Network Security and Applied Cryptography Laboratory

http://crypto.cs.stonybrook.edu

Secure Data Outsourcing

Tutorial @ COMAD 2006, New Delhi, India

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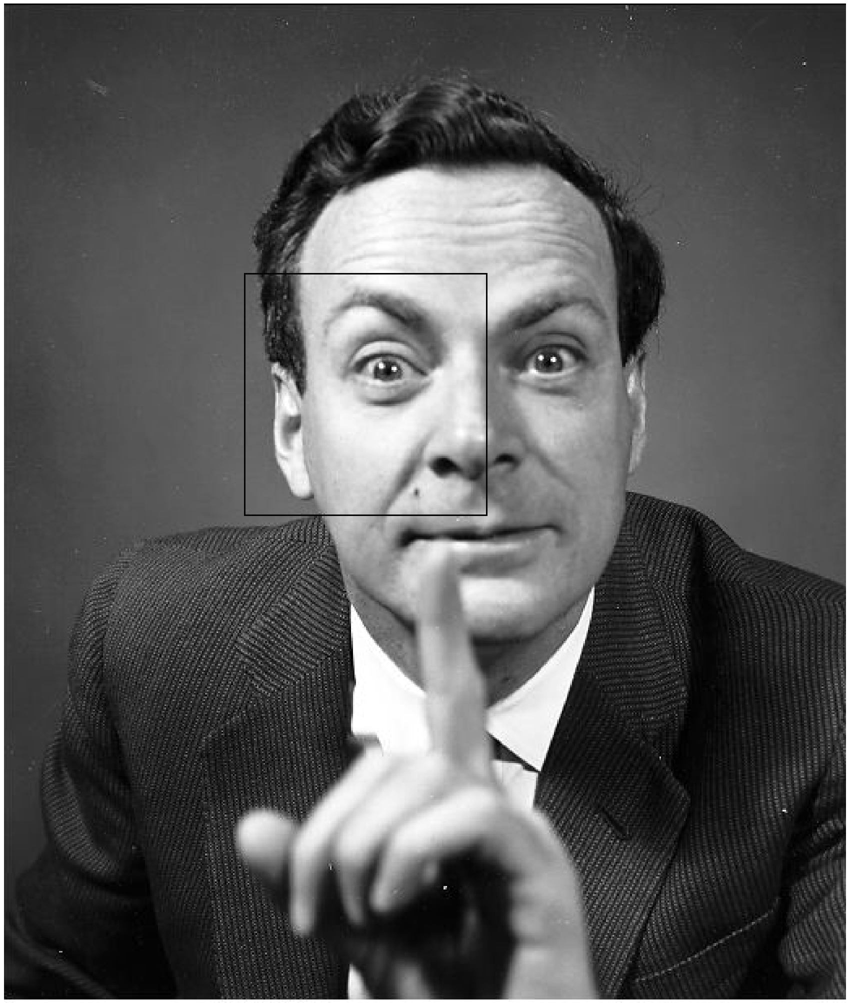
Feynman moment



"I have much experience only in teaching graduate students [...] and as a result [...] I know that I don't know how to teach."

Overview

- *Crypto Crash Course*
- *Data Outsourcing*
- *Query Correctness*
- *Data Confidentiality*
- *Access Privacy*
- *Searching on Encrypted Data*
- *Trusted Hardware*

Crypto Crash Course

- *Randomness*
- *Crypto Hashes*
- *Encryption*
- *Public key encryption*
- *Signatures*
- *Ciphers*
- *Semantic Security*
- *Forward Secrecy*
- *Performance*
- *Merkle/Hash trees*

Crypto: Meet the cast

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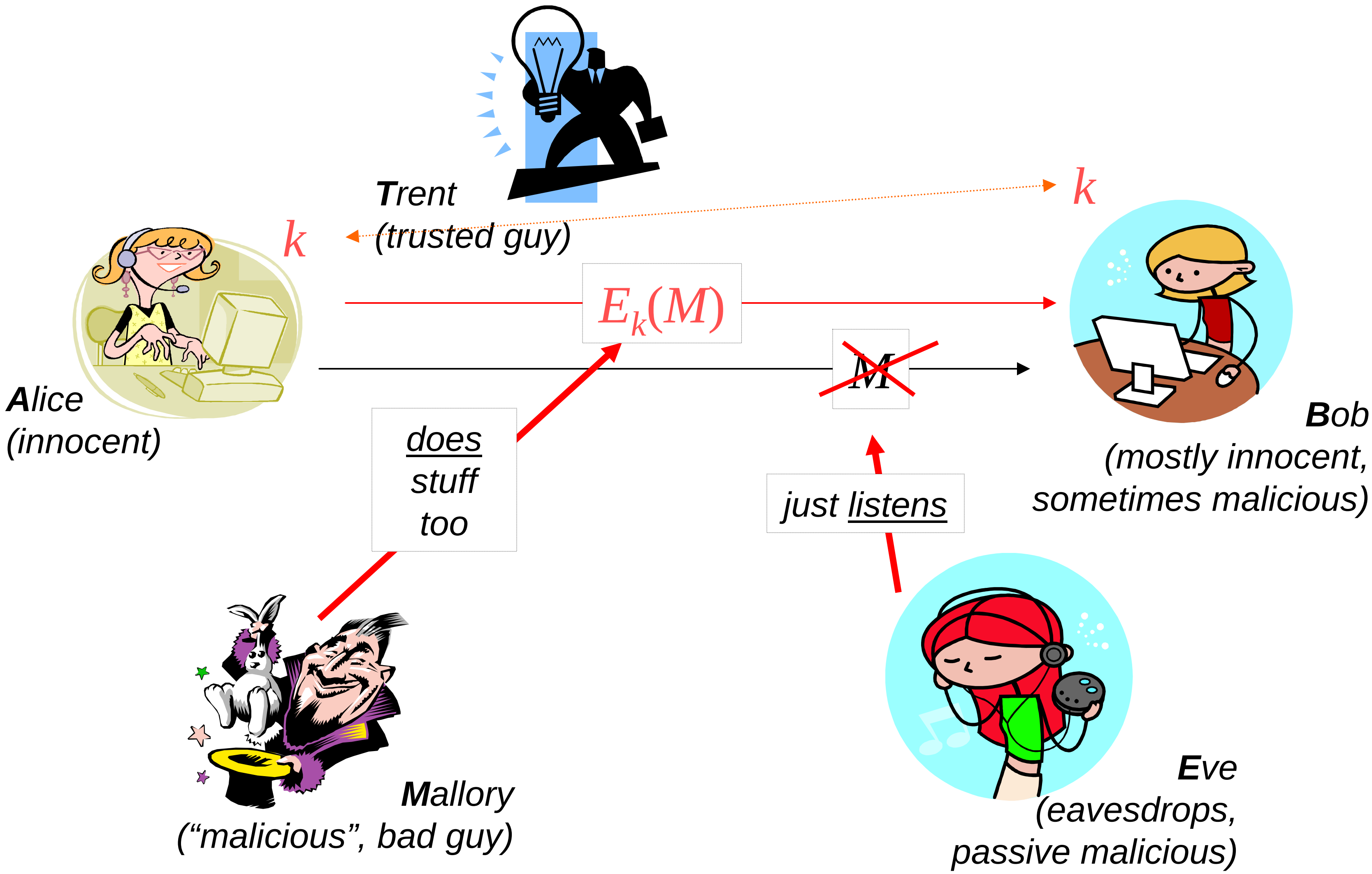


Crypto: Randomness

Cryptographically random numbers: a sequence of numbers X_1, X_2, … such that for any integer $k > 0$, it is **impossible** for an observer to predict X_k even if all of X_1, …, X_{k-1} are known.

Problem: True RNGs cannot be deterministically algorithmic in a closed system. “Anyone who considers arithmetic methods … is in a state of sin” (von Neuman)

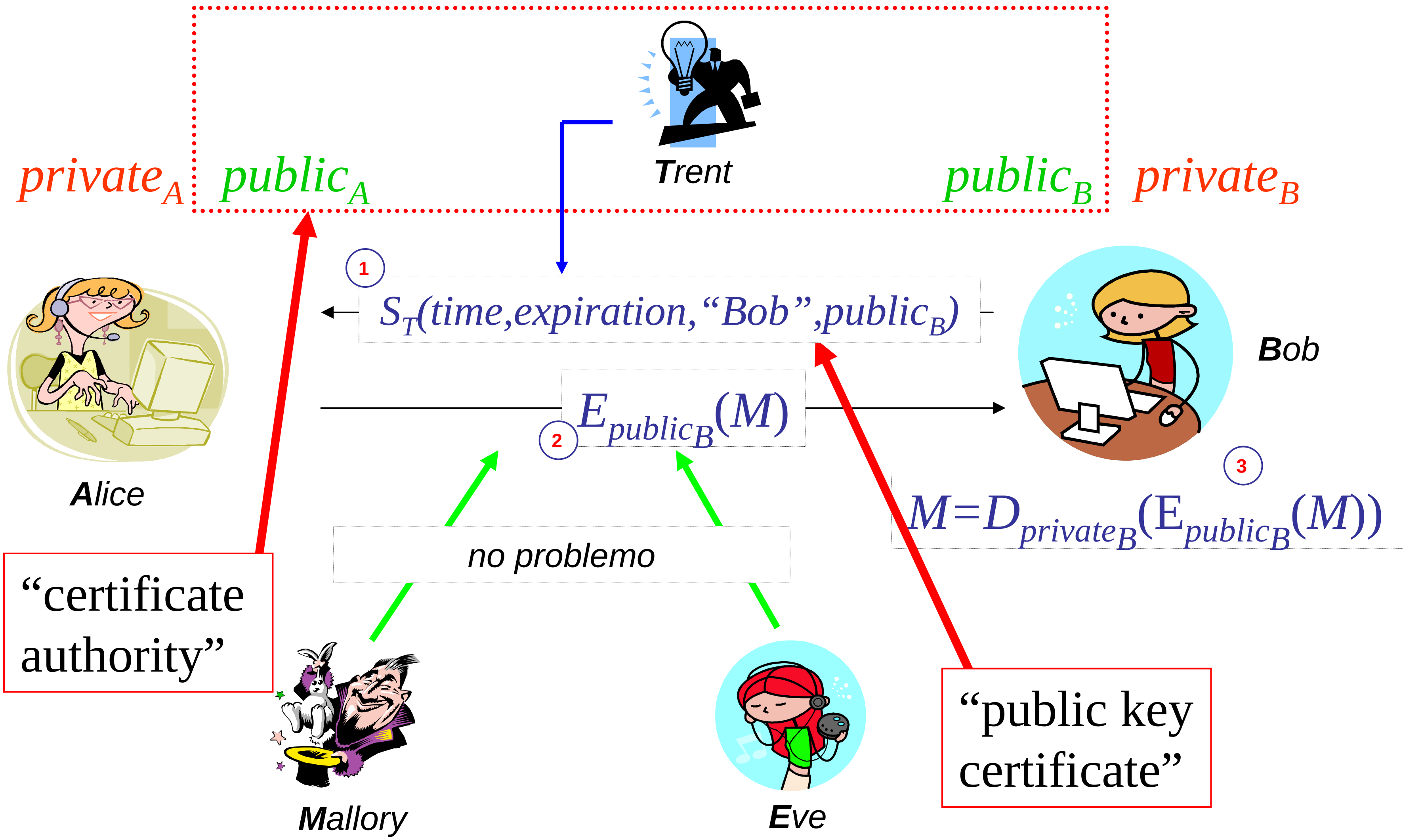
Being creative: simulate a sequence of cryptographically random numbers but generate them by an algorithm.

Pseudo-random numbers: a sequence of numbers X_1, X_2, … such that for any integer $k > 0$, it is **hard** for an observer to predict X_k even if all of X_1, …, X_{k-1} are known.

Crypto: Hashes

- A hash is a **one-way, non-invertible** function of that produces **unique** (with *high likelihood*), **fixed-size** outputs for different inputs.
- The probability of any bit "flipping" in the output bit-string should be always ½ for any change (even one bit) in the input ("randomness").

Crypto: PKI


private_A
public_A
Trent
public_B
private_B
1
S_T(time,expiration,"Bob",public_B)
Alice
Bob
2
E_publicB(M)
3
M=D_privateB(E_publicB(M))
no problemo
"certificate authority"
"public key certificate"
Mallory
Eve

Crypto: Signatures

$$M=D_{private_A}(E_{public_A}(M))=D_{public_A}(E_{private_A}(M))$$

$private_A$ $public_A$ $public_B$ $private_B$

Alice

1 $S_A(M)=E_{private_A}(M)$ M

Bob

2 $M=D_{public_A}(S_A(M))$?

no problemo

***M**allory*

***E**ve*

Crypto: RSA in a nutshell

1. $n=pq$
2. $e=17$
3. Extended Euclidean → $d = e^{-1} \bmod (p-1)(q-1)$

message $m<n$ → RSA Encryption →

4. $c=m^e \bmod n$ → RSA Decryption →
5. $m=c^d \bmod n$

Alice

Bob

Crypto: Condensed RSA

messages $\{\mathbf{m_i}\}$

RSA Signature (1)

$\{\mathbf{s_i = m_i^{d} \bmod n}\}$

"Condensed RSA Signature" (2)

$\mathbf{s = \prod s_i}$

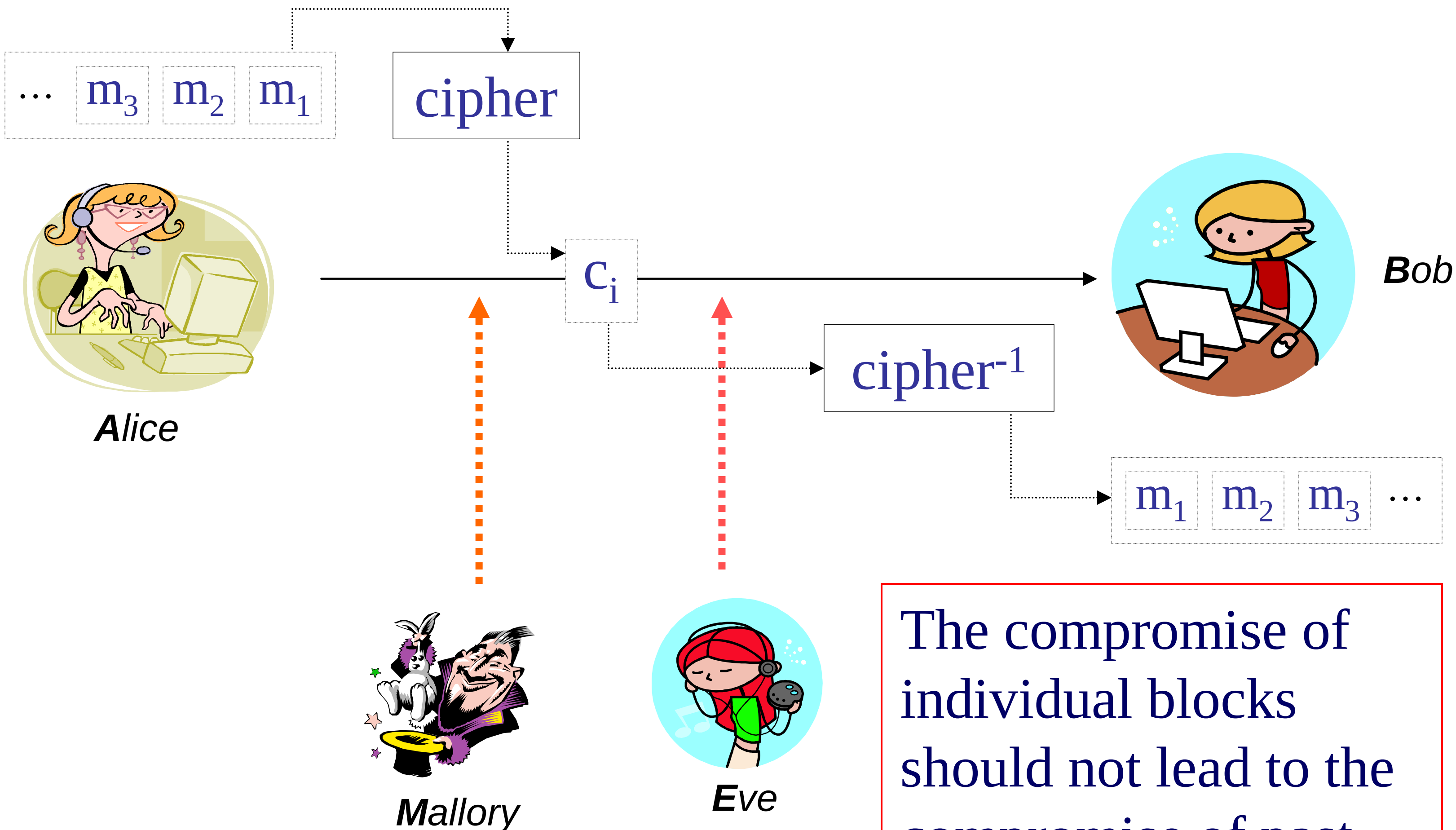
verification: (3)
check that $\mathbf{s = (\prod m_i)^e}$

Alice

***B**ob*

unforgeable against adaptive chosen message attacks

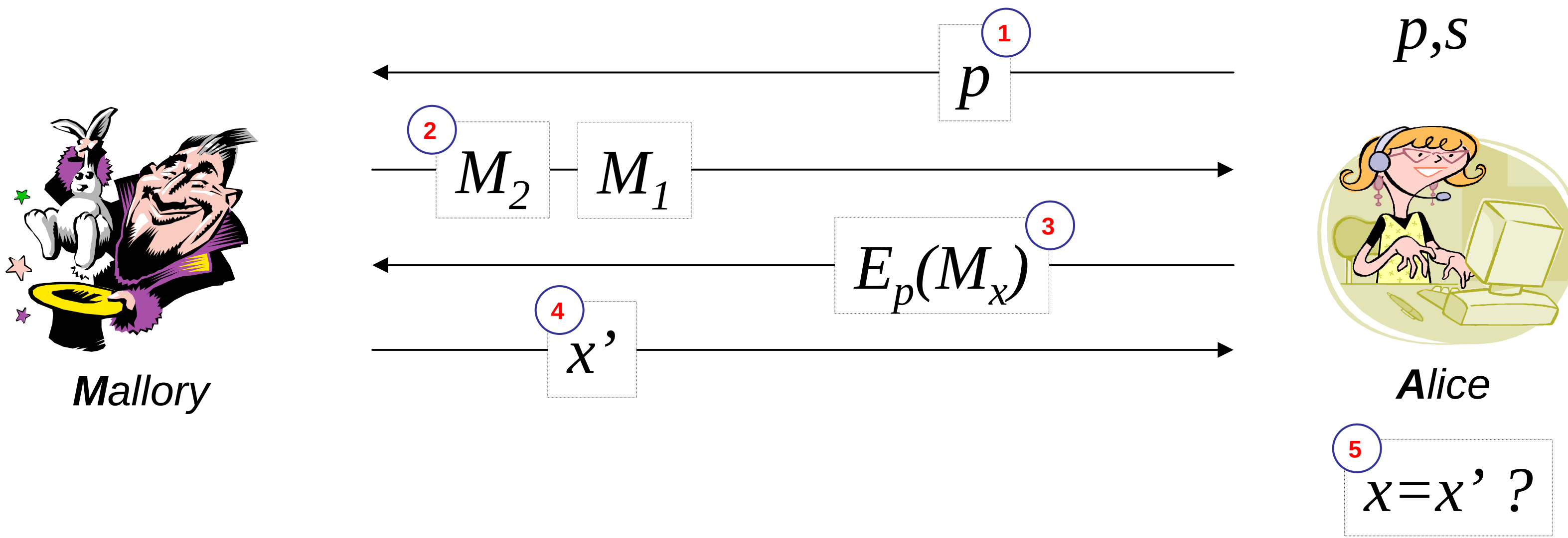
Crypto: Ciphers



The compromise of individual blocks should not lead to the compromise of past communication !

