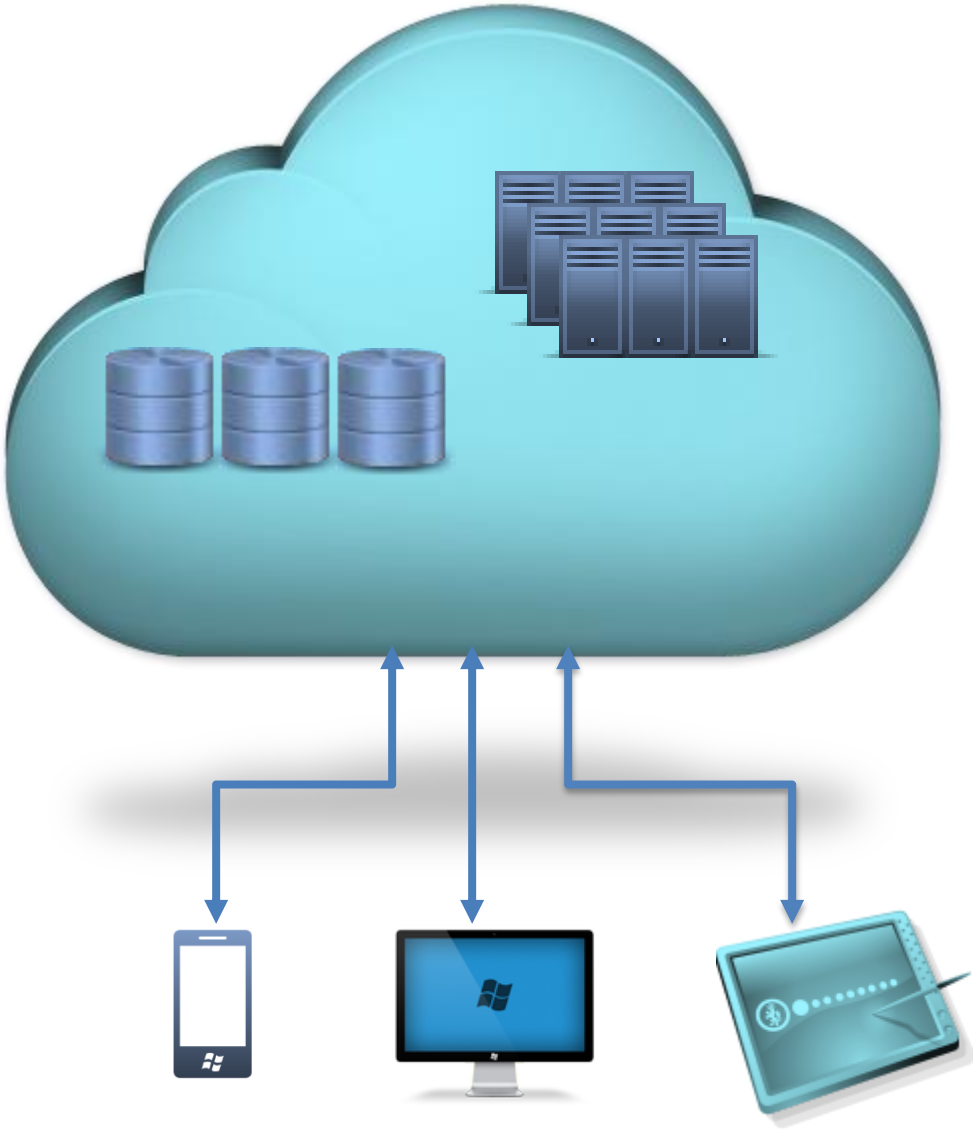
Querying Encrypted Data

Arvind Arasu, Ken Eguro,

Ravi Ramamurthy, Raghav Kaushik

Microsoft Research

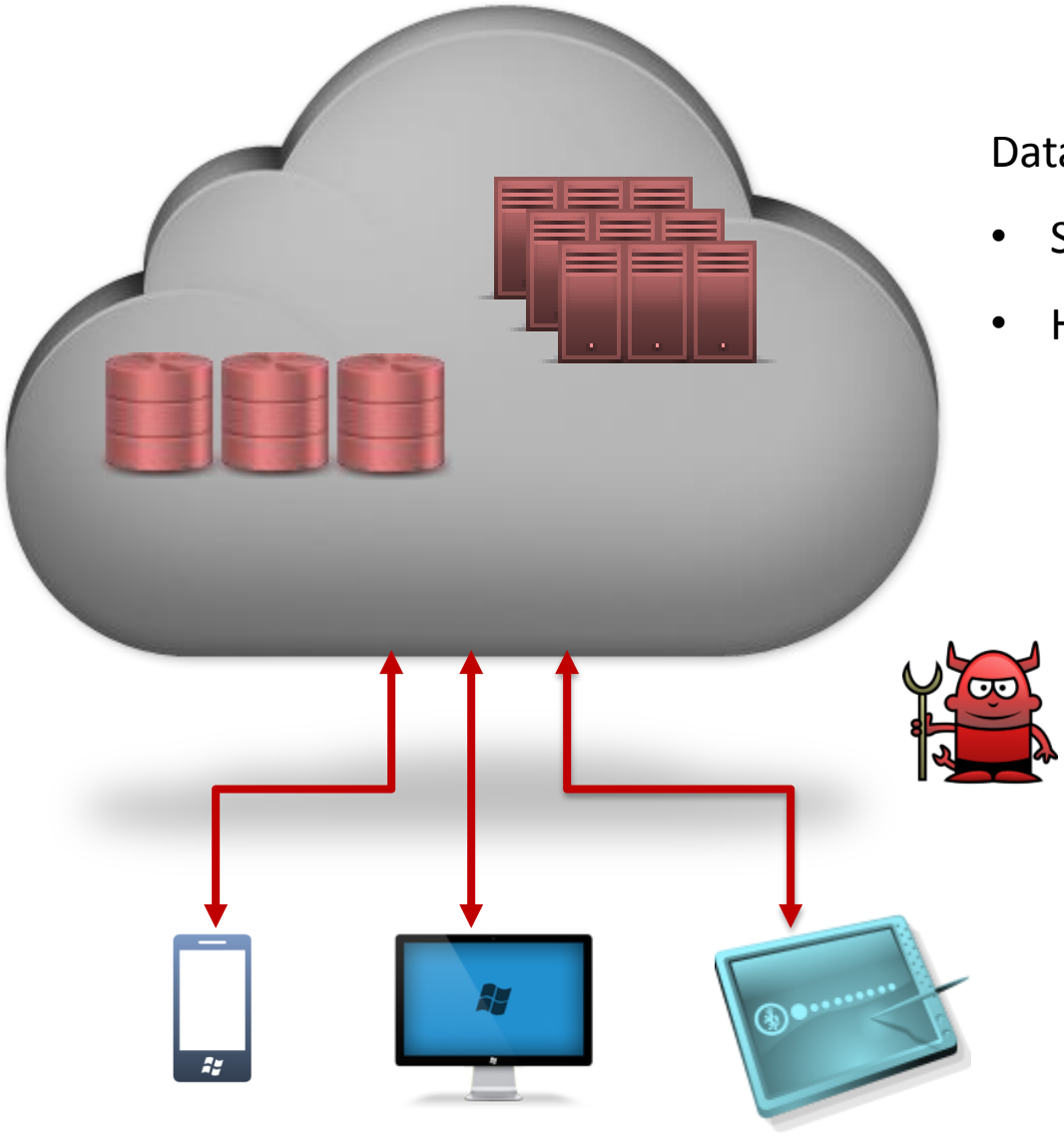
Cloud Computing



- Well-documented benefits
- Trend to move computation and data to cloud
- Database functionality
  - Amazon RDS
  - Microsoft SQL Azure
  - Heroku PostegreSQL
  - Xeround

[AF+09, NIST09]

Security Concerns

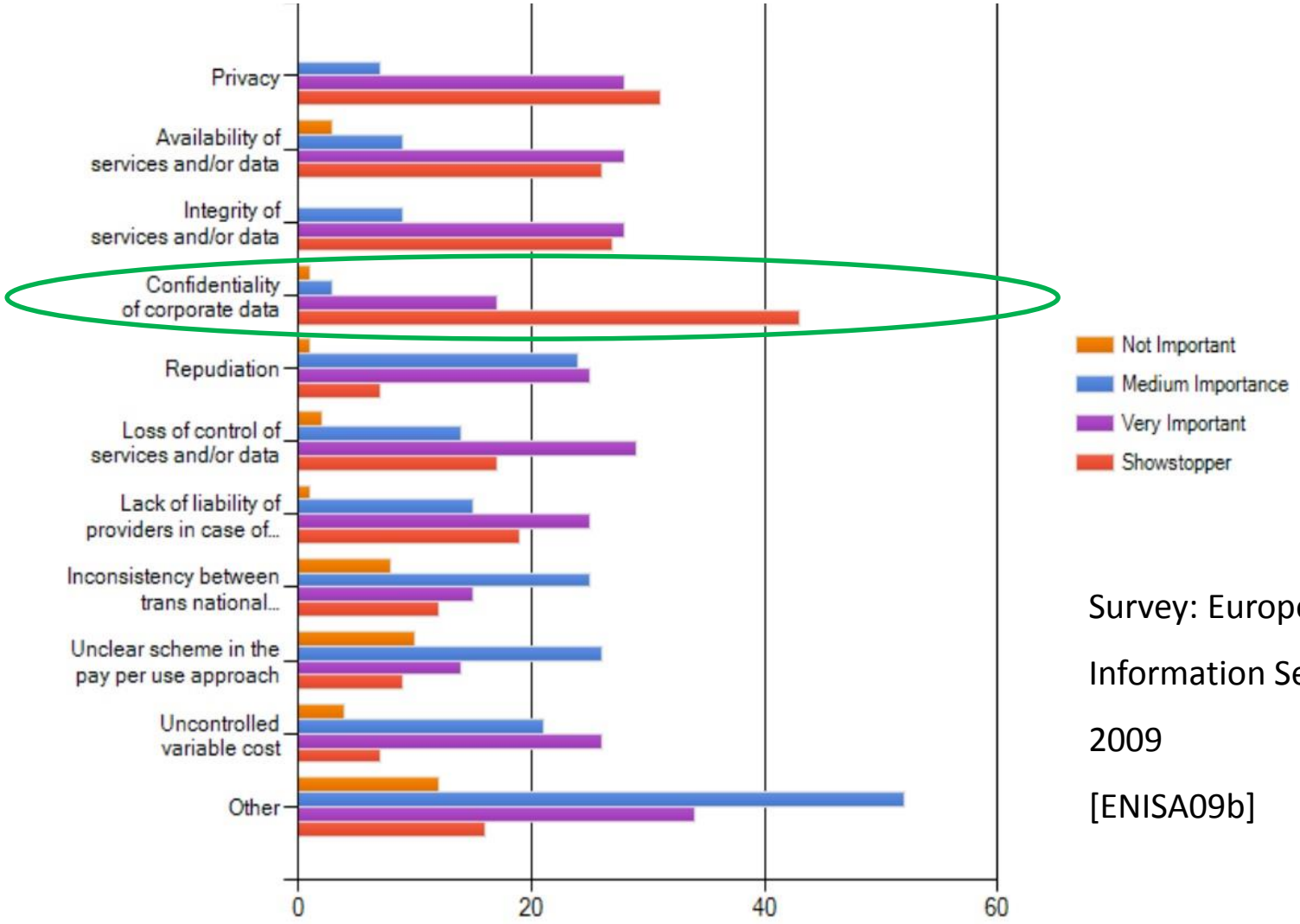


Data in the cloud vulnerable to:

- Snooping administrators
- Hackers with illegal access
  - Compromised servers

[CPK10, ENISA09a]

What are your main cloud computing concerns?



Survey: European Network and Information Security Agency, Nov 2009

[ENISA09b]

Sensitive Data in the Cloud: Examples

Software as a Service Applications

Billing

- Aria Systems
- eVapt
- nDEBIT
- Redi2
- Zuora

CRM

- 37 Signals
- Capsule
- Dynamics
- Intouchcrm
- LiveOps
- Oracle CRM
- Parature
- Responsys
- RO|Enablement
- Salesforce.com
- Save My Table
- Solve 360

Corporate data

ERP

- Acumatica ERP
- Blue Link Elite
- Epicor Express
- NetSuite
- OrderHarmony
- Plex Online

Health

- CECity
- SNO

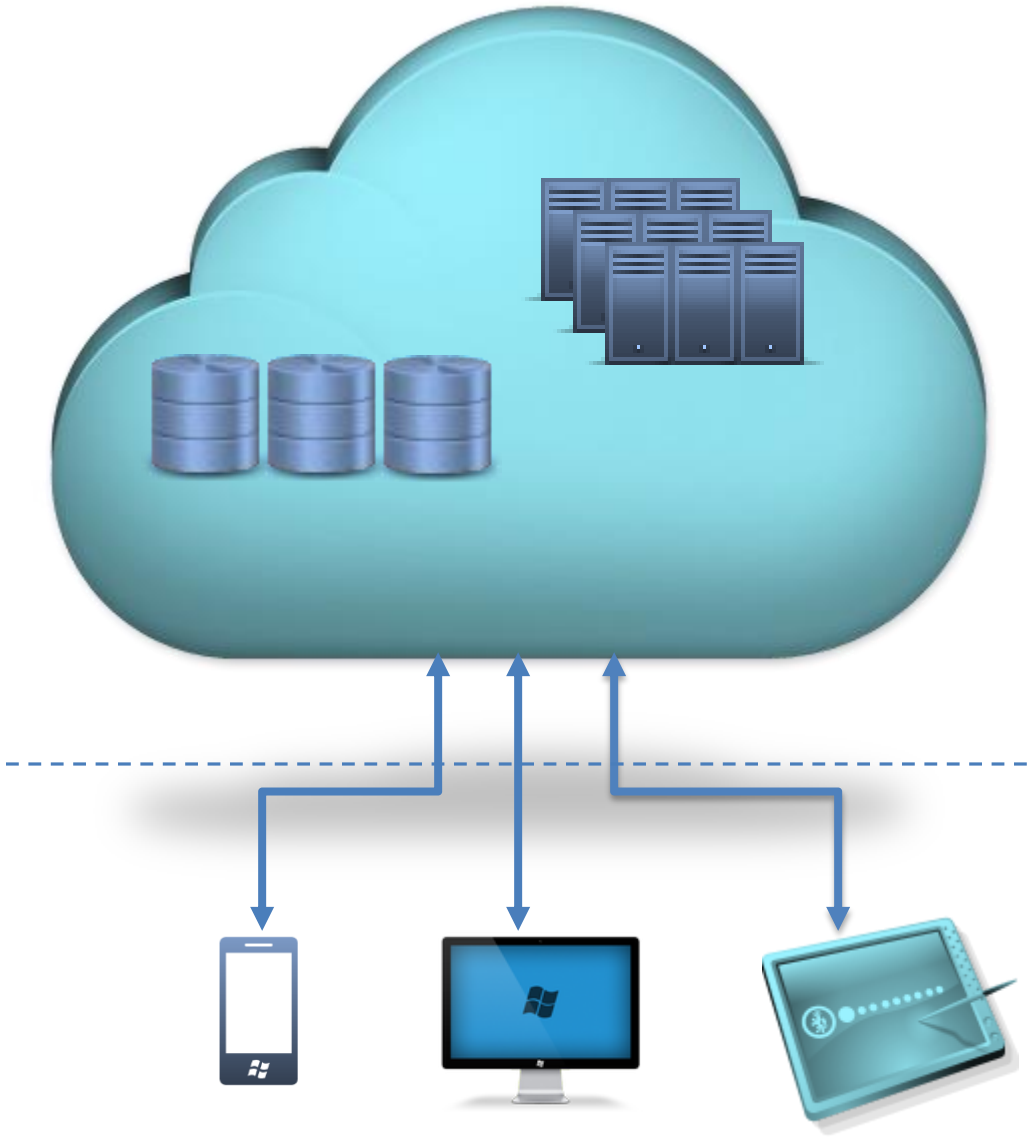
Personal Data

- Google Docs
- Microsoft Office
- Mint.com

Personal data

Source: http://cloudtaxonomy.opencrowd.com/taxonomy/

Data Encryption

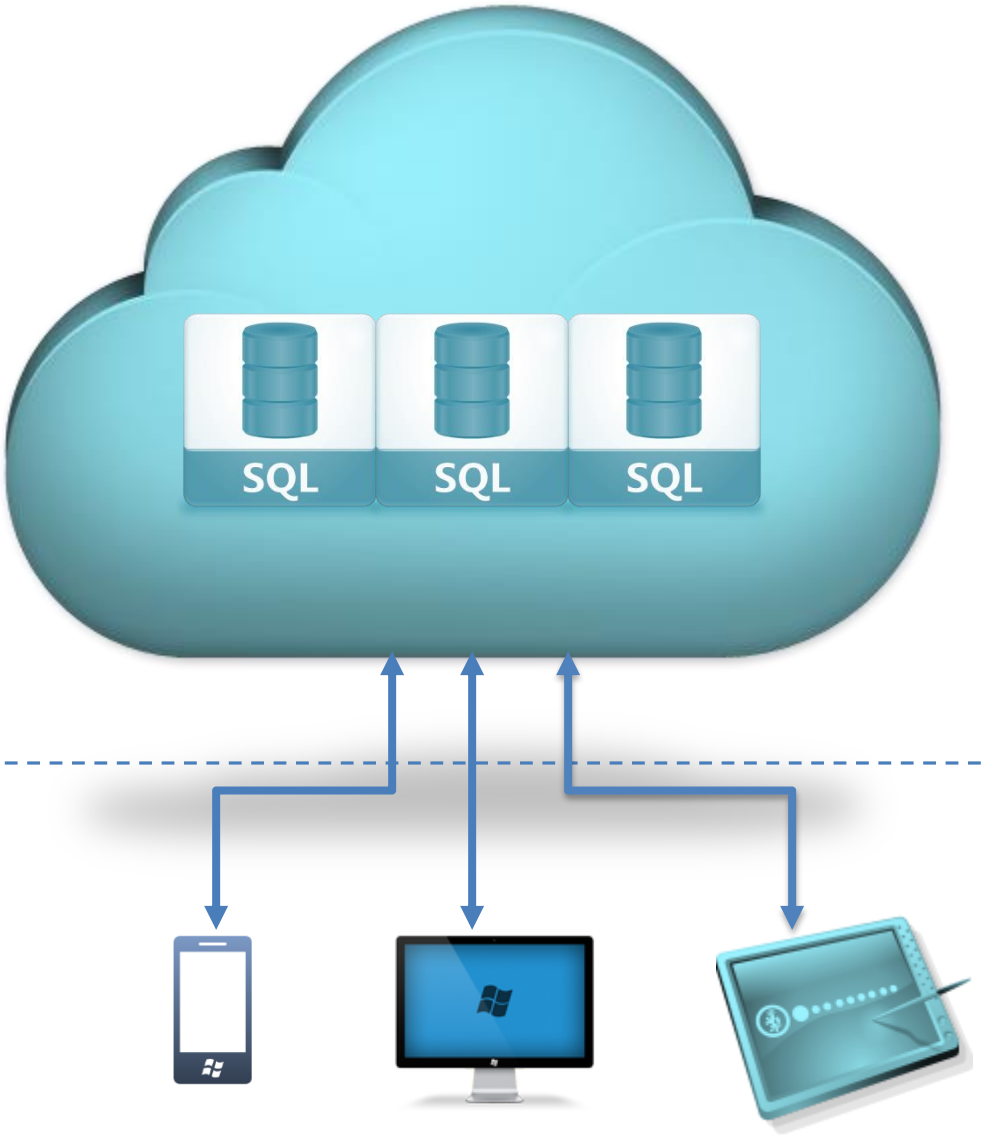


AWS Security Advice

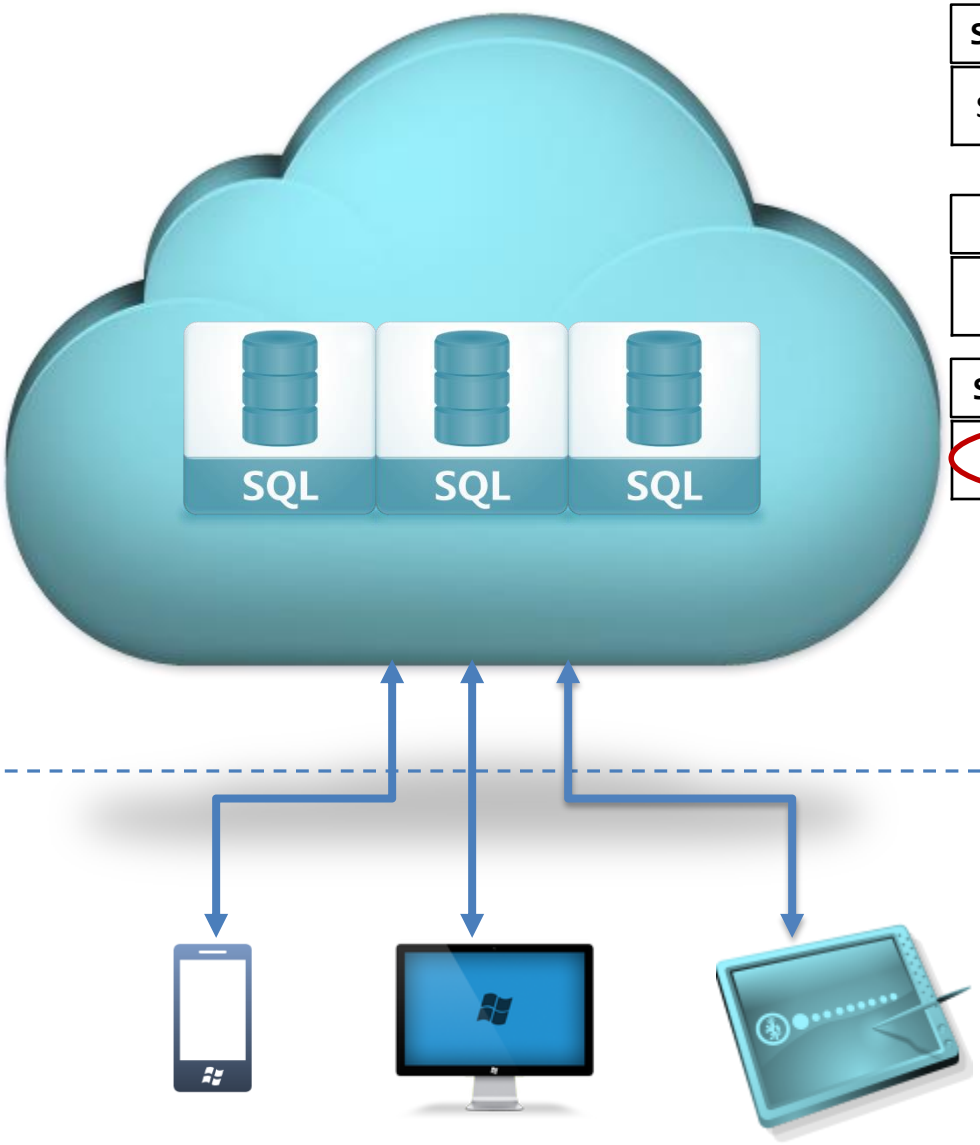
7.2. Security. We strive to keep Your Content secure, but cannot guarantee that we will be successful at doing so, given the nature of the Internet. Accordingly, without limitation to Section 4.3 above and Section 11.5 below, you acknowledge that you bear sole responsibility for adequate security, protection and backup of Your Content. We strongly encourage you, where available and appropriate, to use encryption technology to protect Your Content from unauthorized access and to routinely archive Your Content. We will have no liability to you for any unauthorized access or use, corruption, deletion, destruction or loss of any of Your Content.

Source: http://aws-portal.amazon.com/gp/aws/developer/terms-and-conditions.html

Encryption and DbaaS: Functionality



Example: Online Course Database



Student

StudentId	Name	Addr	GPA	CreditCard	…

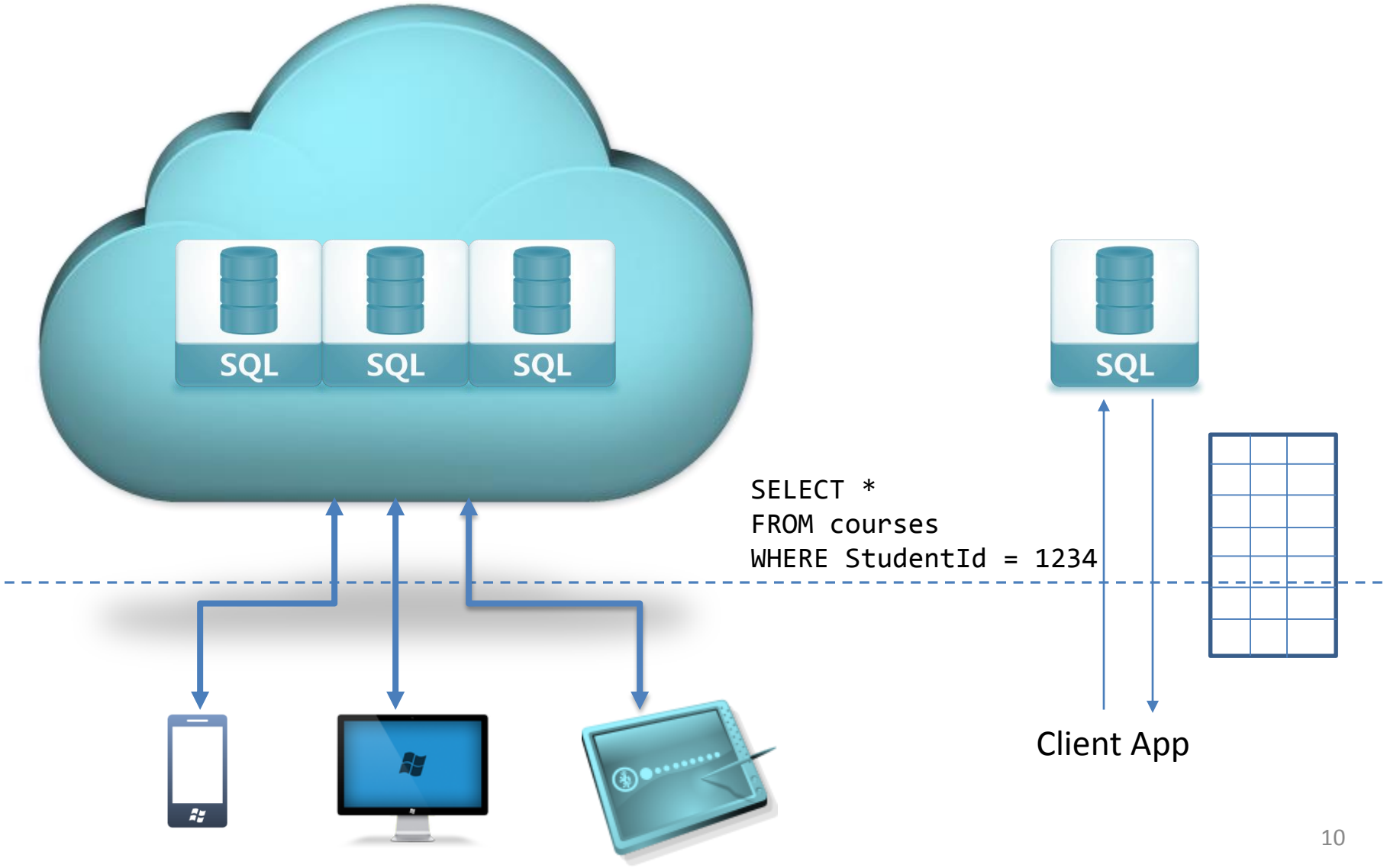
Course

CourseId	Name	InstrId	…

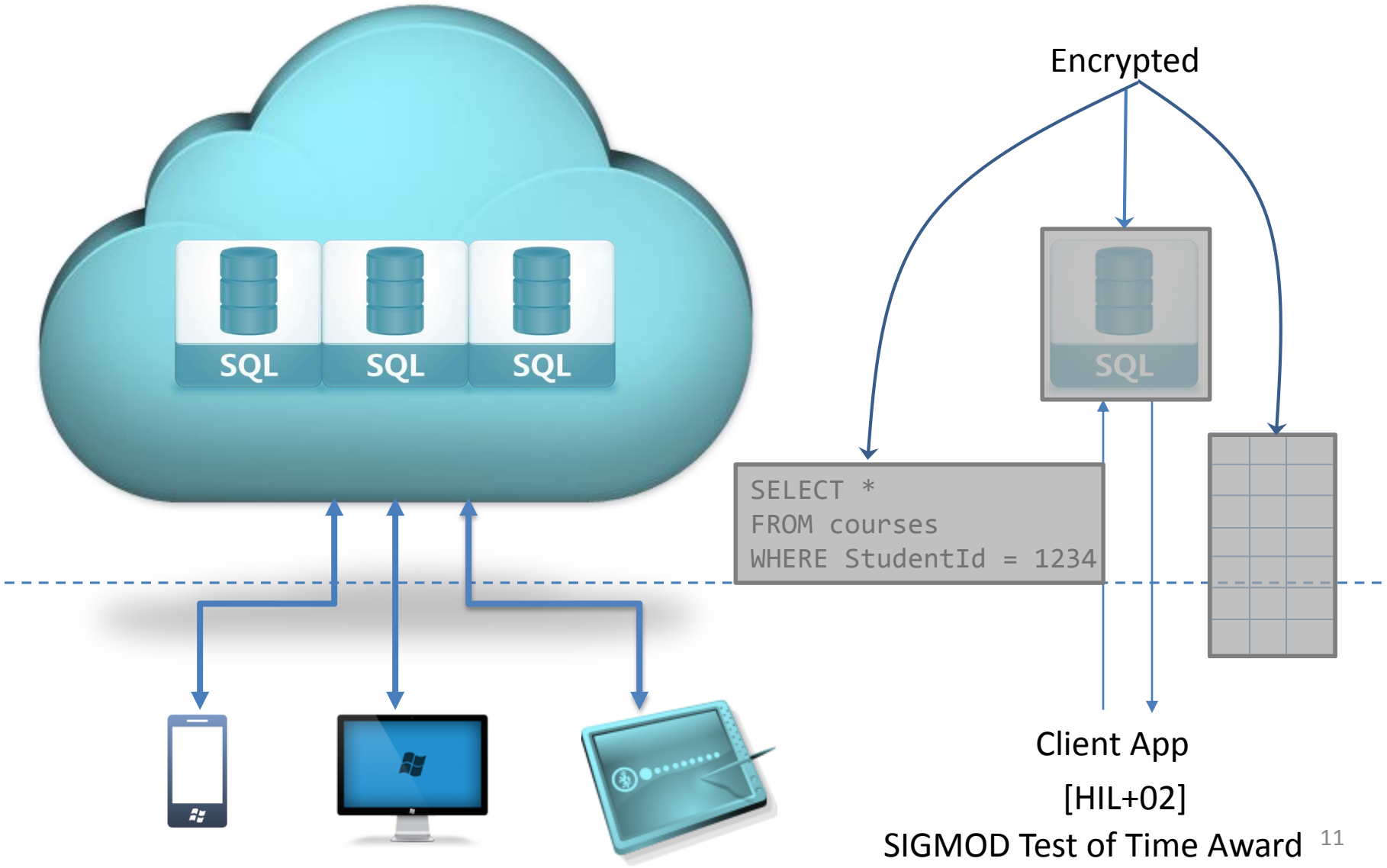
StudentCourse

CourseId	StudentId	Grade	…

Encryption and DbaaS: Functionality



Encryption and DbaaS: Functionality



[HIL+02]
SIGMOD Test of Time Award

Tutorial Overview

- Survey of existing work
  - Building blocks
  - End-to-end systems
    - Security-Performance-Generality tradeoff
    - Taxonomy, organization
- Open problems & Challenges
- Random pontifications

