7	Steve	M	31	CPD5	HIV

$S_1 : \Pi_{DS}\sigma_{AGE<30}$

RID	NM	SEX	AGE	DC	DS
r_1	Joe	M	28	CPD5	HIV
r_2	Alice	F	24	CPD5	α
r_3	Maggy	F	33	CPD5	α
r_4	Phil	M	43	CPD5	HIV
r_5	Peter	M	39	CPD5	HIV
r_6	Ray	M	52	CPD5	HIV
r_7	Steve	M	31	CPD5	HIV

$S_2 : \Pi_{DS}\sigma_{SEX=F}$

: sensitive data

Encryption for Multiple SCs

Theorem (NP-Completeness)

Given a dataset D and $k > 1$ SCs $\mathcal{S}$, the problem of finding the optimal robust scheme that enforces $\mathcal{S}$ on D against the FD attack is NP-complete.

RID	NM	SEX	AGE	DC	DS
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r_2	Alice	F	24	CPD5	α
r_3	Maggy	F	33	CPD5	α
r_4	Phil	M	43	CPD5	HIV
r_5	Peter	M	39	CPD5	HIV
r_6	Ray	M	52	CPD5	HIV
r_7	Steve	M	31	CPD5	HIV

$$S(S_1) = \{r_1, r_2\}$$
$$E(S_1) = \{r_4, r_5, r_6, r_7\}$$

RID	NM	SEX	AGE	DC	DS
r_1	Joe	M	28	CPD5	α
r_2	Alice	F	24	CPD5	α
r_3	Maggy	F	33	CPD5	α
r_4	Phil	M	43	CPD5	HIV
r_5	Peter	M	39	CPD5	HIV
r_6	Ray	M	52	CPD5	HIV
r_7	Steve	M	31	CPD5	HIV

$$S(S_2) = \{r_2, r_3\}$$
$$E(S_2) = \{r_4, r_5, r_6, r_7\}$$

: sensitive data
: sensitive records
: evidence records

Encryption for Multiple SCs

Theorem (NP-Completeness)

Given a dataset D and $k > 1$ SCs $\mathcal{S}$, the problem of finding the optimal robust scheme that enforces $\mathcal{S}$ on D against the FD attack is NP-complete.

Four solutions

Solution 1: encrypt $S(S_1)$ and $S(S_2)$

RID	NM	SEX	AGE	DC	DS
r_1	Joe	M	28	β	α
r_2	Alice	F	24	β	α
r_3	Maggy	F	33	β	α
r_4	Phil	M	43	CPD5	HIV
r_5	Peter	M	39	CPD5	HIV
r_6	Ray	M	52	CPD5	HIV
r_7	Steve	M	31	CPD5	HIV

encryption overhead $= 3$

Solution 2: encrypt $S(S_1)$ and E

RID	NM	SEX	AGE	DC	D
r_1	Joe	M	28	β	
r_2	Alice	F	24	β	
r_3	Maggy	F	33	CPD5	
r_4	Phil	M	43	β	H
r_5	Peter	M	39	β	H
r_6	Ray	M	52	β	H
r_7	Steve	M	31	β	H

encryption overhead $= 6$

: sensitive data
: additional encrypted data

Encryption for Multiple SCs

Theorem (NP-Completeness)

Given a dataset D and $k > 1$ SCs $\mathcal{S}$, the problem of finding the optimal robust scheme that enforces $\mathcal{S}$ on D against the FD attack is NP-complete.

Four solutions

Solution 3: encrypt $E(S_1)$ and $S(S_2)$

RID	NM	SEX	AGE	DC	DS
r_1	Joe	M	28	CPD5	α
r_2	Alice	F	24	β	α
r_3	Maggy	F	33	β	α
r_4	Phil	M	43	β	HIV
r_5	Peter	M	39	β	HIV
r_6	Ray	M	52	β	HIV
r_7	Steve	M	31	β	HIV

encryption overhead $= 6$

Solution 4: encrypt $E(S_1)$ and E

RID	NM	SEX	AGE	DC	
r_1	Joe	M	28	CPD5	
r_2	Alice	F	24	CPD5	
r_3	Maggy	F	33	CPD5	
r_4	Phil	M	43	β	H
r_5	Peter	M	39	β	H
r_6	Ray	M	52	β	H
r_7	Steve	M	31	β	H

encryption overhead $= 4$

: sensitive data
: additional encrypted data

Encryption for Multiple SCs

We design an efficient heuristic algorithm *GMM*:

Do Pick the option with the smallest overhead.