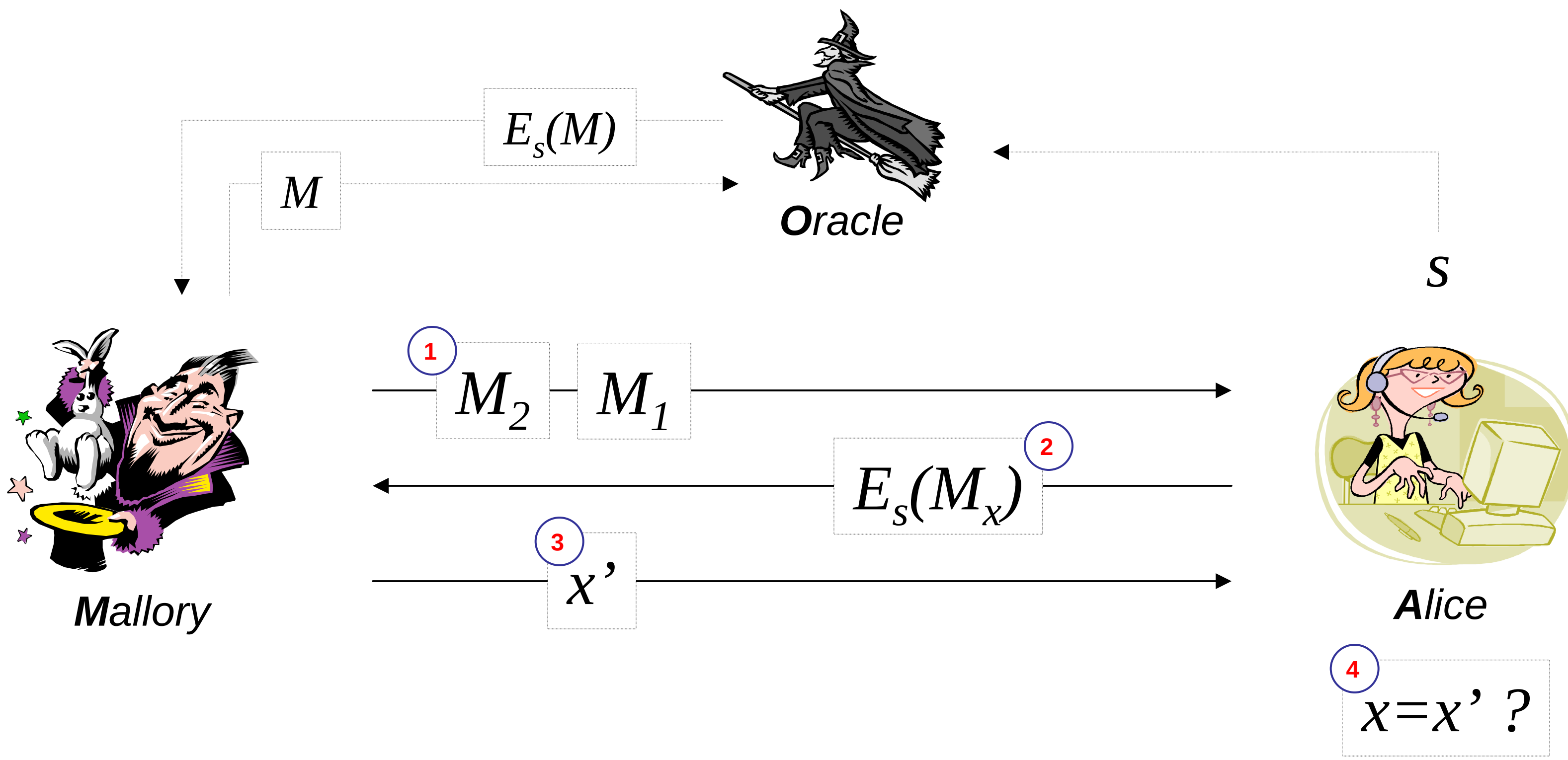
Crypto: Semantic Security

len(M1)=len(M2) ?



E() is **indistinguishable under a chosen plaintext attack** (IND-CPA, "semantically secure") if no probabilistic polynomial time-bounded Mallory can succeed in finding x', significantly better than guessing.

Crypto: Semantic Security



Crypto: Semantic Security

- Deterministic + stateless = insecure !
- Semantic security implies *bit security* !
- RSA : non-semantically secure ! Why ?!
- RSA + padding (e.g., RSA-OAEP): ok

Crypto: Forward Secrecy

Future compromise (e.g., of PK secrets) should not propagate backwards in time.

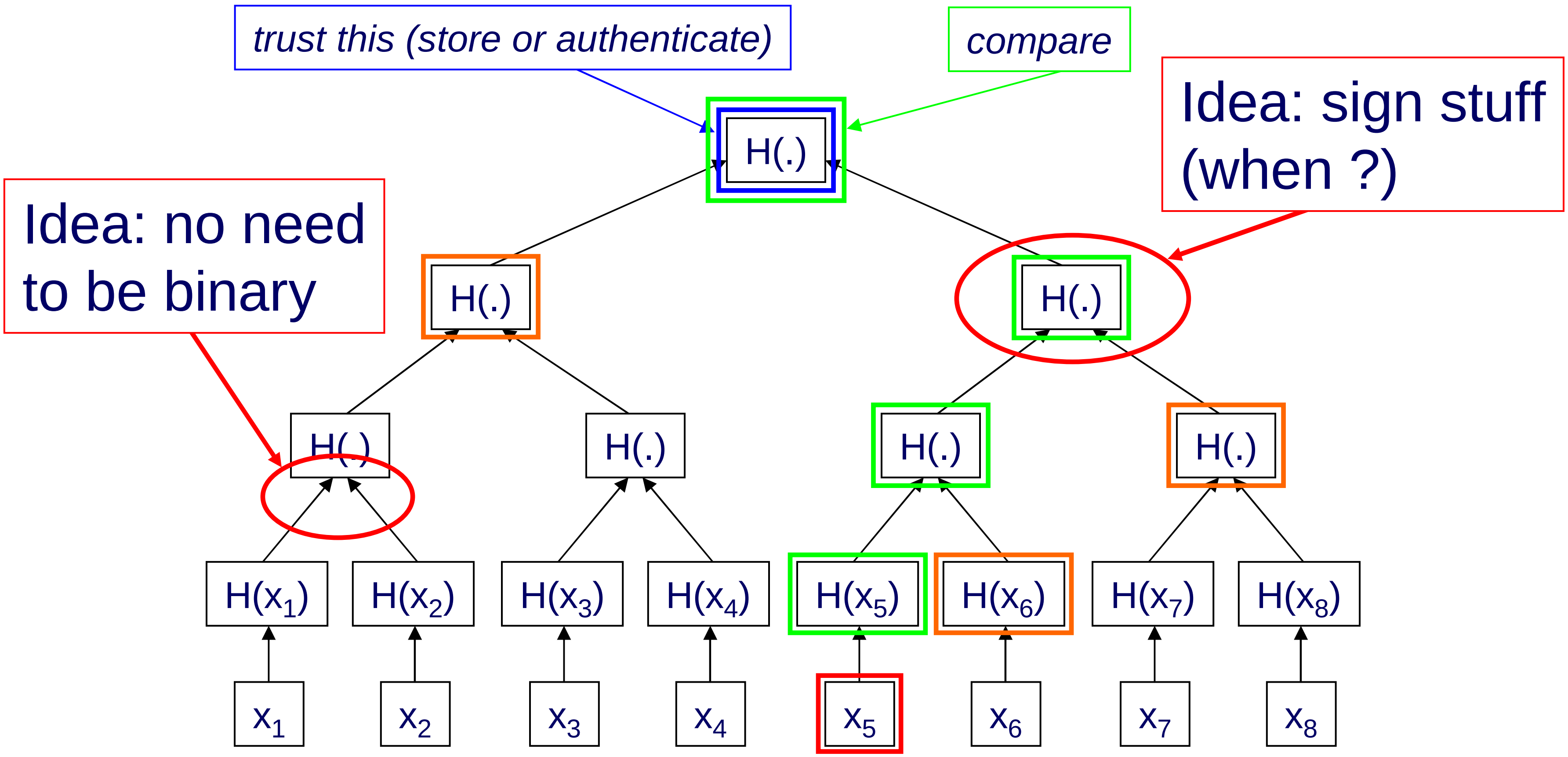
Crypto: Performance

Illustrative baseline.
Pentium 4. 3.6GHz.
1GB RAM. 11000 MIPS.
OpenSSL 0.9.7f

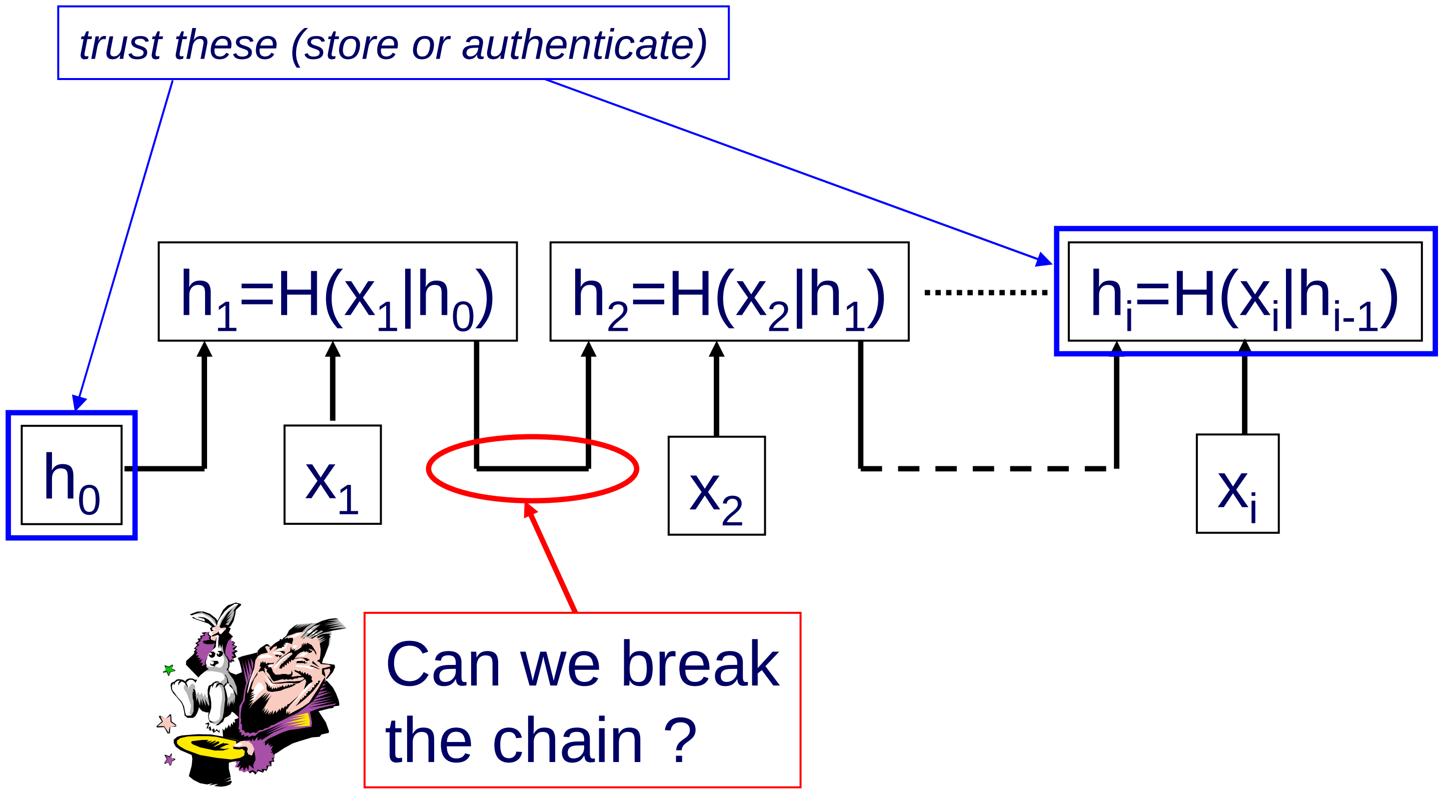
DES/CBC: **70MB/sec**
RC4: **138MB/sec**
MD5: **18-615MB/sec**
SHA1: **18-340MB/sec**

Modular MUL 1024: **273000/sec**
RSA1024 Sign: **261/sec**
RSA1024 Verify: **5324/sec**
3DES: **26MB/sec**

Crypto: Merkle/Hash trees



Crypto: Hash chains



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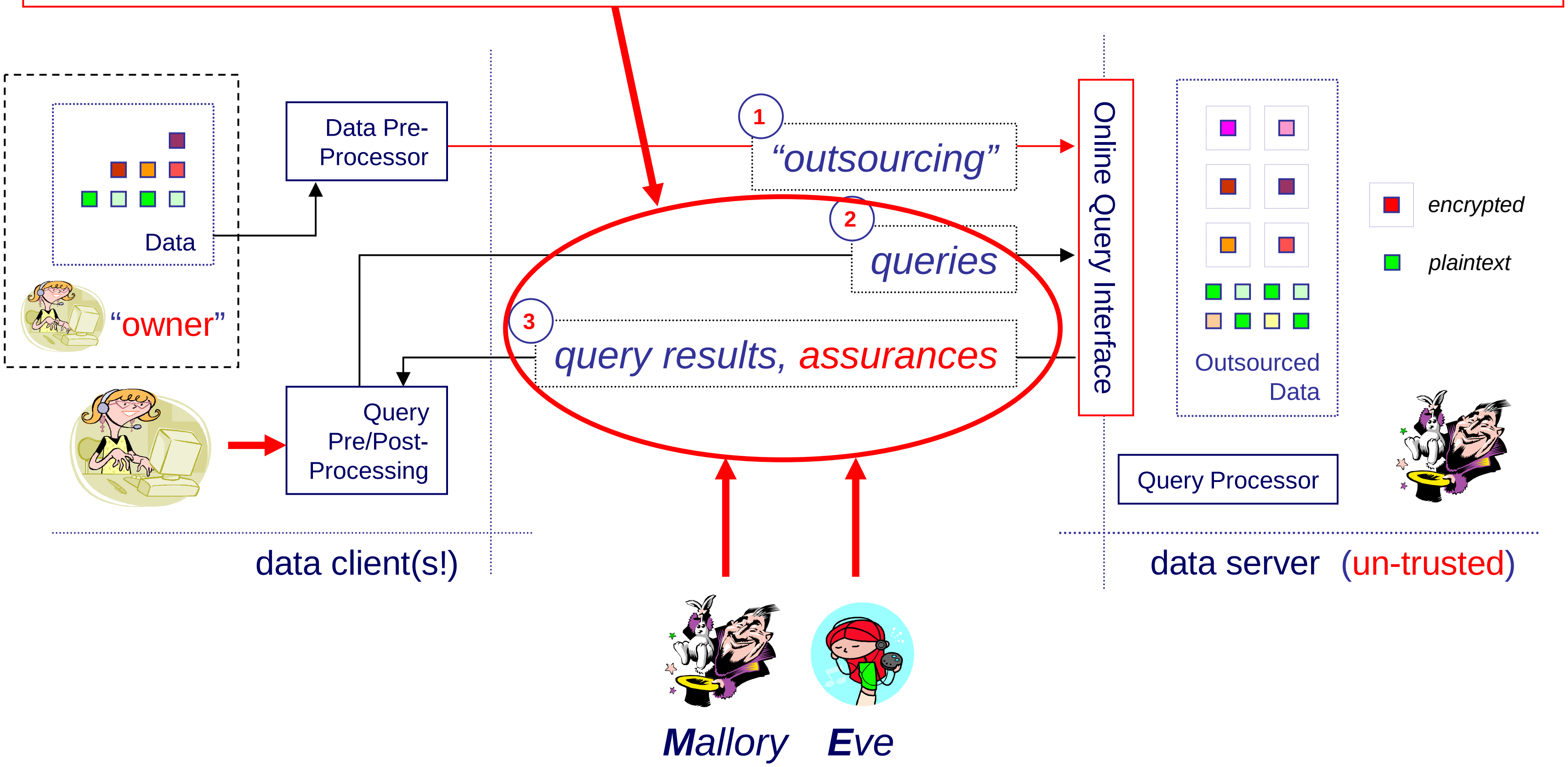
Data Outsourcing

assurances ⊆ {query correctness, data confidentiality, access privacy}



Outsourcing Challenges

Un-trusted server:

- lazy: incentives to perform less
- curious: incentives to acquire information
- malicious:
  - denial of service
  - incorrect results
  - possibly compromised

Why is this hard ?

- how ?
- arbitrary expressivity
- overheads
  - network
  - computational costs

What do we do ?

- query assurances
- full privacy
  - of queries (even encrypted)
  - of access patterns
- data confidentiality

Hacigumus (2002)

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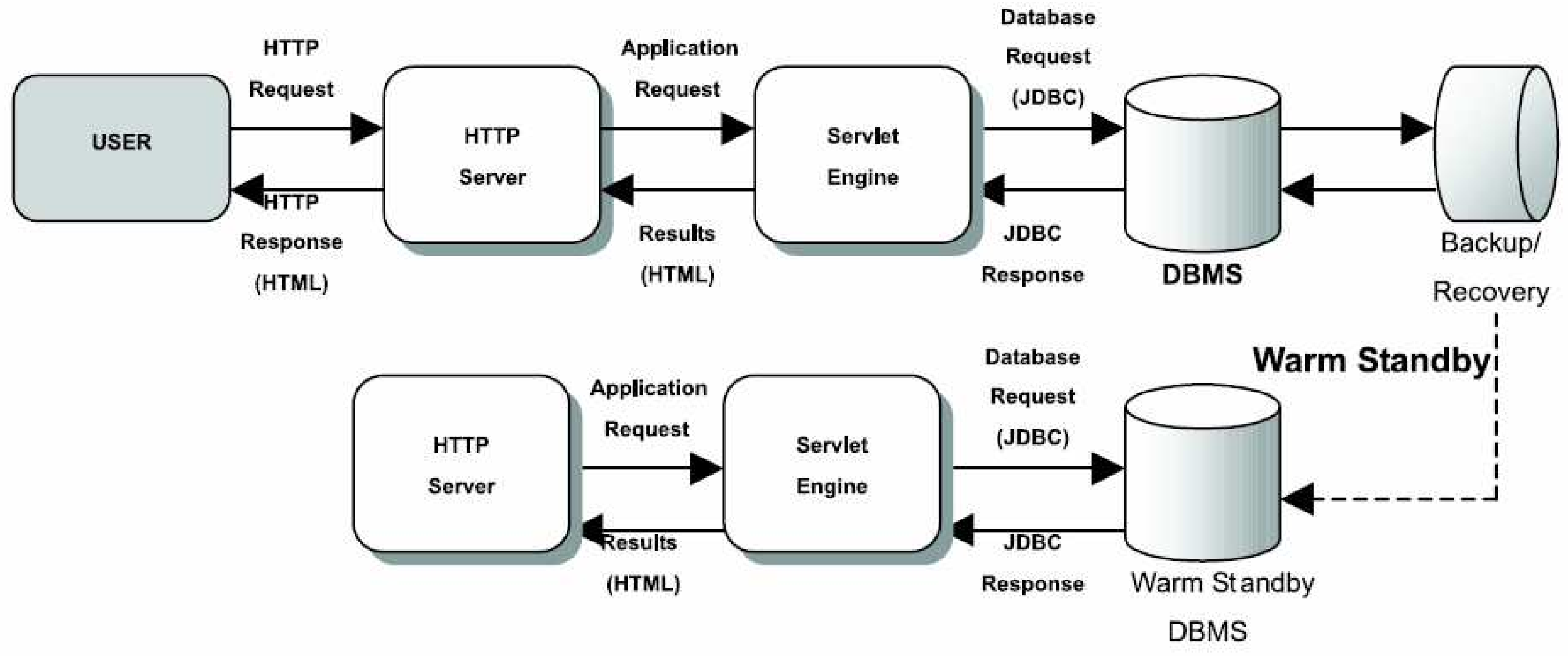

System architecture of NetDB2

Stored Data Confidentiality

```
SELECT decrypt(discount,key)
FROM lineitem
WHERE custid = 300
```

H. Hacigumus, B. R. Iyer, and S. Mehrotra. Providing database as a service, ICDE 2002.

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Correctness

Client requires quantifiable assurances that query results are correct, for arbitrary query types in the presence of a server that could be …

… lazy

… and/or fully malicious (!)