Tutorial Goals & Non-Goals

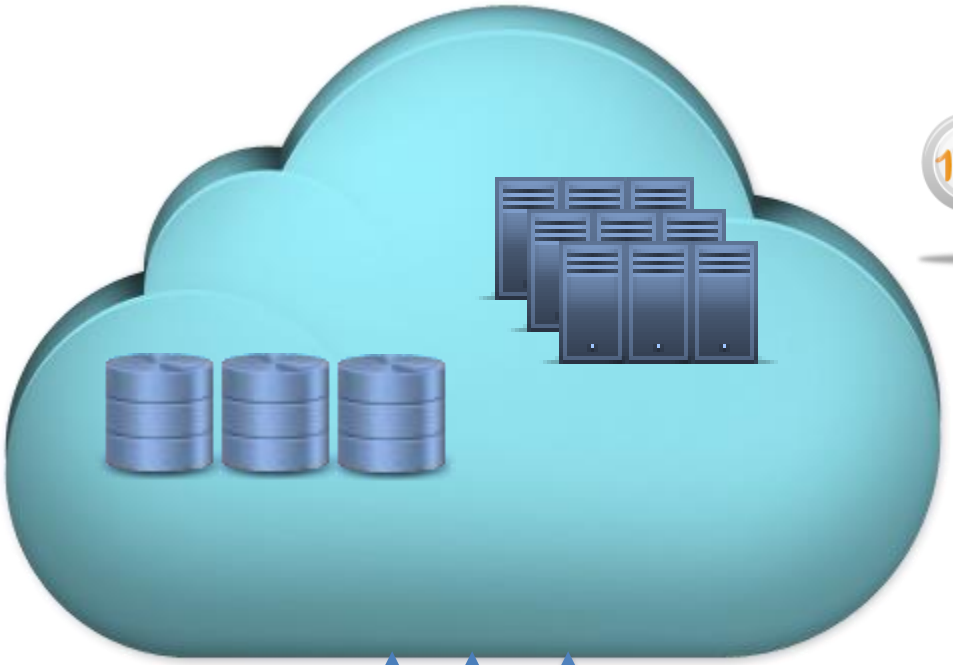
- Takeaway goals:
  - Interesting & Important area
  - Lots of open (systems) problems
  - Multi-disciplinary
- Non-goals:
  - Latest advances Elliptic Curve Cryptography

Related tutorial:
Secure and privacy preserving Database Services in the Cloud

Roadmap

- Introduction
- Overview
- Basics of Encryption
- Trusted Client based Systems
- Secure In-Cloud Processing
- Security
- Conclusion

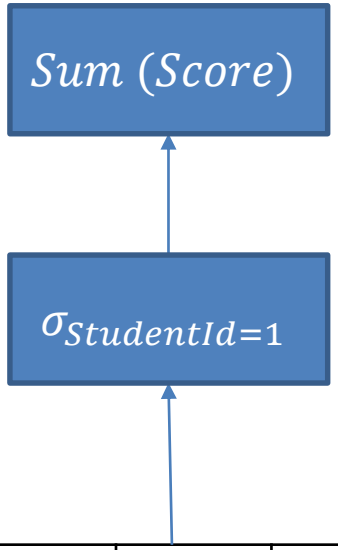
Passive Adversary



- Passive
- Honest but curious
- Does not alter:
  - Database
  - Results

Design systems for active adversary

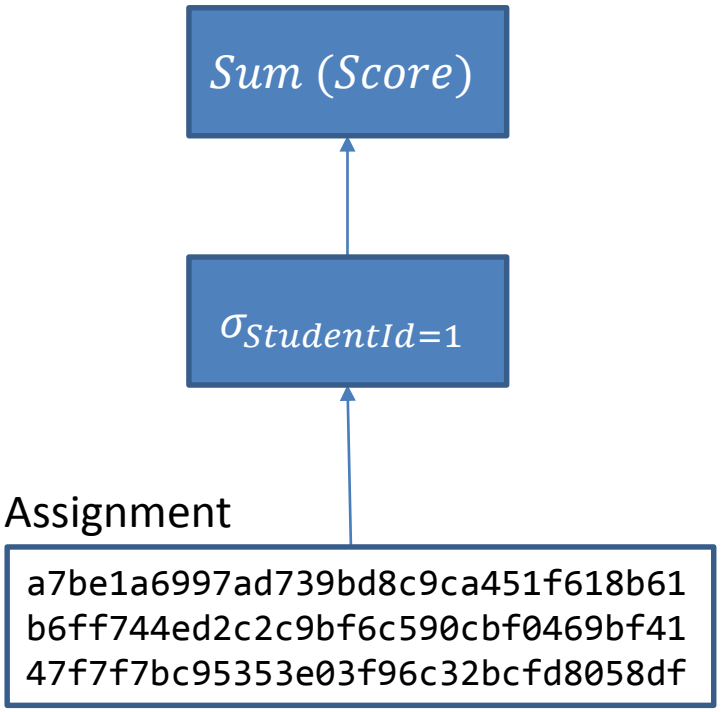
Encryption: Fundamental Challenge



StudentId	AssignId	Score
1	1	68
1	2	71
3	4	99
…	…	…

```
Select Sum (Score)
From Assignment
Where StudentId = 1
```

Encryption: Fundamental Challenge

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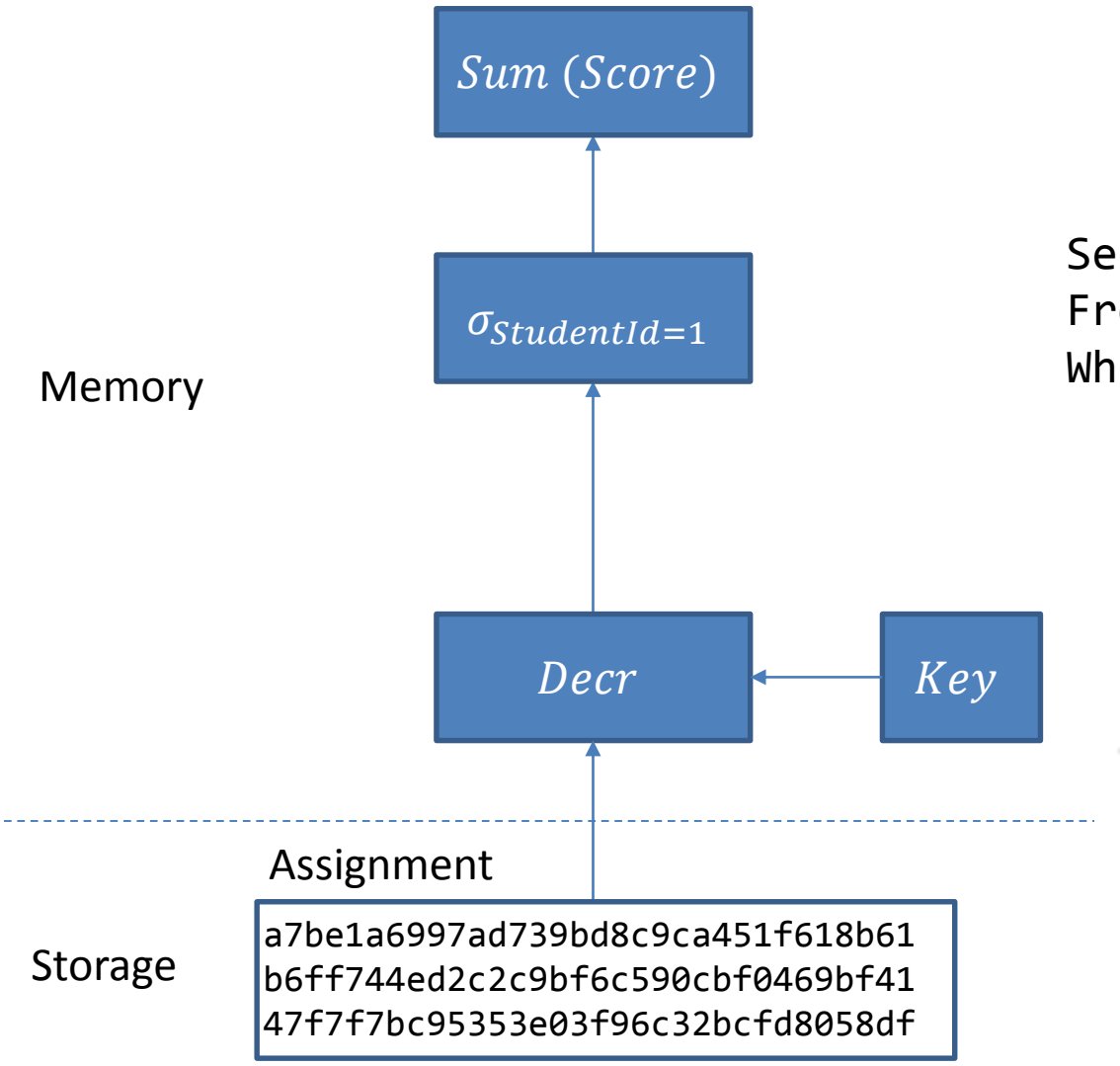
Encryption: Fundamental Challenge



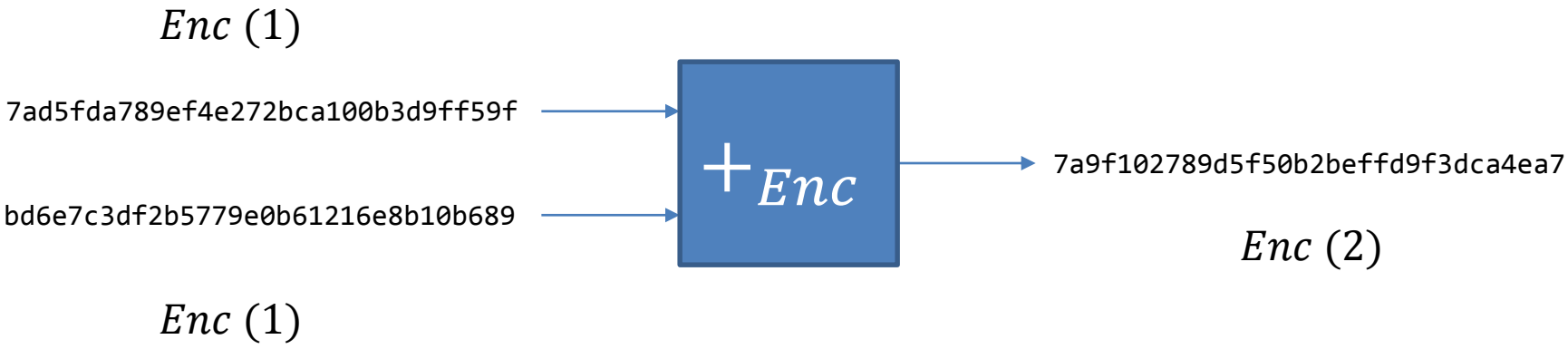

```
Select Sum (Score)
From Assignment
Where StudentId = 1
```

Industry state-of-the-art:
[OTDE, STDE]

Solution Landscape

- Two fundamental techniques
  - Directly compute over encrypted data
    - Special ***homomorphic*** encryption schemes

Homomorphic Encryption

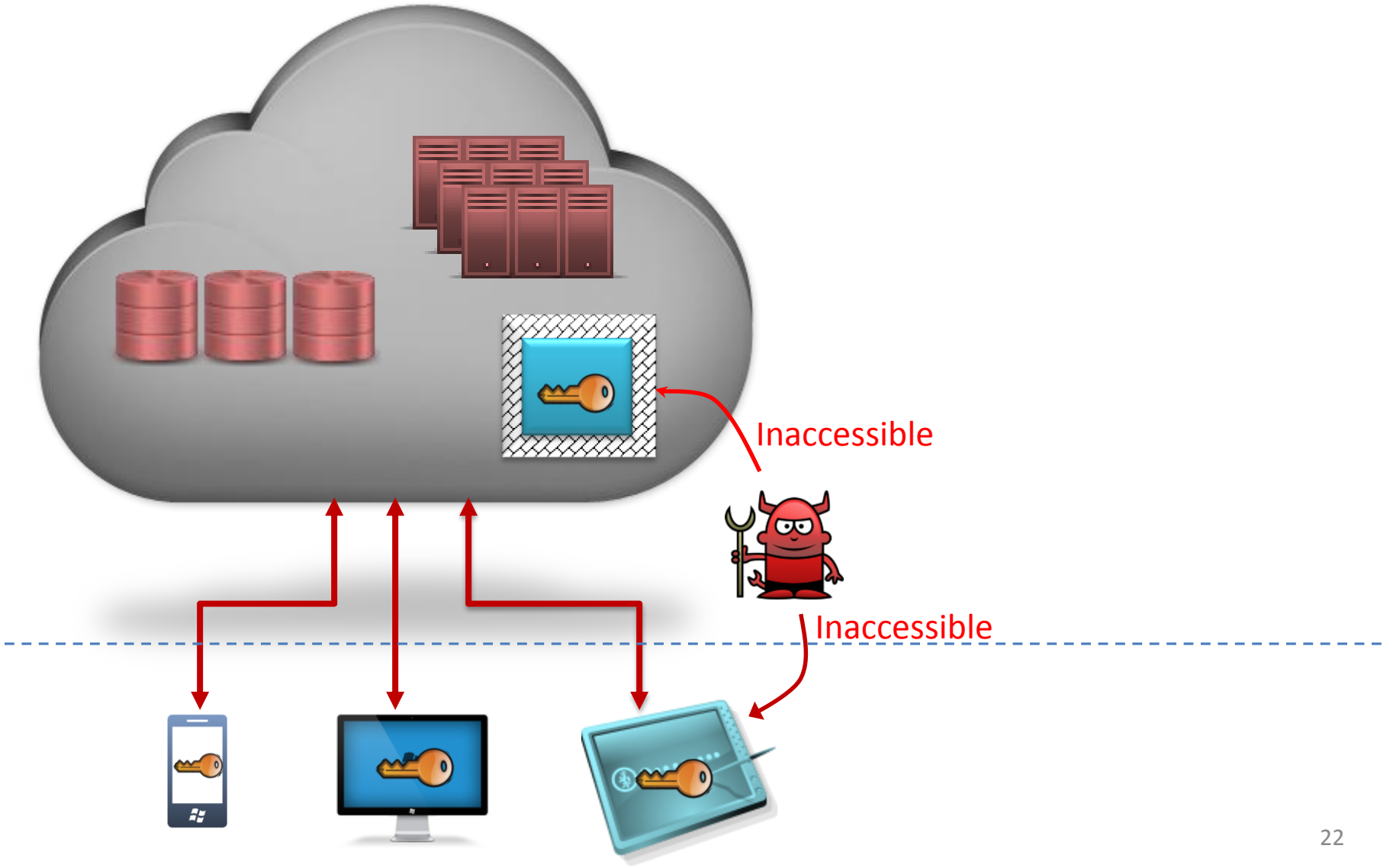


Encryption key is not an input

Solution Landscape

- Two fundamental techniques
  - Directly compute over encrypted data
    - Special ***homomorphic*** encryption schemes
    - Challenge: limited class of computations
  - Use a “secure” location
    - Computations on plaintext

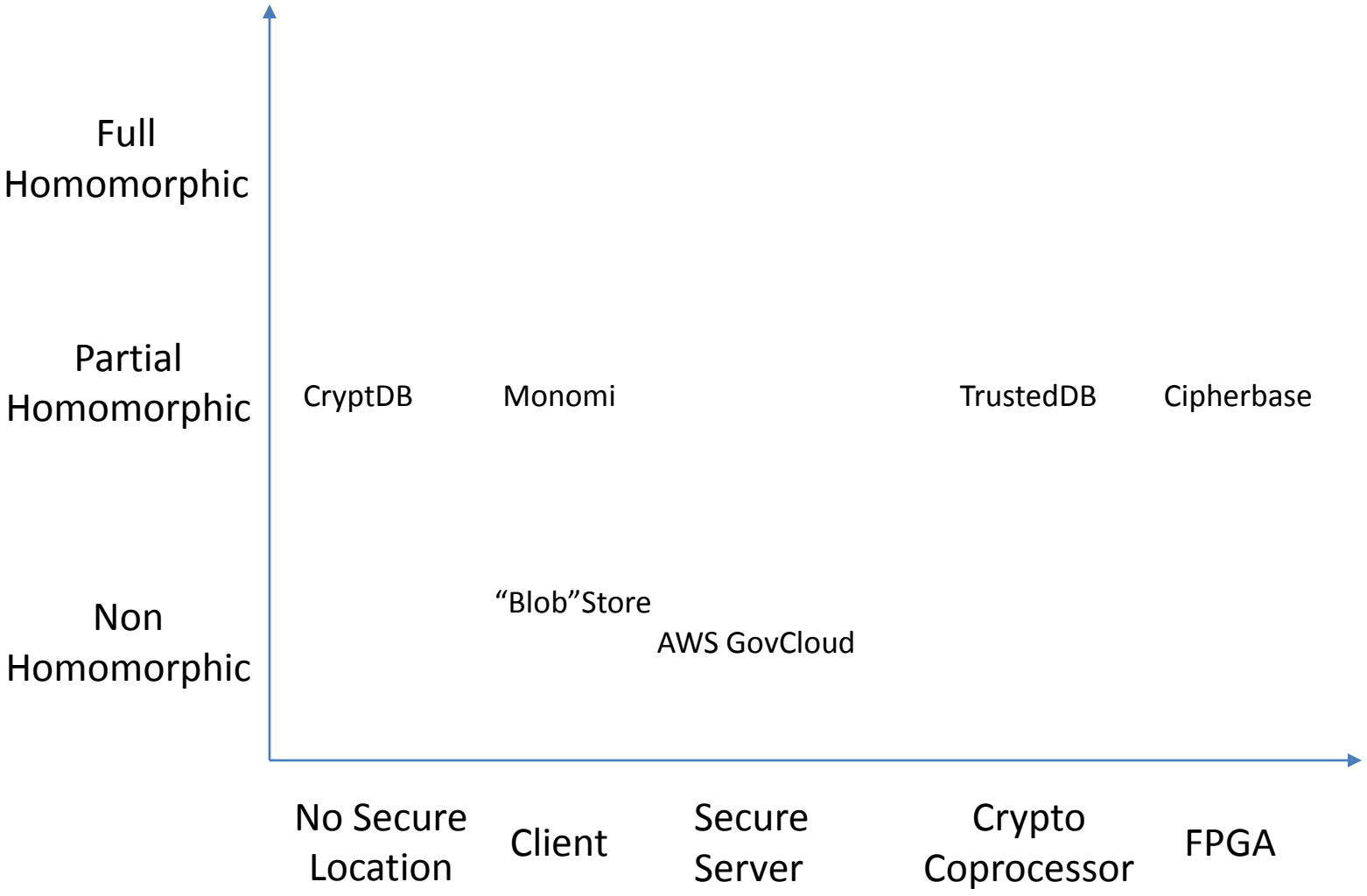
Secure Location



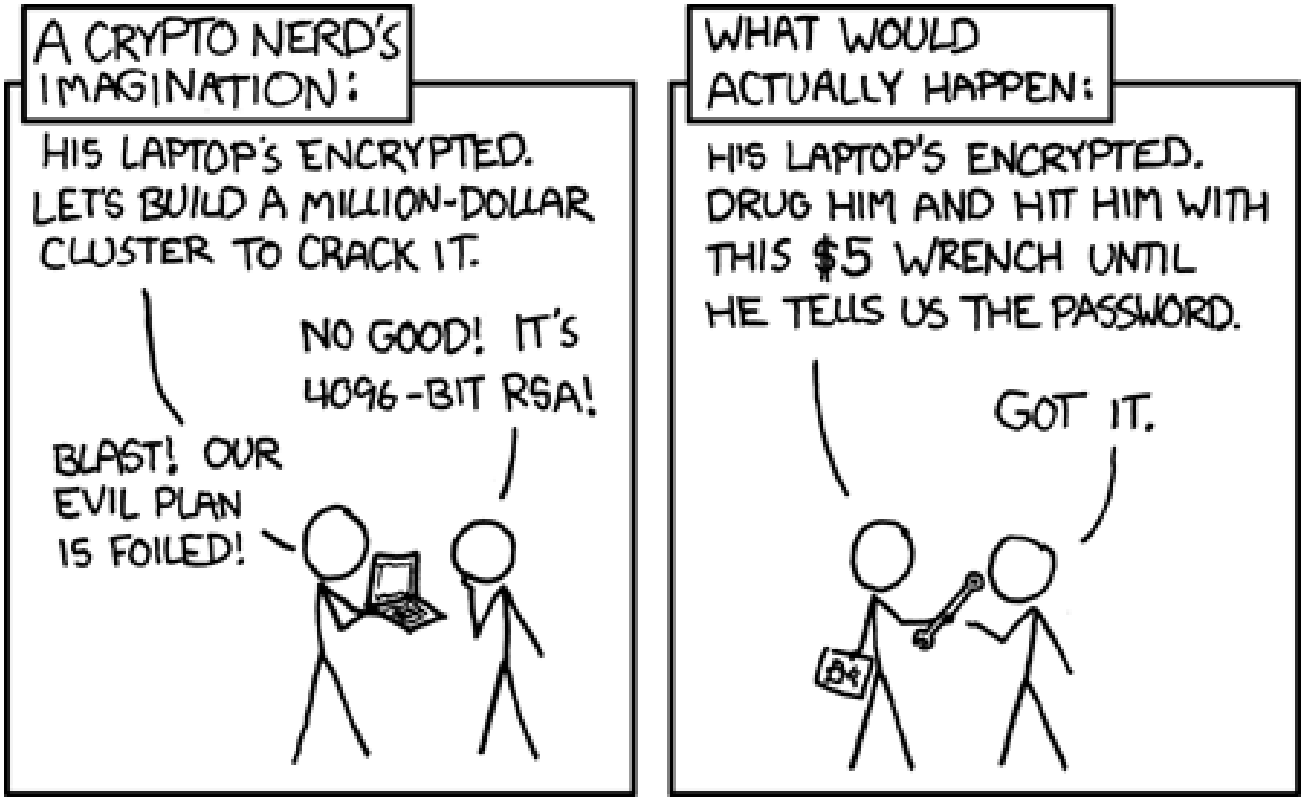
Solution Landscape

- Two fundamental techniques
  - Directly compute over encrypted data
    - Special ***homomorphic*** encryption schemes
    - Challenge: limited class of computations
  - Use a "secure" location
    - Computations on plaintext
    - Challenge: Expensive

Systems Landscape



Encryption == Security?



Source: http://xkcd.com/538/

Roadmap

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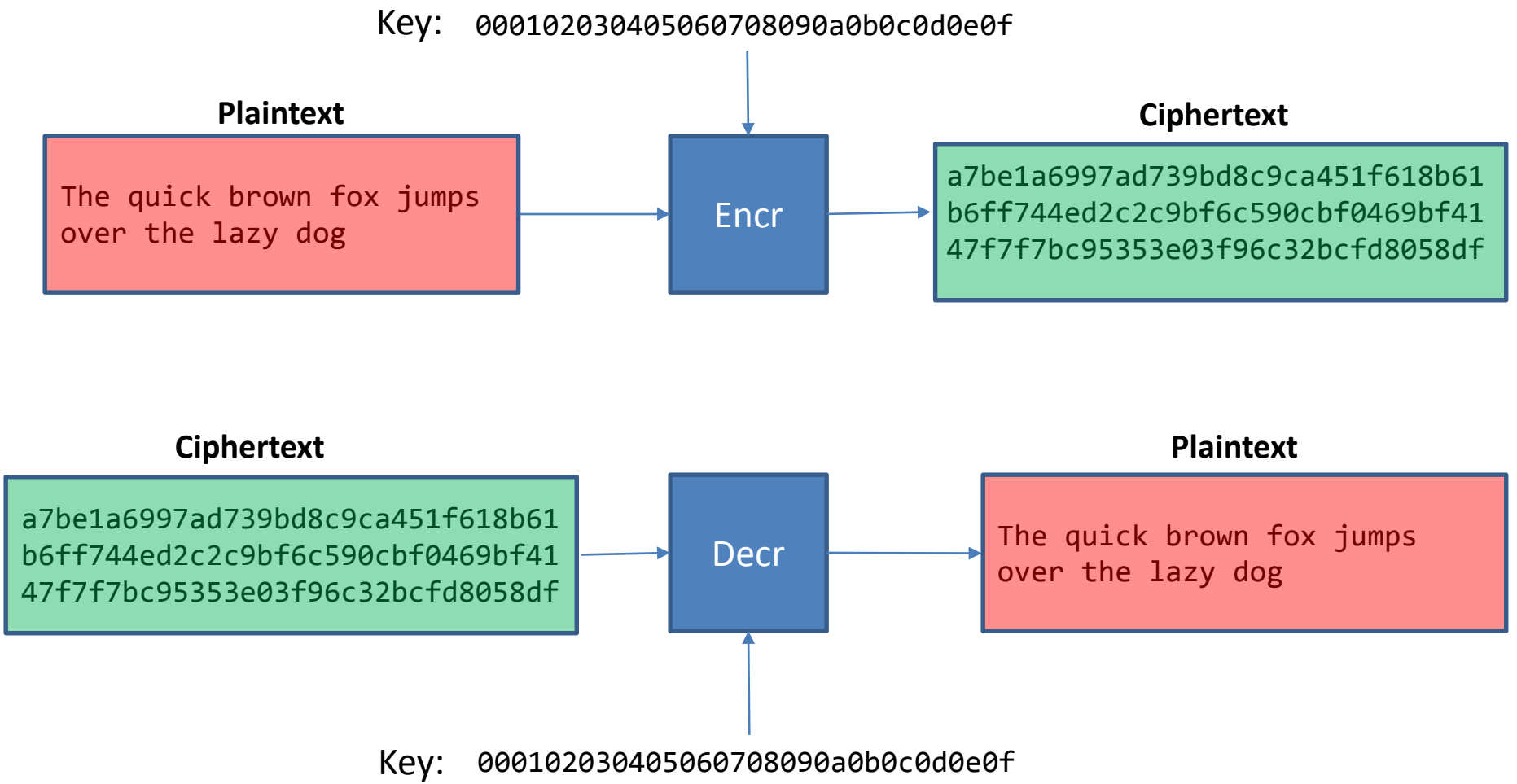
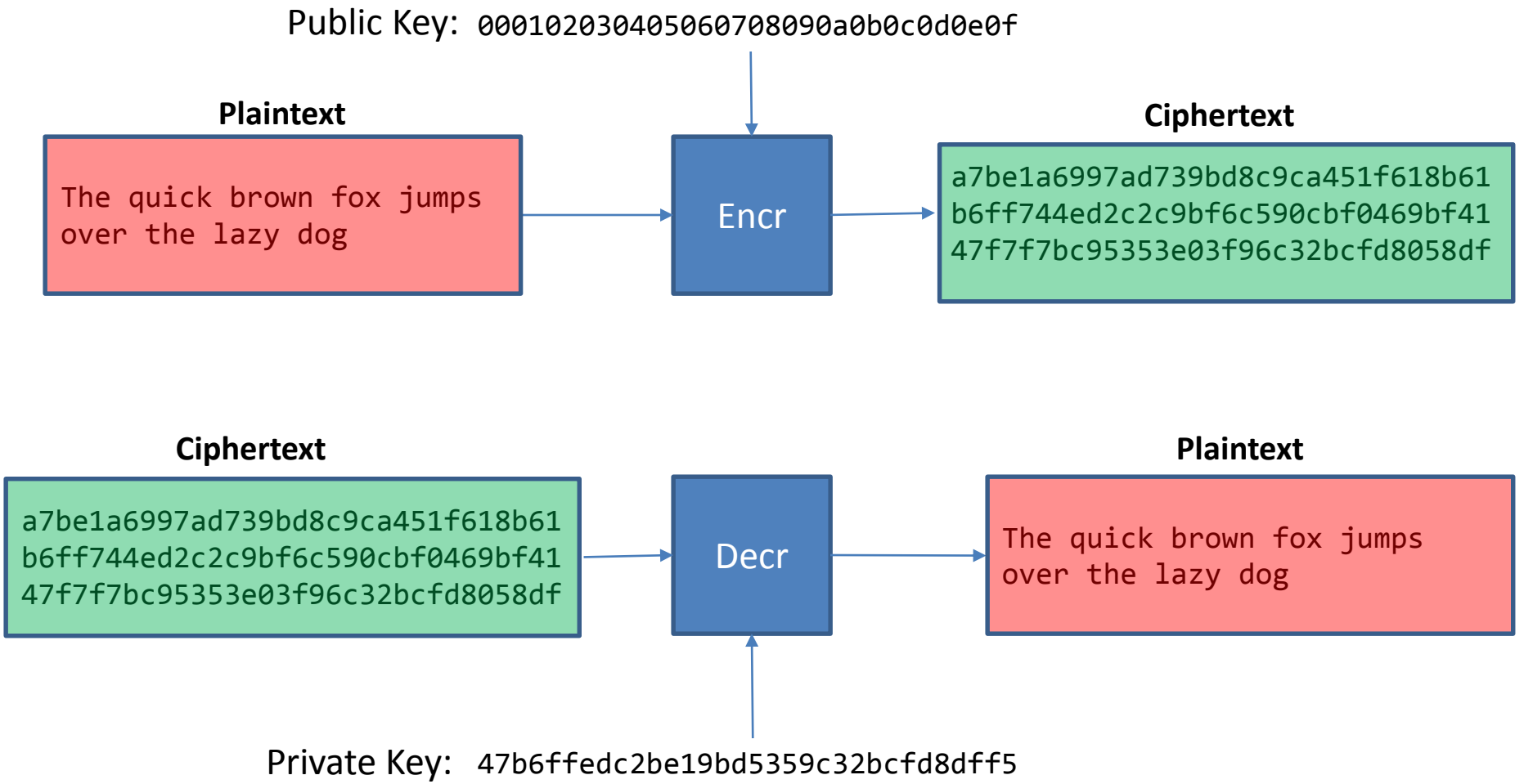
Encryption Scheme