While unsafe against FD attack

RID	NM	SEX	AGE	DC	DS
r_1	Joe	M	28	CPD5	α
r_2	Alice	F	24	CPD5	α
r_3	Maggy	F	33	CPD5	α
r_4	Phil	M	43	CPD5	HIV
r_5	Peter	M	39	CPD5	HIV
r_6	Ray	M	52	CPD5	HIV
r_7	Steve	M	31	CPD5	HIV

$$S(S_1) = \{r_1, r_2\}$$
$$E(S_1) = \{r_4, r_5, r_6, r_7\}$$

RID	NM	SEX	AGE	DC	DS
r_1	Joe	M	28	CPD5	α
r_2	Alice	F	24	CPD5	α
r_3	Maggy	F	33	CPD5	α
r_4	Phil	M	43	CPD5	HIV
r_5	Peter	M	39	CPD5	HIV
r_6	Ray	M	52	CPD5	HIV
r_7	Steve	M	31	CPD5	HIV

$$S(S_2) = \{r_2, r_3\}$$
$$E(S_2) = \{r_4, r_5, r_6, r_7\}$$

: sensitive data
: sensitive records
: evidence records

Encryption for Multiple SCs

Do Pick the option with the smallest overhead.

While unsafe against FD attack

Step 1: encrypt $S(S_1)$

RID	NM	SEX	AGE	DC	DS
r_1	Joe	M	28	β	α
r_2	Alice	F	24	β	α
r_3	Maggy	F	33	CPD5	α
r_4	Phil	M	43	CPD5	HIV
r_5	Peter	M	39	CPD5	HIV
r_6	Ray	M	52	CPD5	HIV
r_7	Steve	M	31	CPD5	HIV

$S(S_2) = \{r_3\}, E(S_2) = \{r_4, r_5, r_6, r_7\}$

Step 2: encrypt $S(S_2)$

RID	NM	SEX	AGE	DC	DS
r_1	Joe	M	28	β	α
r_2	Alice	F	24	β	α
r_3	Maggy	F	33	β	α
r_4	Phil	M	43	CPD5	HI
r_5	Peter	M	39	CPD5	HI
r_6	Ray	M	52	CPD5	HI
r_7	Steve	M	31	CPD5	HI

encryption overhead $= 3$

: sensitive data
: additional encrypted data

Experiment Setup

- Environment

  Language Java
  Testbed 2.4*GHz* Intel Core *i*5 CPU, 4*GB* RAM, Mac OS X 10.9

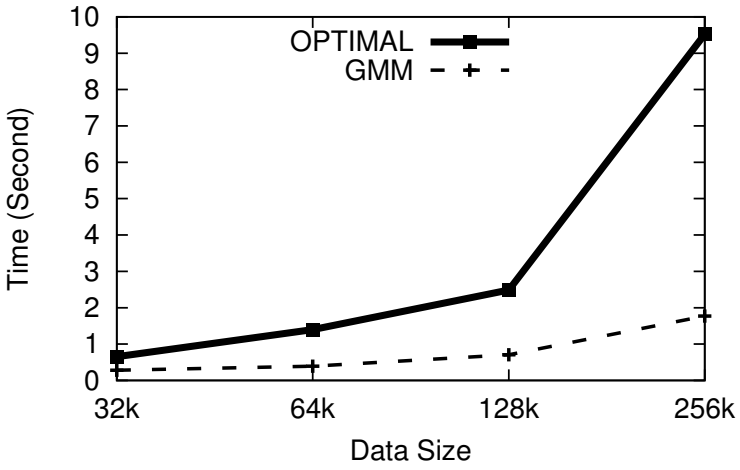
- Datasets:

  Adult UCI machine learning repository
  Orders TPC-H benchmark

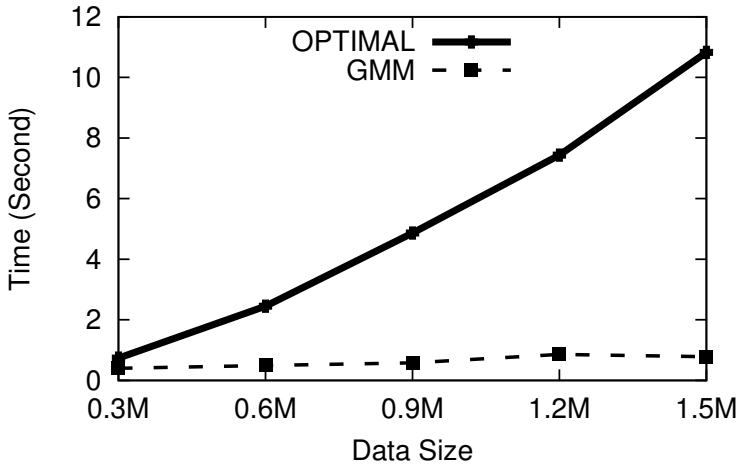
- Approaches

  GMM Our heuristic approach
  OPTIMAL The exhaustive search algorithm

Time Performance

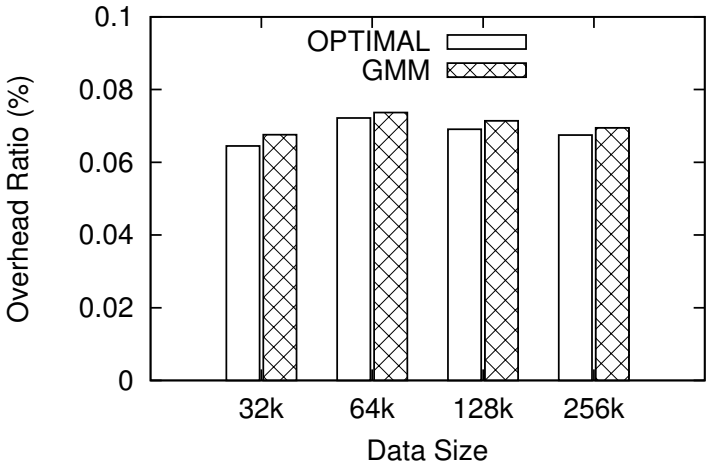


(a) Adult dataset

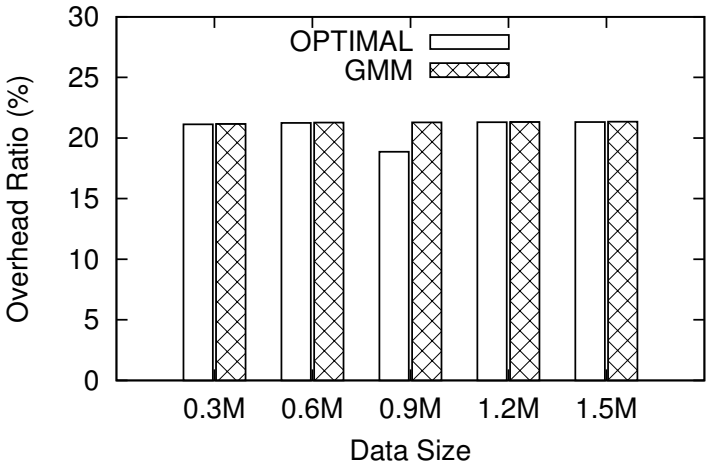


(b) Orders dataset

Encryption Overhead



(a) Adult dataset



(b) Orders dataset

Conclusion

A scheme against FD-based attack in the DaS model based on encryption.

- Formalize the FD attack.
- Prove that finding an optimal scheme with minimal overhead is NP-complete.
- Design efficient heuristic approaches to construct robust schemes with small overhead.

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Q & A

Thank you!

Questions?