Devanbu et. al. (2000)

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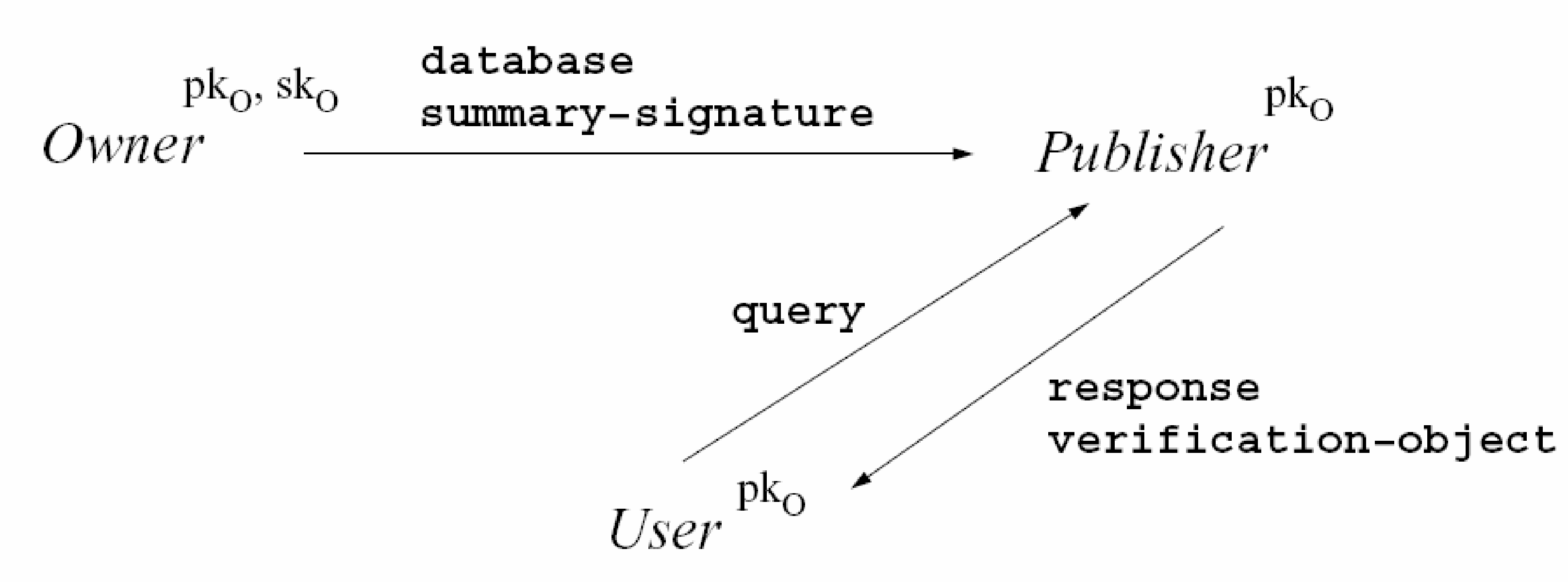
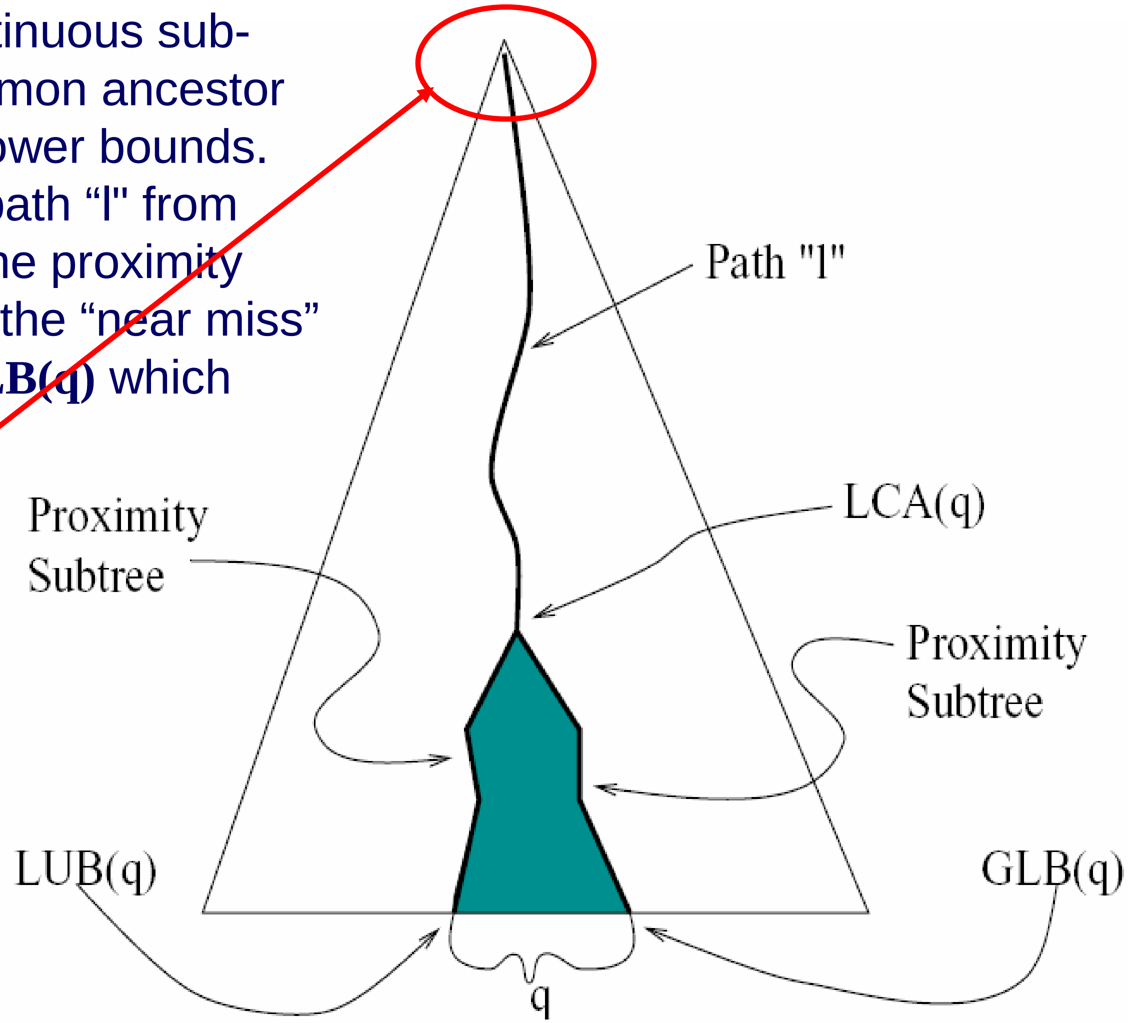


The owner provides database updates and summary signatures to the un-trusted publisher. When users make inquiries with the publisher, they get responses which can be verified using a returned verification-object. Only $\mathbf{sk_o}$ is secret, $\mathbf{pk_o}$ is authenticated.

Devanbu et. al. (2000)

A Merkle tree, with a continuous sub-range **q**, with a least common ancestor **LCA(q)**, and upper and lower bounds. Note the verifiable hash path "l" from **LCA(q)** to the root, and the proximity sub-trees (thick lines) for the "near miss" tuples for **LUB(q)** and **GLB(q)** which show that q is complete.

authenticated via signature

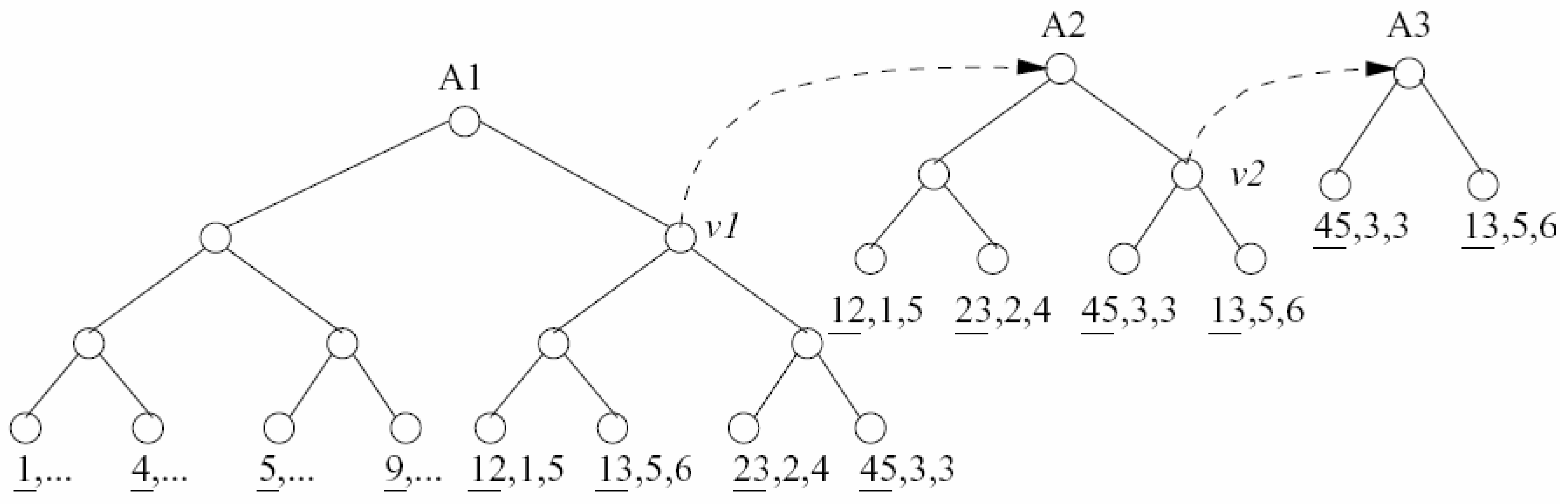


Devanbu et. al. (2000)

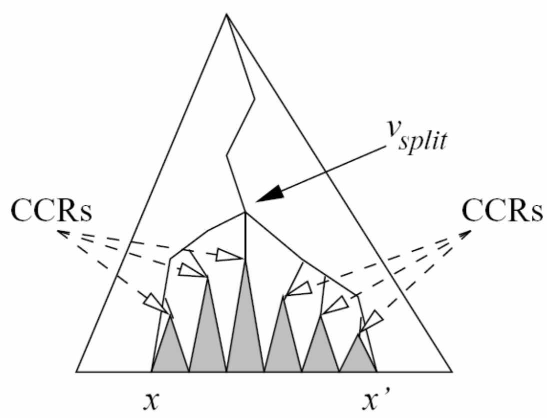
Supported claimed operations:

- selections
- projections
  - (1) maintaining VOs before duplicate elimination
  - (2) pre-computing VOs for common projections
- equiJOIN
  - (1) keep materialized cartesian product S x R
    - construct VO on sorted version of product (according to difference (S.A-R.A)) – this yields 3 types of leaf nodes (“0”,”<“,”>”) in Merkle tree
  - (2) all kinds of other tricks
- set operations
  - union (client does it and verifies VOs for input sets)
  - intersection (?)
  - multi-dimensional range queries (generalizing hash tree to “multi-dimensional range tree”)

Devanbu et. al. (2000)

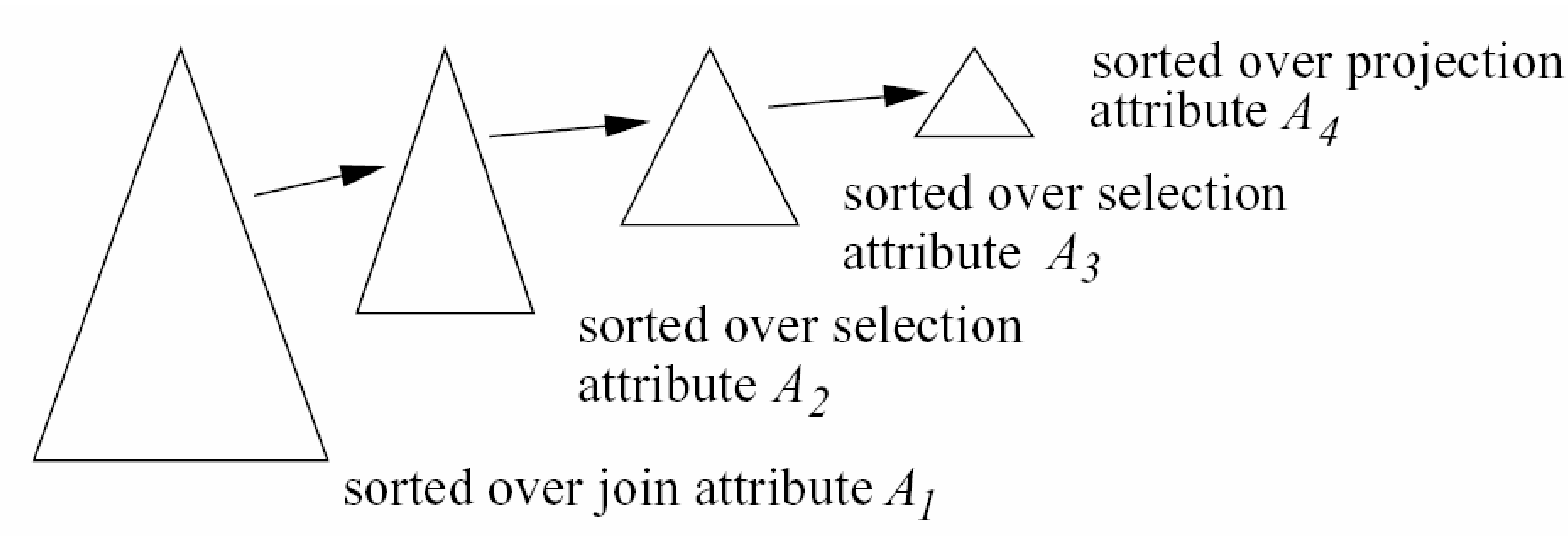


Excerpt of a 3-dimensional range tree, sorted by attributes A_1, A_2 and A_3



Covering canonical roots (**CCR**): roots of the canonical sub-trees precisely covering the leaves with values in the interval.

Devanbu et. al. (2000)




```
SELECT S.A4 FROM S,R
WHERE S.A1=R.A1 AND A2<10 AND A3>17
```

Devanbu et. al. (2000)

Issues:

- query expressiveness
- query flexibility
  - works only on data with VOs
- “universe split” phenomenon
  - use timestamps, expiration times
- expensive operations (!)

Mykletun et.al. (NDSS 2004)

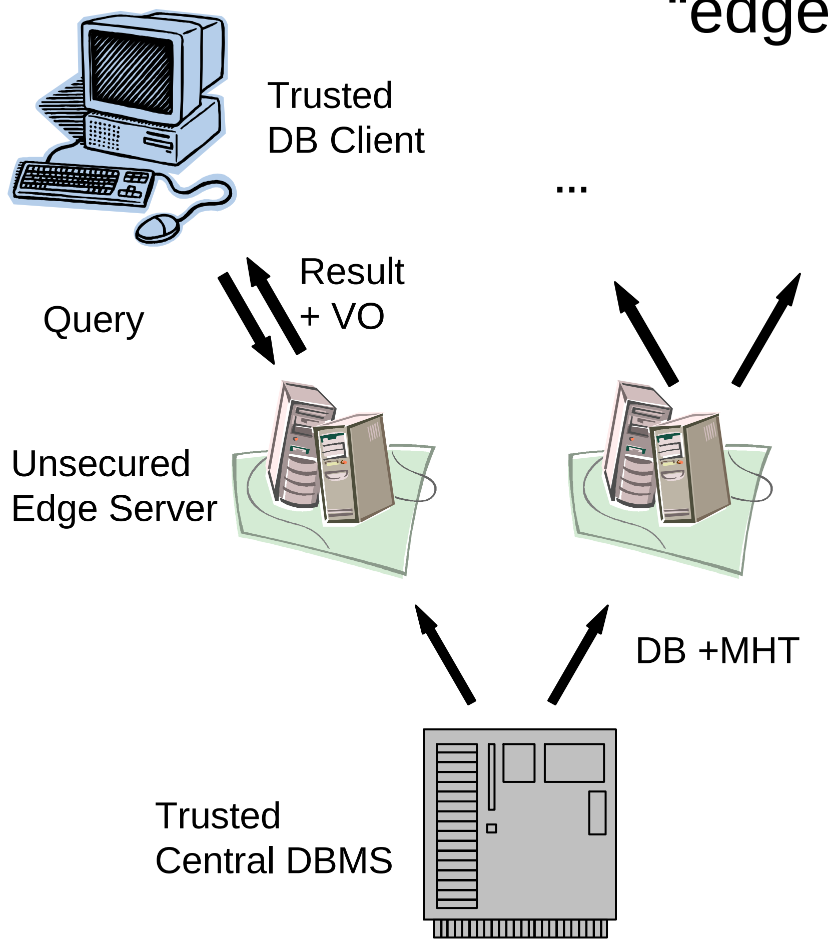
Discusses the use of batch verification of signatures and similar techniques (condensed RSA) to authenticate results.

		Condensed-RSA	Batch-DSA	BGLS
Sign	1 signature	6.82	3.82	3.54
Verify	1 signature	0.16	8.52	62
	t = 1000, k = 1	44.12	1623.59	184.88
	t = 100, k = 10	45.16	1655.86	463.88
	t = 1000, k = 10	441.1	16203.5	1570.8

Cost comparison (in msecs): verification and signing. Notation: t – # signatures, k – # signers

Pang et. al. (ICDE 2004)

“edge computing”



Claimed problems with [Devanbu 2000]

- A hash tree is needed for every sort-order
- VOs need to contain links all the way to the root,
  - VOs grow linearly to query result and logarithmic to base table size
- Projections may have to be performed by clients
- No provision for dynamic updates on the database

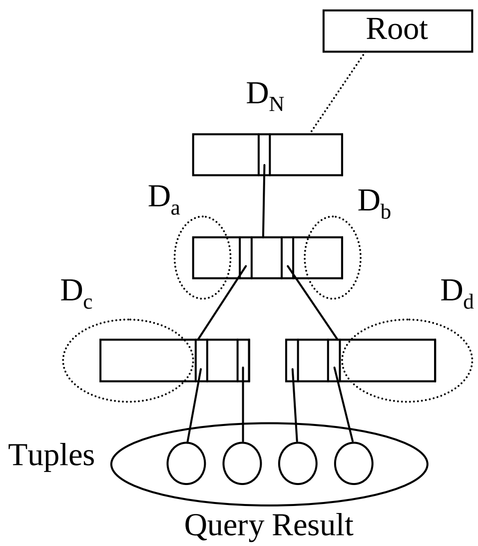
Aim 1: VO size just linear in query result
Aim 2: do not push projections to client

Idea: use different hash function

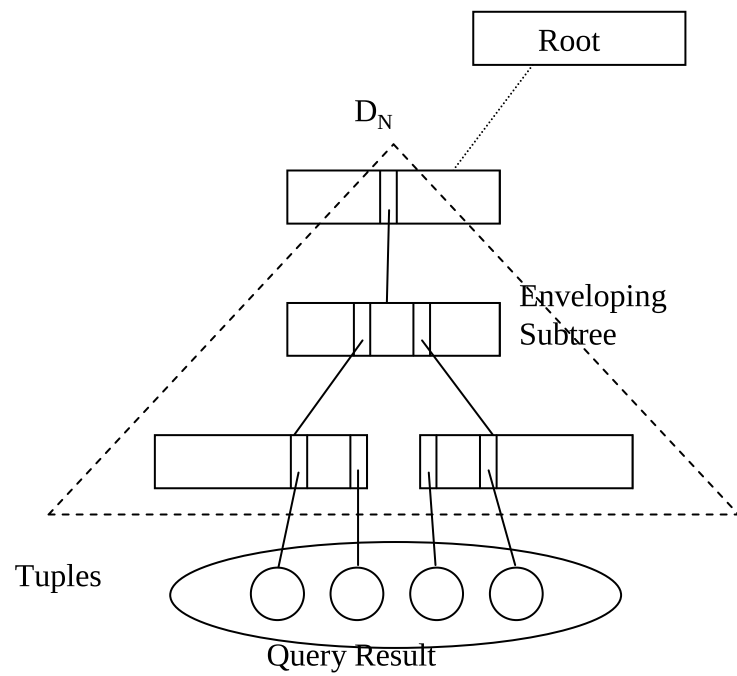
- $h(x) = g^x \bmod q$
- h is commutative, h(x+y) = h(y+x)
  - Digests can be combined arbitrarily
  - Projection can be performed at the edge servers
  - Facilitates insertion of new tuples with minimal effect on other digests

  - but: significantly (1000-10000 times) slower
  - trade-off: computation vs. communication

Pang et. al. (ICDE 2004)



Verification object = $D_N + D_S$
where $D_S = \{D_a, D_b, D_c, D_d\}$



Verifying Selection

(no need to go up to the root

as everything is also signed)

Pang et. al. (SIGMOD 2005)

Similar expressiveness. But …

Asks: what about access control rules ?
(Devanbu seems to reveal too much: boundary tuples)