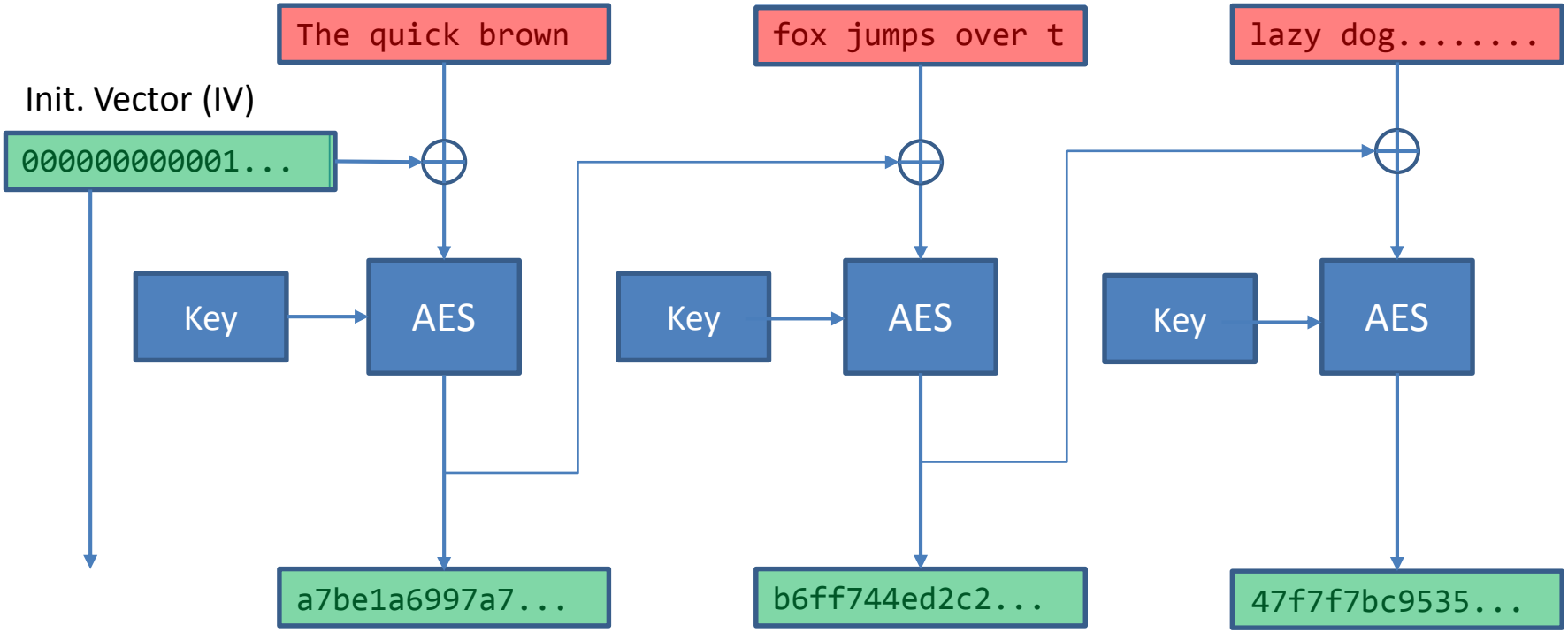
Crypto Textbook: [KL 07]

Encryption Scheme



Crypto Textbook: [KL 07]

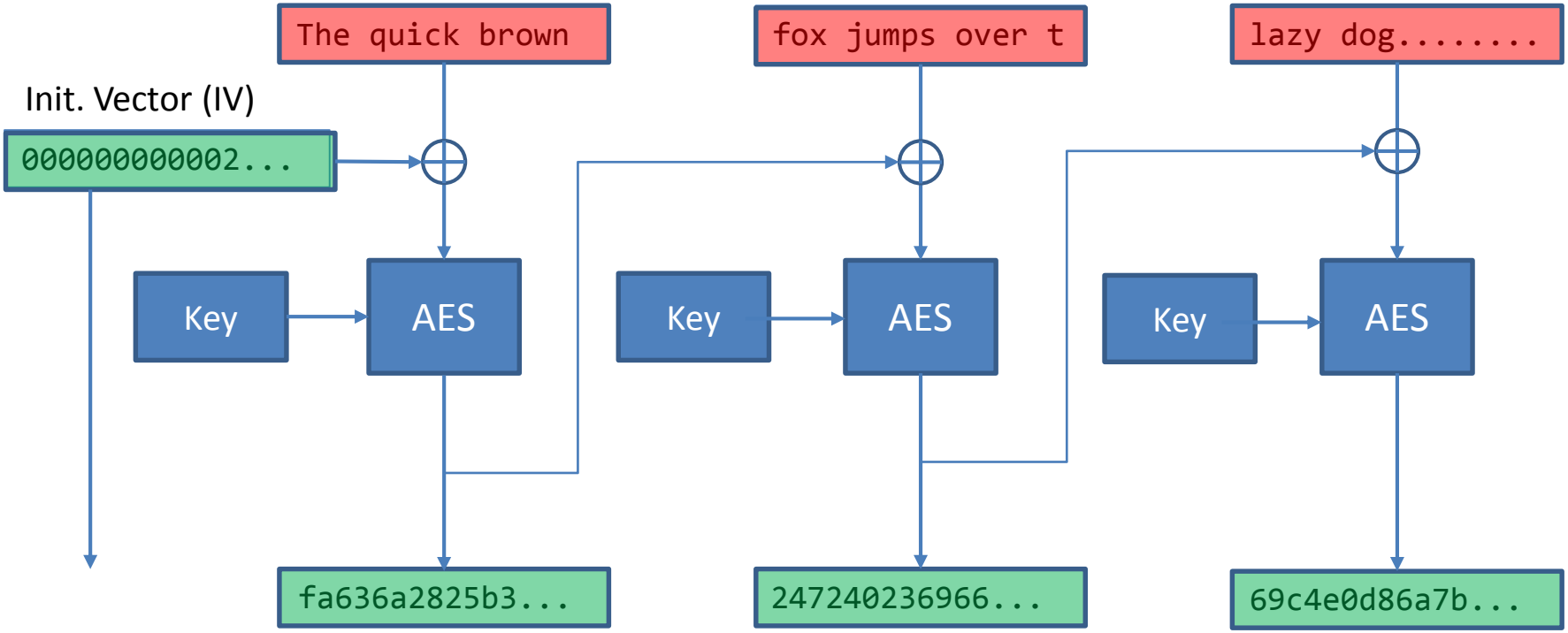
AES + CBC Mode



Variable IV => Non-deterministic

[AES, KL 07]

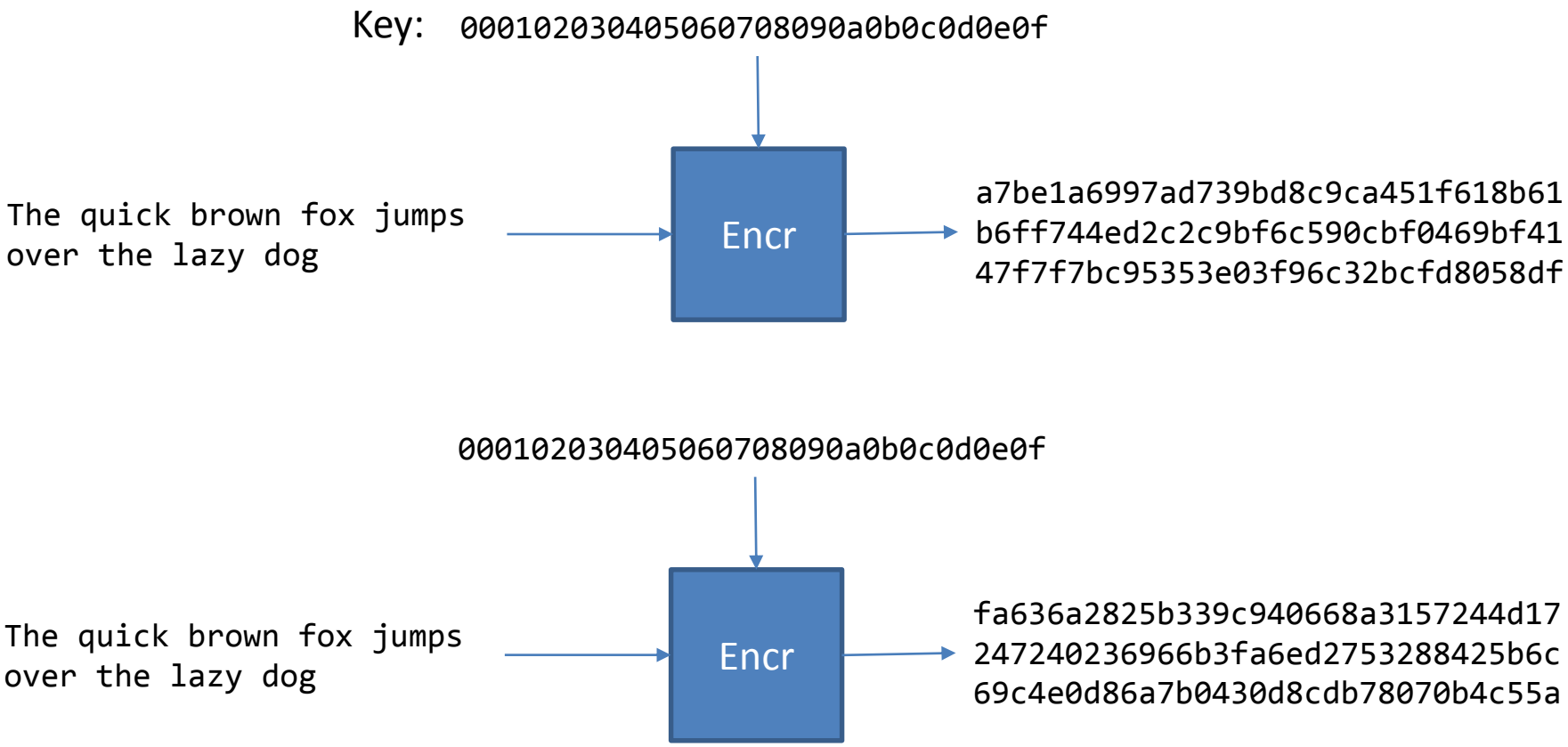
AES + CBC Mode



Variable IV => Non-deterministic

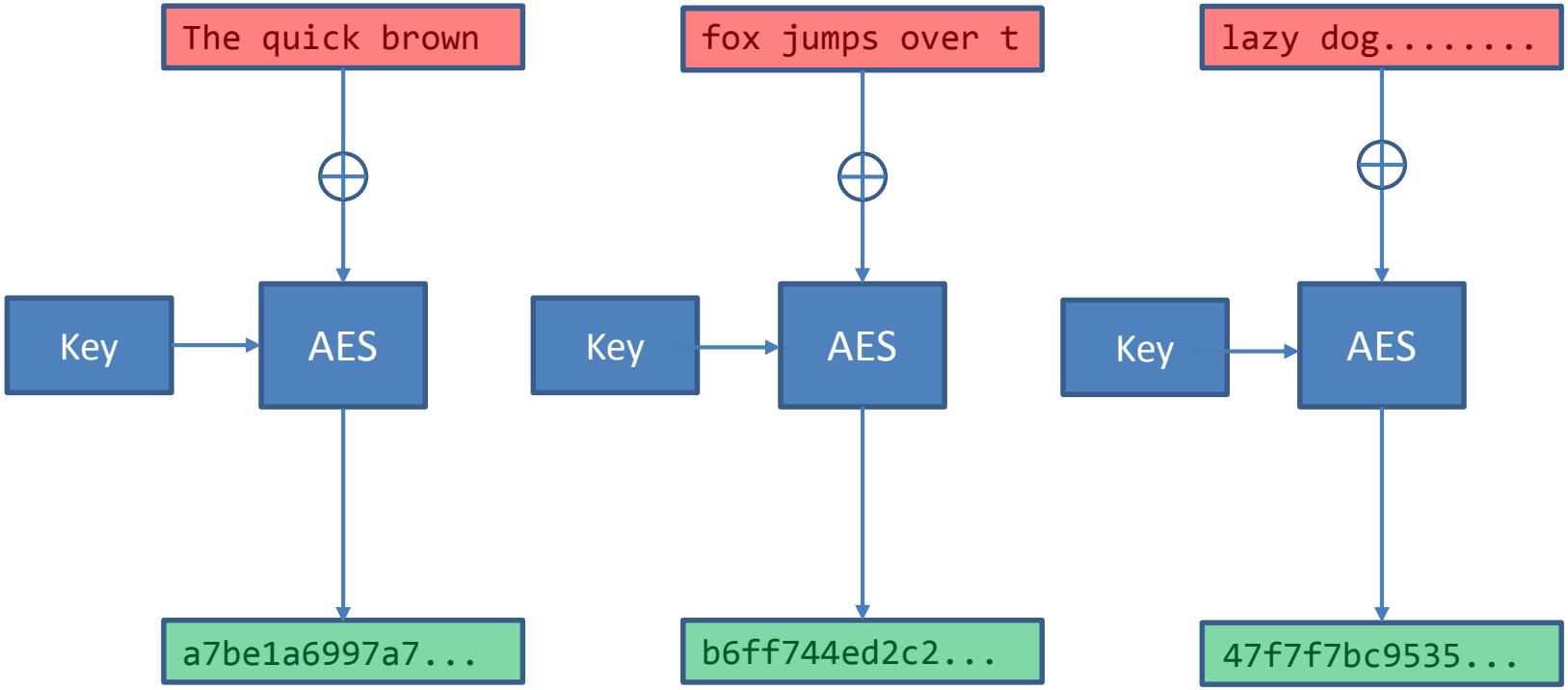
[AES, KL 07]

Nondeterministic Encryption Scheme



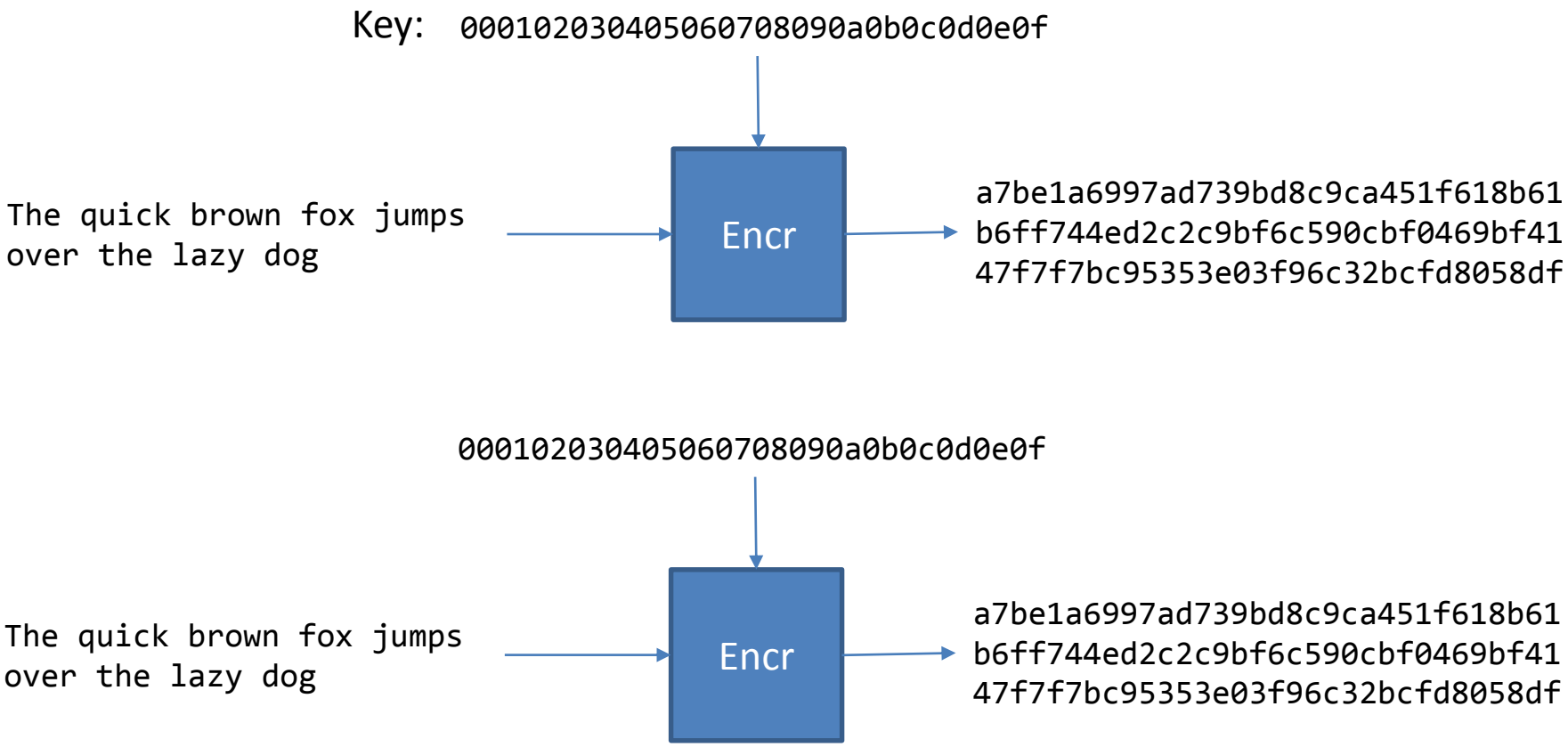
Example: AES + CBC + variable IV

AES + ECB Mode



[AES, KL 07]

Deterministic Encryption Scheme

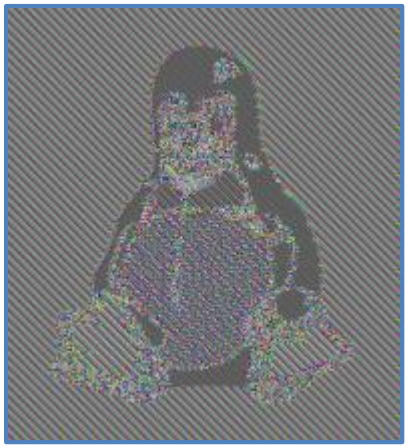


Example: AES + ECB

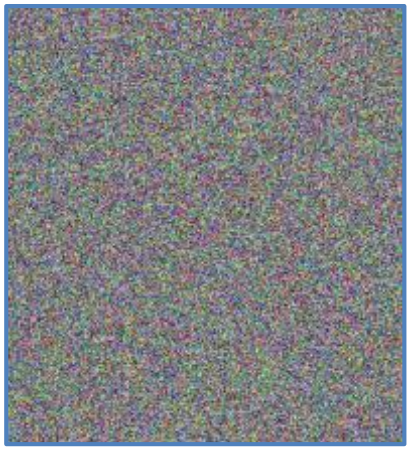
More secure deterministic encryption: [PRZ+11]

Strong Security => Non-Deterministic

Original



Deterministic

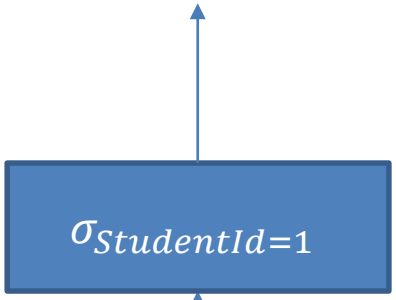


Non-Deterministic

Source: http://en.wikipedia.org/wiki/Block_cipher_modes_of_operation

Deterministic Encryption

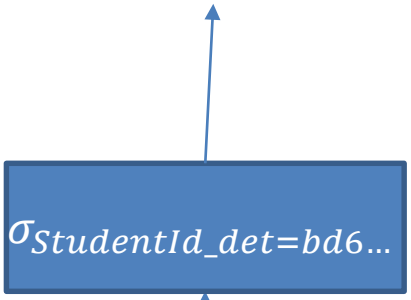
```
select *
from assignment
where studentid = 1
```



StudentId	AssignId	Score
1	1	68
1	2	71
3	4	99
…	…	…

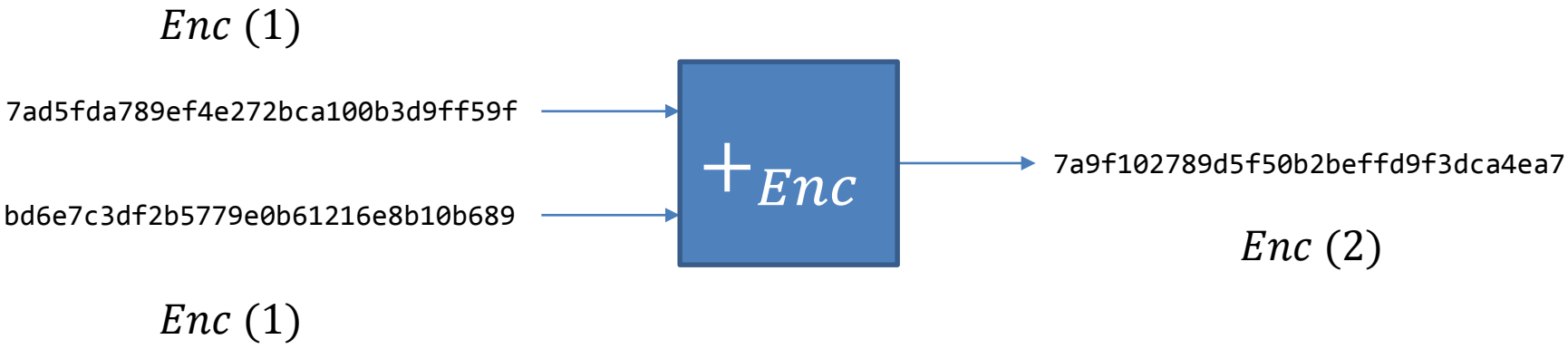
Deterministic Encryption

```
select *
from assignment
where studentid_det = bd6e7c3df2b5779e0b61216e8b10b689
```



StudentId_DET	AssignId	Score
bd6e7c3df2b5779e0b61216e8b10b689	1	68
bd6e7c3df2b5779e0b61216e8b10b689	2	71
7ad5fda789ef4e272bca100b3d9ff59f	4	99
…	…	…

Homomorphic Encryption



Encryption key is not an input

Order Preserving Encryption

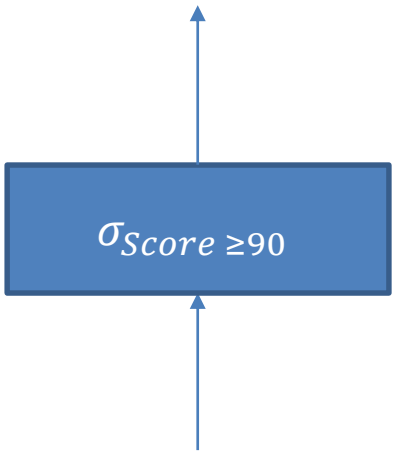
Value	Enc (Value)
1	0x0001102789d5f50b2beffd9f3dca4ea7
2	0x0065fda789ef4e272bcf102787a93903
3	0x009b5708e13665a7de14d3d824ca9f15
4	0x04e062ff507458f9be50497656ed654c
5	0x08db34fb1f807678d3f833c2194a759e

$$x < y \rightarrow Enc(x) < Enc(y)$$

[BCN11, PLZ13]

Order-Preserving Encryption

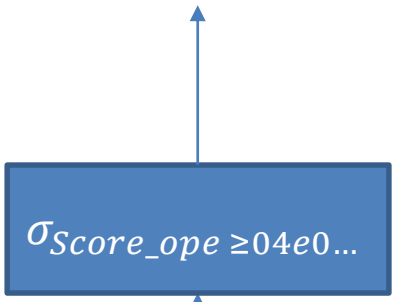
```
select *
from assignment
where score >= 90
```



StudentId	AssignId	Score
1	1	68
1	2	71
3	4	99
…	…	…

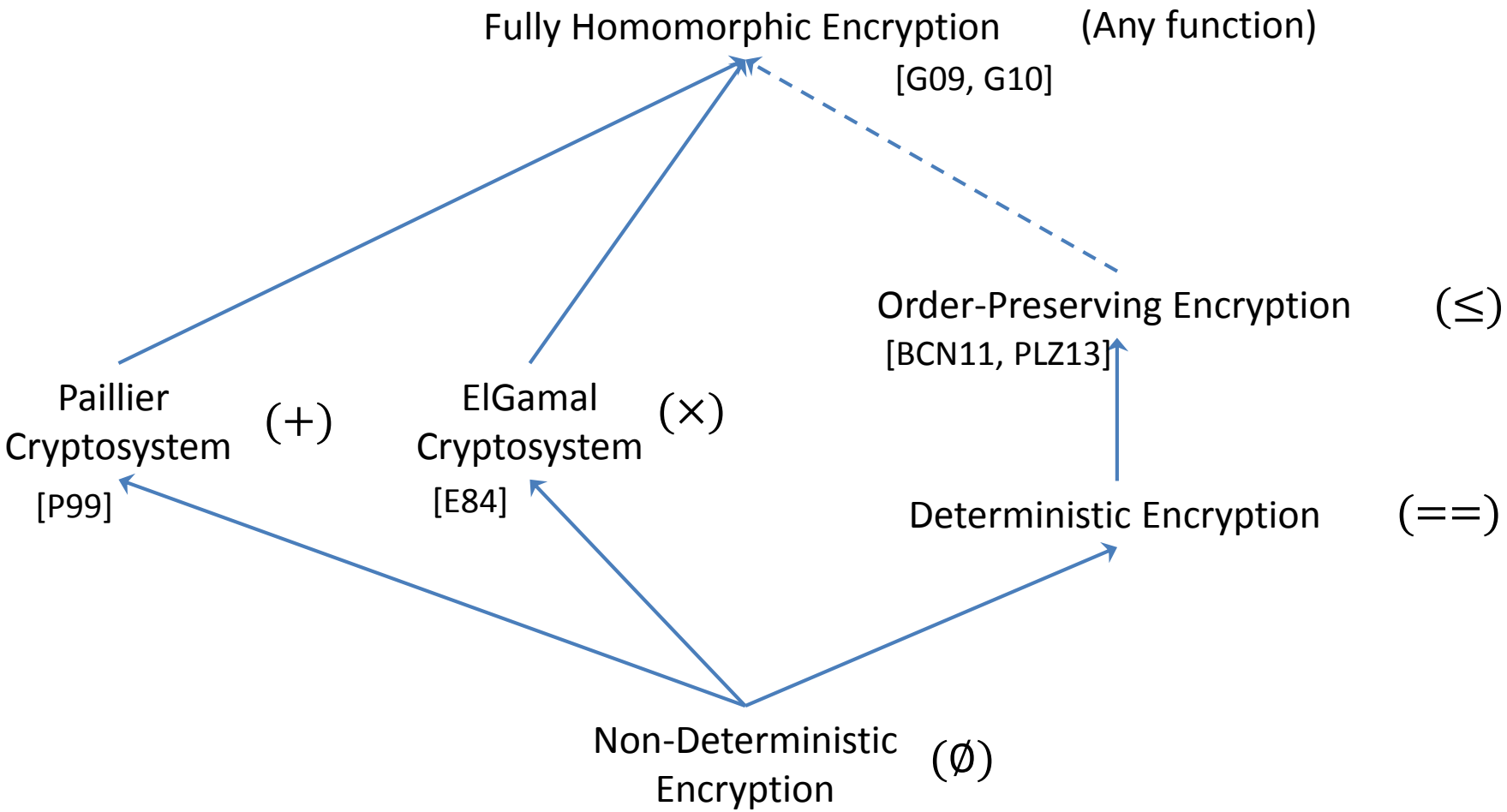
Order-Preserving Encryption

```
select *
from assignment
where score_OPE >= 0x04e062ff507458f9be50497656ed654c
```

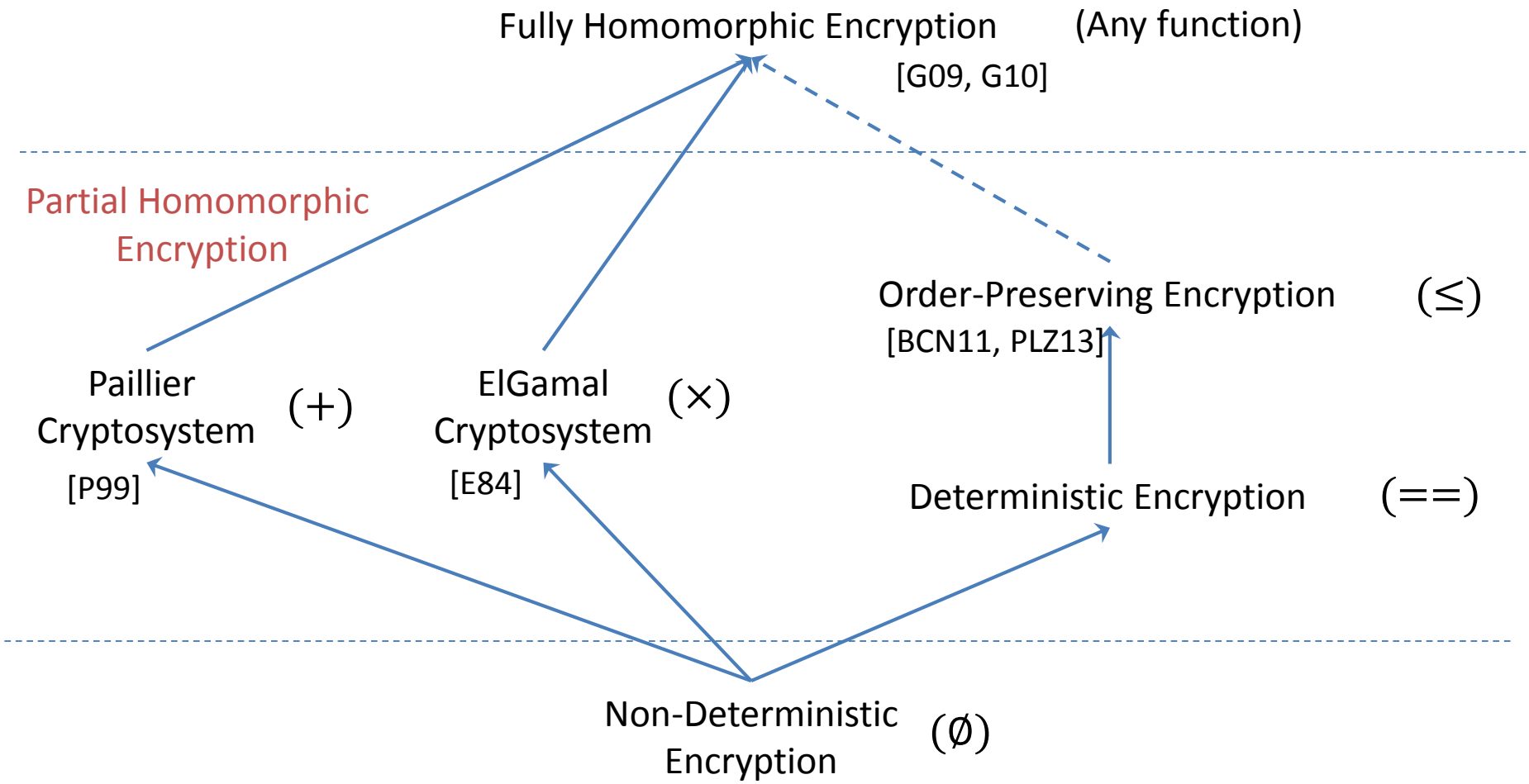


StudentId	AssignId	Score_OPE
1	1	0x0065fda789ef4e272bcf102787a93903
1	2	0x009b5708e13665a7de14d3d824ca9f15
3	4	0x08db34fb1f807678d3f833c2194a759e
…	…	…

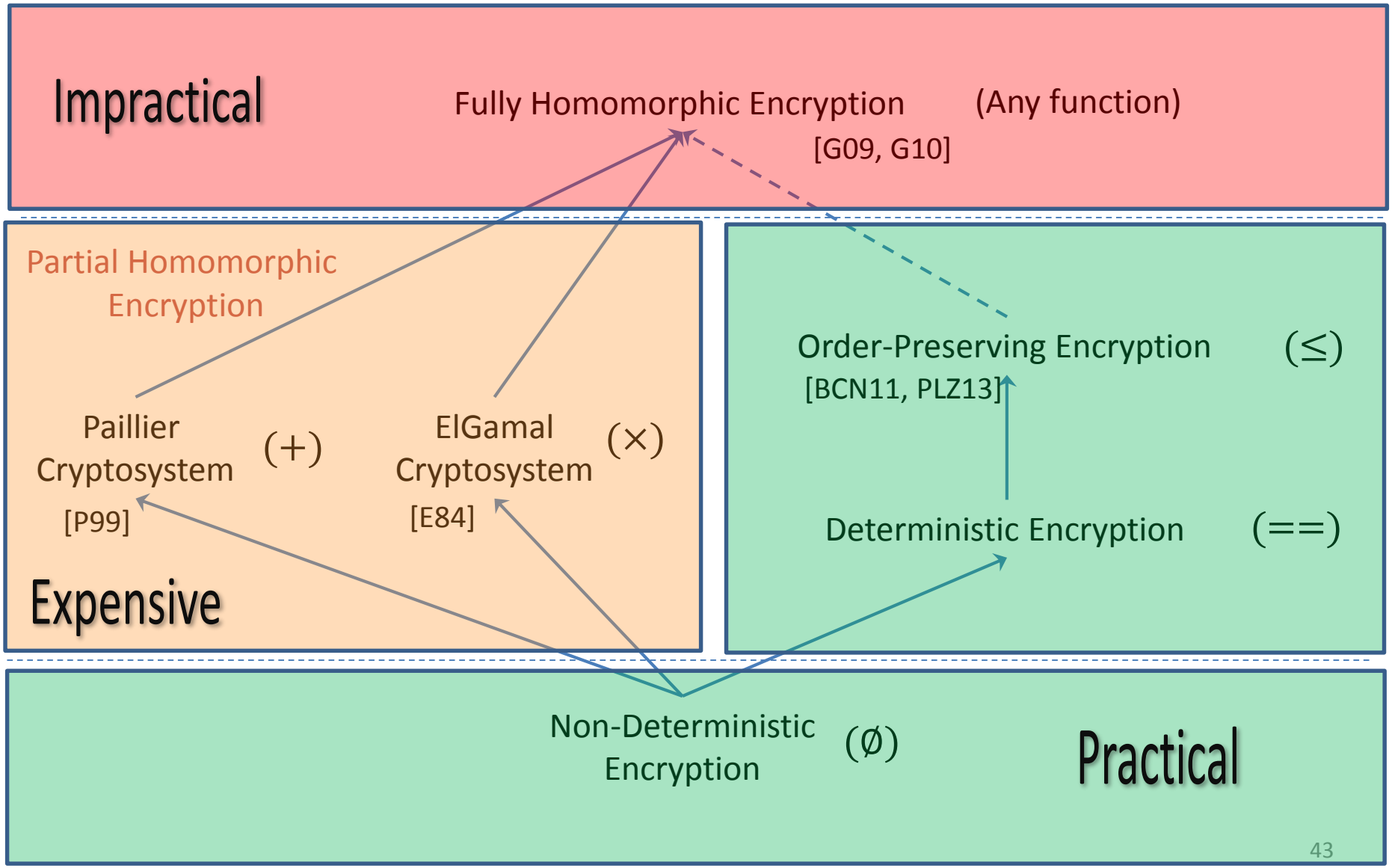
Homomorphic Encryption Schemes



Homomorphic Encryption Schemes



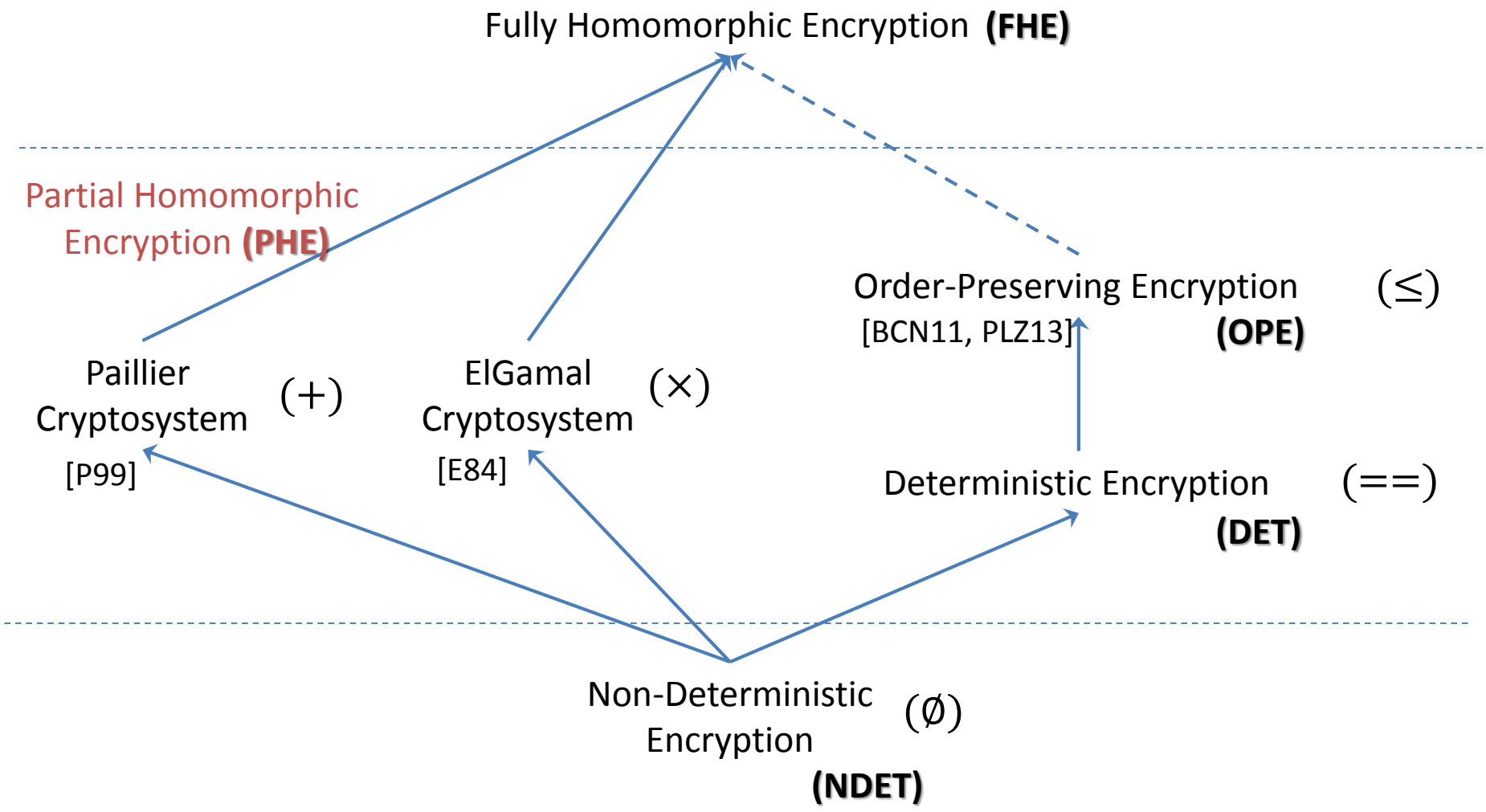
Homomorphic Encryption Schemes



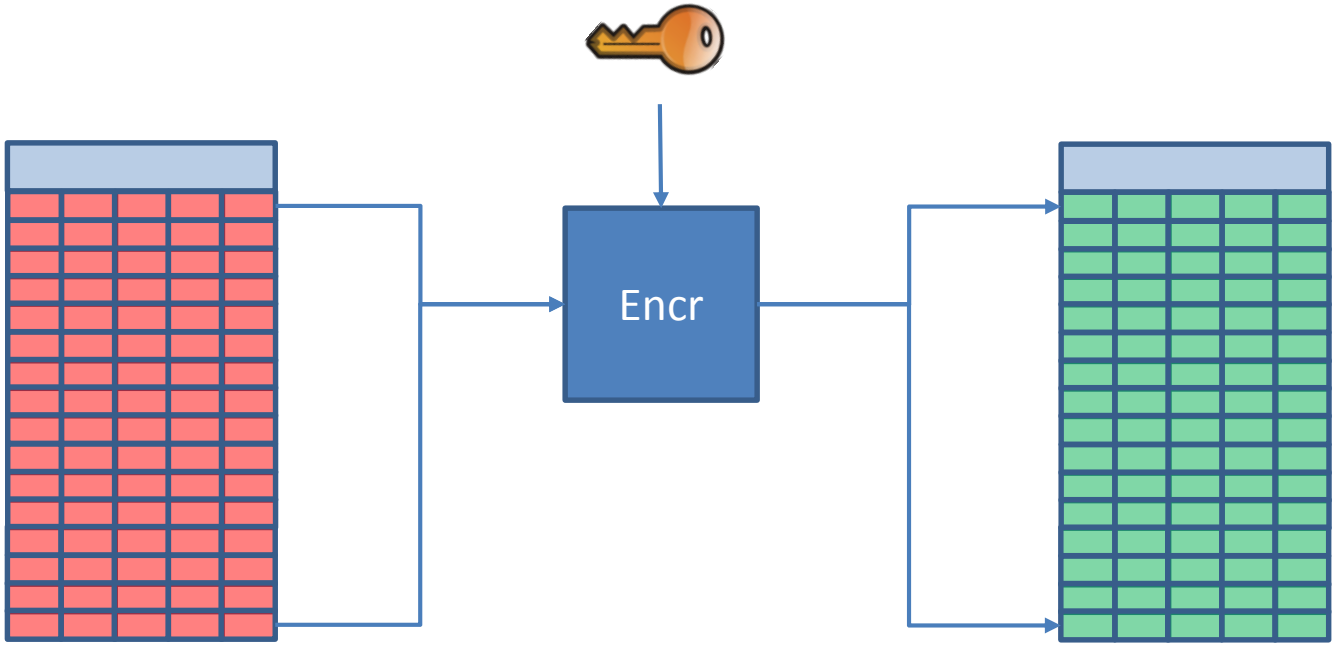
Homomorphic Encryption Schemes: Performance

Scheme	Space for 1 integer (bits)	Time for 1 operation
Fully Homomorphic Encryption	2^{14}	Cosmic time scales
Paillier ElGamal	2048	$\approx$ ms
Deterministic Order-preserving	128	$\approx$ µs

Homomorphic Encryption Schemes: Notation



How do I Encrypt a Database?

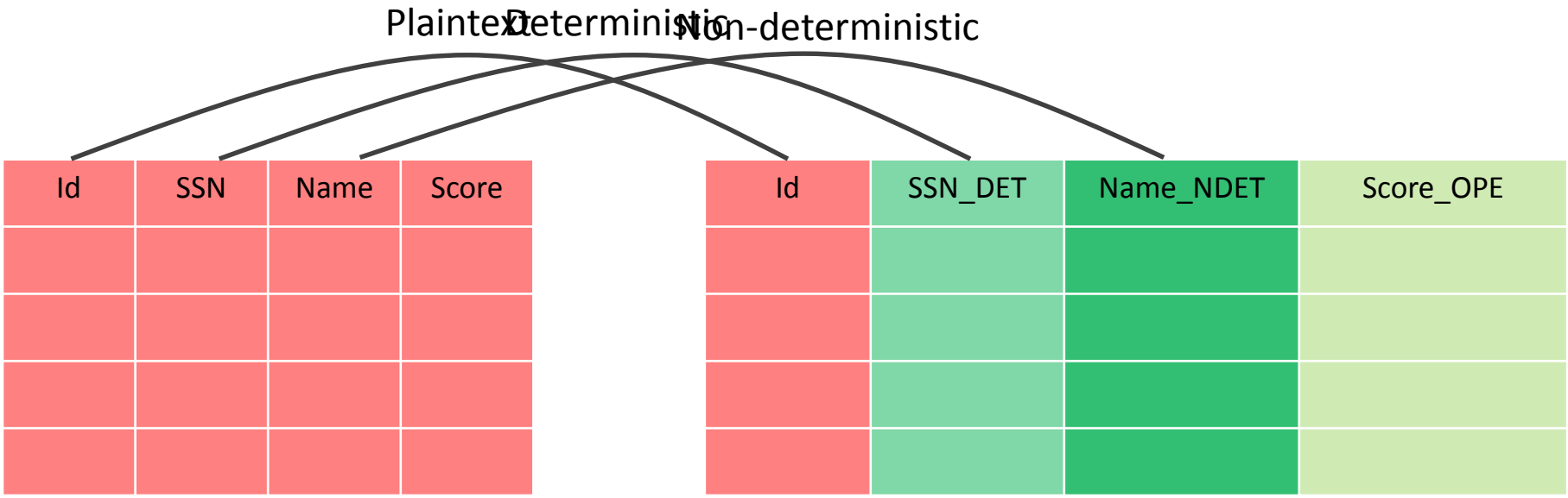


Cell granularity

Advantage:

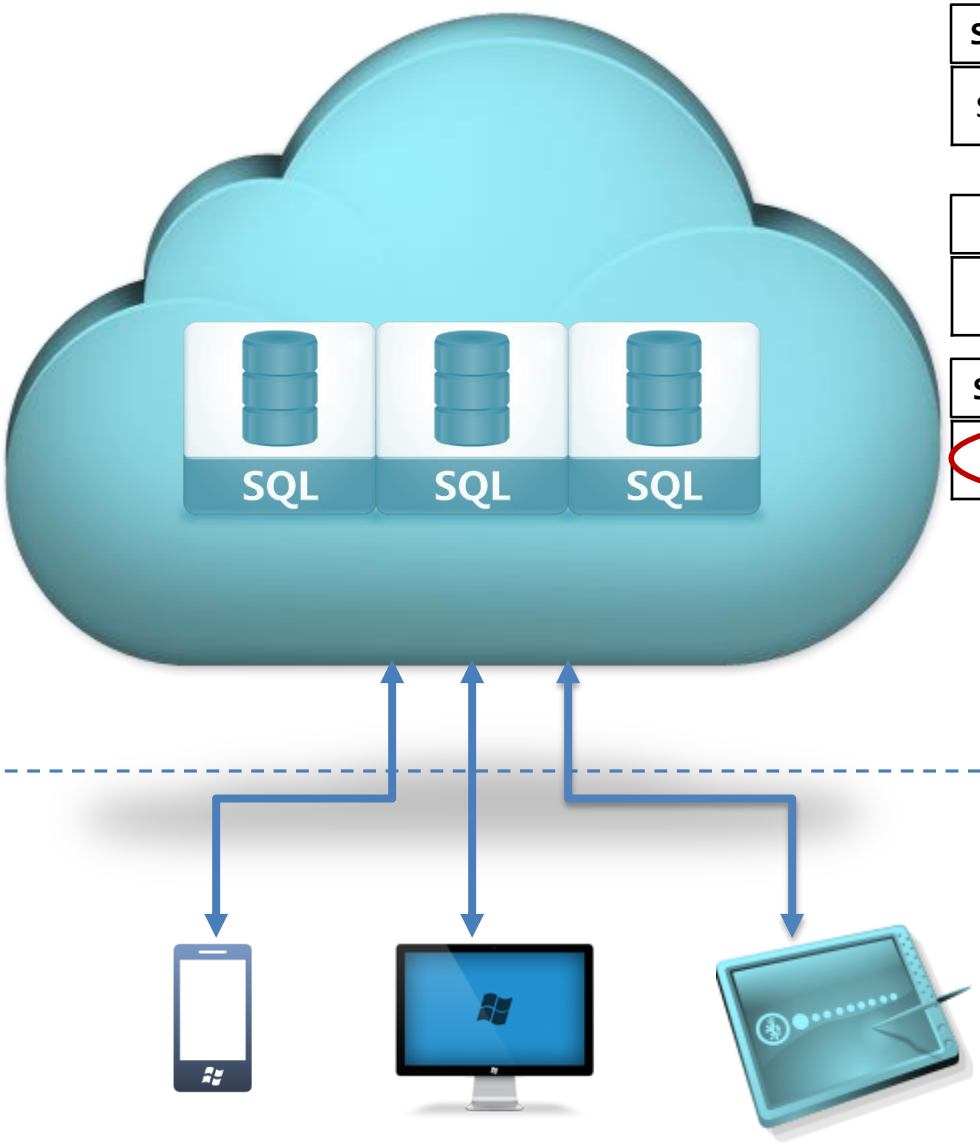
- Random access to a cell contents
- Mix n Match encryption

Mix n Match Encryption



Not covered: Deriving multiple keys. See [PRZ+11] for an example.

Example: Online Course Database



Student

StudentId	Name	Addr	GPA	CreditCard	…

Course

CourseId	Name	InstrId	…

StudentCourse

CourseId	StudentId	Grade	…

Roadmap

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- Secure In-Cloud Processing
- Security
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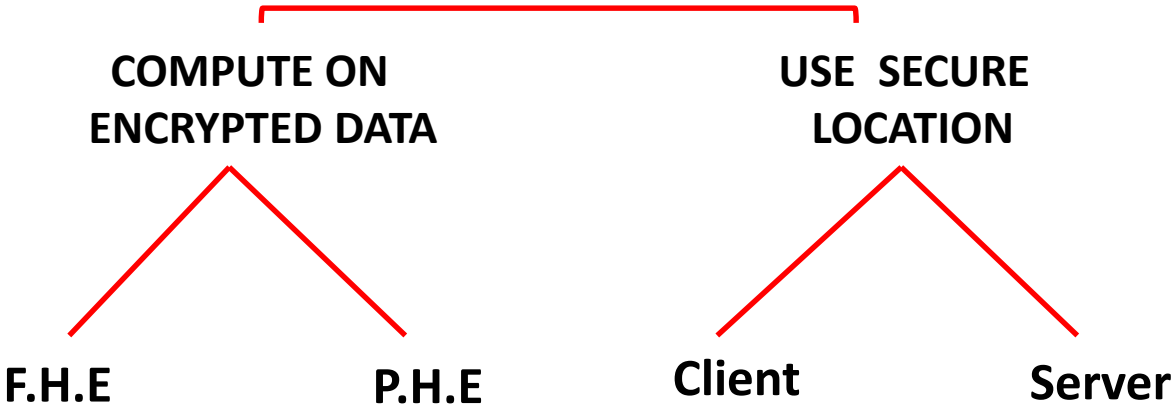
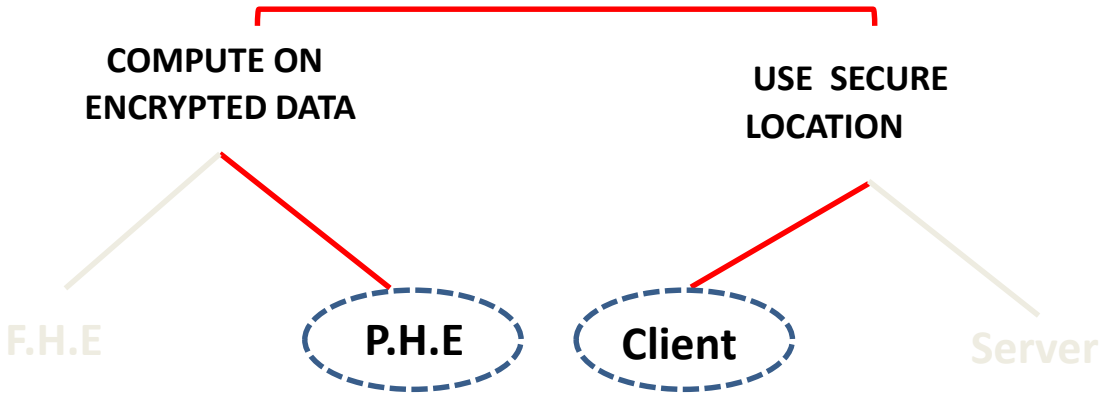
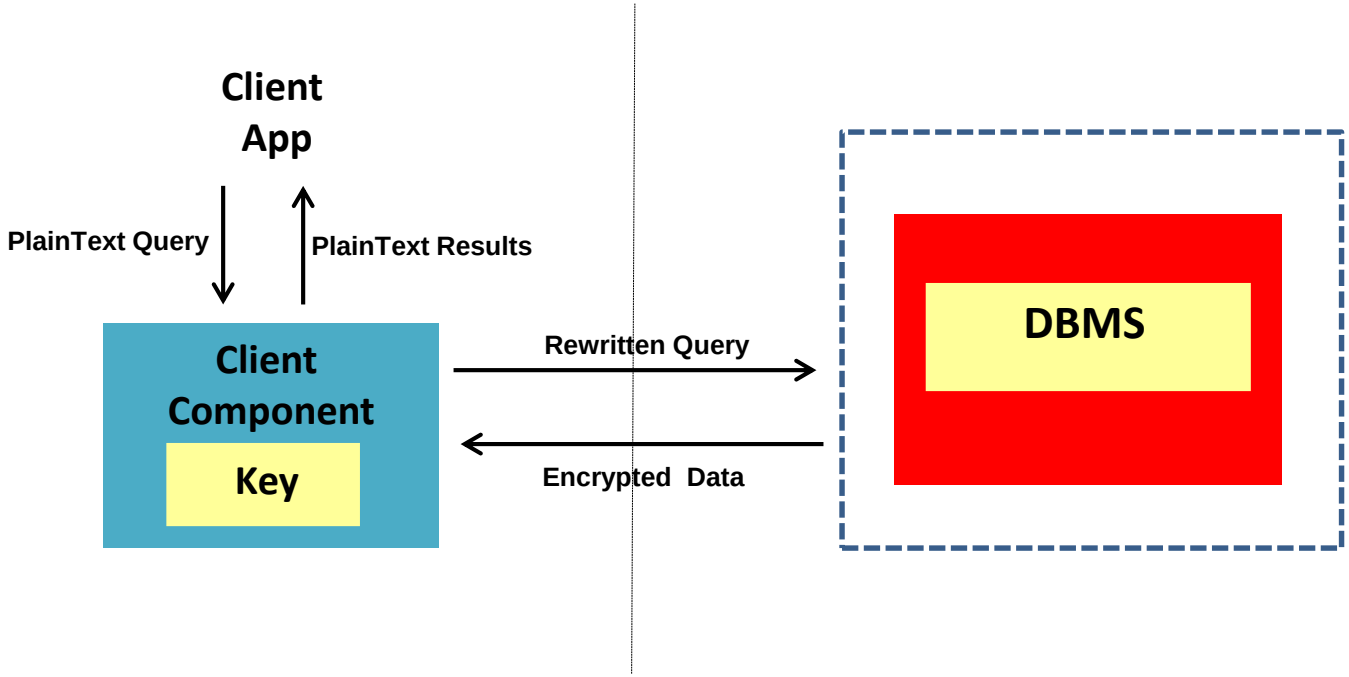
Design Choices



Trusted Client based Systems



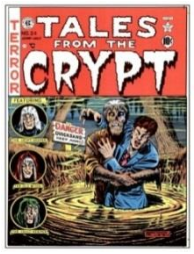
Trusted Client Architecture

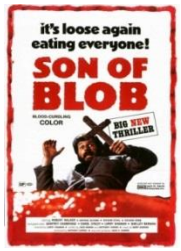


- Data not decrypted in DBMS
  - Only ciphertext seen in the DBMS
- No changes to DBMS/Client App

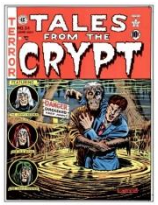
Systems

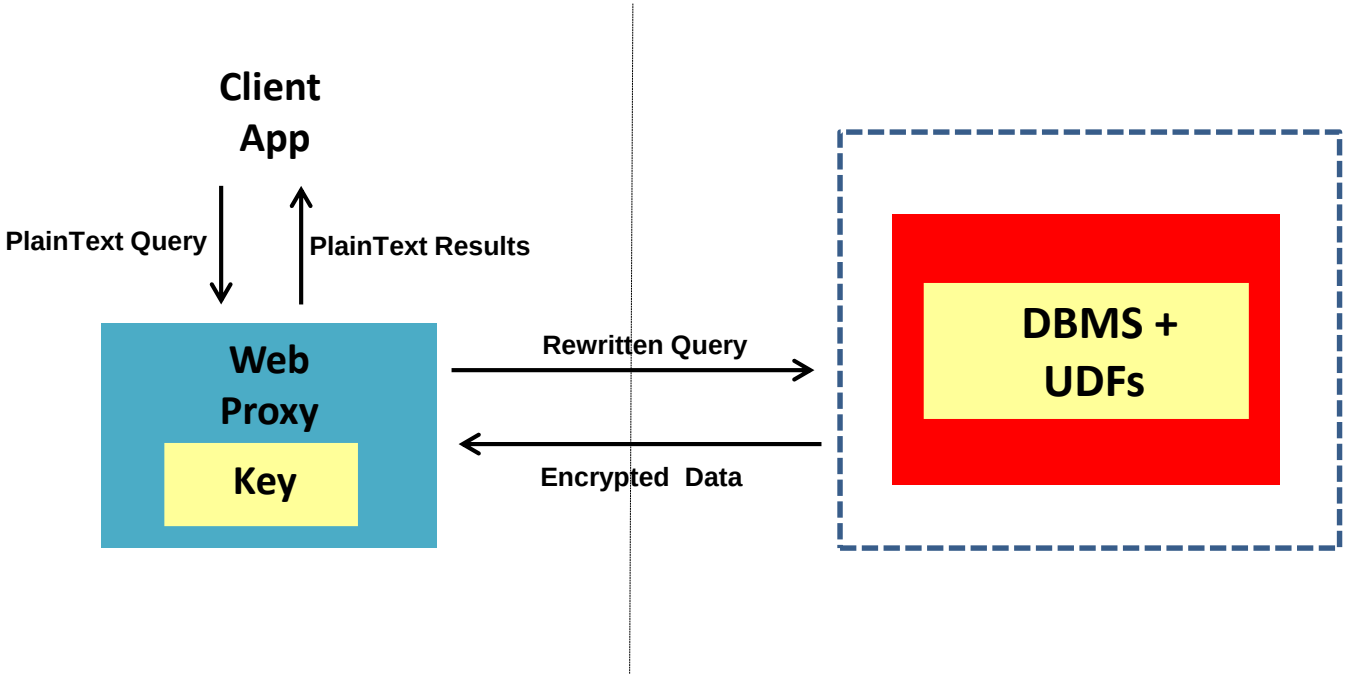
- Minimal Client Computation
  - Use P.H.E (Cryptdb)
- Residual Query Processing in Client
  - Blob Store
  - Use in conjunction with P.H.E (Monomi)