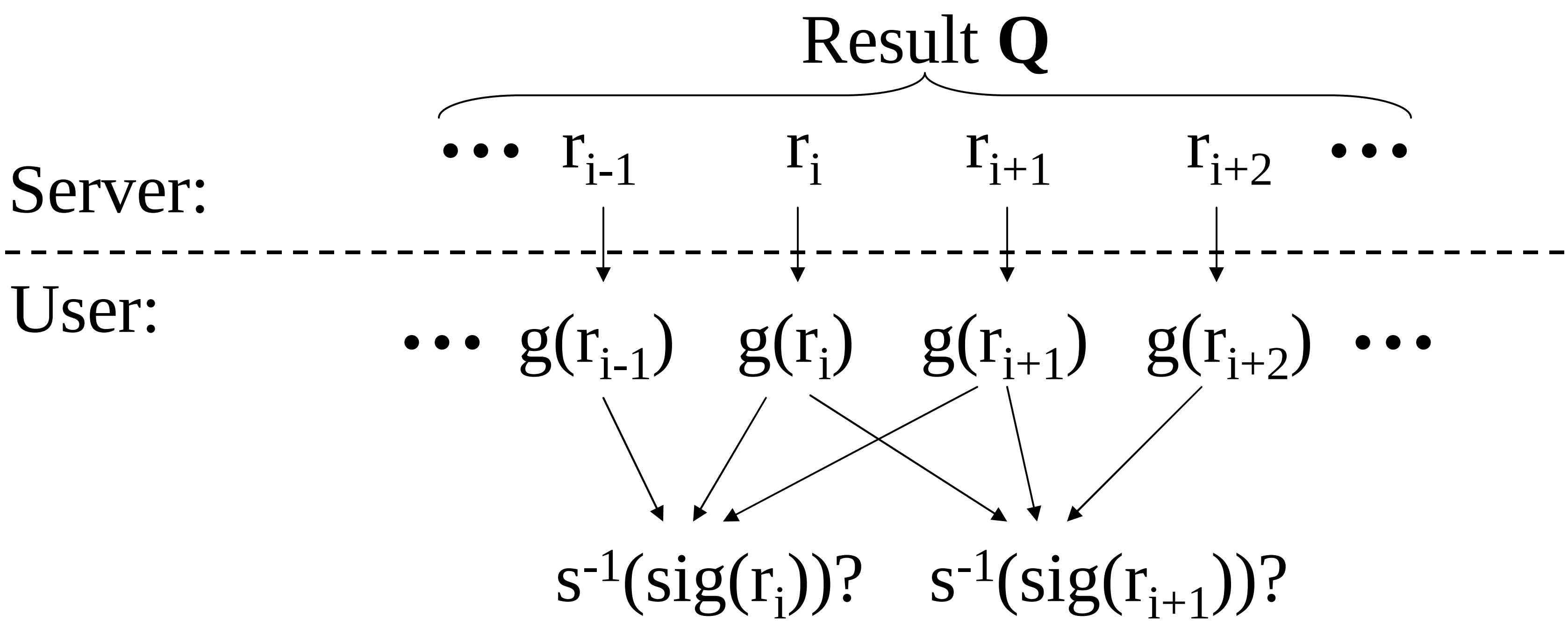
Also claims: lower overheads for queries and updates.

Introduces “precision” (only data matching the query should be returned)

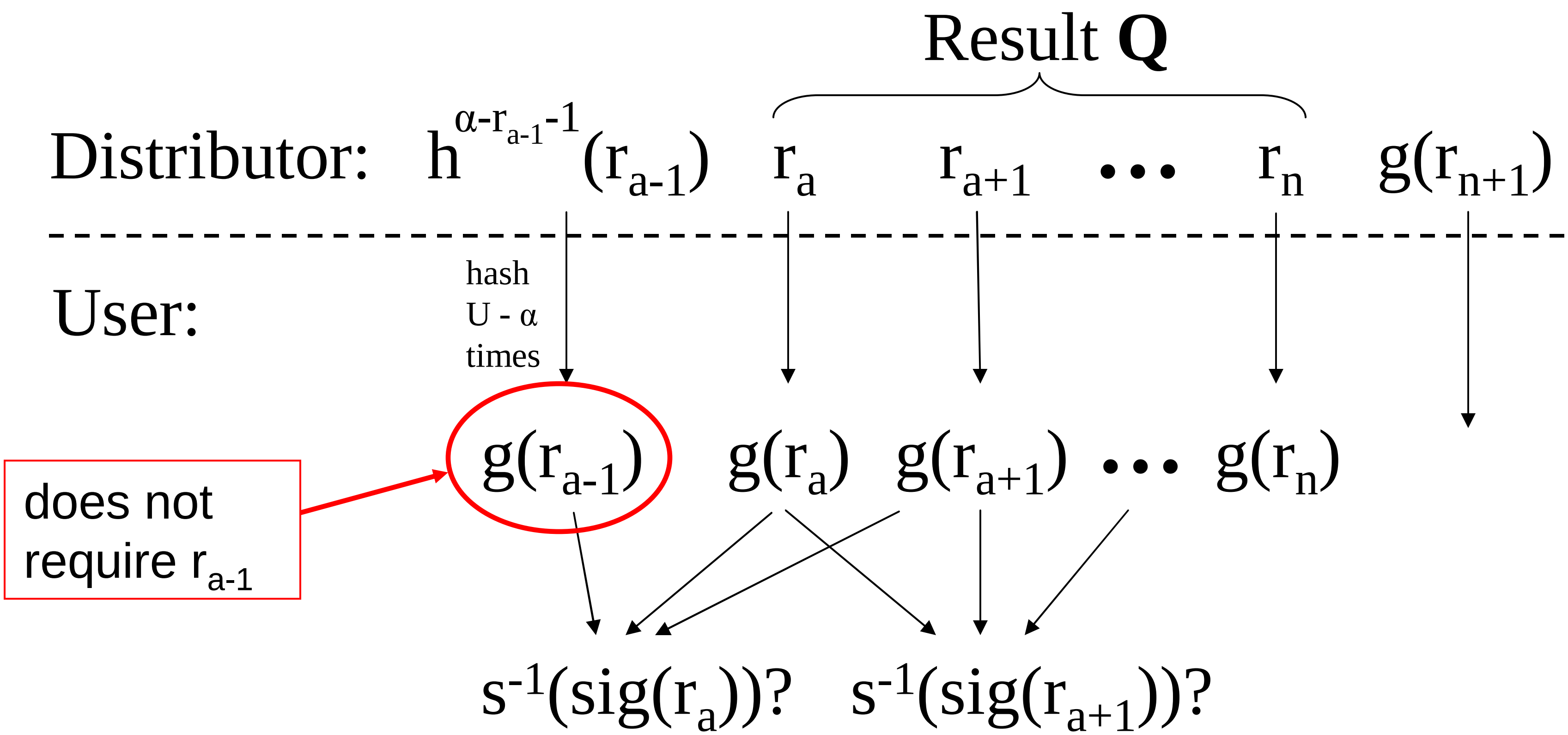
Pang et. al. (SIGMOD 2005)

Idea: use signature chains – thus no need to reveal boundary elements.

$sig(r_i) = s(h(g(r_{i-1}) \mid g(r_i) \mid g(r_{i+1})))$



But what is g: $g(r) = h^{U-r-1}(r)$

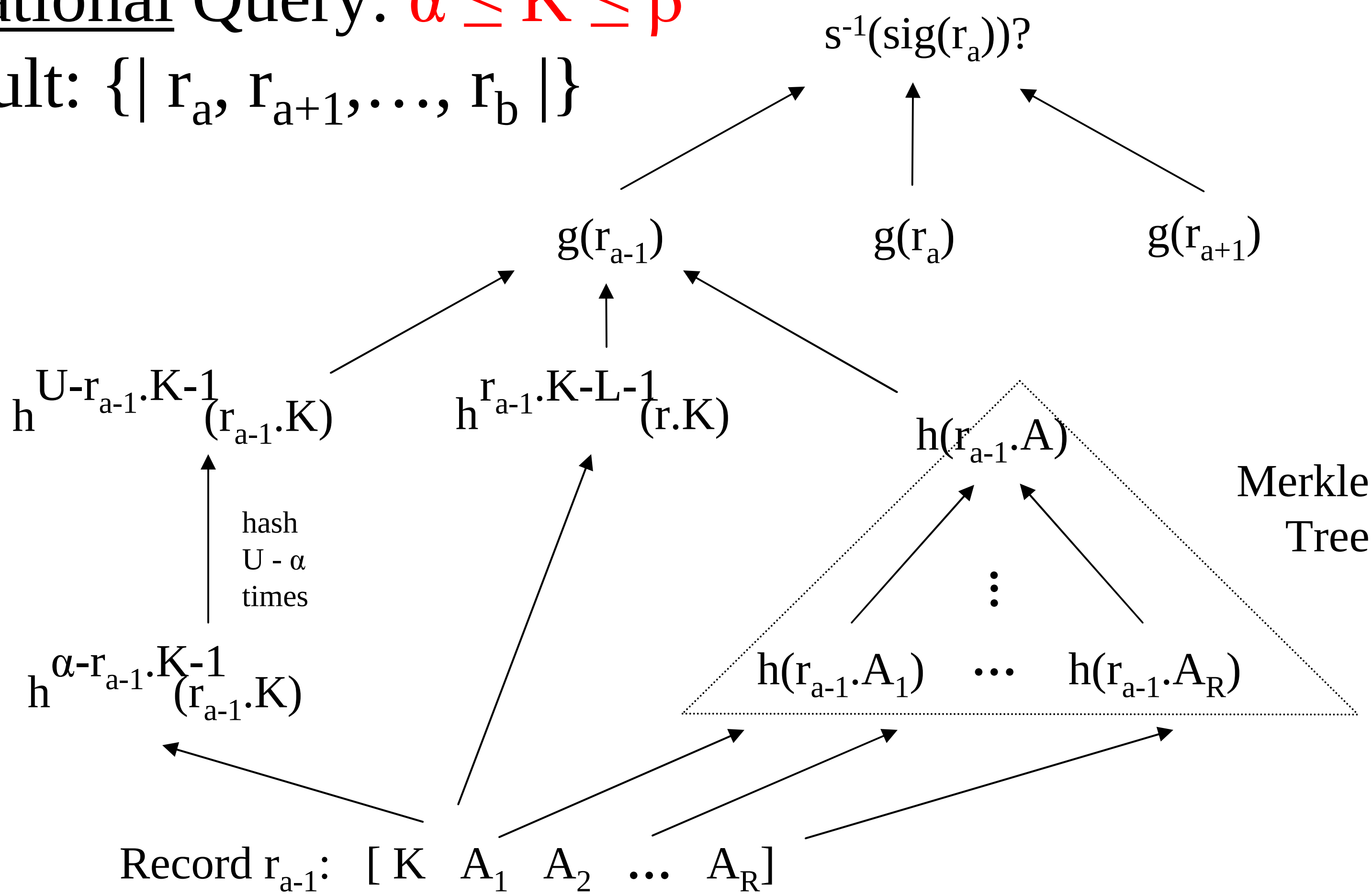


Query: $\alpha \leq r$

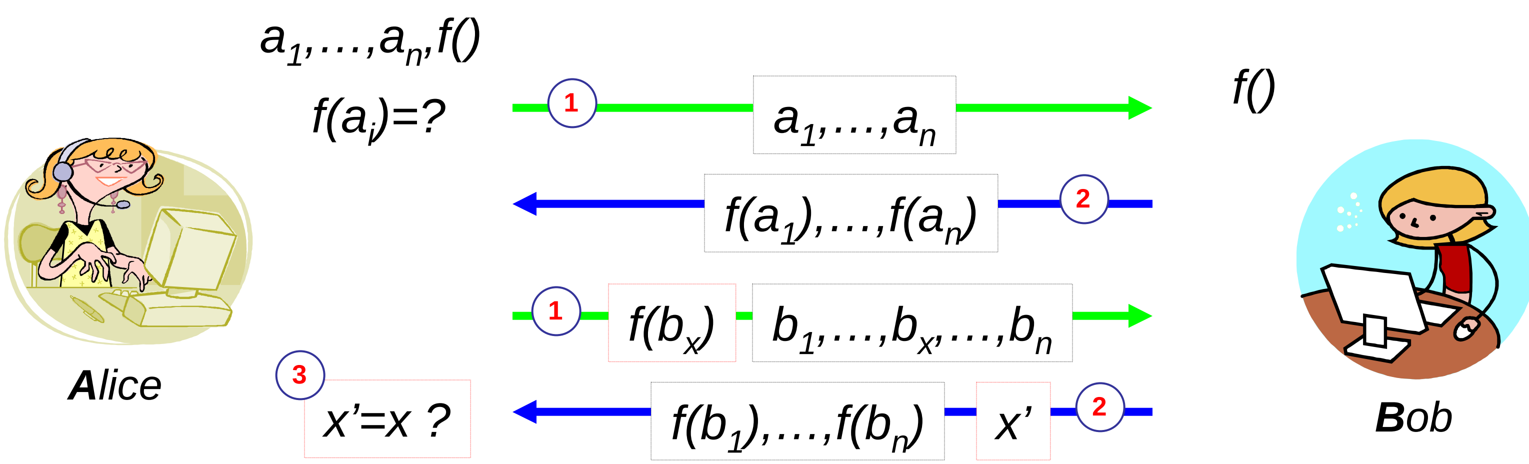
Pang et. al. (SIGMOD 2005)

Relational Query: $\alpha \leq K \leq \beta$

Result: $\{| r_a, r_{a+1}, \ldots, r_b |\}$



Asks: What about arbitrary queries ?



P. Golle and I. Mironov,*"Uncheatable Distributed Computations"*, RSA 2001 (Cryptographer's track)

Sion: Execution Proofs

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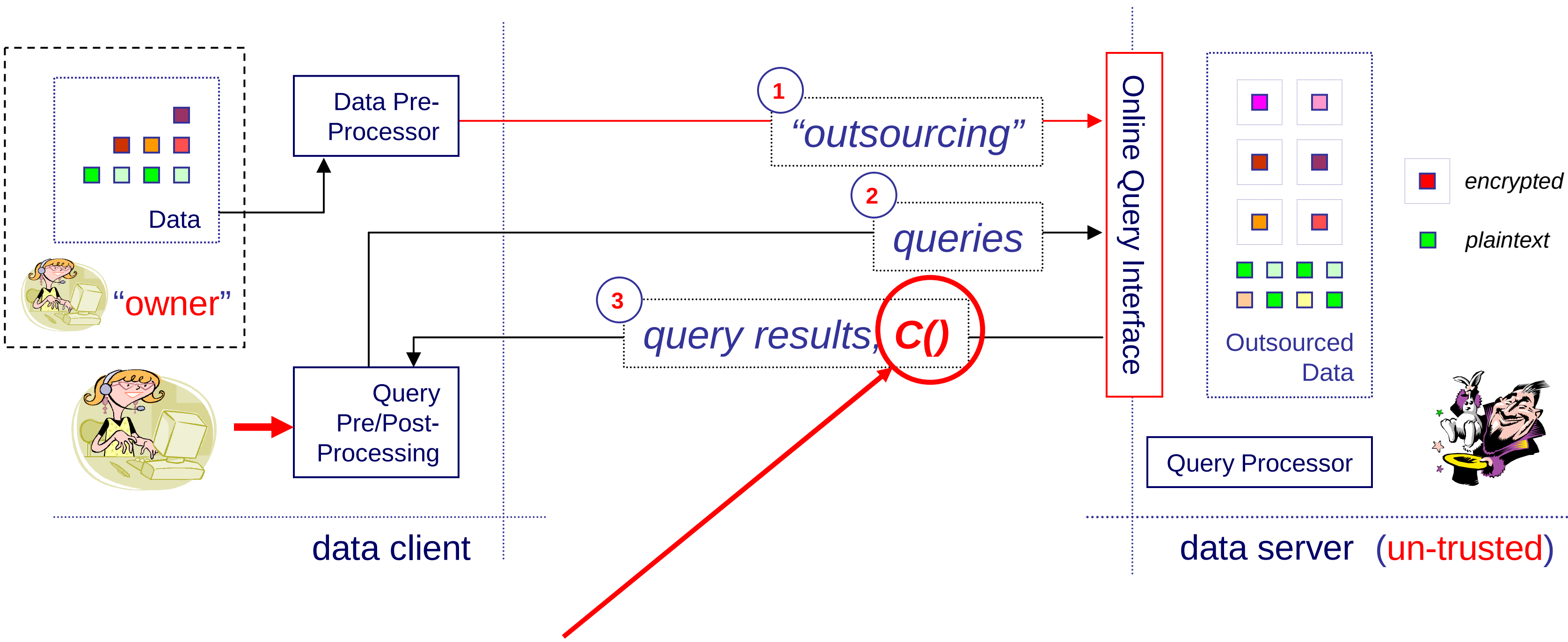

$$C(\mathbb{Q}, x, \epsilon) = \{H(\epsilon || \rho(Q_x)), \epsilon\}$$

A challenge token (computed by client) is sent together with the batch of queries. Upon return, batch execution is proved if x=x'.

Sion: Cheating Probability

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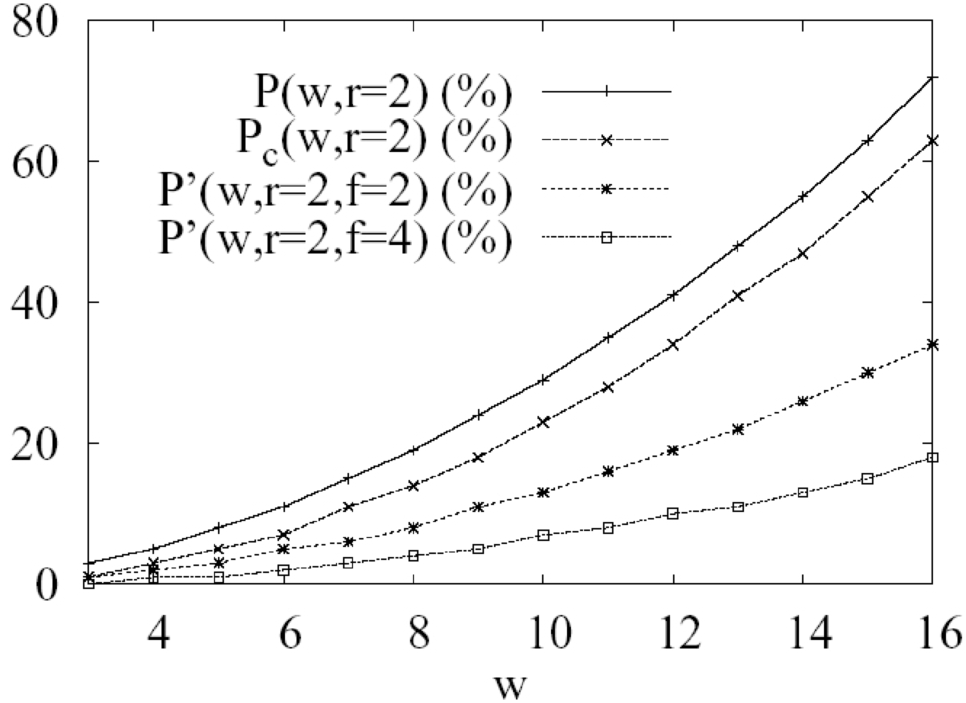

The behavior of $\mathtt{P'(w,r,f)}$ (fake tokens) plotted against $\mathtt{P_c(w,r)}$ (client-side result checking mechanism) showing that the query execution proof mechanism (with fake tokens) significantly decreases the ability to "get away" with less work.

Only handles lazy server !