CryptDB Architecture





- Web proxy rewrites queries, decrypts result
- Leverage P.H.E techniques

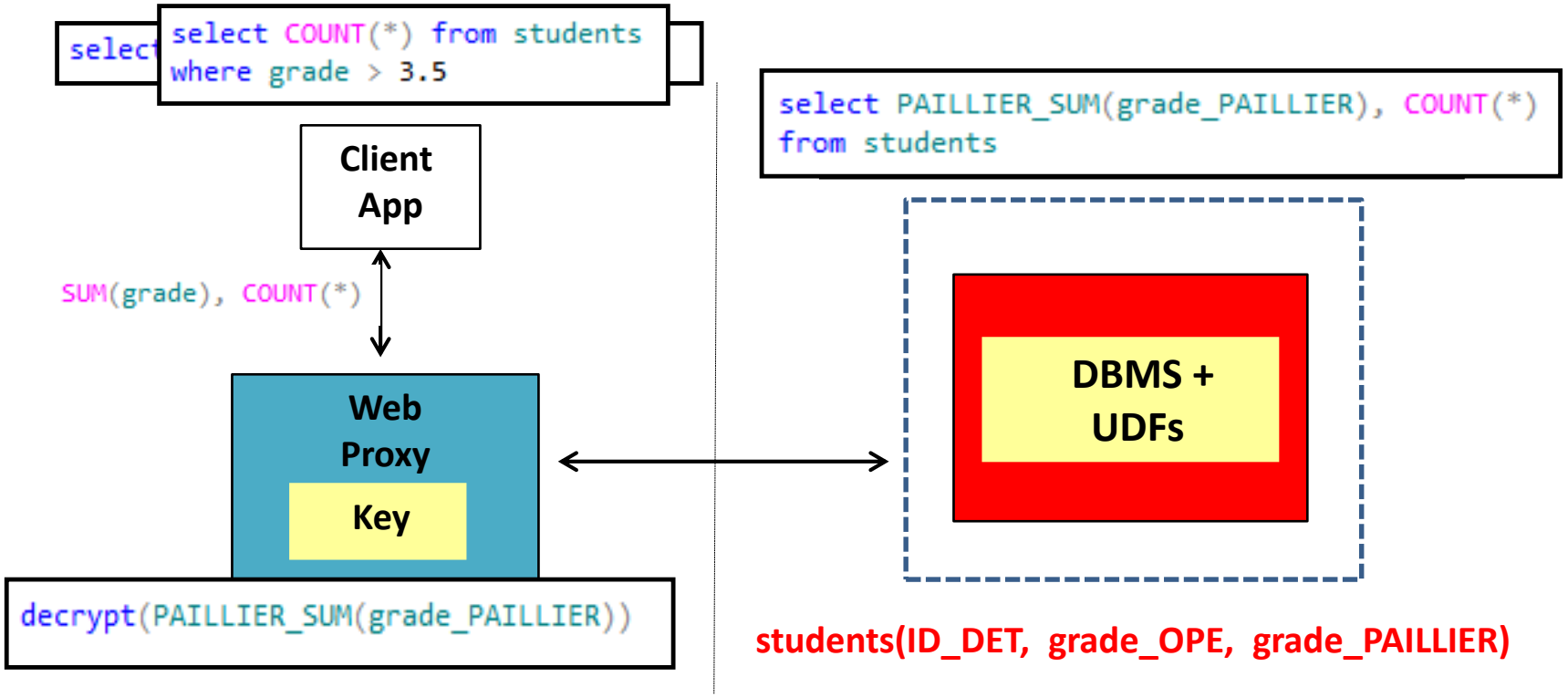
[PRZ+11]

Database Design

- students(ID, grade)
  - Point Lookups on ID column
  - SELECT and AGGREGATION queries on grade
- students(ID_DET, grade_OPE)
- students(ID_DET, grade_OPE, grade_PAILLIER)
  - Need to store columns encrypted in multiple ways
  - Static/Dynamic design based on workload

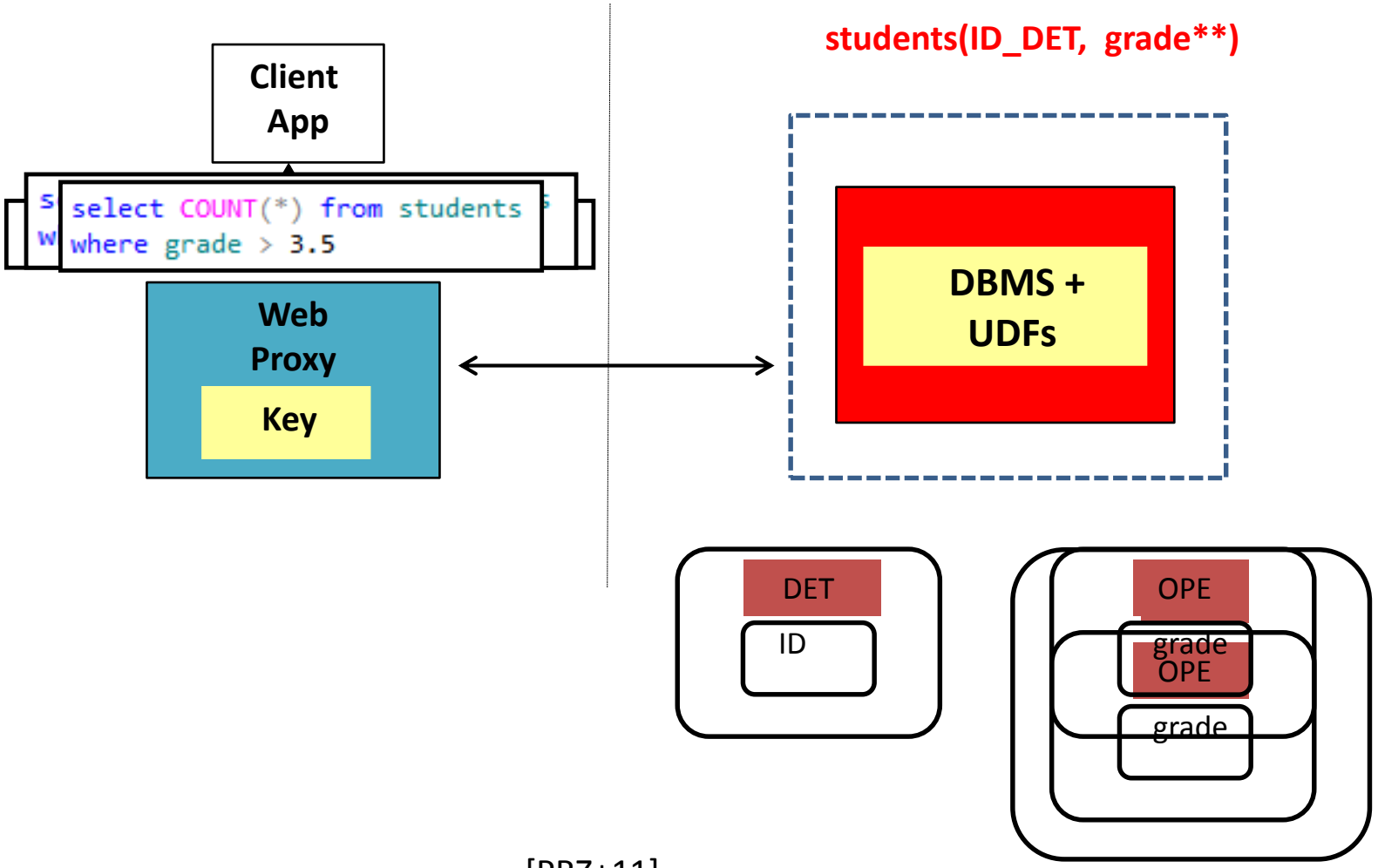
[PRZ+11]

Query Processing



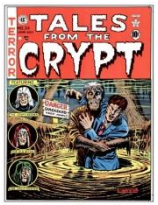
[PRZ+11]

Dynamic Database Design



[PRZ+11]

Summary



- P.H.E is not “free” – space overheads
  - For Paillier, to store one integer (32 bits), the ciphertext need to use 2048 bits!
  - Compact representation for paillier that is updatable – open problem.

- P.H.E is inherently limited – cannot address all of SQL

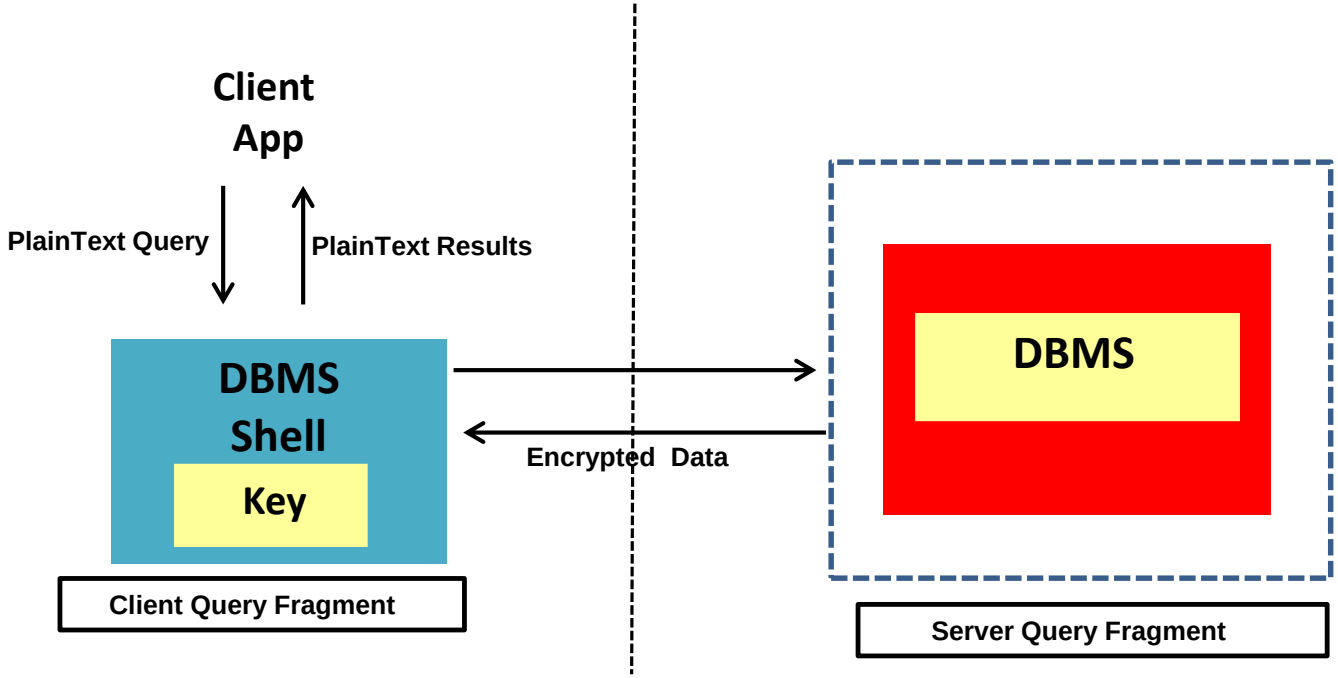
```
select STDEV(grade) from students
```

[GZ07]

Systems

- No Client Computation
  - Leverage P.H.E
  - e.g., Cryptdb
- Residual Query Processing on Client
  - e.g., Blob store
  - Use in conjunction with P.H.E (e.g., Monomi)

Computation in Trusted Client



- Distributed query processing between DBMS shell and untrusted DBMS

[HMI02] [HIL+02] [HMH08] [TFM13]

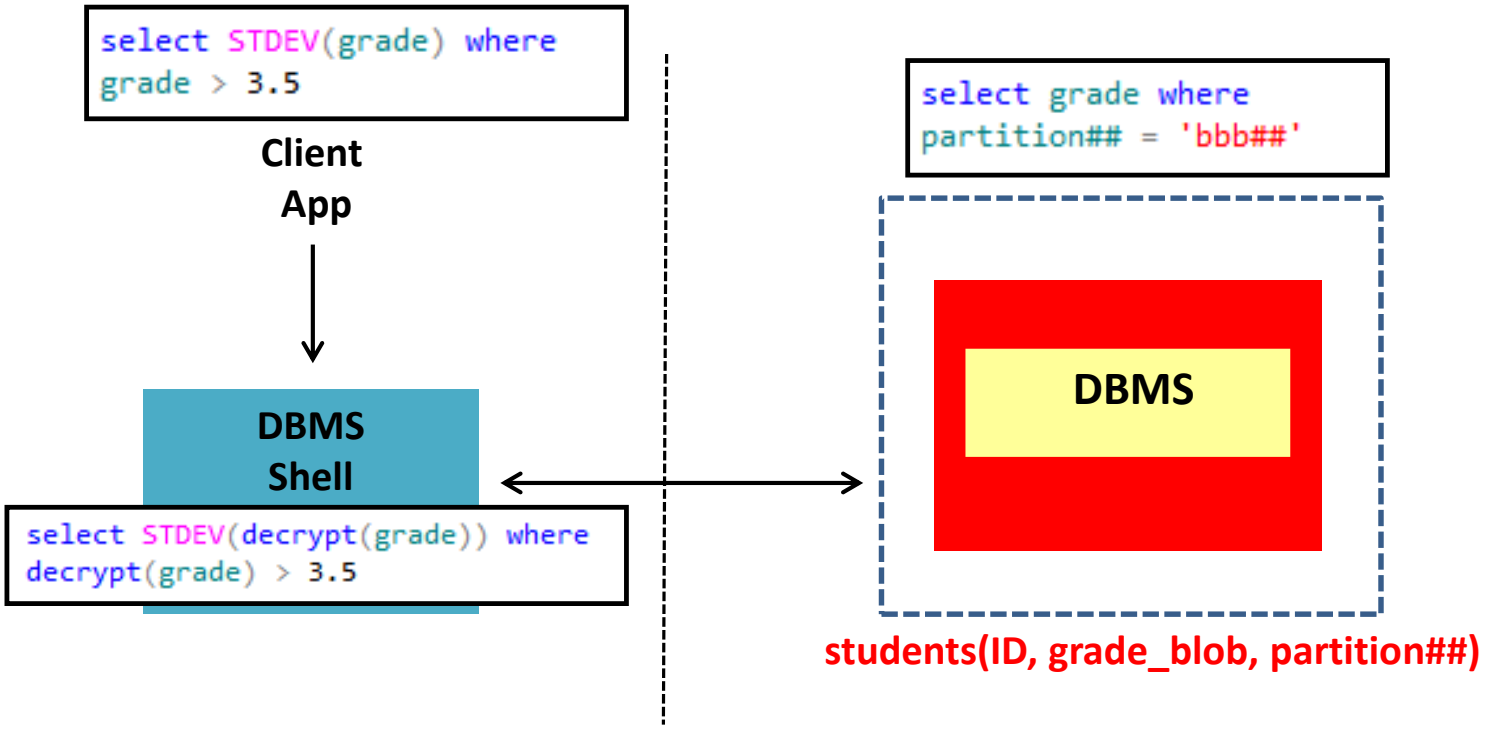
Blob Store: Database Design

- Encrypted data stored as ‘blobs’ (No computation)
  - students(ID, grade_blob)
- Use additional “fake” partitions to index blobs
  - students(ID, grade_blob, partition##)

grade	partition##
0 - 1.0	ccc##
1.0 – 2.0	aaa##
2.0 – 3.0	ddd##
3.0 – 4.0	bbb##

[HIL+02]

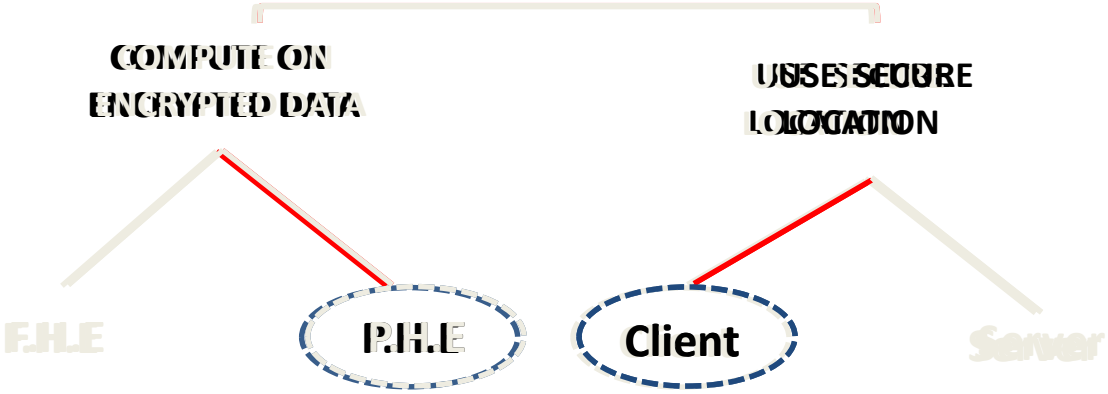
Blob Store: Query Processing



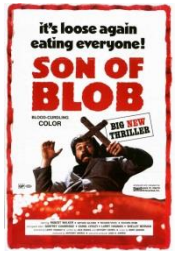
- Distributed query processing
  - Choosing appropriate partitioning
  - "Optimal" Query Splitting

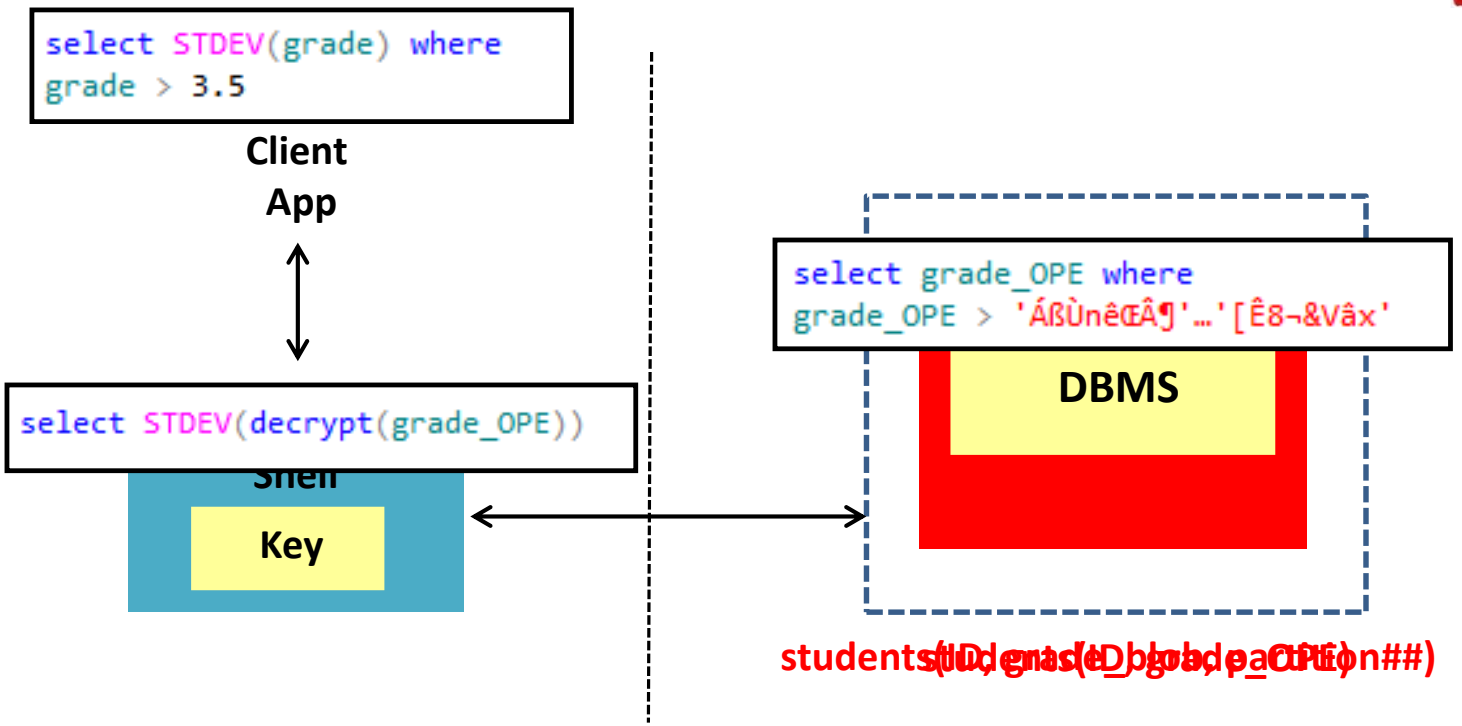
[HIL+02] [HIM05] [HMT04]

Trusted Client based Systems



Augmenting Blob Store





- Use P.H.E to push more computation to DBMS
  - Monomi

Pre-computation for complex queries

- Find student submissions that have been handled in a day late

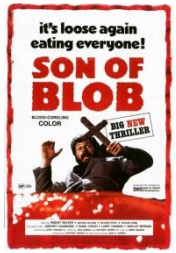
```
select id, count(*) from students
where submissiondate = deadline + 1
group by id
```

- Students(ID_DET, submissiondate_DET, deadline_DET, deadline_PAILLIER, deadlineplusone_DET)
  - Cannot "Mix and Match" different encryptions

```
select id, count(*) from students
where submissiondate = deadline_plusone
group by id
```

[TFM13]

Trusted Client: Summary



- No Server changes required to DBMS
- Works well for workloads where amount of data shipped is small
  - Physical Design is important for distributed queries
  - Pre-computation is not free
- Generality of approach is unproven
  - Integrity constraints, Triggers etc.
  - Automated tools to migrate database applications

“Key” Limitation: Robustness

- Stored procedure to find student submissions that have been handed in late (with delay as a parameter)

```
create procedure ComputeLateSubmissions (@delay)
as
  select id, count(*) from students
  where submissiondate = deadline + @delay
  group by id
```

- Cannot pre-compute all possible input values
  - why store the table in the cloud!

TakeAway Quiz

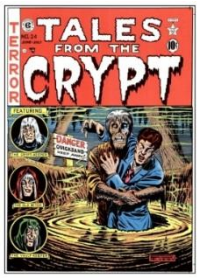
The Trusted Client approach:

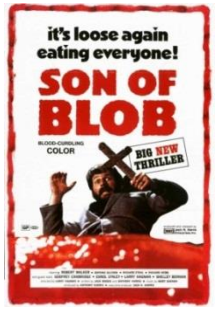
a) ~~Is "Dead" on arrival~~

b) ~~Adding BLOB() keyword to SQL~~

c) Is effective when most work can be offloaded to the server

d) Is not a robust solution for general purpose queries





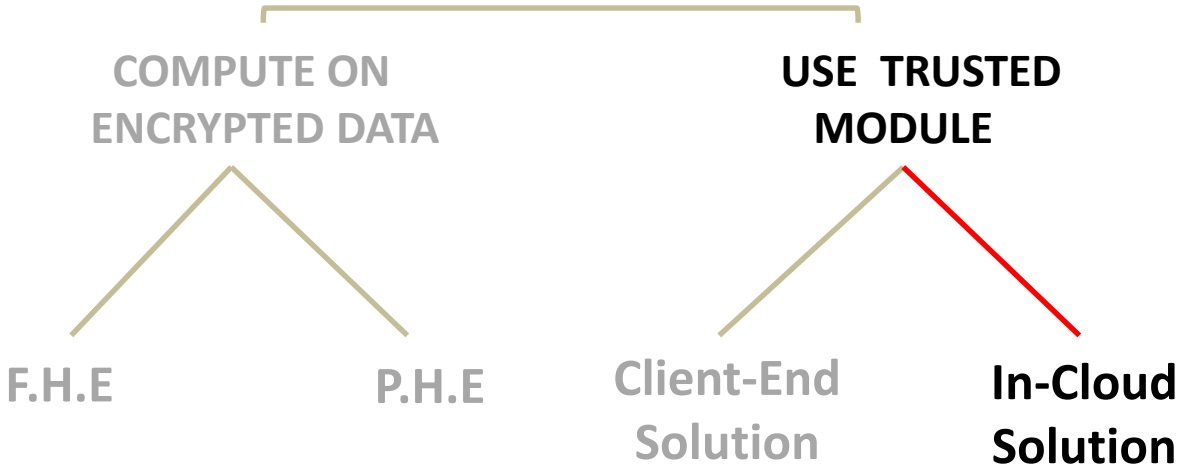
Still to come …

Is it possible to design a system where only the results are shipped to the client irrespective of query complexity ?

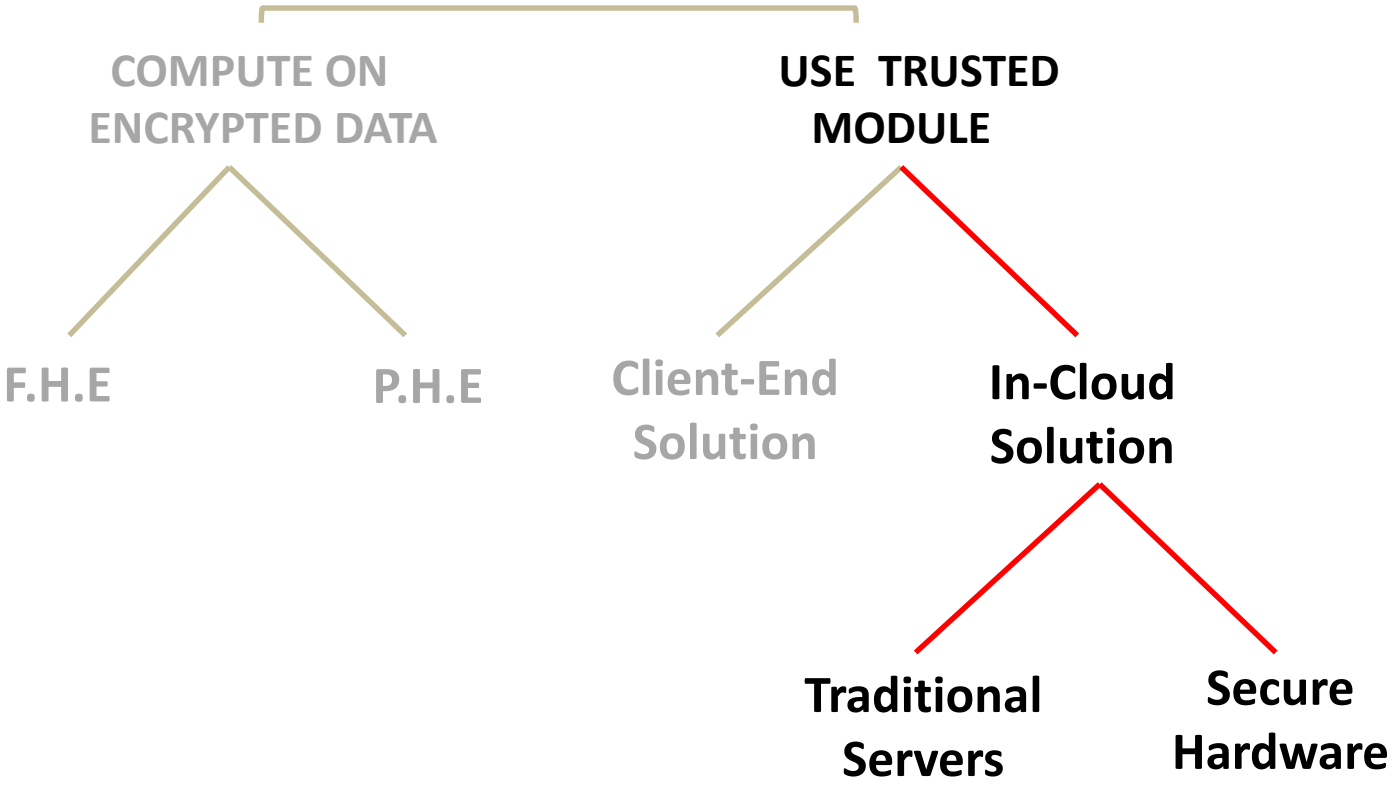
Roadmap

- Introduction
- Overview
- Basics of Encryption
- Trusted Client based Systems
- Secure In-Cloud Processing
- Security
- Conclusion

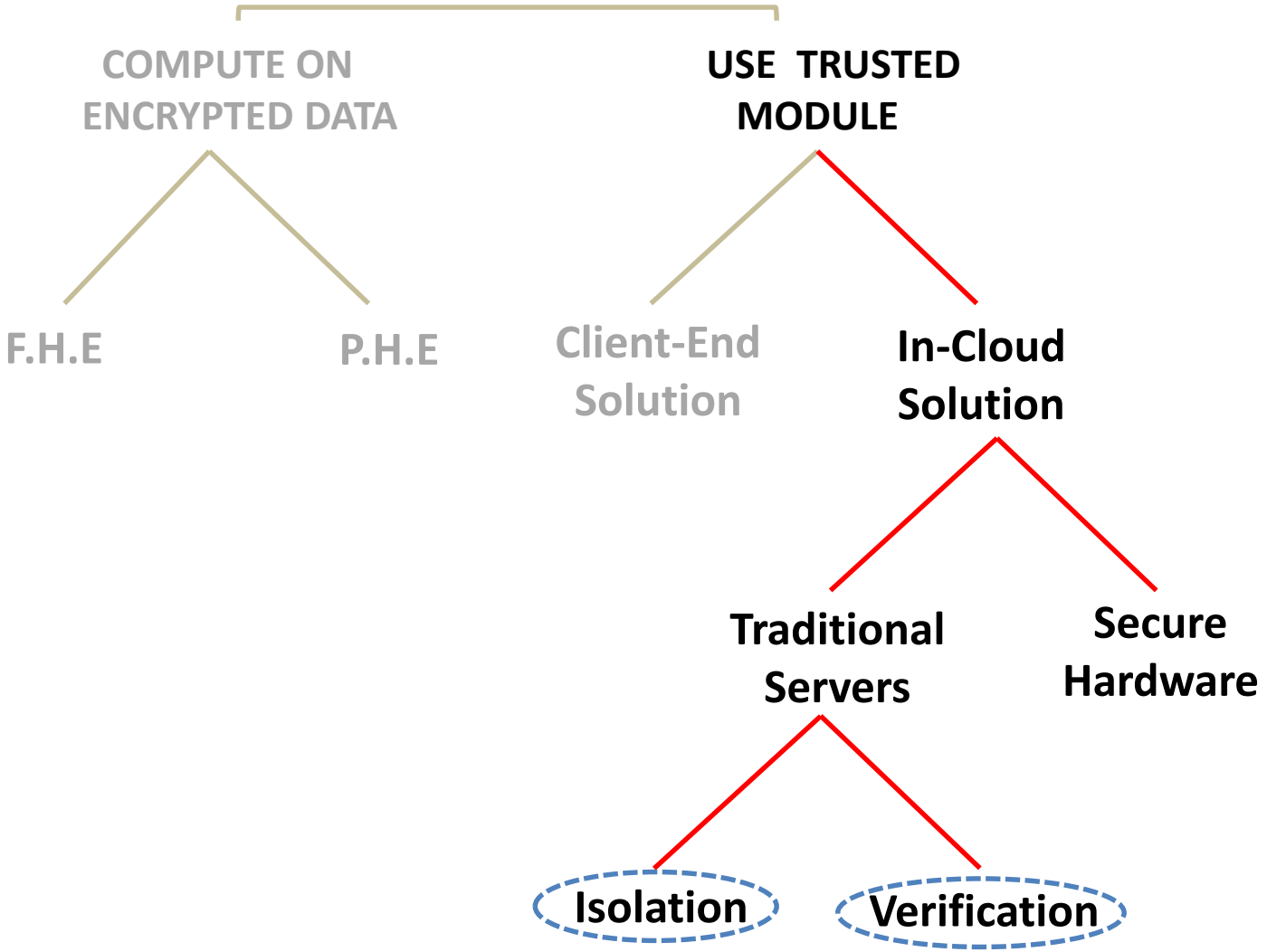
Secure In-Cloud Processing



Secure In-Cloud Processing



Secure In-Cloud Processing



Securing Traditional Servers

- Isolation
  - Physical (location, network)
  - Logical (hypervisor/VM, strict policies)
- Verification

Example: Amazon GovCloud [AWSGC]

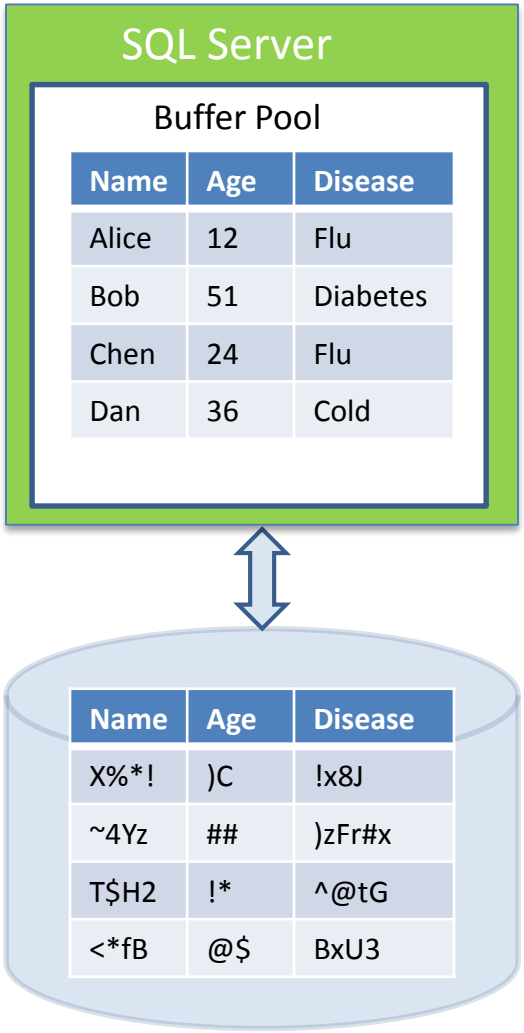
Securing Traditional Servers

- Isolation
- Verification
  - Static (TPM authenticated boot)
  - Dynamic (malware detectors)

[TCGNotes, TPMSpec]

Secure Server Advantages

- Lowest impact solution
  - Use existing components, software and policies
  - We can all go home!