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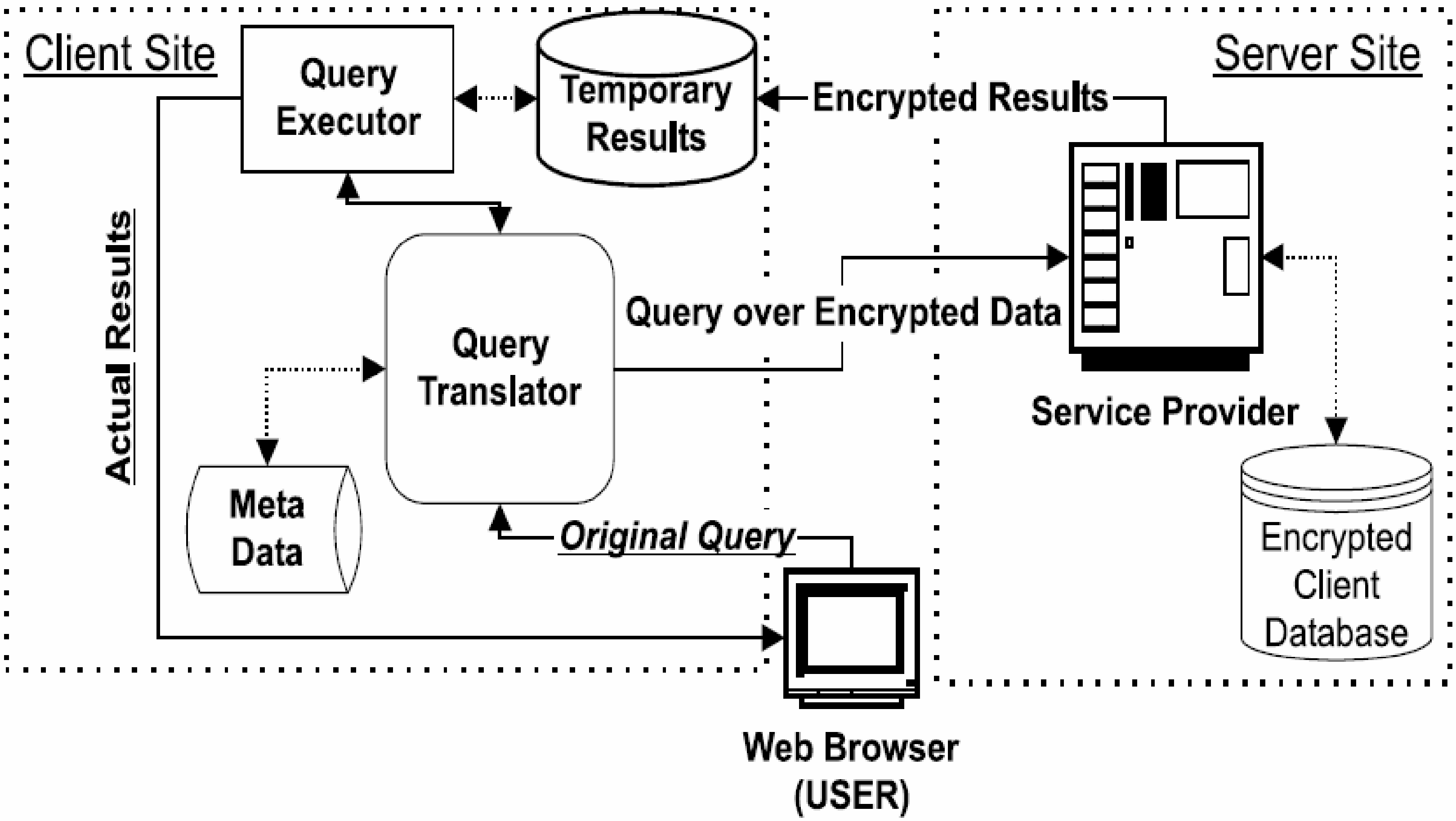
Hacigumus (SIGMOD 2002)



Hacigumus (SIGMOD 2002)

Main Steps:

1. Partition sensitive domains
   - Order preserving: supports comparison
   - Random: query rewriting becomes hard
2. Rewrite queries to target partitions
3. Execute queries and return results
4. Prune/post-process results on client

Hacigumus (SIGMOD 2002)

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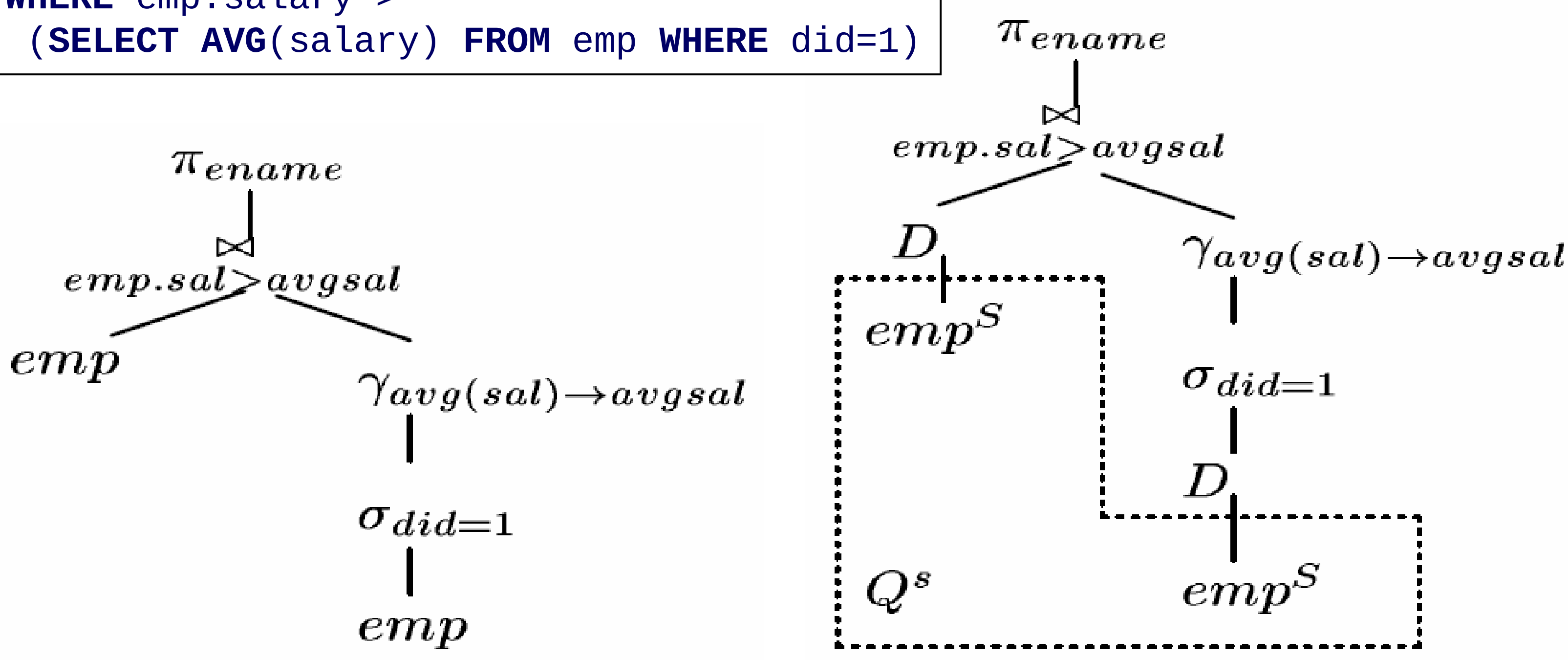
```
SELECT emp.name FROM emp
WHERE emp.salary >
 (SELECT AVG(salary) FROM emp WHERE did=1)
```



(a) Original query tree.

(b) Replacing encrypted relations.

Hacigumus (SIGMOD 2002)

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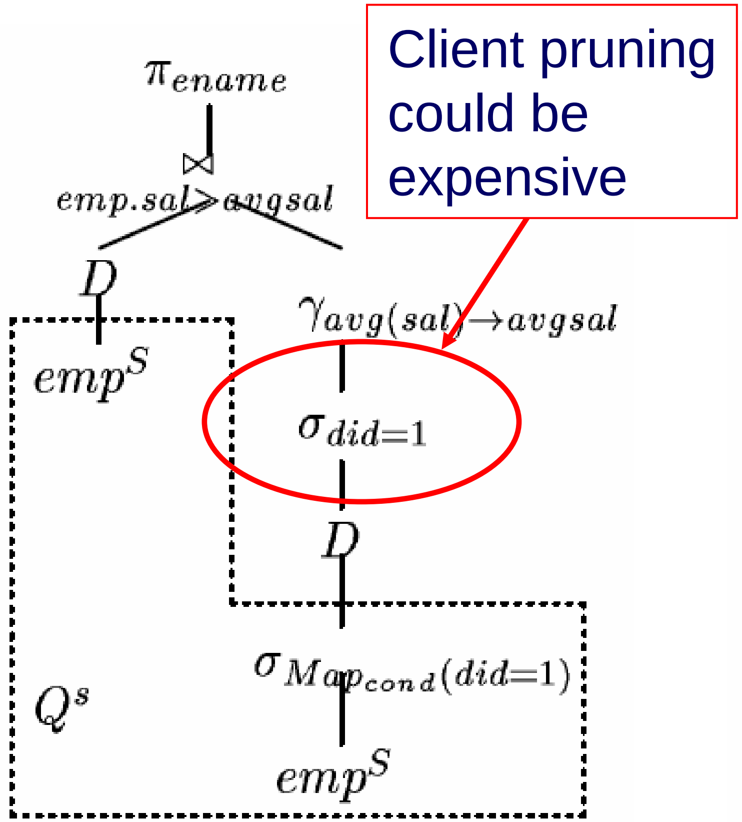
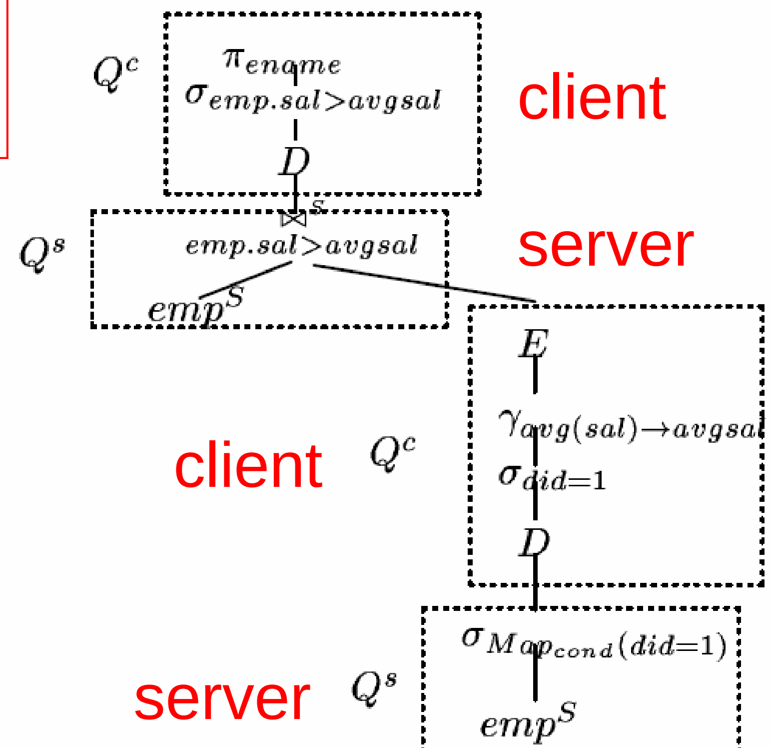


(c) Doing selection at server.



(d) Multiple interactions between Client and Server.

Confidentiality-Overhead Trade-off

Larger segments ==
increased privacy ==
increased overheads

Hore (VLDB 2004)

Goal: For a uniform distribution of queries - minimize any leaks to any adversaries (even) knowing segmentation parameters.

Idea 1: Maximize variance of distribution of values in segment
Idea 2: Increase segment entropy

Issue: What about performance ?

Solution: “Controlled Diffusion”

Idea:

1. design for efficiency, then …
2. … diffuse (re-distribute) elements inside the segments to increase per-segment entropy and variance

Hacigumus (DASFAA 2005)

Asks: Similarly, how to structure query trees to optimally balance the security-efficiency trade-off in [Hacigumus 2002].

Idea: client generates optimal partitioned query execution plans given statistics and metadata input from the server.

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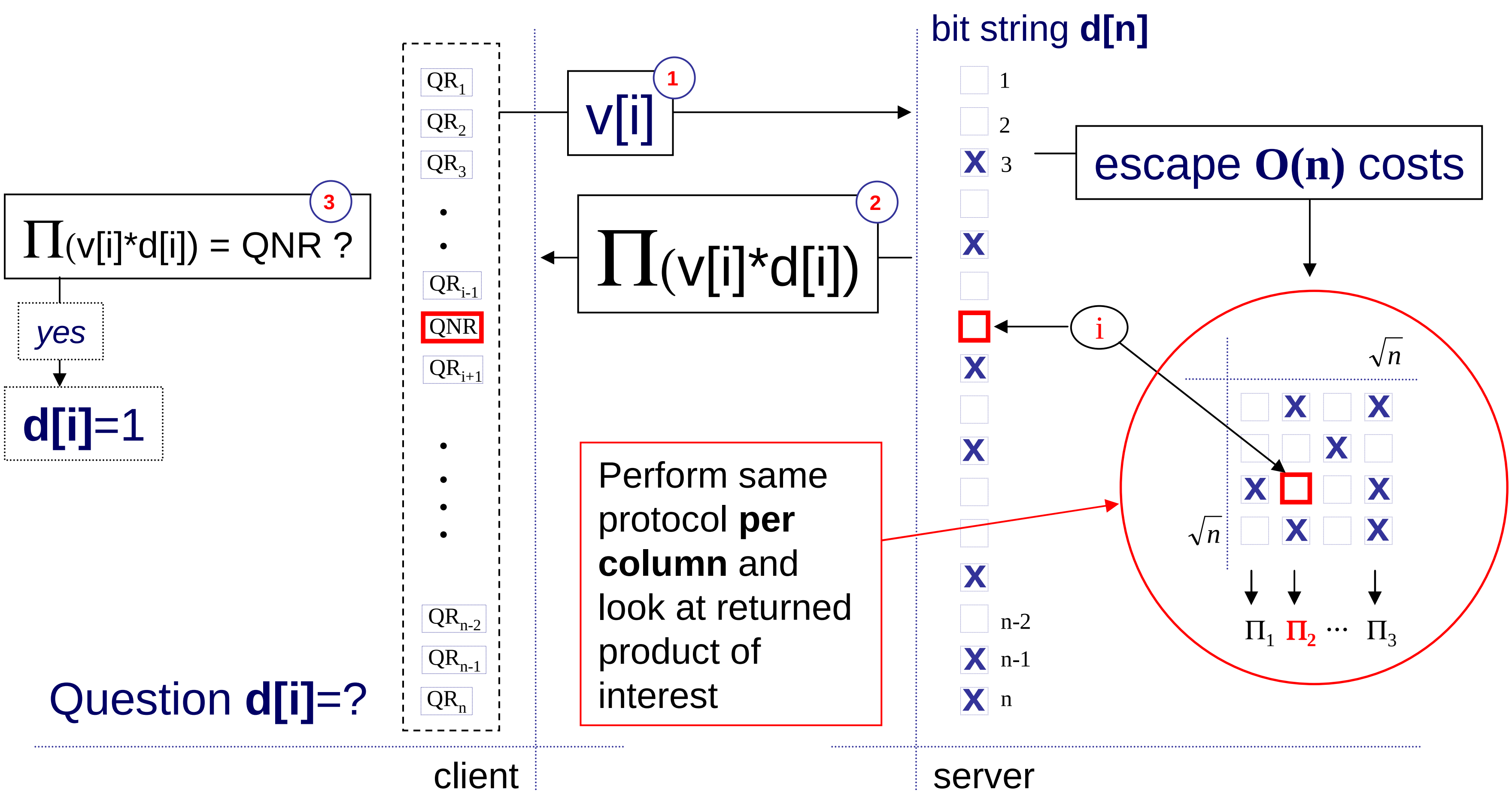
QR PIR



bit string d[n]
QR1
QR2
QR3
QRi-1
QNR
QRi+1
QRn-2
QRn-1
QRn
1
v[i]
2
Π(v[i]*d[i])
3
Π(v[i]*d[i]) = QNR ?
yes
d[i]=1
escape O(n) costs
1
2
3
i
n-2
n-1
n
√n
√n
Π1 Π2 ··· Π3
Perform same protocol per column and look at returned product of interest
Question d[i]=?
client
server

QR PIR

The n bits of the database are organized logically at the server as a bi-dimensional matrix M of size $\sqrt{n} \times \sqrt{n}$. To retrieve bit $M(x, y)$ with computational privacy, the client:

- randomly chooses two prime numbers p and q of similar bit length, computes their product, $N = pq$ and sends it to the server.
- generates $\sqrt{n}$ numbers $s_1, s_2, \ldots, s_{\sqrt{n}}$, such that s_x is a quadratic non-residue (QNR) and the rest are quadratic residues (QR) in $\mathbb{Z}_N^*$.
- sends $s_1, s_2, \ldots, s_{\sqrt{n}}$ to the server.

For each "column" $j \in (1, \sqrt{n})$ in the $\sqrt{n} \times \sqrt{n}$ matrix, the server:

- computes the product $r_j = \prod_{0<i<\sqrt{n}} q_{ij}$ where $q_{ij} = s_i^2$ if $M(i, j) = 1$ and $q_{ij} = s_i$ otherwise [2].
- sends $r_1, \ldots, r_{\sqrt{n}}$ to the client

The client then simply checks if r_y is a QR in $\mathbb{Z}_N^*$ which implies $M(x, y) = 1$, else $M(x, y) = 0$.

PIR is (still) impractical

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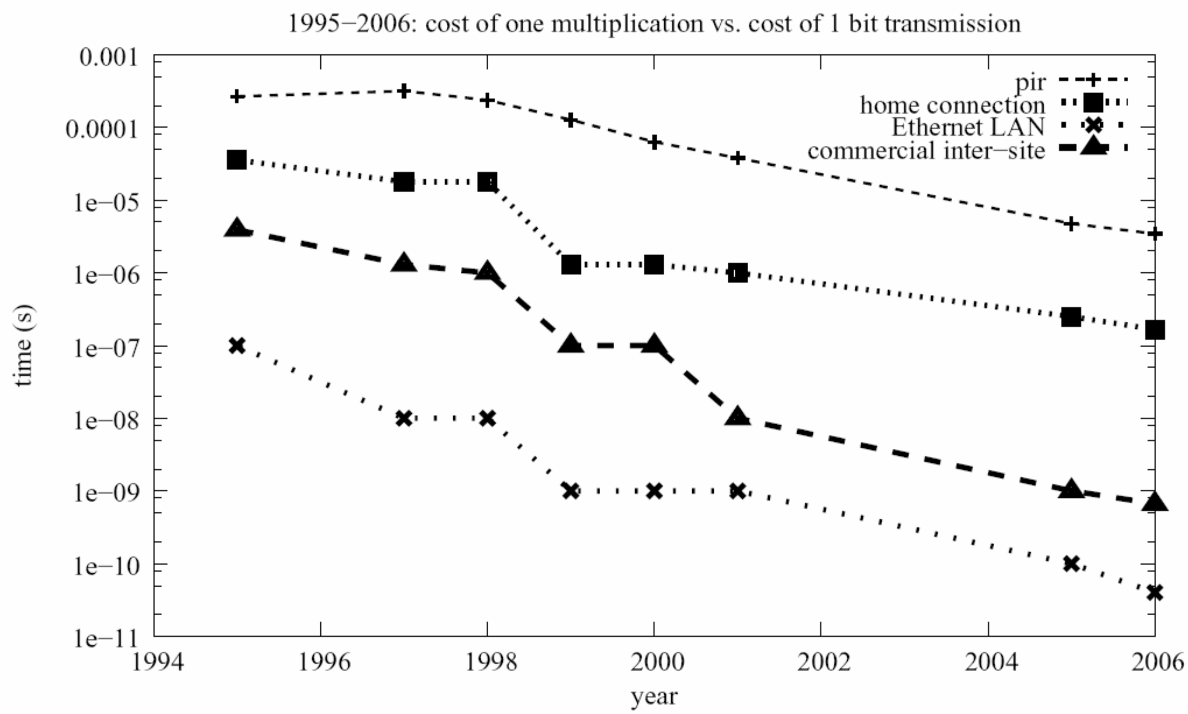

Comparison between the time required to perform PIR and the time taken to transfer the database, between 1995 and 2005. (logarithmic)

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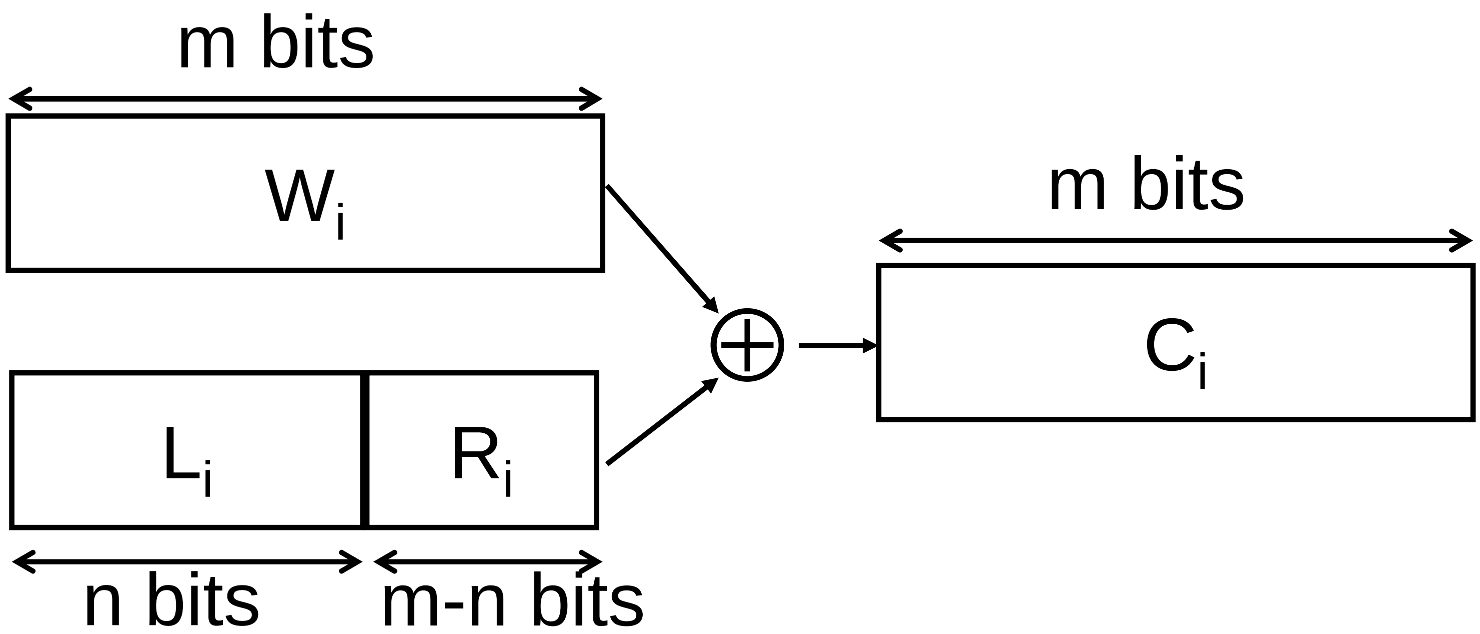
Search on Encrypted Data

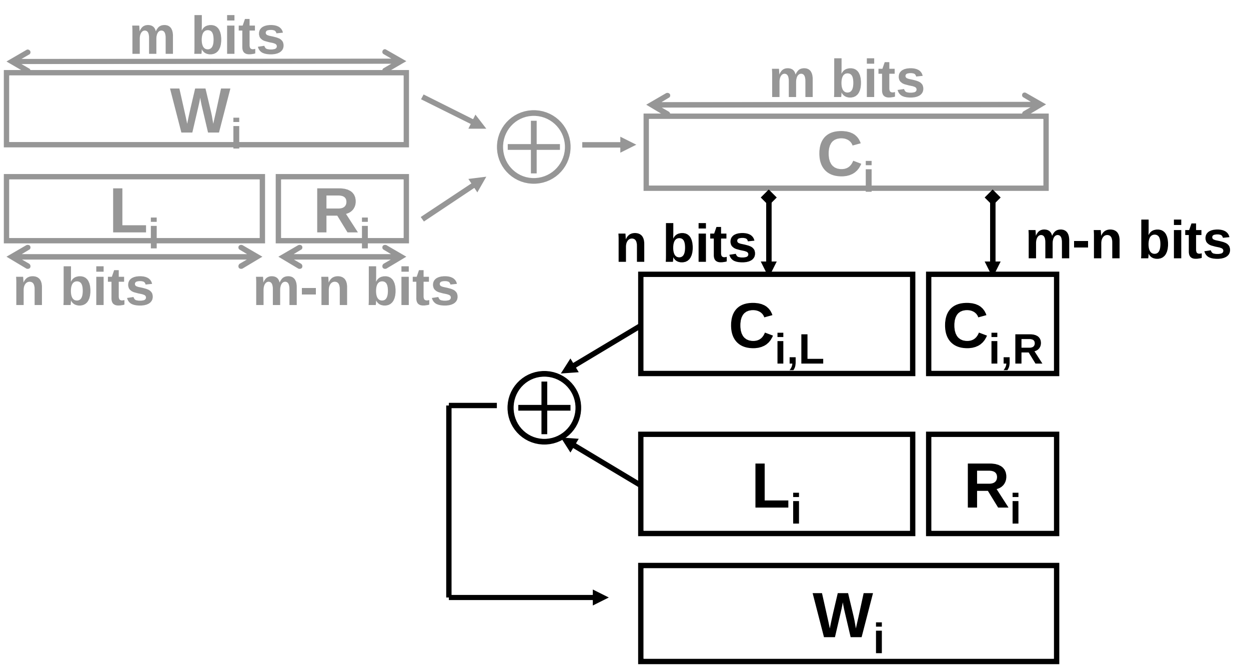
- Sequential Scan
- Index-based

Encryption:



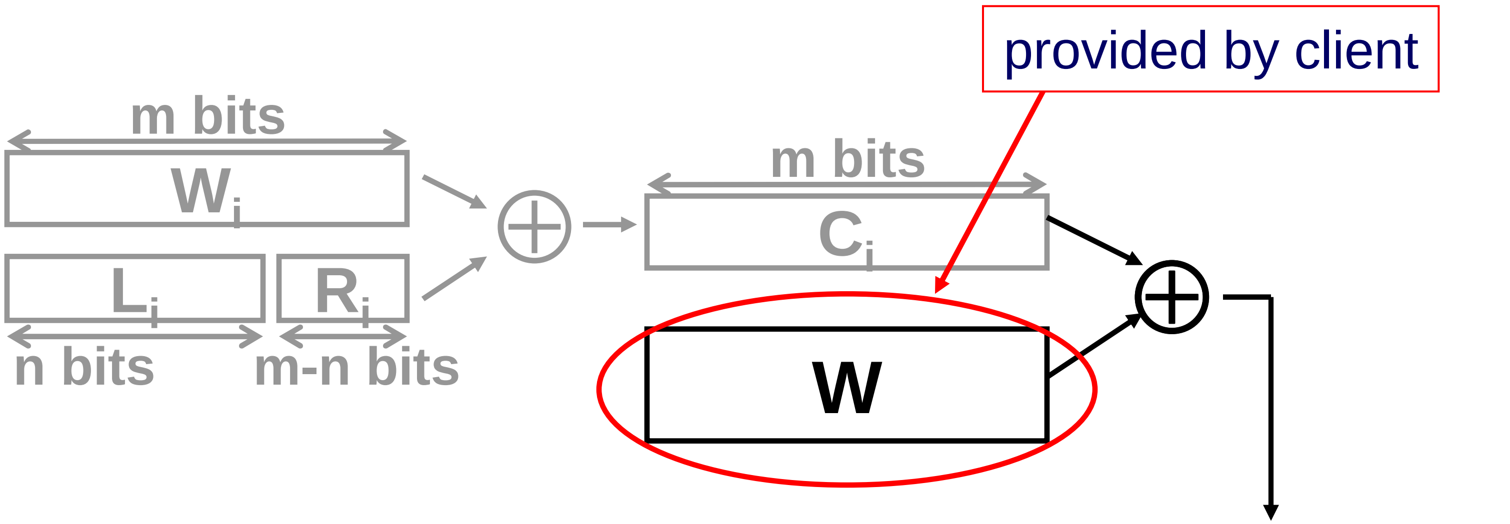
$L_i \leftarrow G_i$ (seed), $R_i \leftarrow F_K(L_i)$

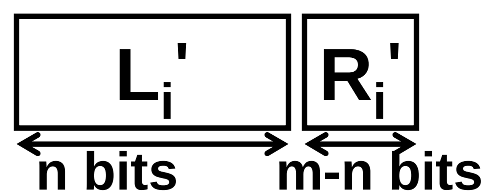
Decryption:



$L_i \leftarrow G_i\ (\text{seed}), \quad R_i \leftarrow F_K(\ L_i\ )$

Search:





Check: $R_i' = F_K (L_i')$?

Yes $\Rightarrow$ **match,**

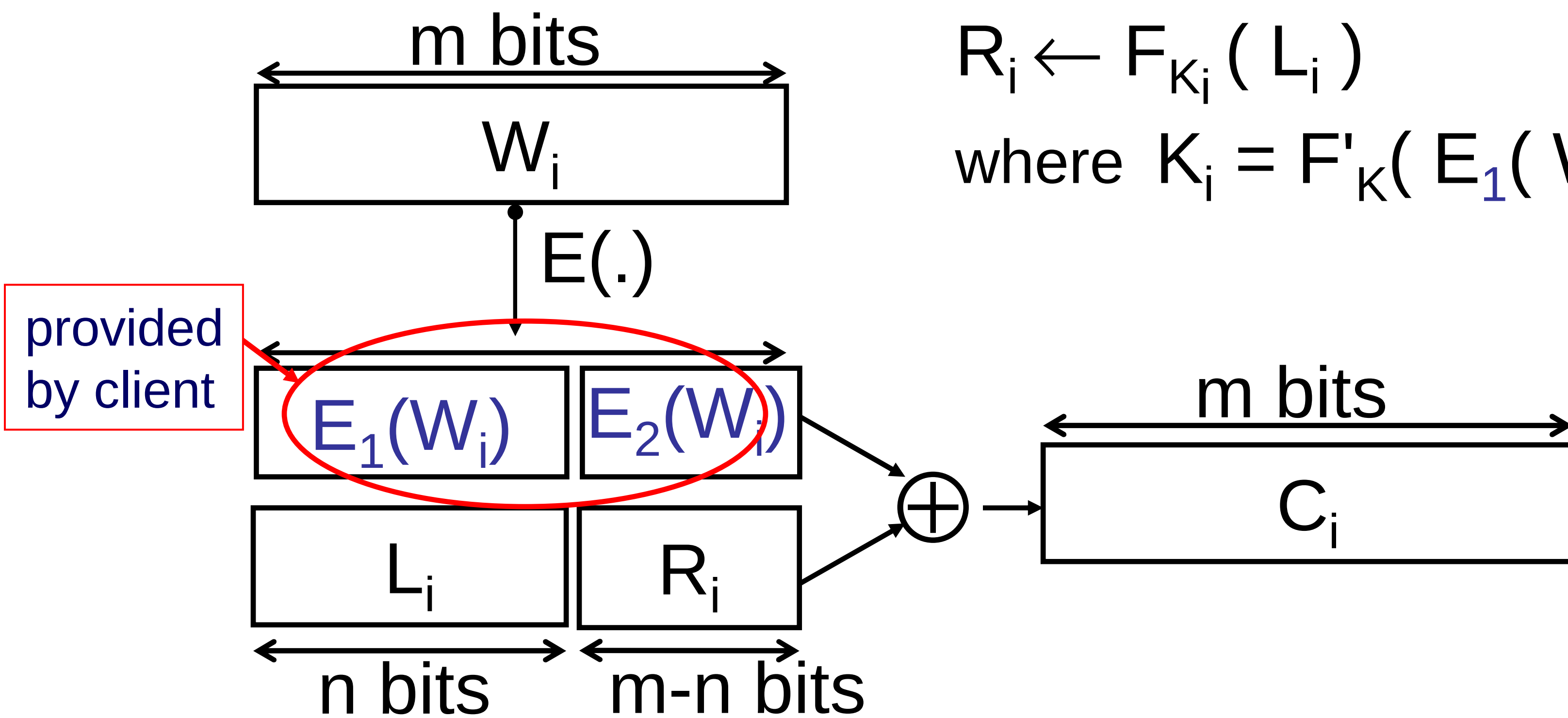
(**false positive rate =** $1 / 2^{m-n}$)

"Hidden" Search:

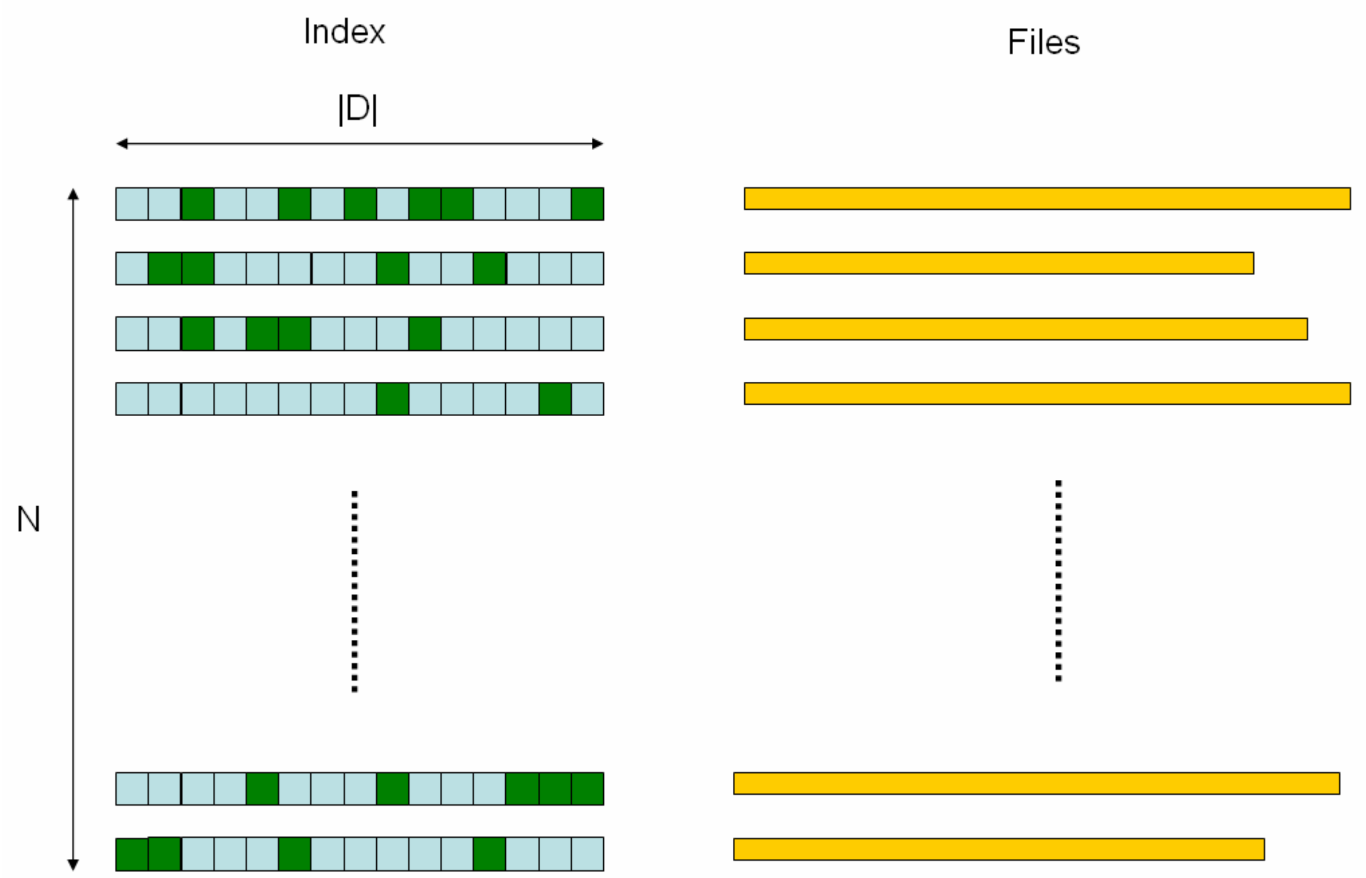
$L_i \leftarrow G_i$ (seed),

$R_i \leftarrow F_{K_i}(L_i)$

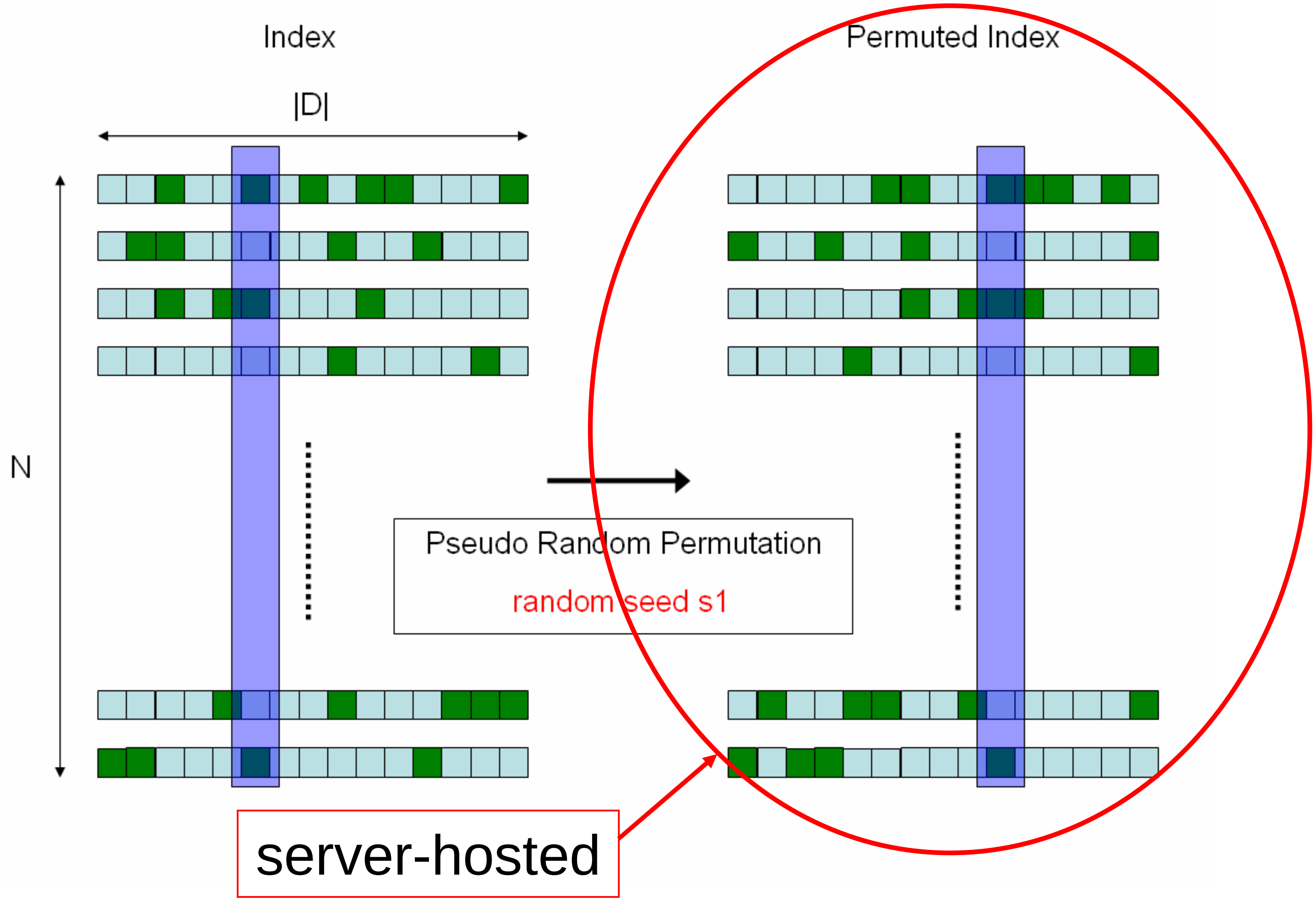
where $K_i = F'_K(E_1(W_i))$



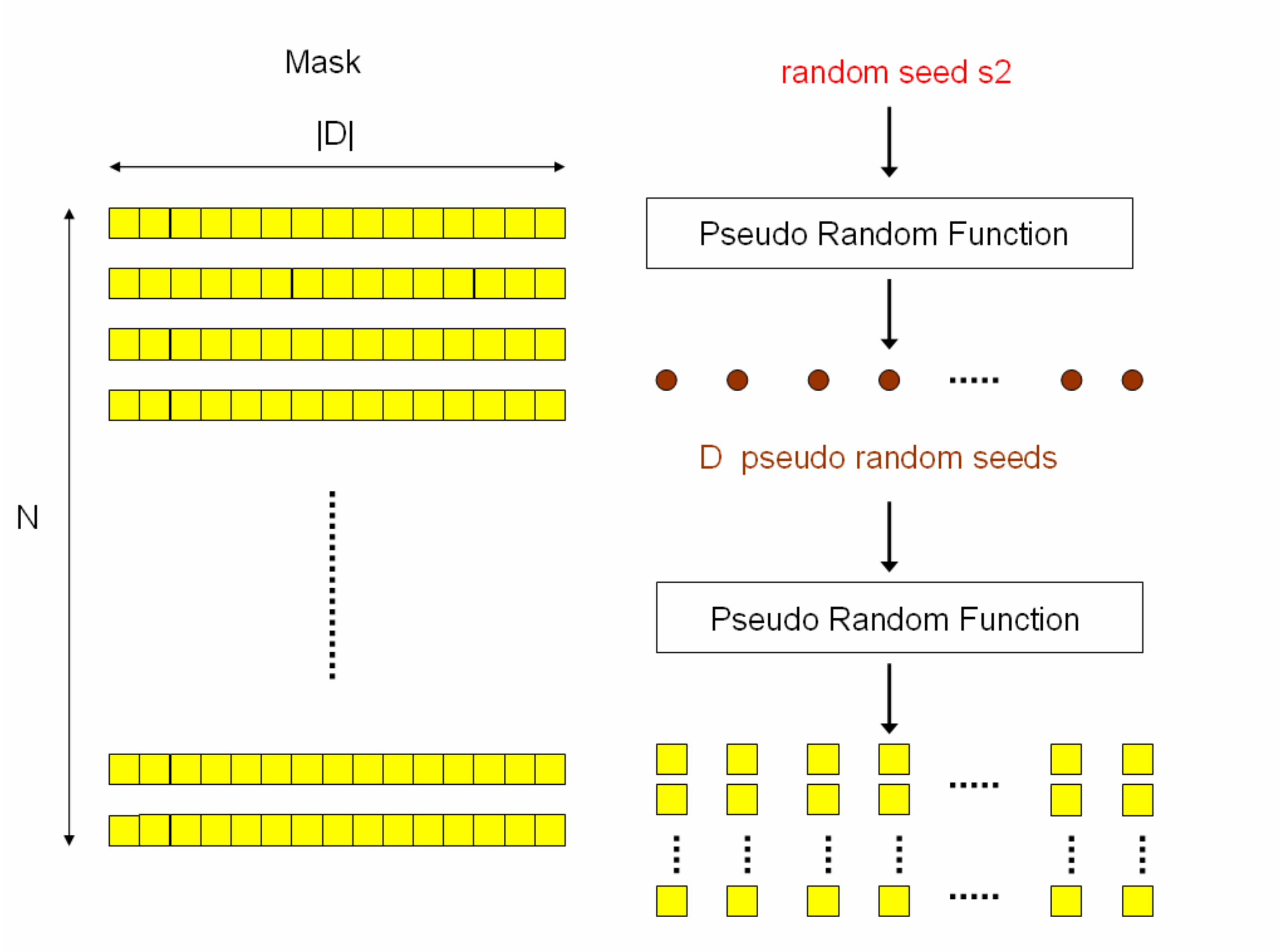
Chang (2004)