Securing a Server is HARD!

What Makes it Hard to Secure a Server?

- Built for flexibility & adaptability
  - General-purpose processors
    - A unified-memory space is a serious vulnerability
    - Security guarantees require 100% bug-free software

What Makes it Hard to Secure a Server?

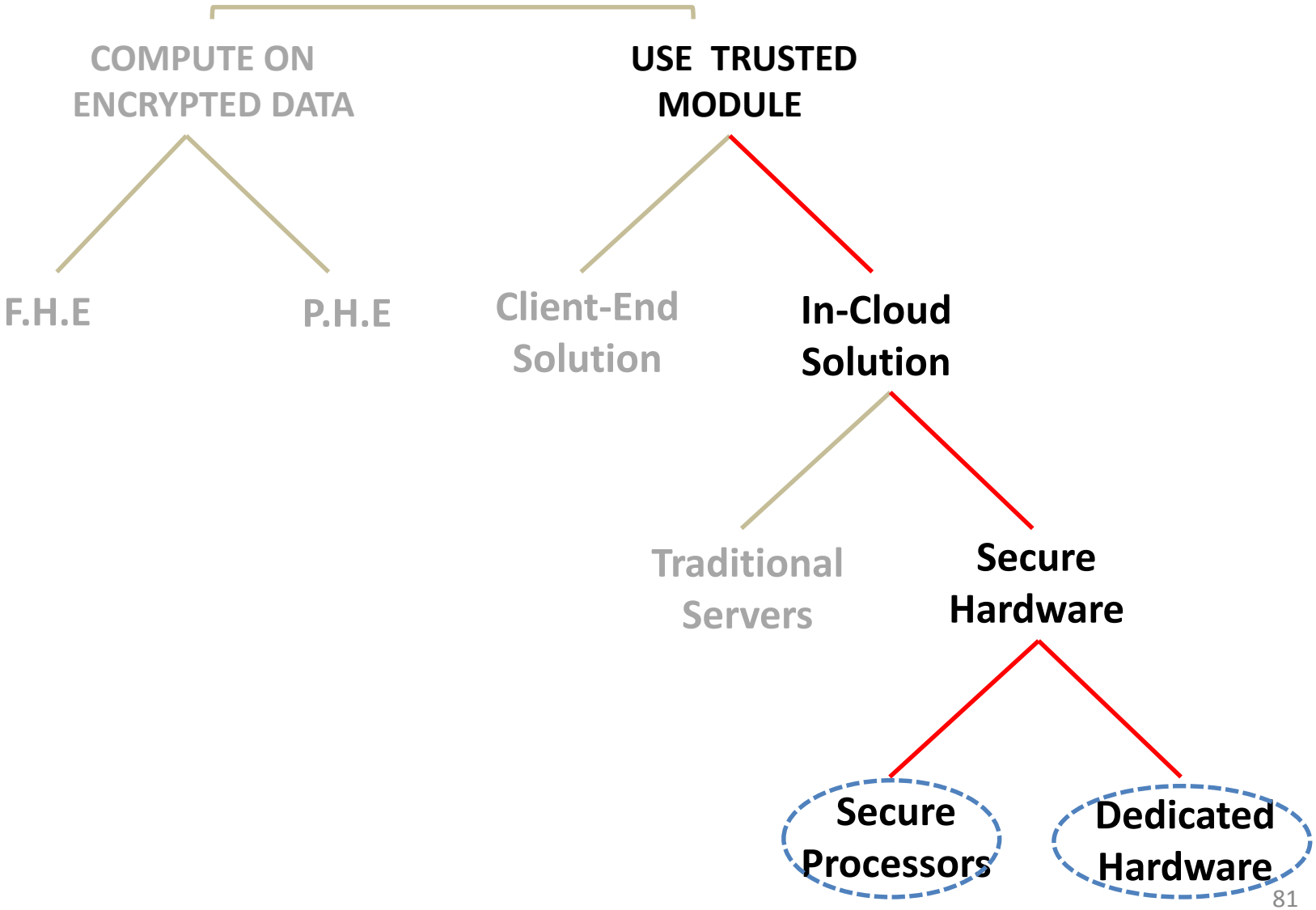
- Complex software stacks make rigorous security guarantees impossible
  - Largest formally verified OS kernel in literature is 8,700 lines of C and 600 lines of assembly
  - i.e. ‘Why don’t they make the whole plane out of that “black box” stuff?’

[K09]

What Makes it Hard to Secure a Server?

- We need to simplify the trusted computing platform!
- Better architectural isolation will also help!

Secure In-Cloud Processing



Previous Use of Secure Hardware

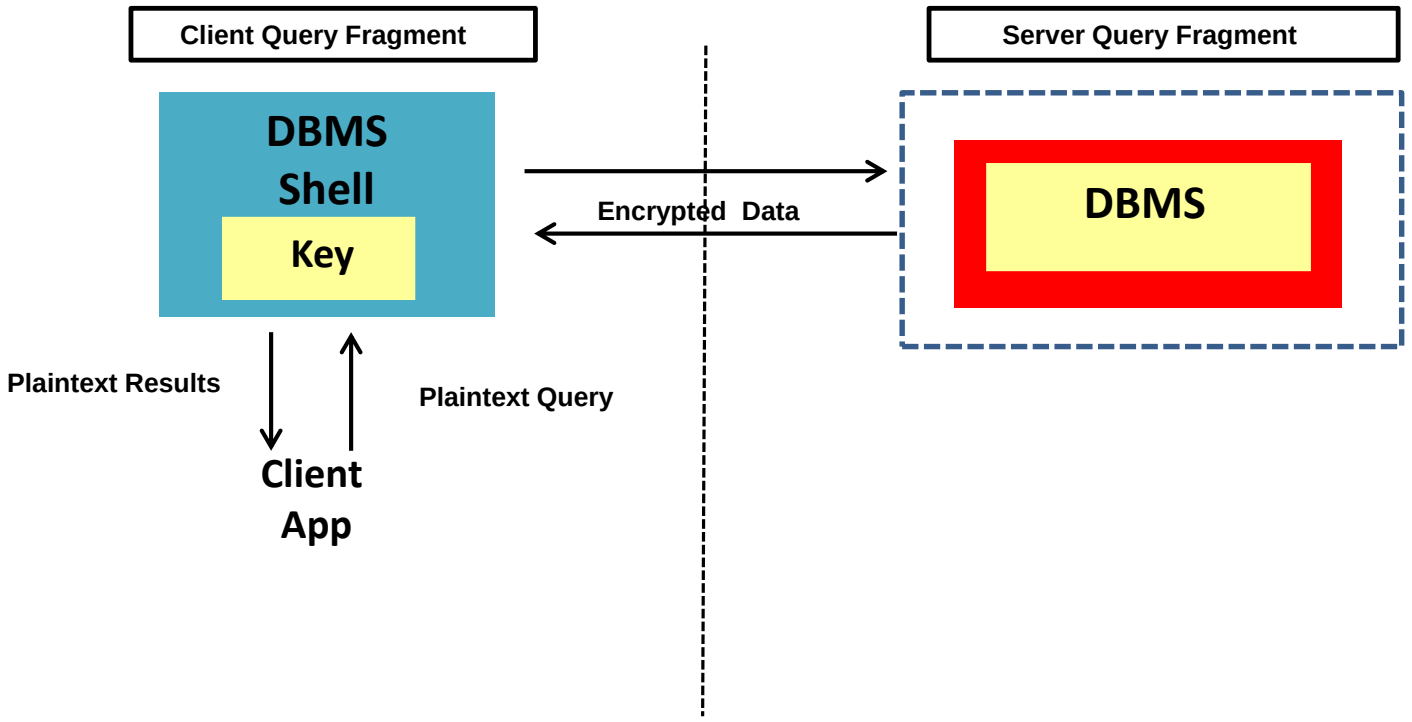
- Secure Co-Processor
  - ATM, smart cards
- Hardware Security Modules
  - Tamper-proof crypto acceleration
- FPGAs
  - Military use
- Limited Resources!

[TCGNotes]

IBM 4764 PCI-X Cryptographic Coprocessor

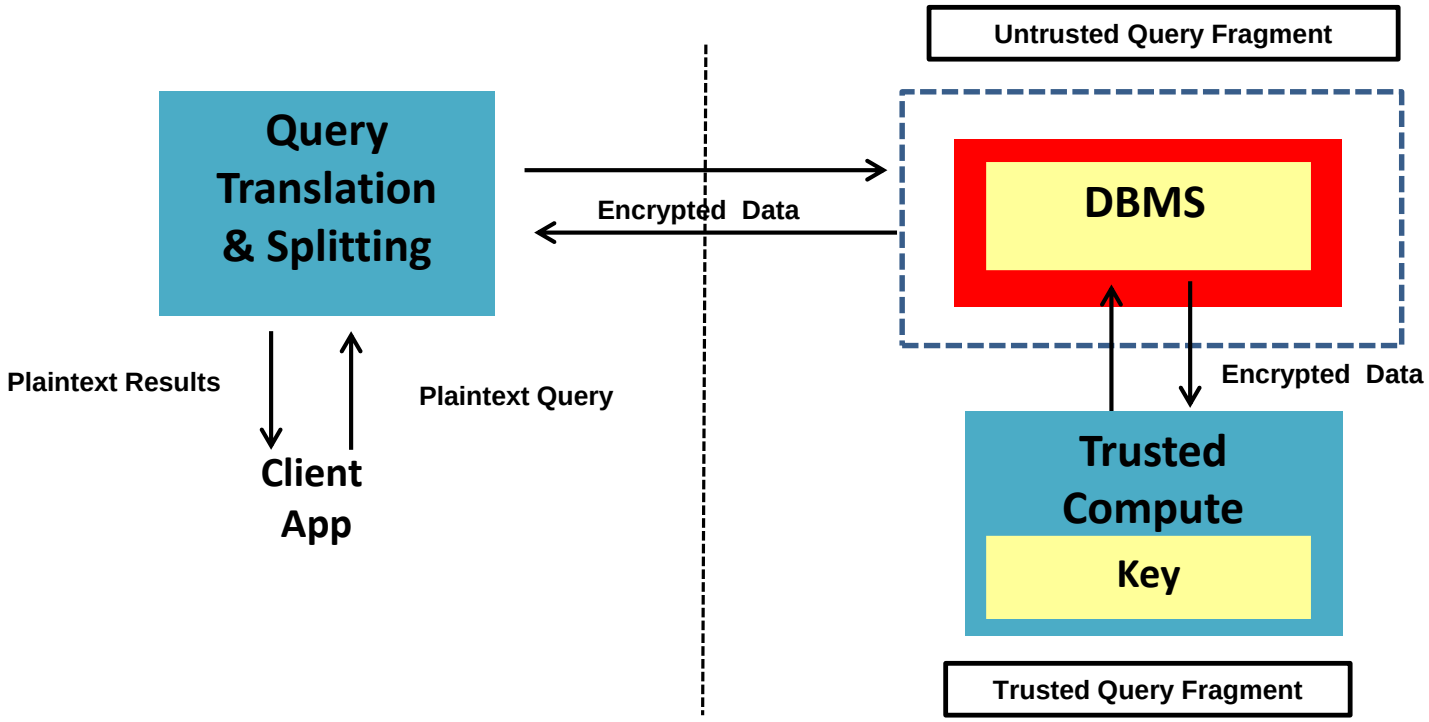
Secure FPGA

Trusted Client Architecture



- Distributed query processing between untrusted DBMS and client-end DBMS shell

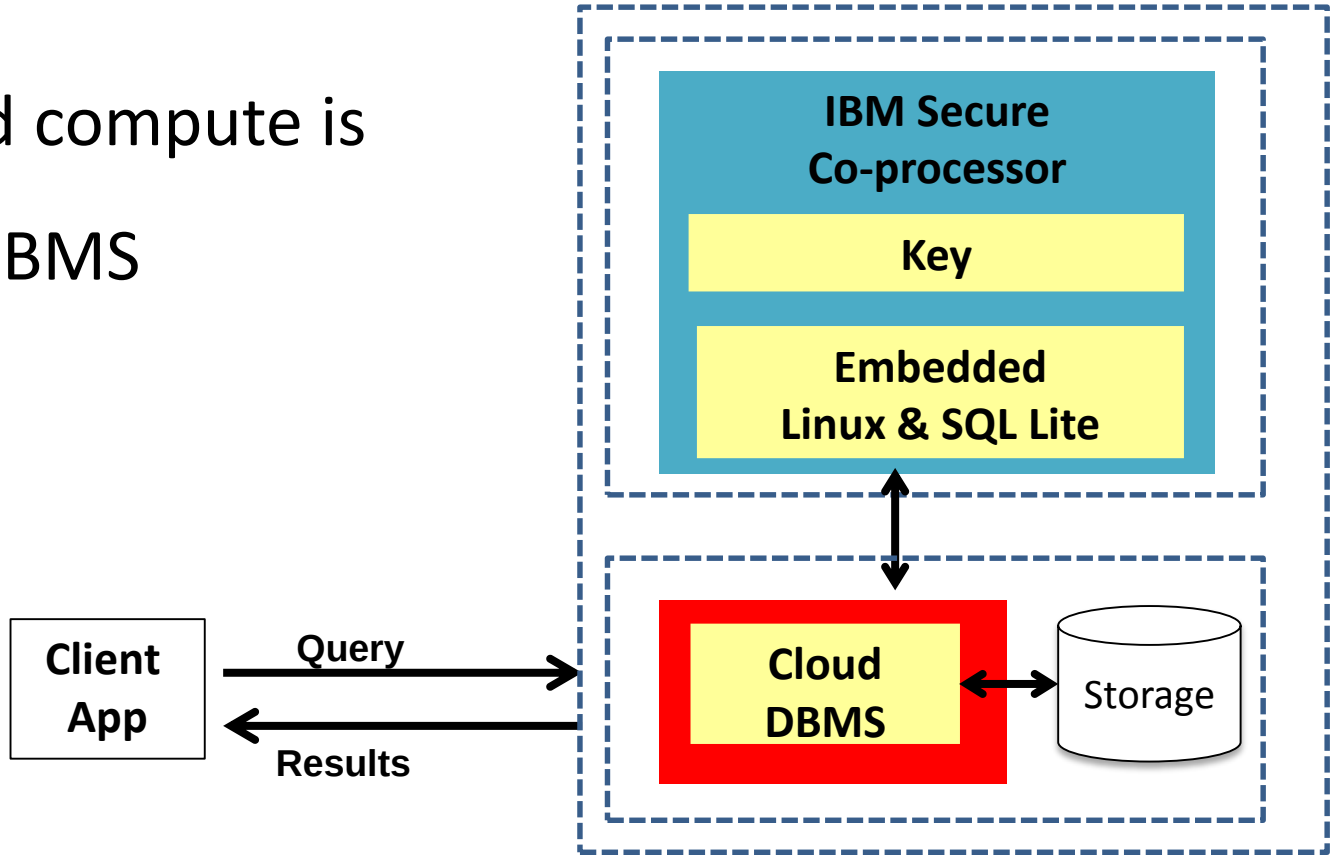
Secure In-Cloud Compute Architecture



- Distributed query processing between untrusted DBMS and trusted cloud compute
- Solutions differ in granularity of integration

Secure Processors

- TrustedDB
  - Trusted compute is a full DBMS



[BS11]

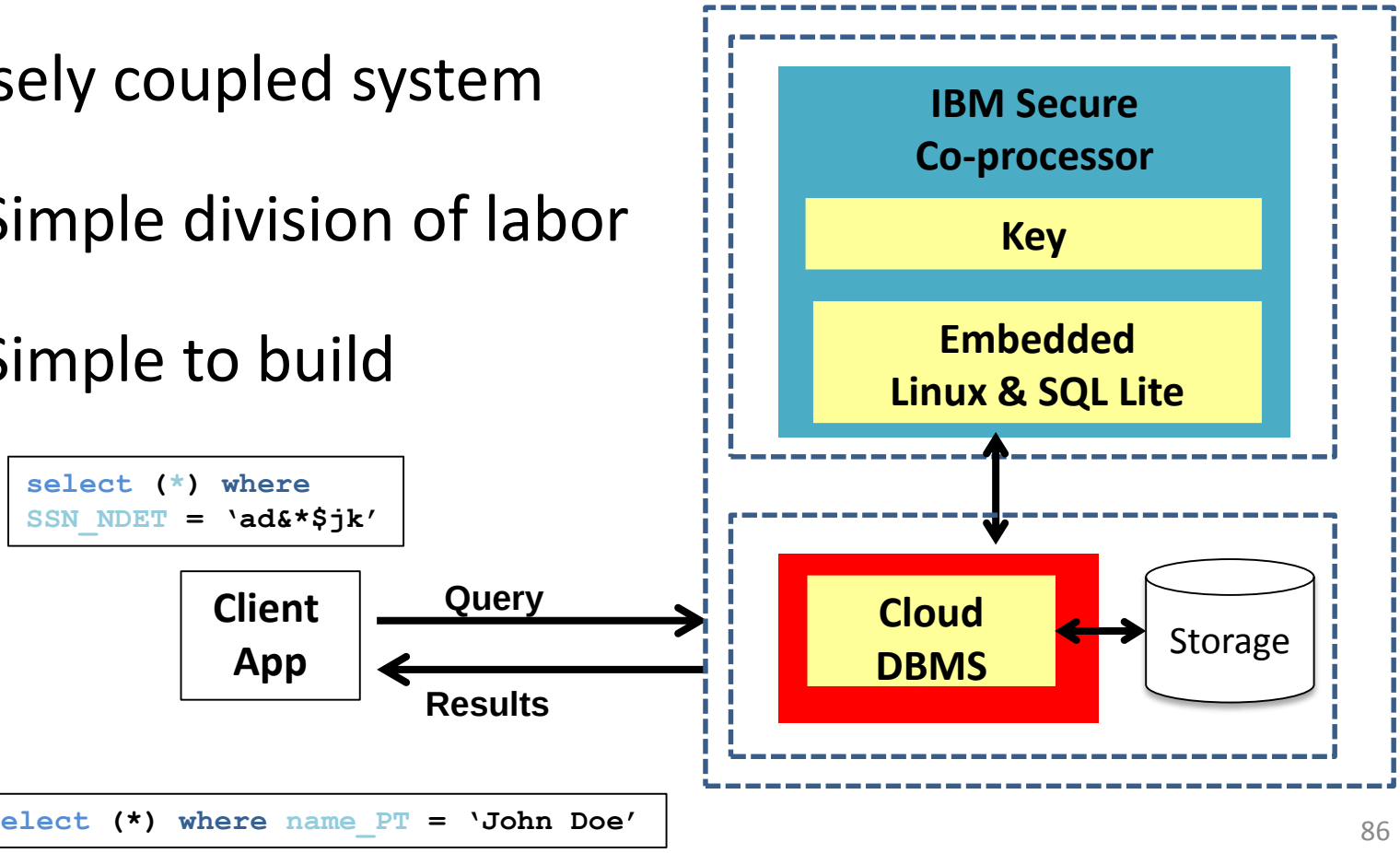
Advantages of Loosely-Coupled Arch.

- Full trusted DBMS ➔

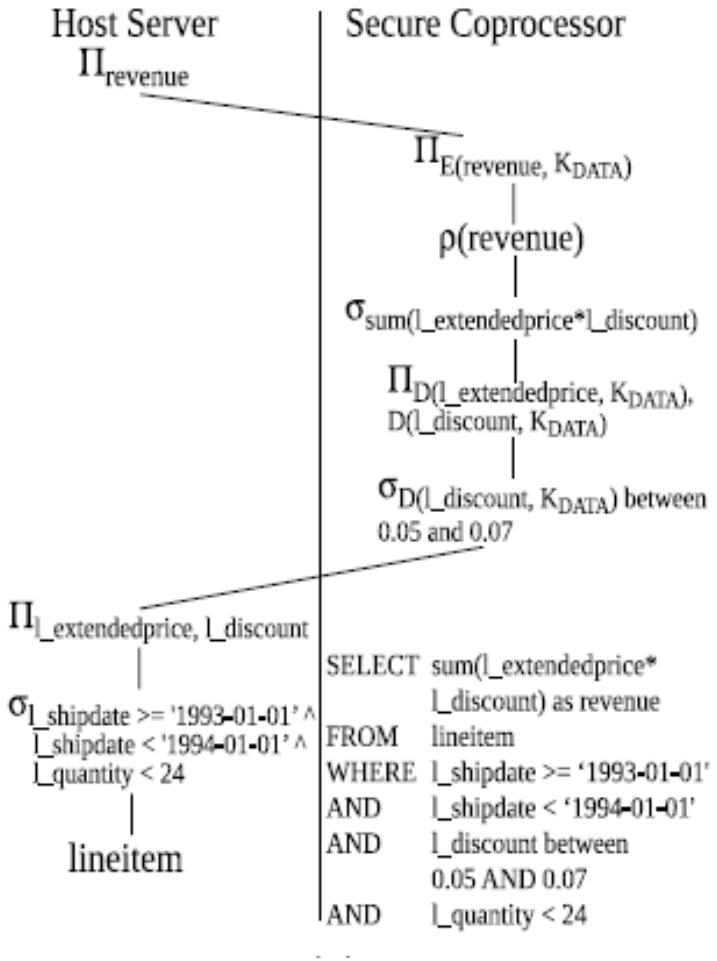
  loosely coupled system

  – Simple division of labor

  – Simple to build



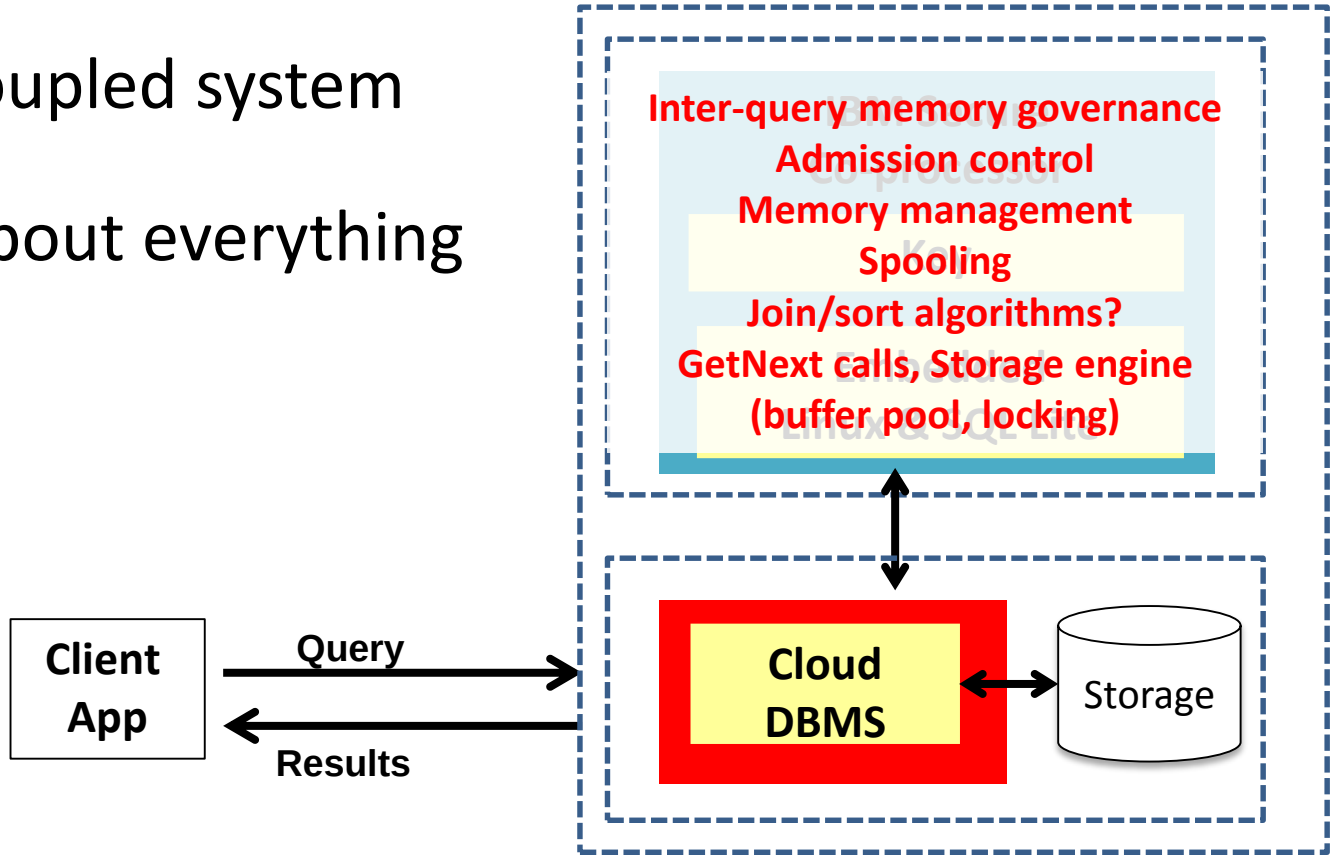
TrustedDB Hybrid Example



[BS11]

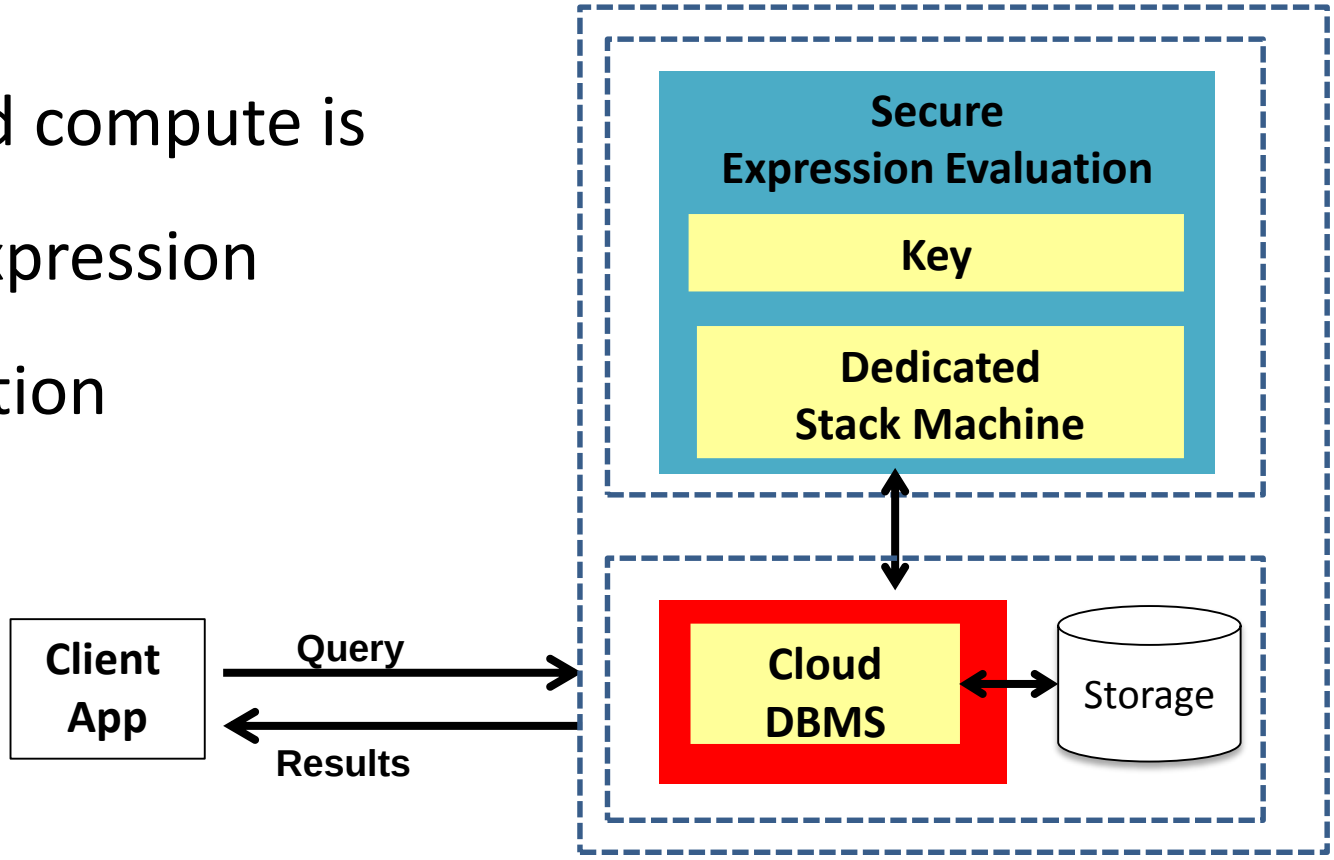
Limitations of Loosely-Coupled Arch.