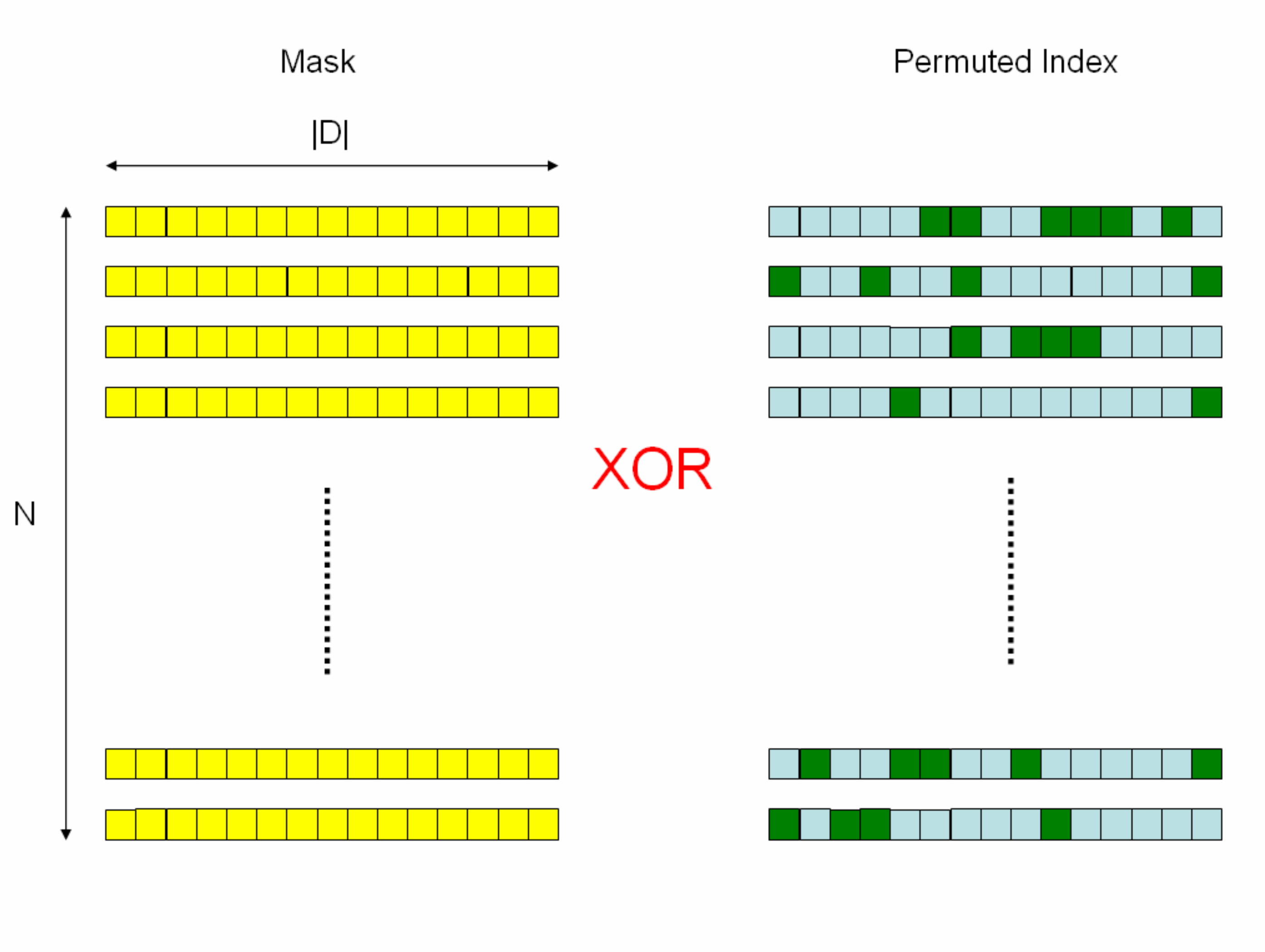
Chang (2004)


Index
|D|
N
Permuted Index
Pseudo Random Permutation
random seed s1
server-hosted

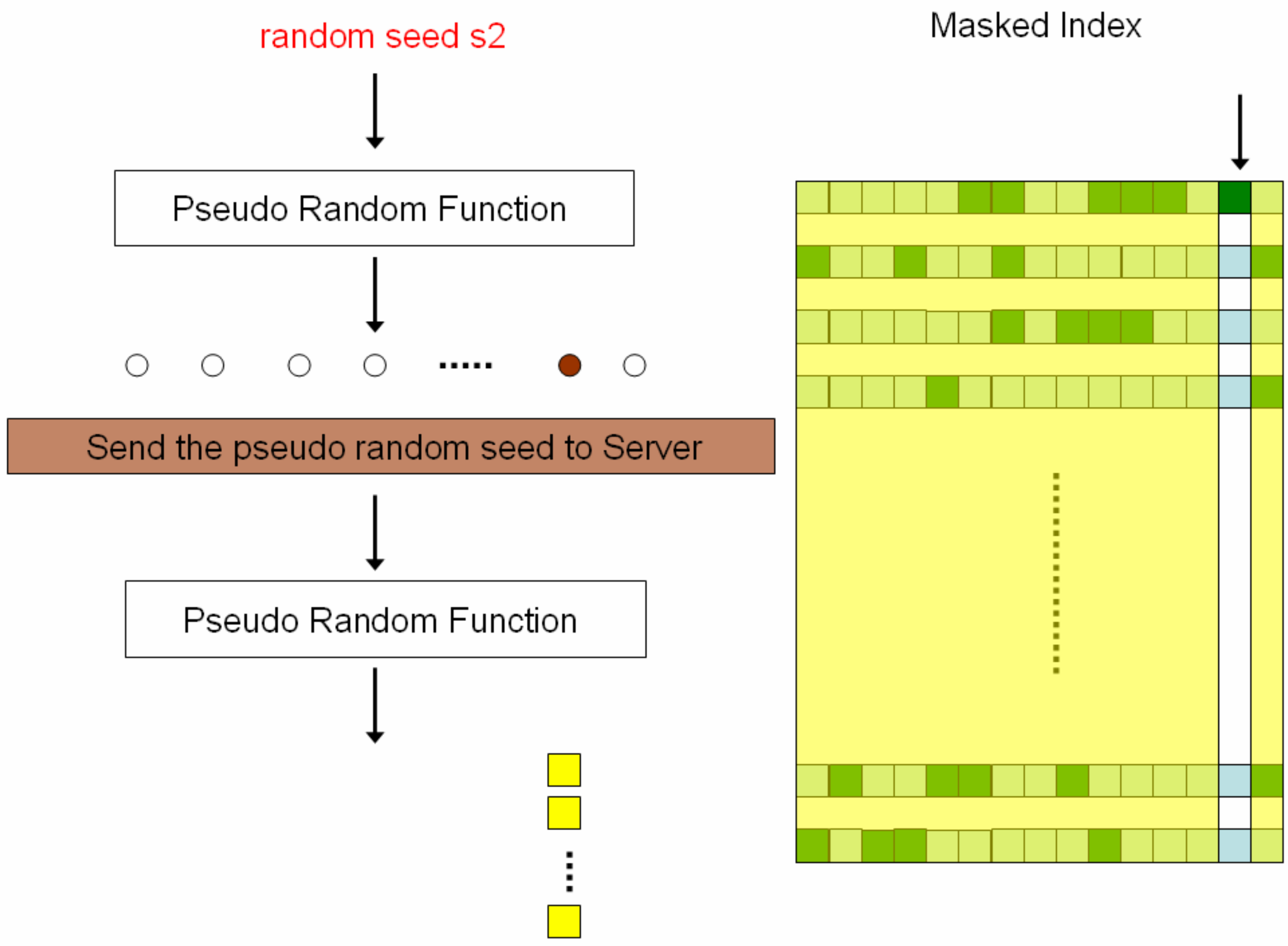
Chang (2004)


Mask
|D|
N
random seed s2
Pseudo Random Function
D pseudo random seeds
Pseudo Random Function

Chang (2004)



Chang (2004)


random seed s2
Pseudo Random Function
Send the pseudo random seed to Server
Pseudo Random Function
Masked Index

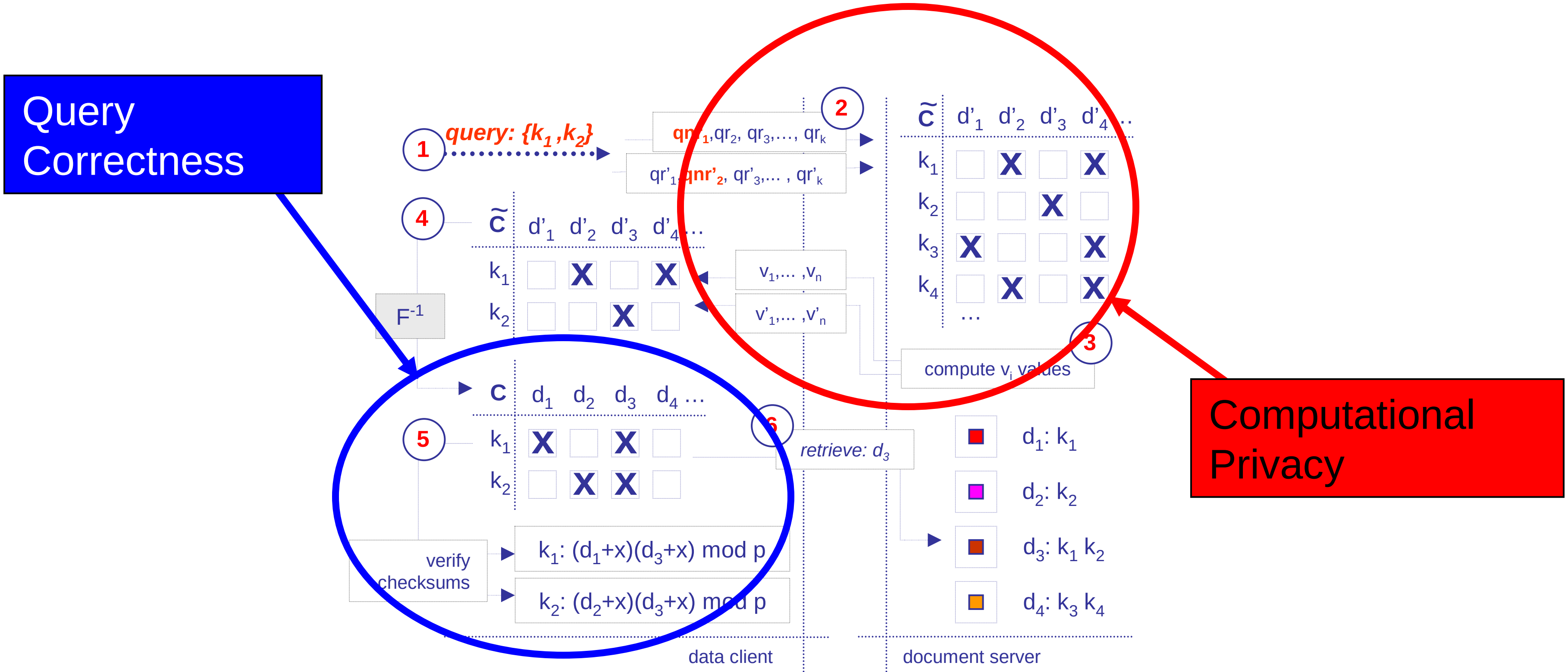
Golle (2004)

Server stores **capabilities** for conjunctive queries (linear in the total number of documents). These can be transferred offline.

The client is required to know before-hand future conjunctive queries.

Query part is sent online at the time of search. It is of constant size (number of keyword fields per documents).

Asks: What about correctness + privacy ?



Idea: Deploy modified version of computational PIR targeted at a server-side index. Augment with "multiplicative checksums".

Overview

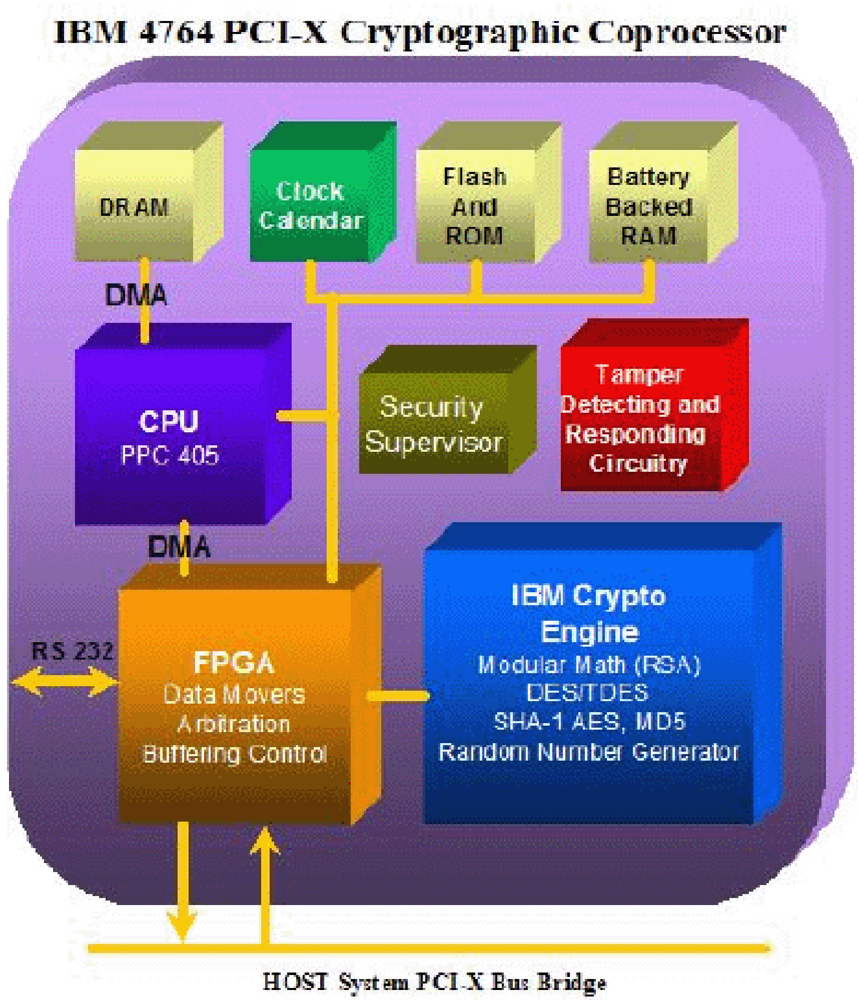
- *Crypto Crash Course*
- *Data Outsourcing*
- *Query Correctness*
- *Data Confidentiality*
- *Access Privacy*
- *Searching on Encrypted Data*
- *Trusted Hardware*