- Full trusted DBMS ➔ loosely coupled system
  - How about everything else?



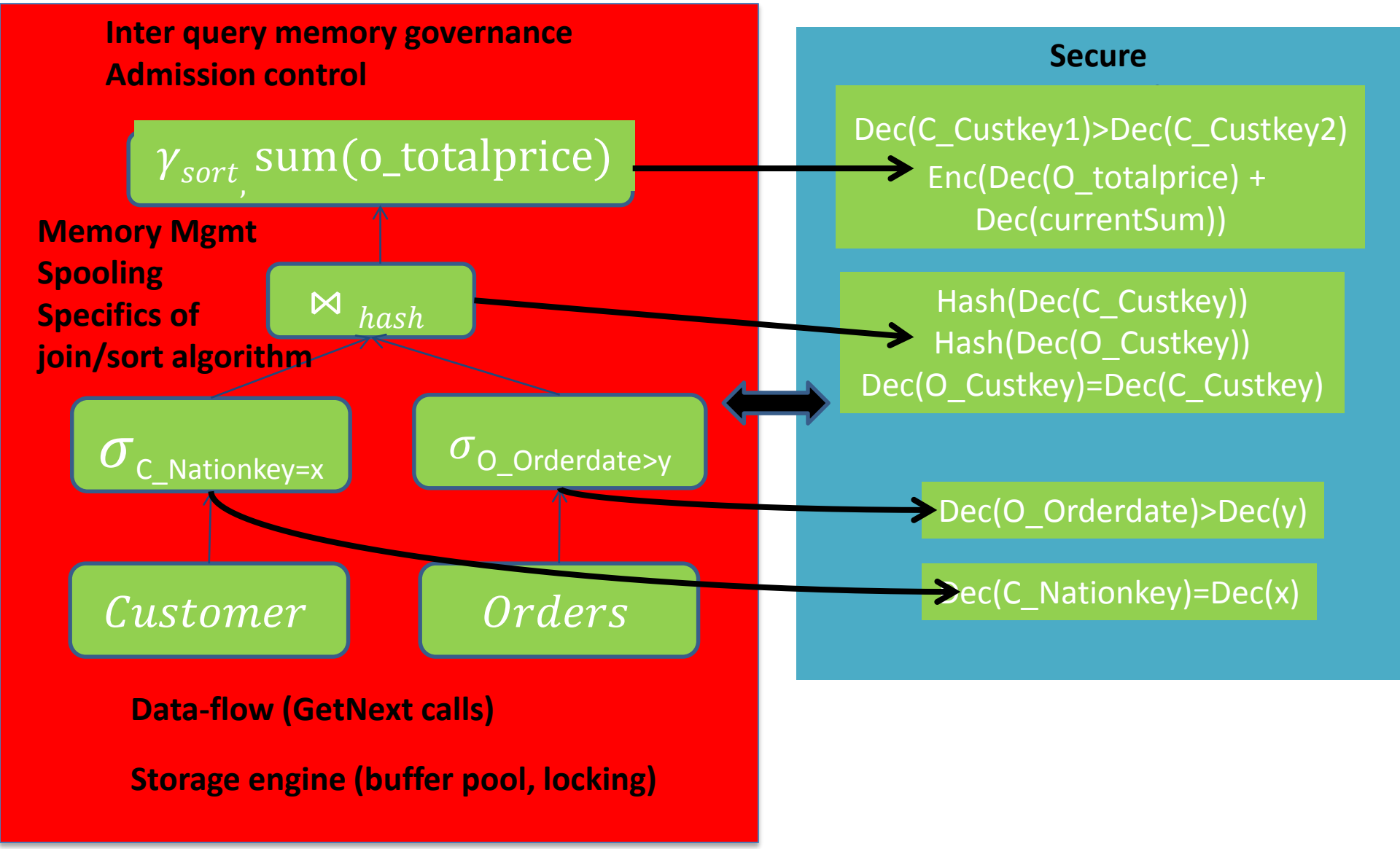
Dedicated Expression Evaluation

- Cipherbase
  - Trusted compute is only expression evaluation



[ABE+12, ABE+13]

Dedicated Expression Evaluation



[ABE+12, ABE+13]

Dedicated Expression Evaluation

- Advantages
  - Efficiency of trusted compute resources
  - Dedicated circuits ➔ virus-proof
  - Small footprint ➔ formal verification
- Drawbacks
  - Fundamentally changes expression evaluation ➔ non-trivial changes to host DBMS

[ABE+12, ABE+13]

Summary

- Secure in-cloud trusted compute resources
- Open issues
  - Query optimization
    - e.g. Statistics on encrypted data, security-aware type matching
  - Execution engine
    - e.g. Data/computation reuse, masking latency to trusted computation
  - Physical Design
    - e.g. Leveraging stronger encryption

Roadmap

- Introduction
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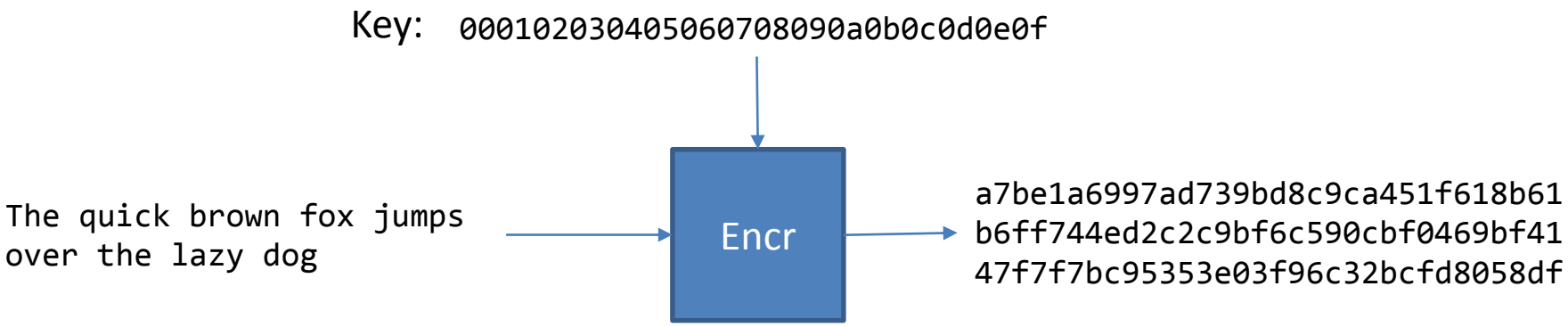
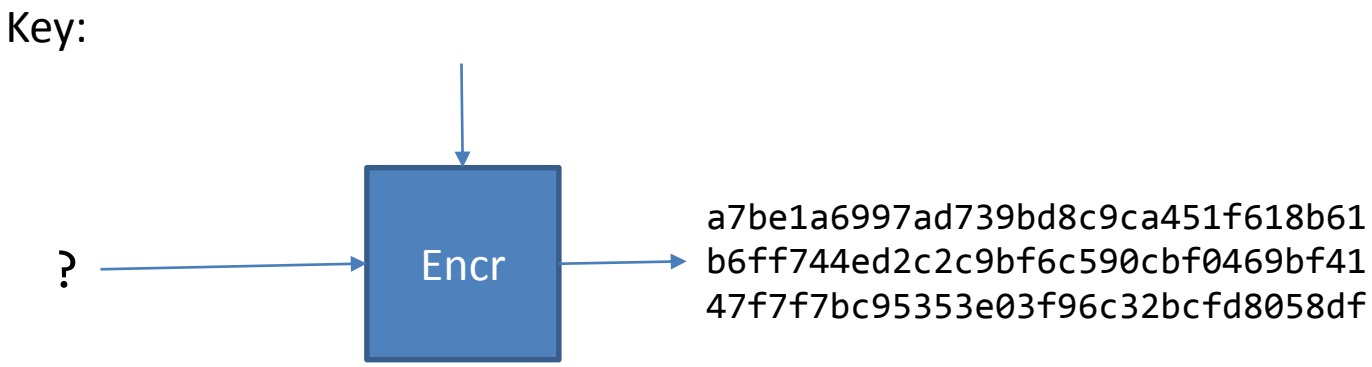
SHOW
ME THE
SECURITY !

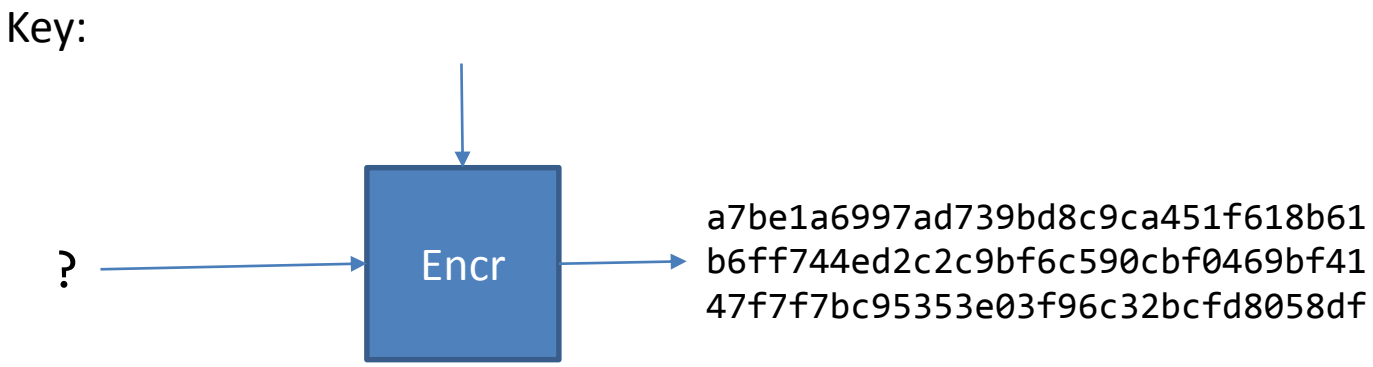
Encryption and Security



Encryption and Security



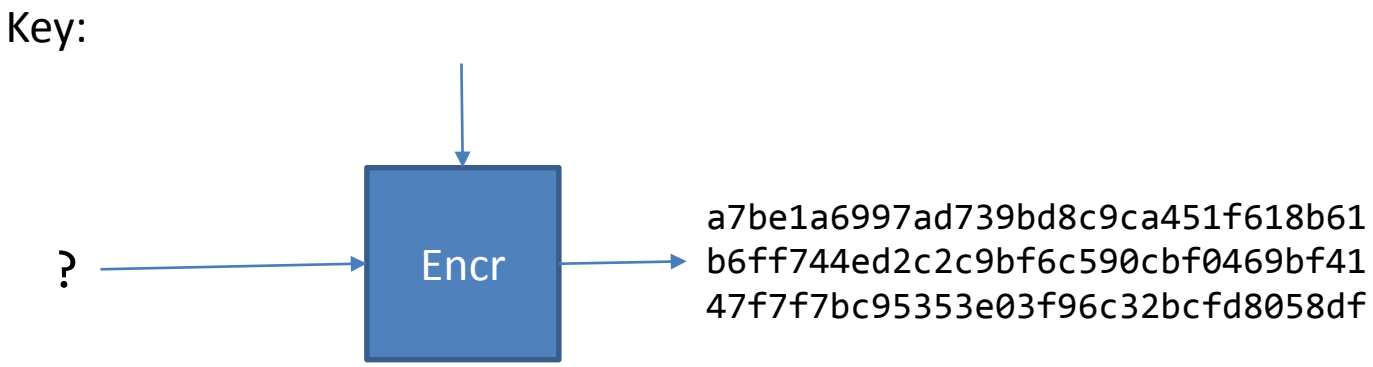
Encryption and Security



- **Semantic security**:
  - No information leakage except input length
- Winner of this year's Turing Award

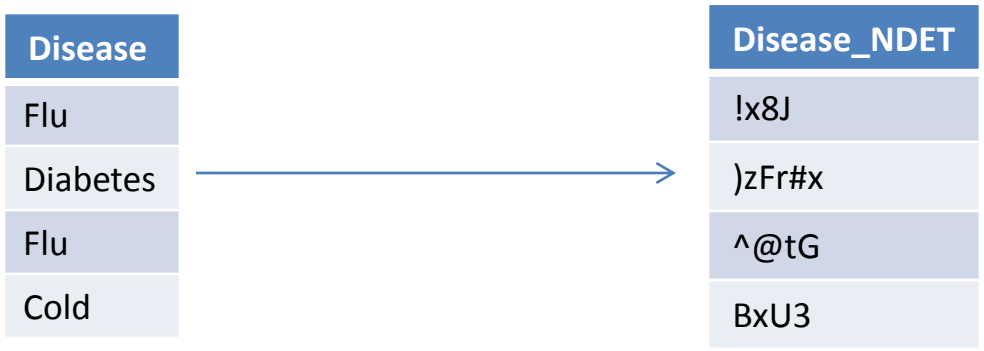
[KL07]

Encryption and Security



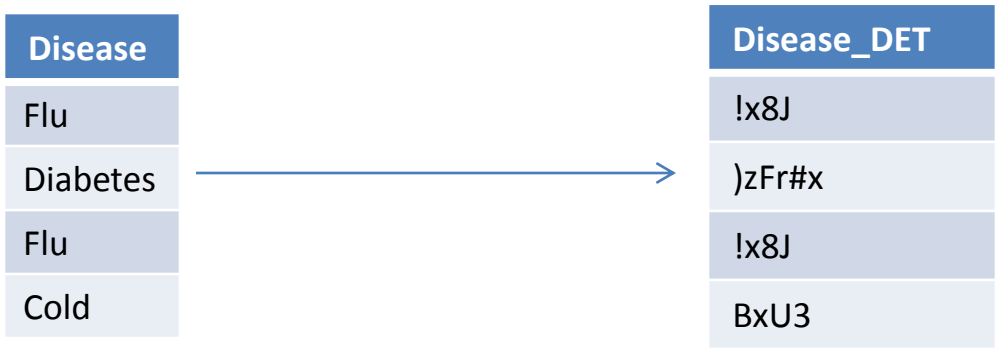
- Encryption schemes such as AES in CBC mode (non-deterministic) are believed to be semantically secure

Security of Database Encryption



- Apply AES-CBC to every cell
- Leaks cell lengths

Deterministic Encryption



- Leaks cell lengths
- Also, no. of distinct values + frequency distribution [BFO+08]

Order-Preserving Encryption

Age
12
51
24
36

Age_OPE
0x000a
0x0f12
0x00a1
0x00b2

- Leaks cell lengths
- Also, order of cell values [AKS+04, BCN11]

Design of order-preserving encryption

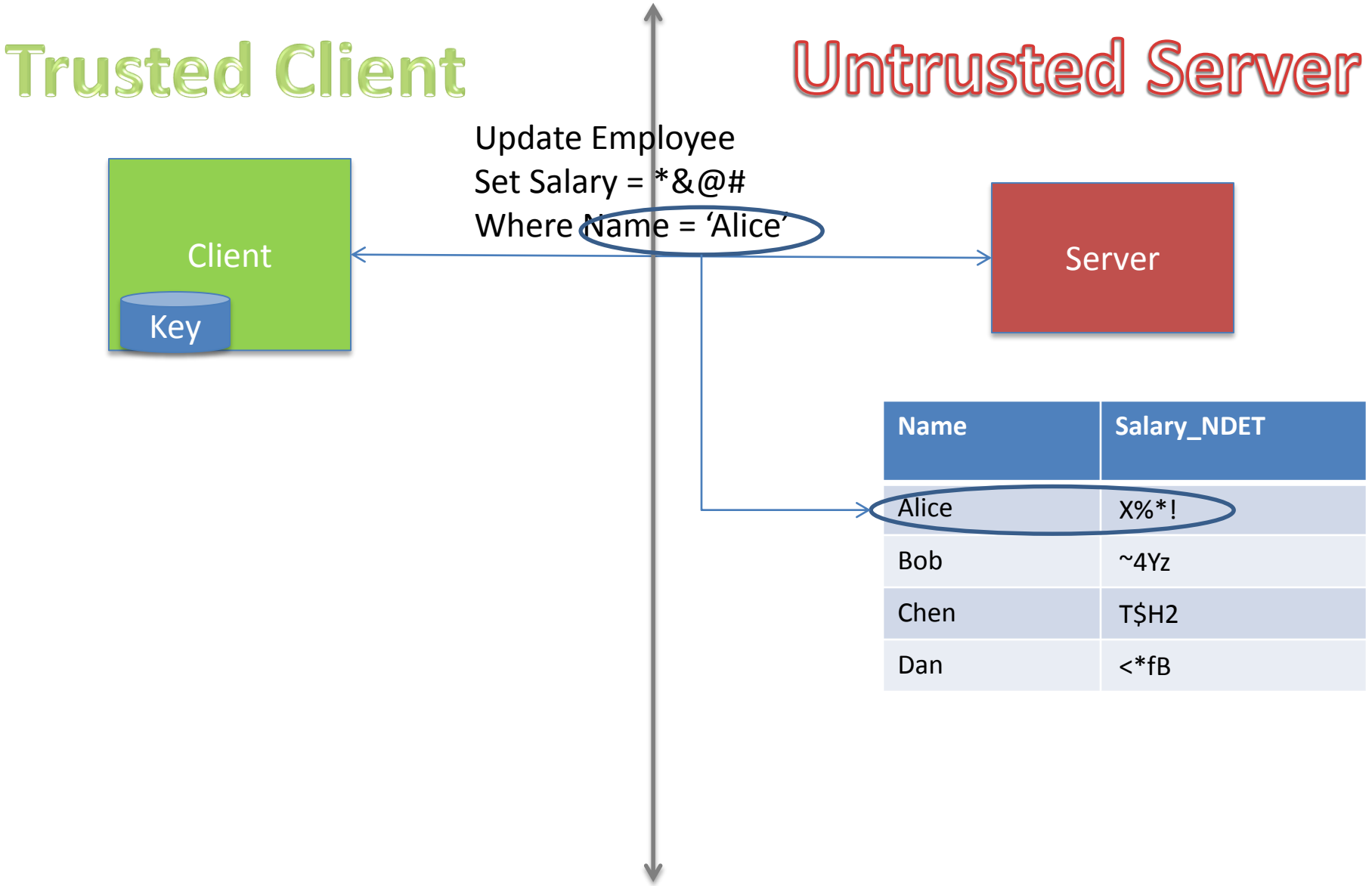
Overall Security of Data Encryption

Name	Age	Disease
Alice	12	Flu
Bob	51	Diabetes
Chen	24	Flu
Dan	36	Cold

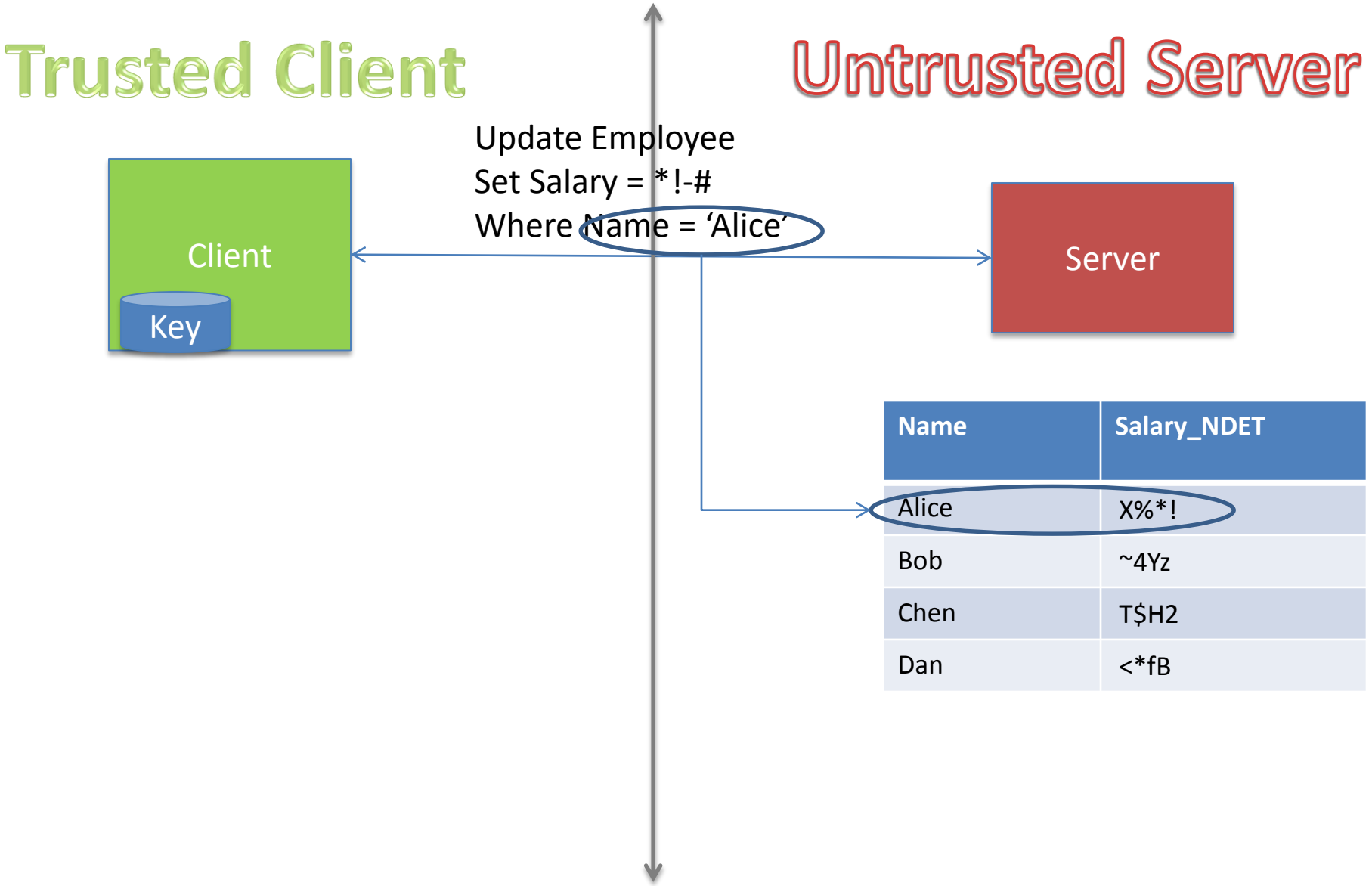
Name_NDET	Age	Disease_DET
X%*!	12	!x8J
~4Yz	51	)zFr#x
T$H2	24	!x8J
<*fB	36	BxU3

- Name: AES-CBC non-deterministic
- Age: Clear-text
- Disease: AES deterministic
- Total information leaked = “sum” of column-level leakage

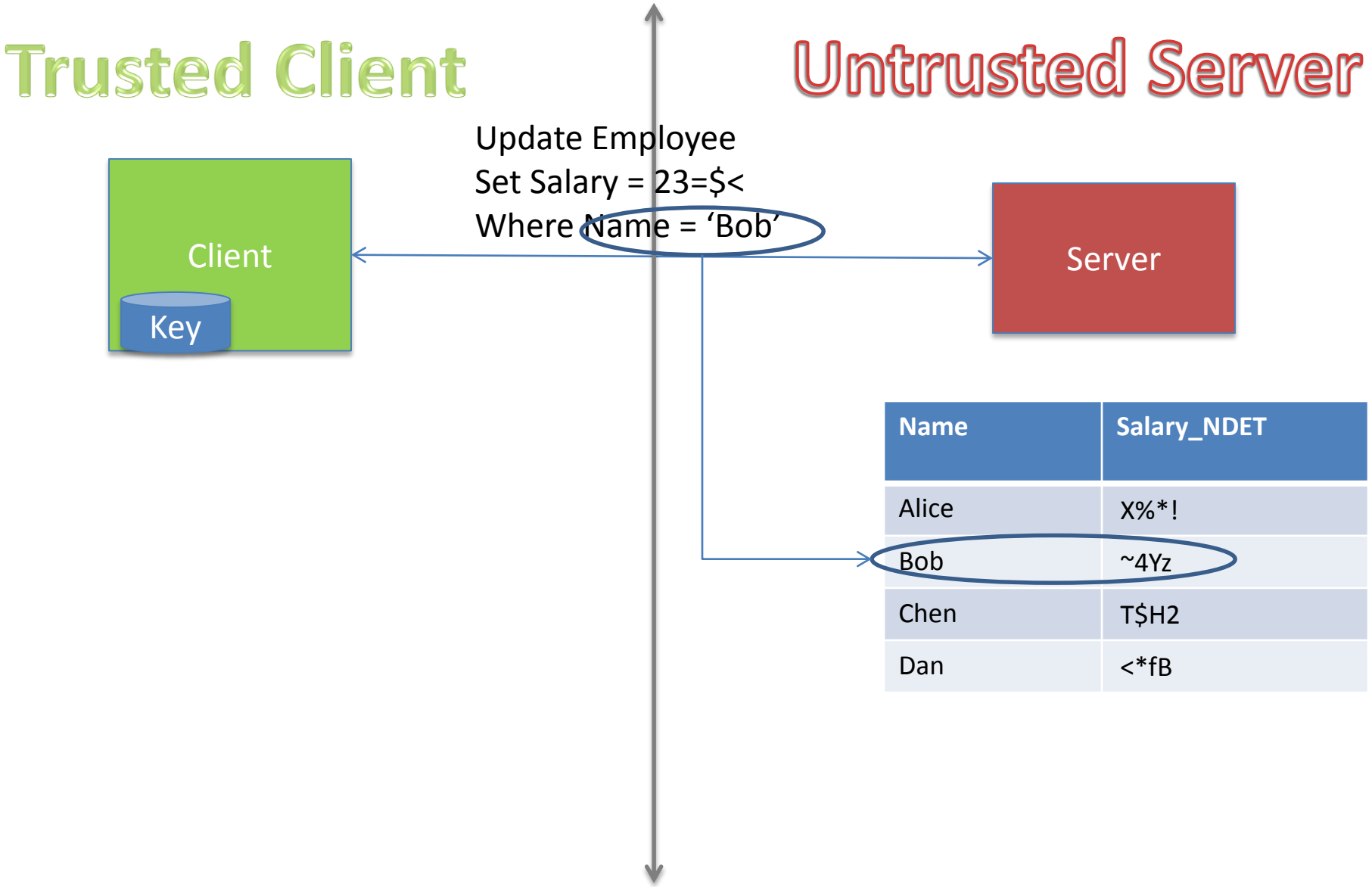
Impact of Querying & Updating



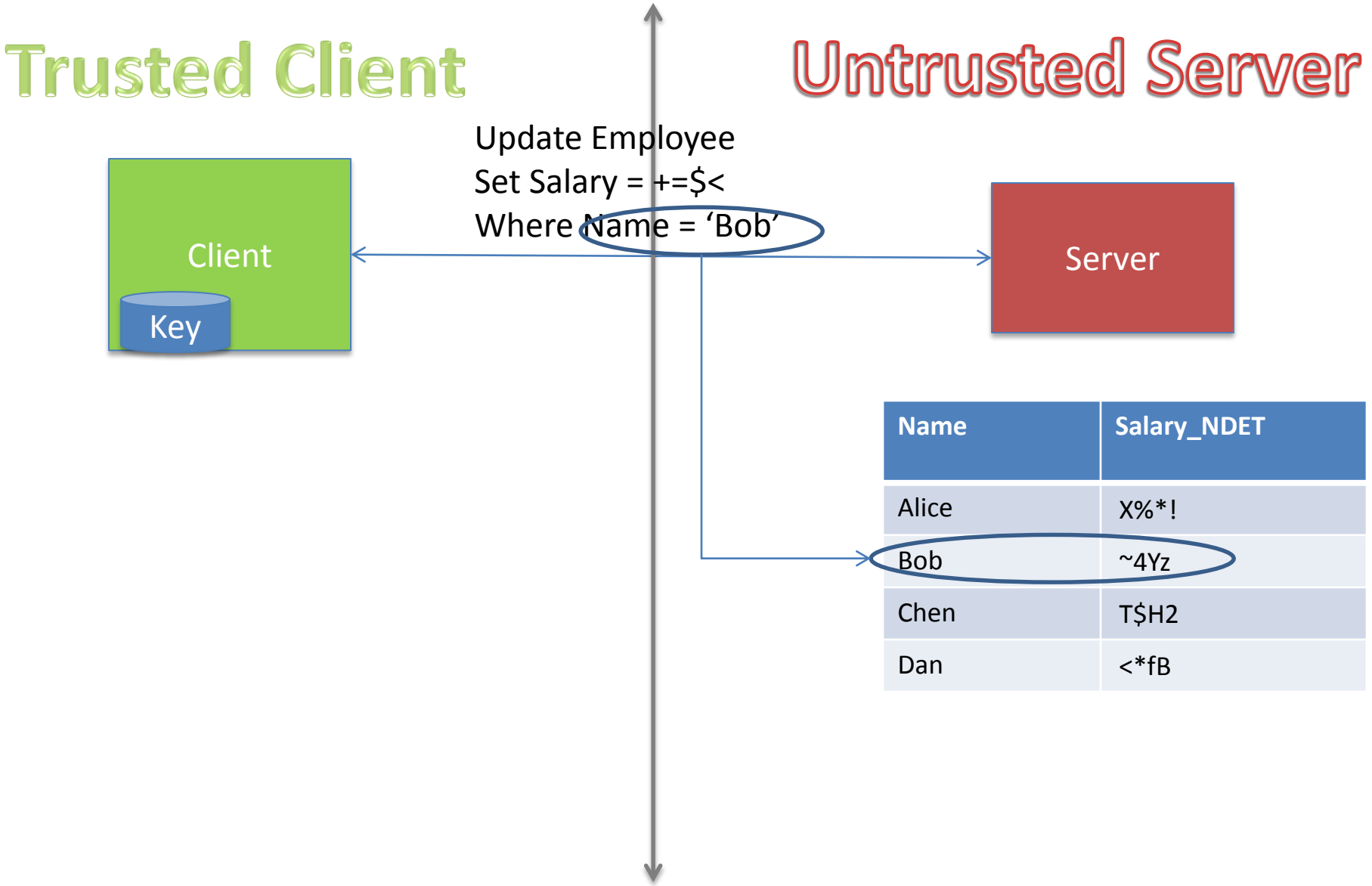
Impact of Querying & Updating



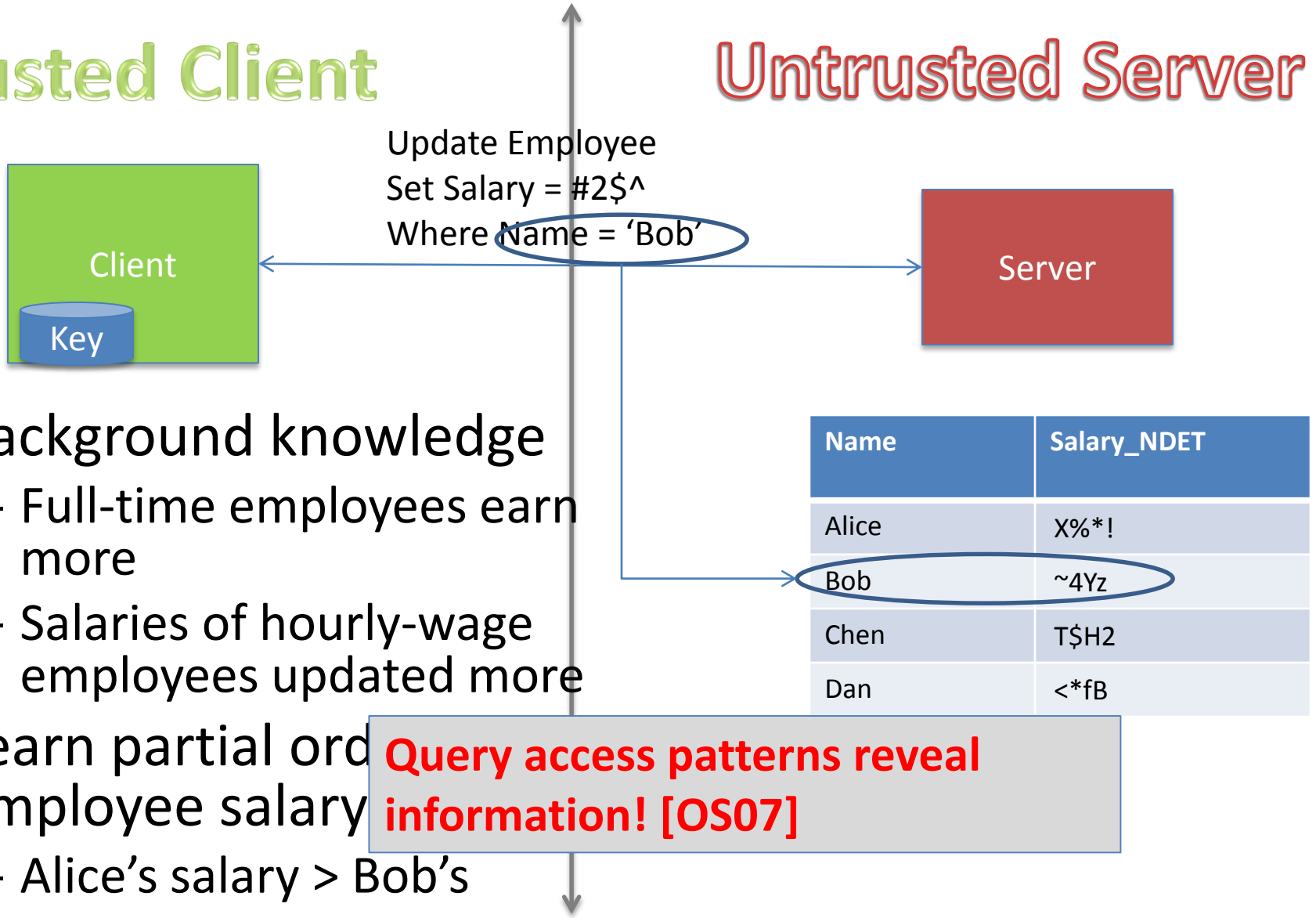
Impact of Querying & Updating



Impact of Querying & Updating

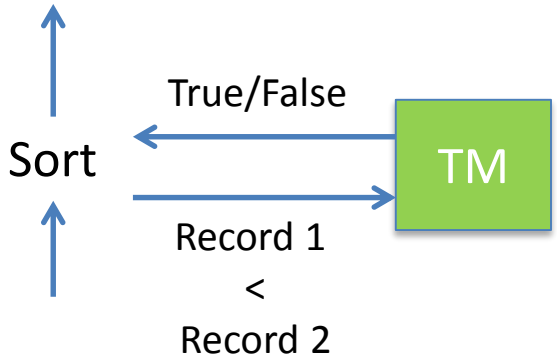


Impact of Querying & Updating



- Background knowledge
  - Full-time employees earn more
  - Salaries of hourly-wage employees updated more
- Learn partial ord employee salary
  - Alice's salary > Bob's

Impact of Querying & Updating

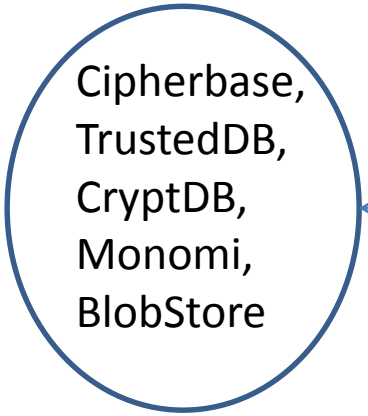


- Sort leaks ordering
- Encryption across the stack (disk + in-memory) does NOT imply no information leakage

The overall query workflow reveals information

***Dynamic* security** (different from security of data at rest)

Design Space



Stop with encryption

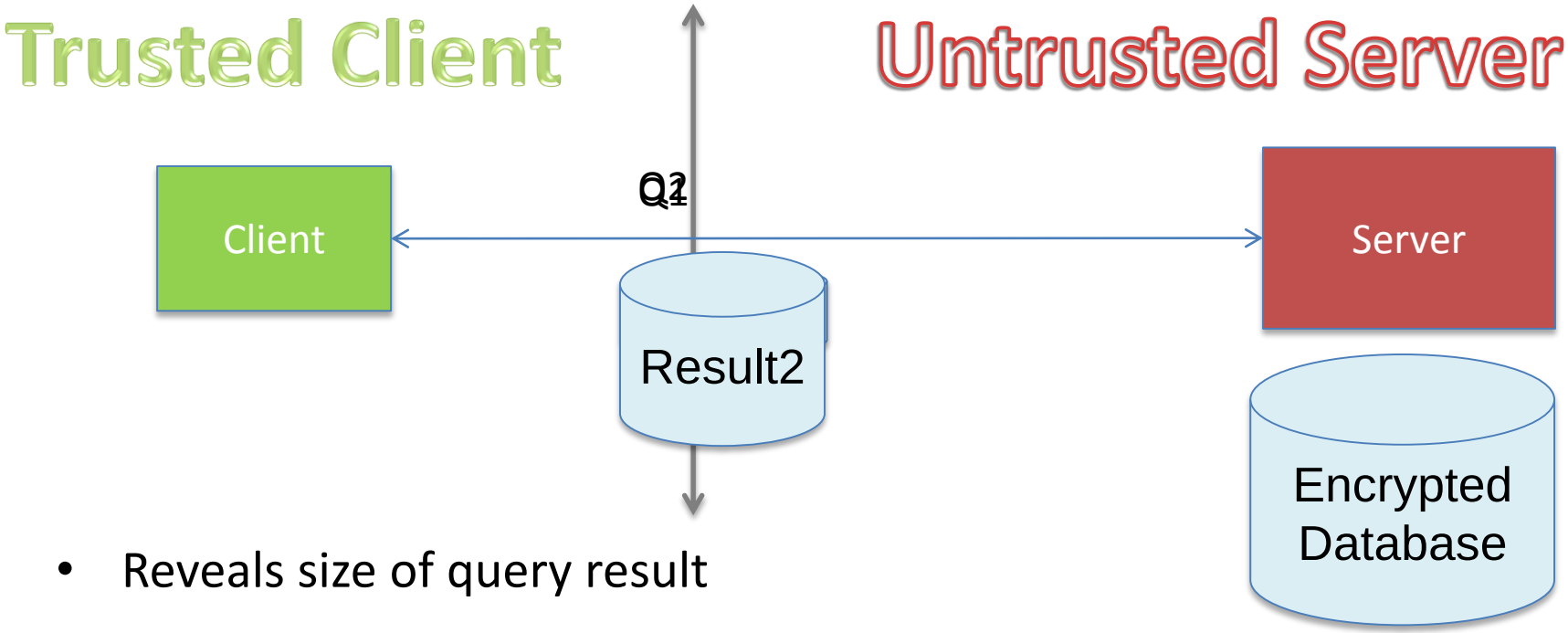
Can we bridge this gap?

Full Leakage

Operations on column	Leakage
Equality (including joins)	Frequency distribution
Indexing/Sorting /range predicates	Order

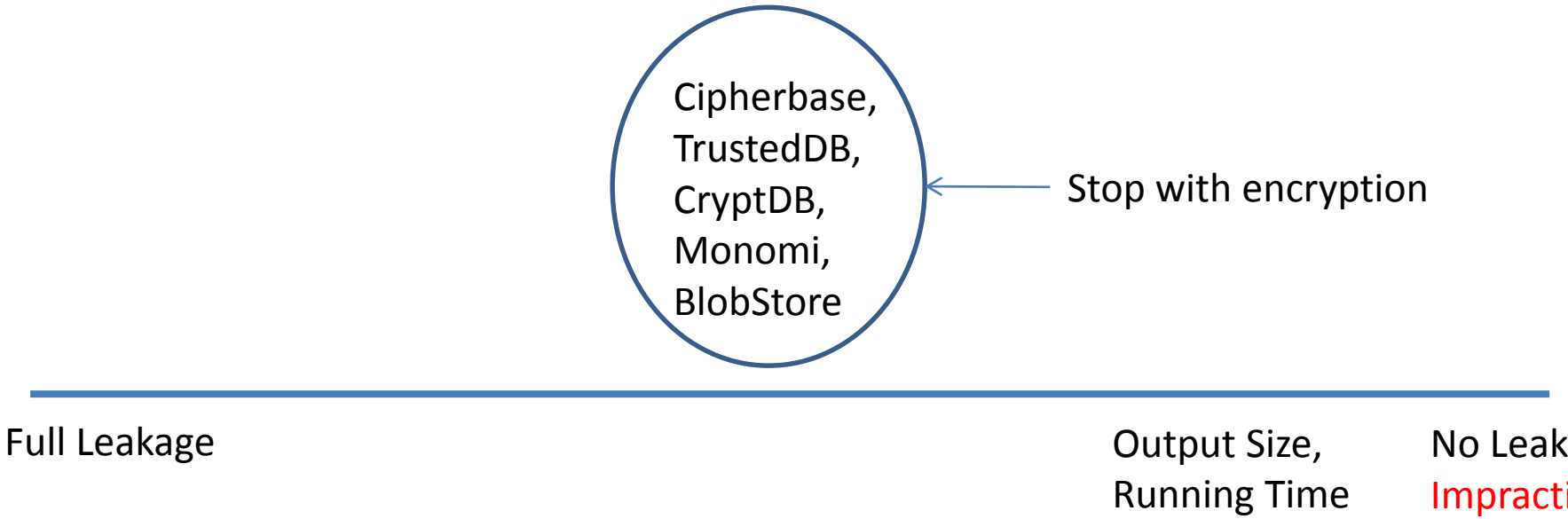
No Leakage

No Leakage

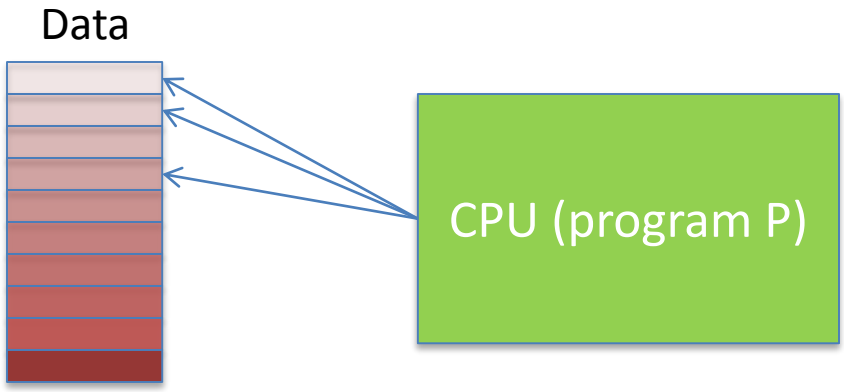


- Reveals size of query result
- Hide query result size by making all query result sizes equal to maximum size
  - Joins reduce to cross products
  - Impractical

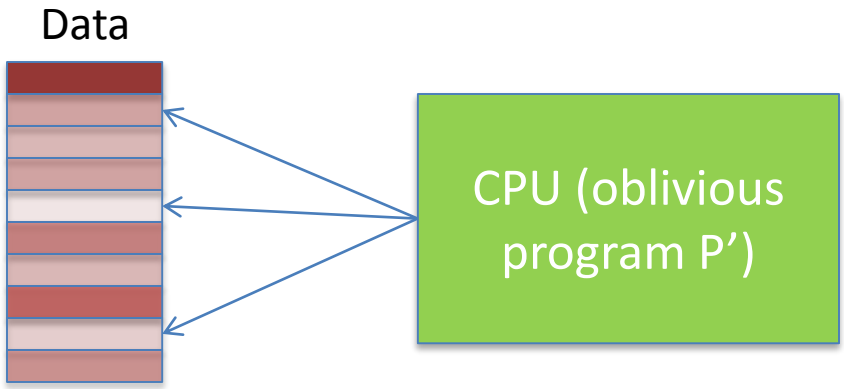
Design Space



Access Patterns Leak Information



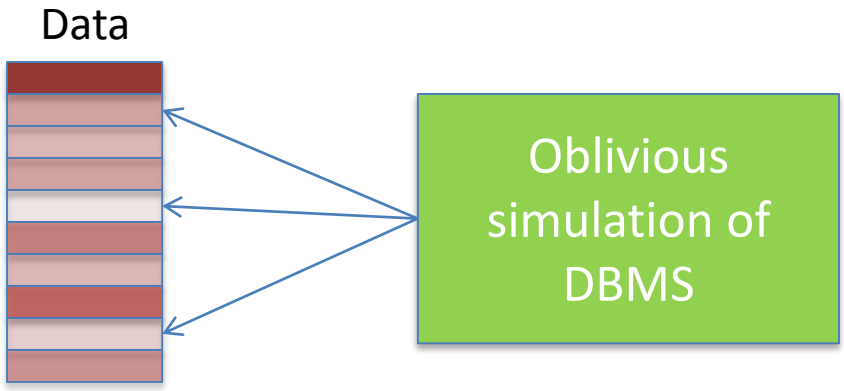
Oblivious Simulation



- Simulation: P' equivalent to P
- Theoretically Efficient: Running time of P' within polylog factor of running time of P
- Oblivious: Access patterns of P' look random
- Information leakage: input size, output size, running time

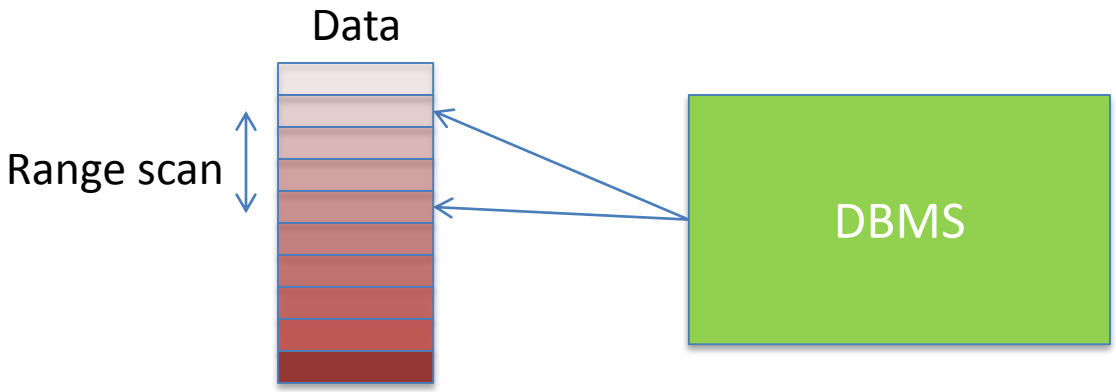
[GO96, W12, SS13]

Application to DBMS



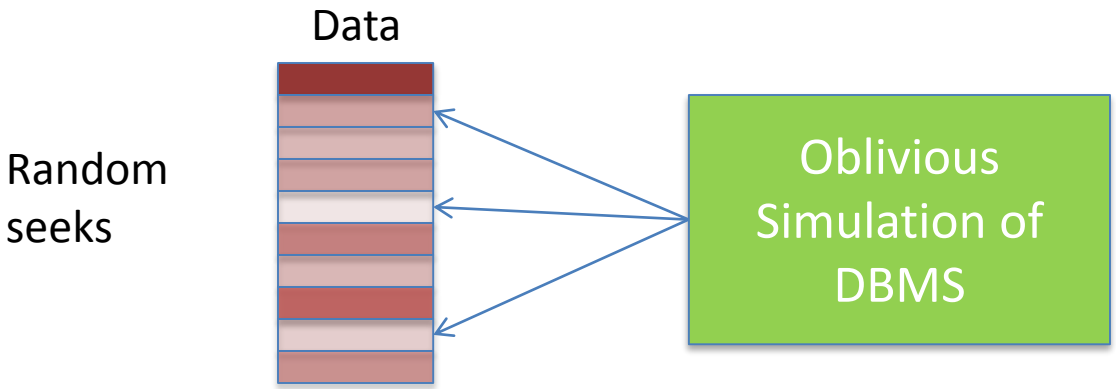
But…

- Destroys spatial and temporal locality of reference



But…

- Destroys spatial and temporal locality of reference



- Range scan of 100M records on hard disk → 100M seeks
  - 10^5 seconds (~1 day)

Design Space

Cipherbase,
TrustedDB,
CryptDB,
Monomi,
BlobStore

Stop with encryption

Full Leakage

Output Size,
Running Time
Impractical

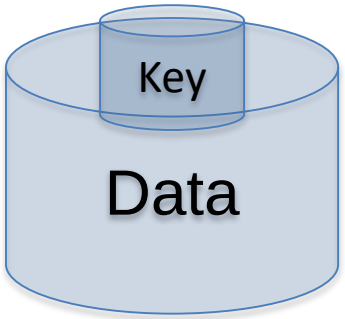
No Leakage
Impractical

Is there a stronger and practically achievable security model?

Summary

Trusted Client

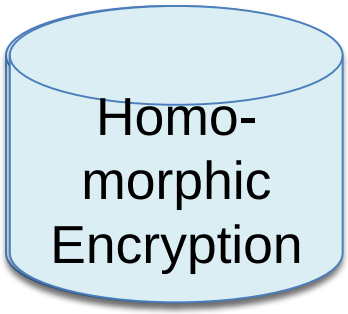
DBMS



Name	Age	Disease
Alice	12	Flu
Bob	51	Diabetes
Chen	24	Flu
Dan	36	Cold

Untrusted Server

DBMS

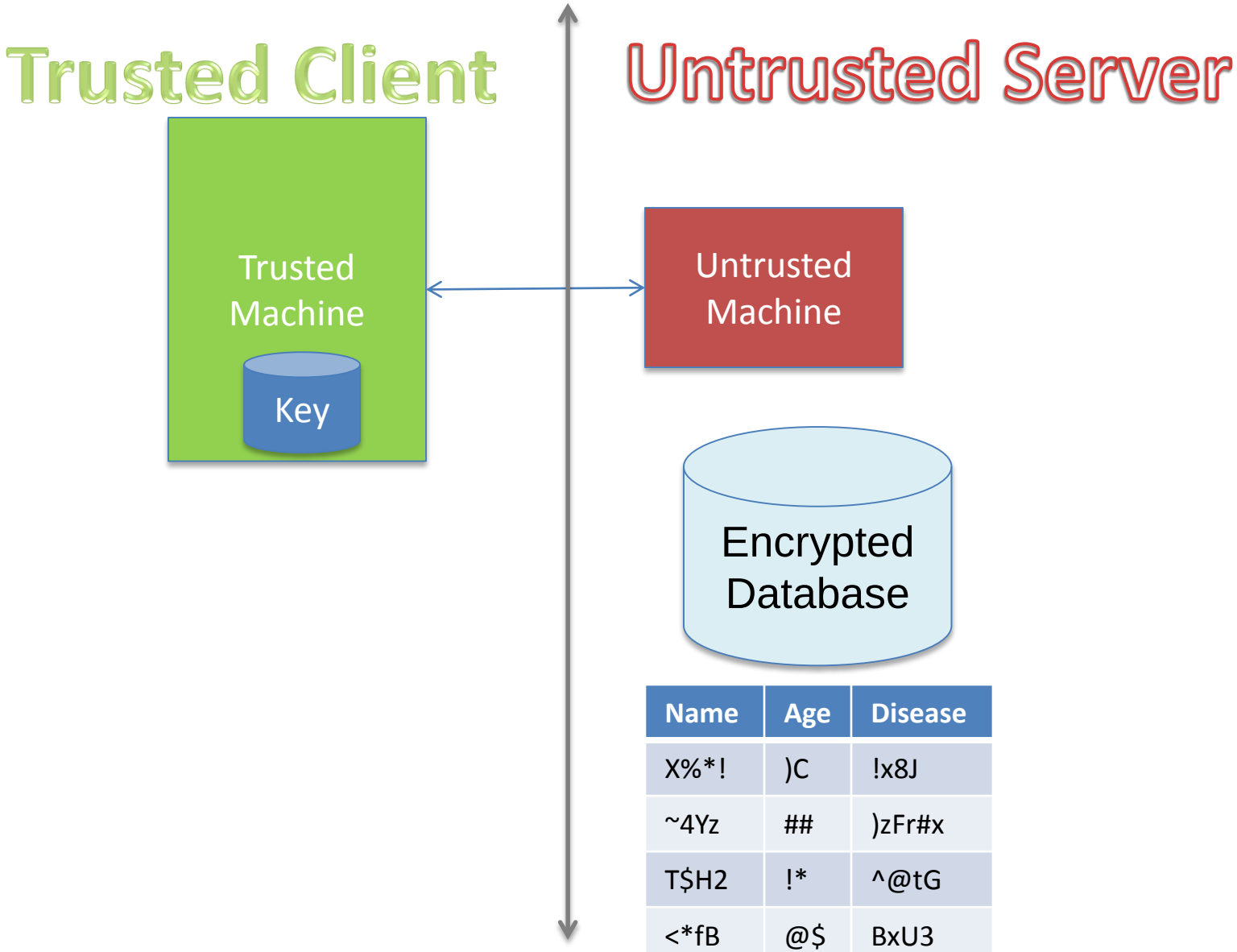


Name	Age	Disease
X%*!	)C	!x8J
~4Yz	##	)zFr#x
T$H2	!*	^@tG
<*fB	@$	BxU3

Cloud Admin

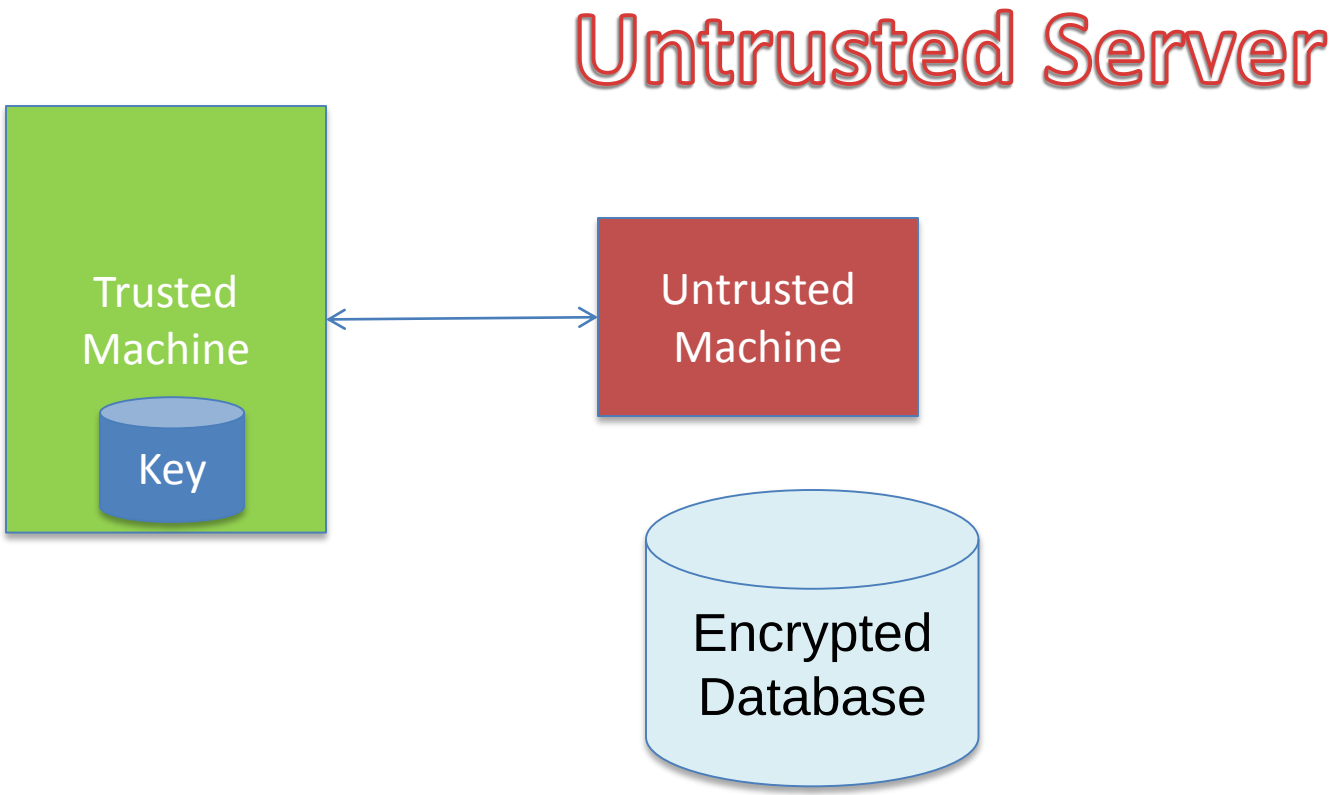
- Super-user with console access

Summary



Name	Age	Disease
X%*!	)C	!x8J
~4Yz	##	)zFr#x
T$H2	!*	^@tG
<*fB	@$	BxU3

Summary



Name	Age	Disease
X%*!	)C	!x8J
~4Yz	##	)zFr#x
T$H2	!*	^@tG
<*fB	@$	BxU3

Other Challenges

- Application Security
  - DBMS is only a part of the overall system stack
- Usability
  - Clients need tools and interpretable security models to navigate security-performance tradeoff
- Connections to other areas of security
  - Data privacy, access control, auditing

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