Trusted Hardware

IBM 47xx

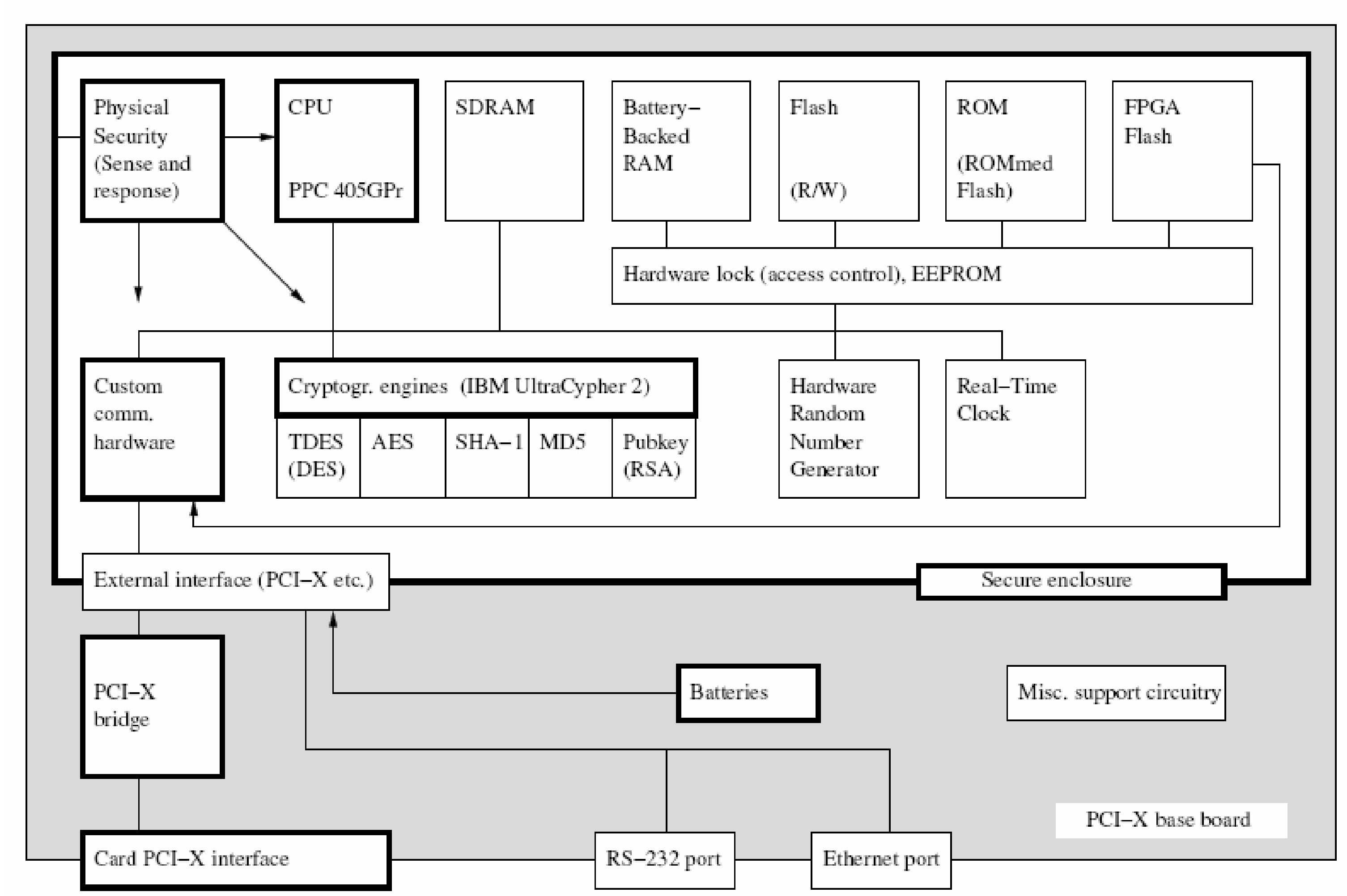
IBM 4764 Architecture

Stony Brook Network Security and Applied Cryptography Lab

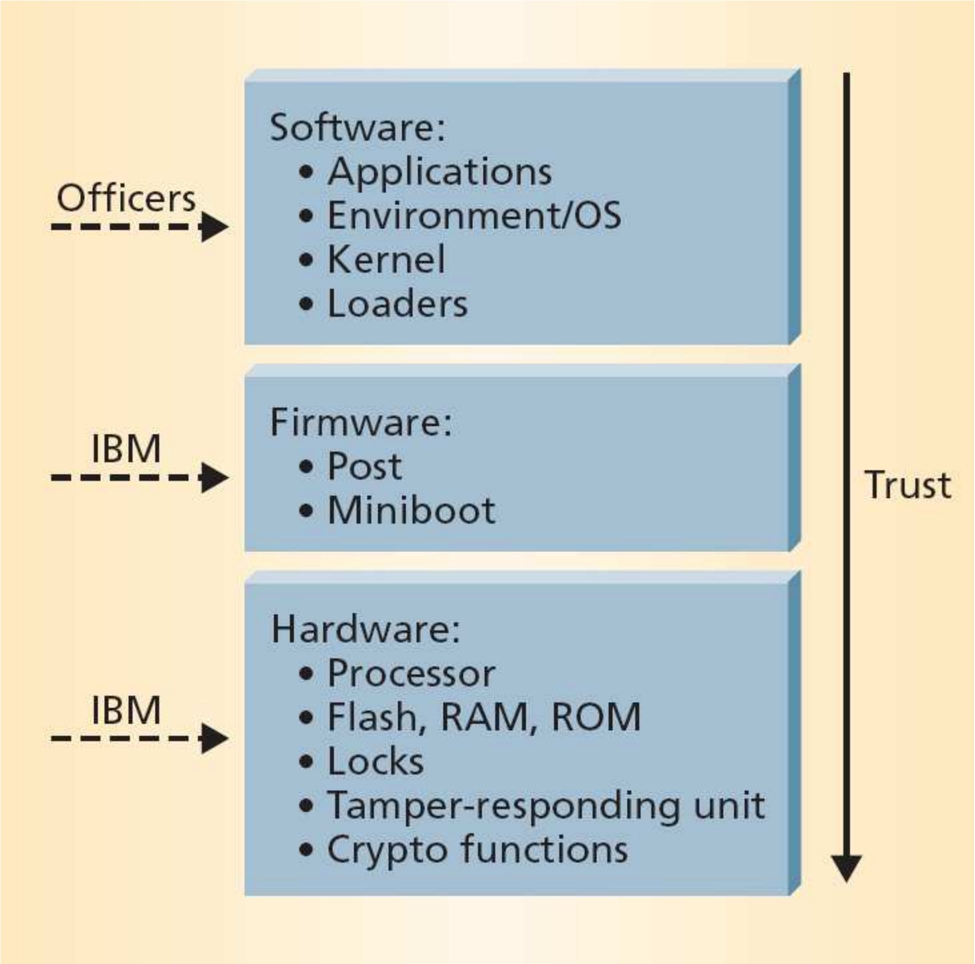


IBM 4764 Architecture

Stony Brook Network Security and Applied Cryptography Lab



Trust Propagation

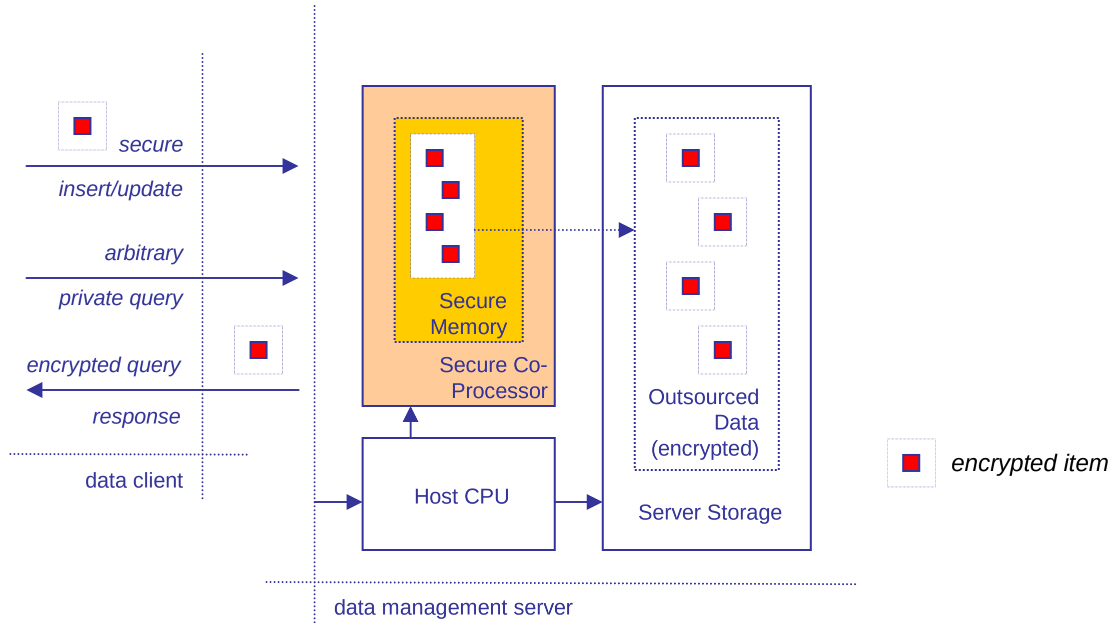


SCPU Performance

RSA1024 Sign: **848/sec**
RSA1024 Verify: **1157/sec**
3DES: **1-8MB/sec**
DES: **1-8MB/sec**
SHA1: **1-21MB/sec**

IBM 4764-001: 266MHz PowerPC. 64KB battery-backed SRAM storage. Crypto hardware engines: AES256, DES, TDES, DSS, SHA-1, MD5, RSA. FIPS 140-2 Level 4 certified.

Possible Benefits



A secure co-processor on the data management side may allow for significant leaps in expressivity for queries where privacy and completeness assurance are important.

Searching

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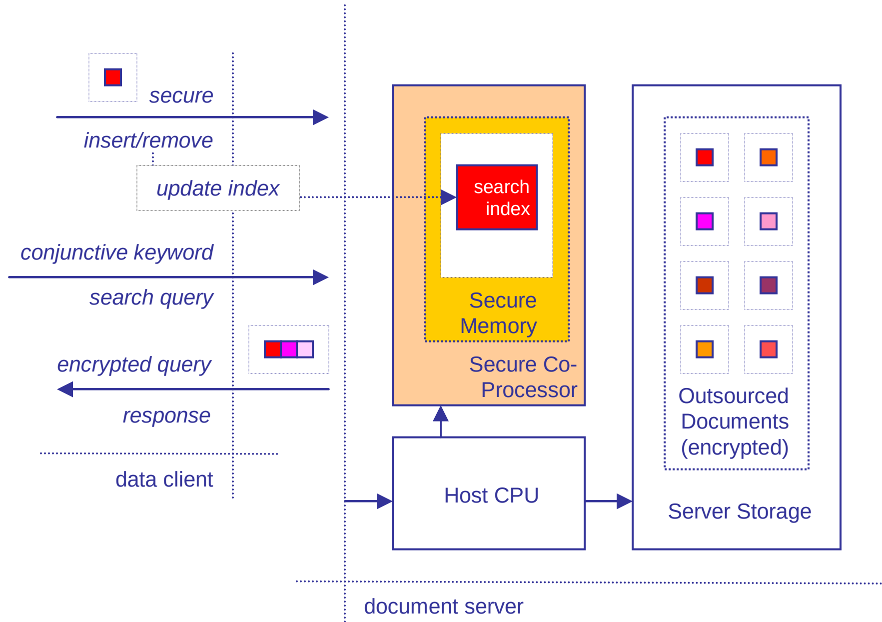
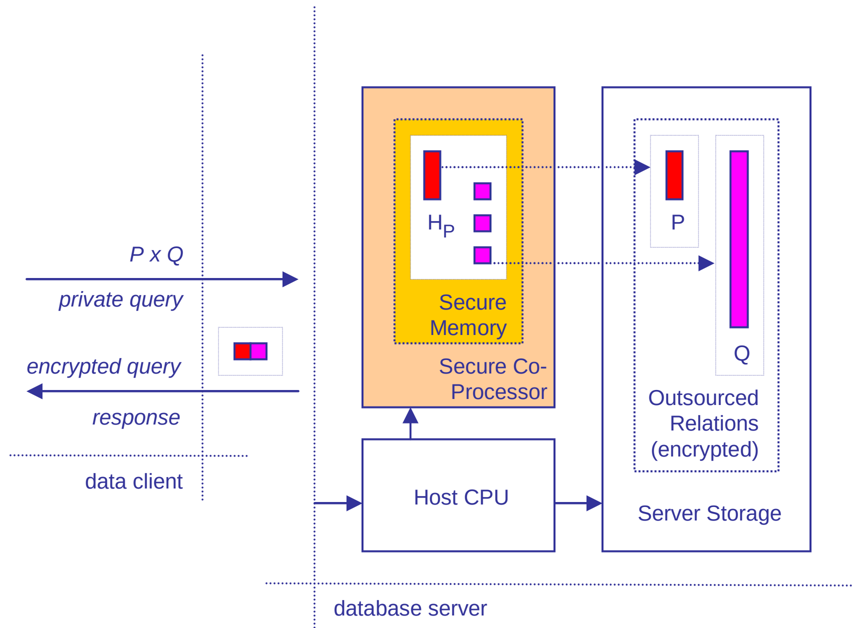


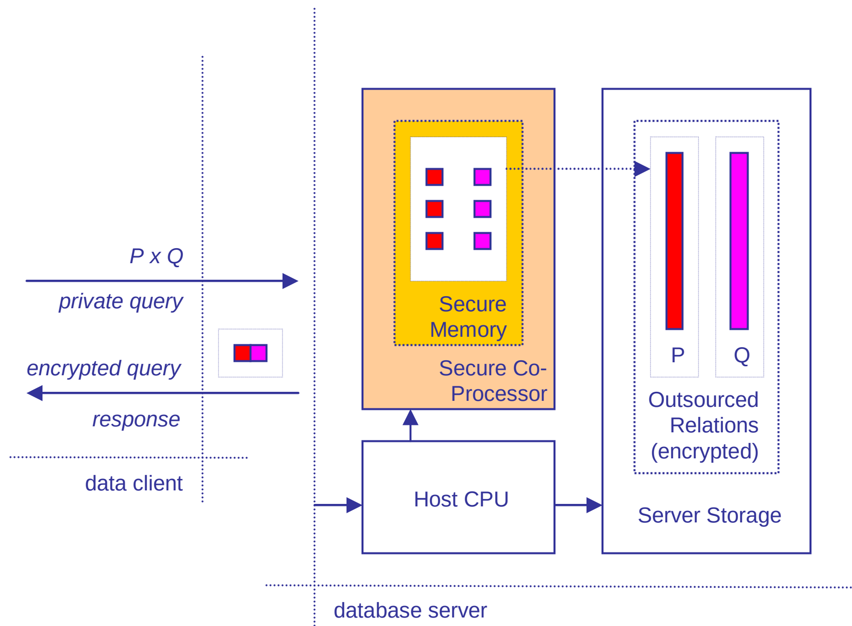
For conjunctive keyword searches on document (email, files) servers, oblivious search index structures could be queried in secure memory achieving a novel zero-leak query model.

Hash-JOIN



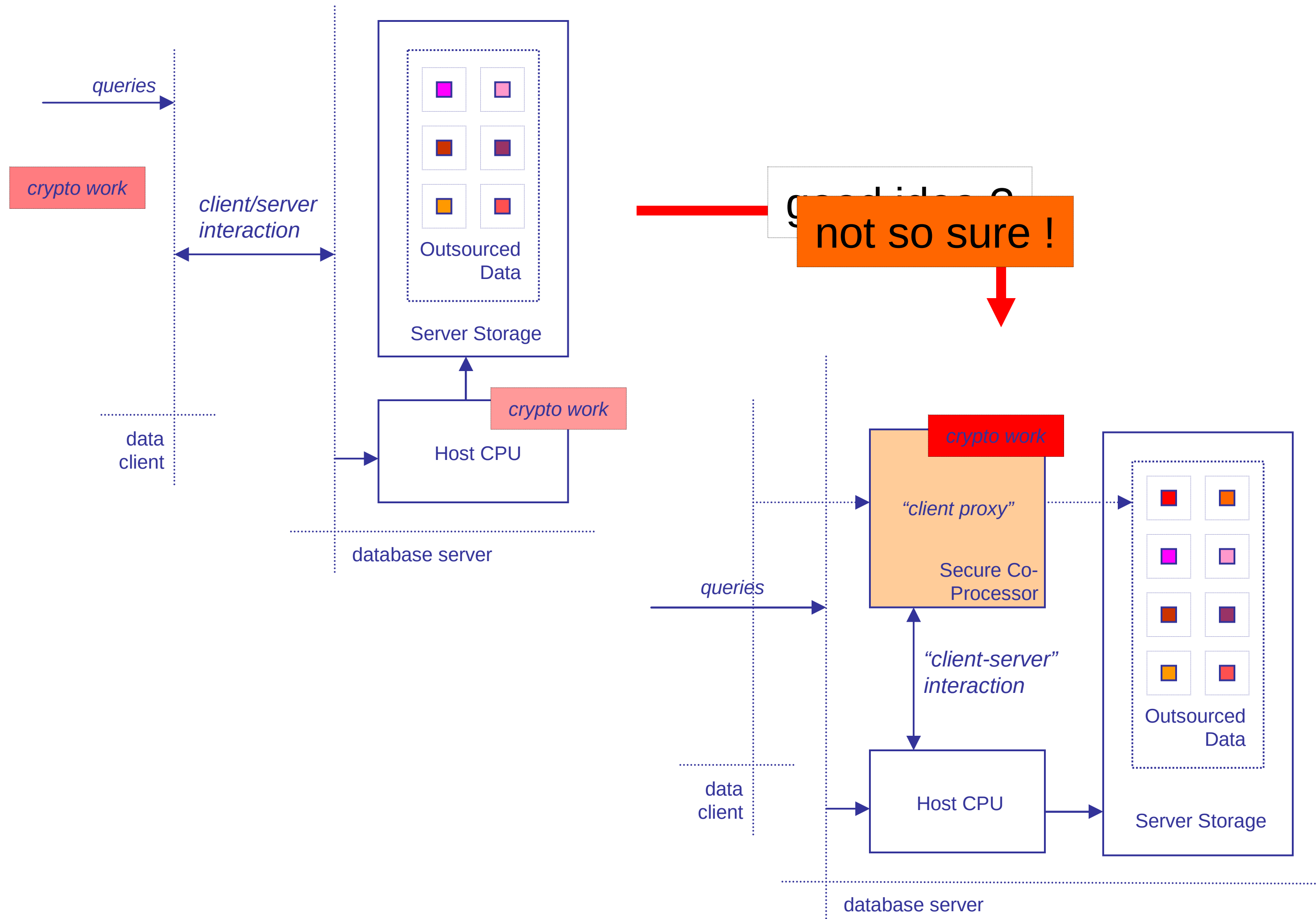
Hash-JOIN could be naturally accommodated.

Merge-JOIN



For Merge-JOIN, order-preserving encryption primitives could be deployed to minimize the amount of data parsing required in the sorting phase.

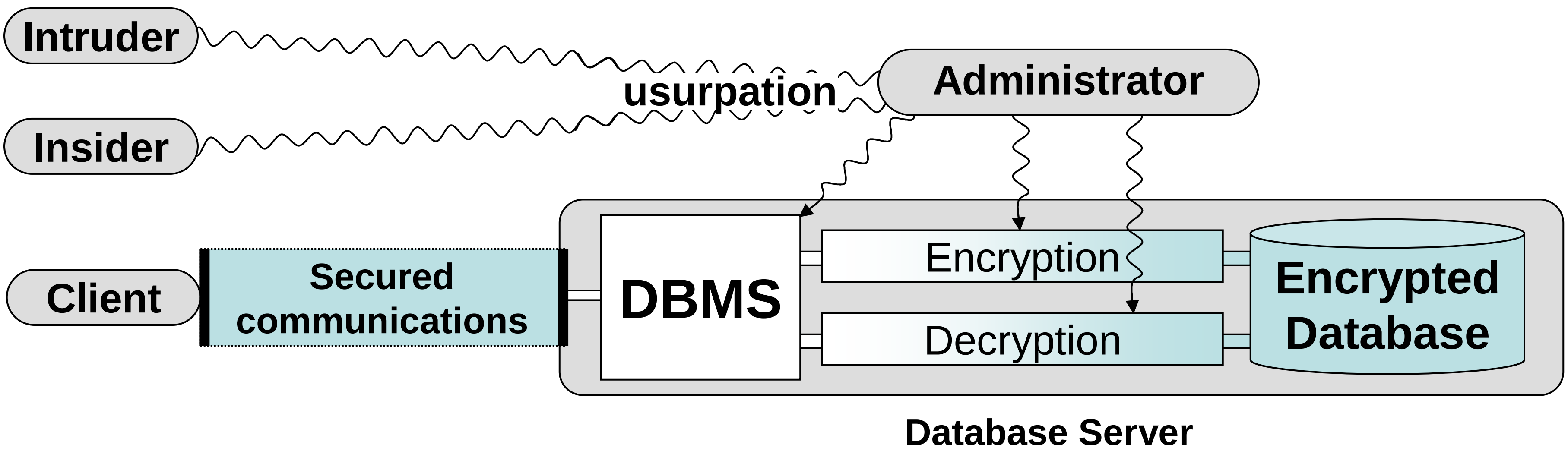
Sample DON'T

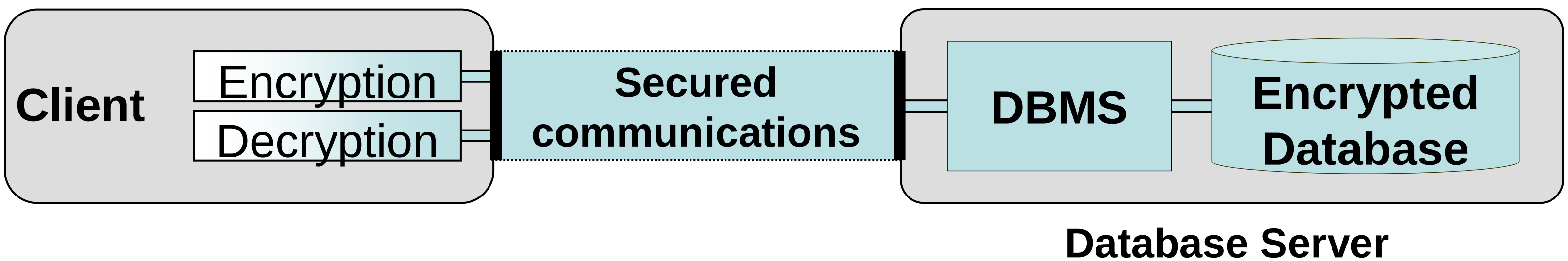

queries
crypto work
client/server
interaction
Outsourced
Data
Server Storage
crypto work
Host CPU
data
client
database server
not so sure !
crypto work
"client proxy"
Secure Co-
Processor
queries
"client-server"
interaction
Host CPU
Outsourced
Data
Server Storage
data
client
database server

Other DON'Ts

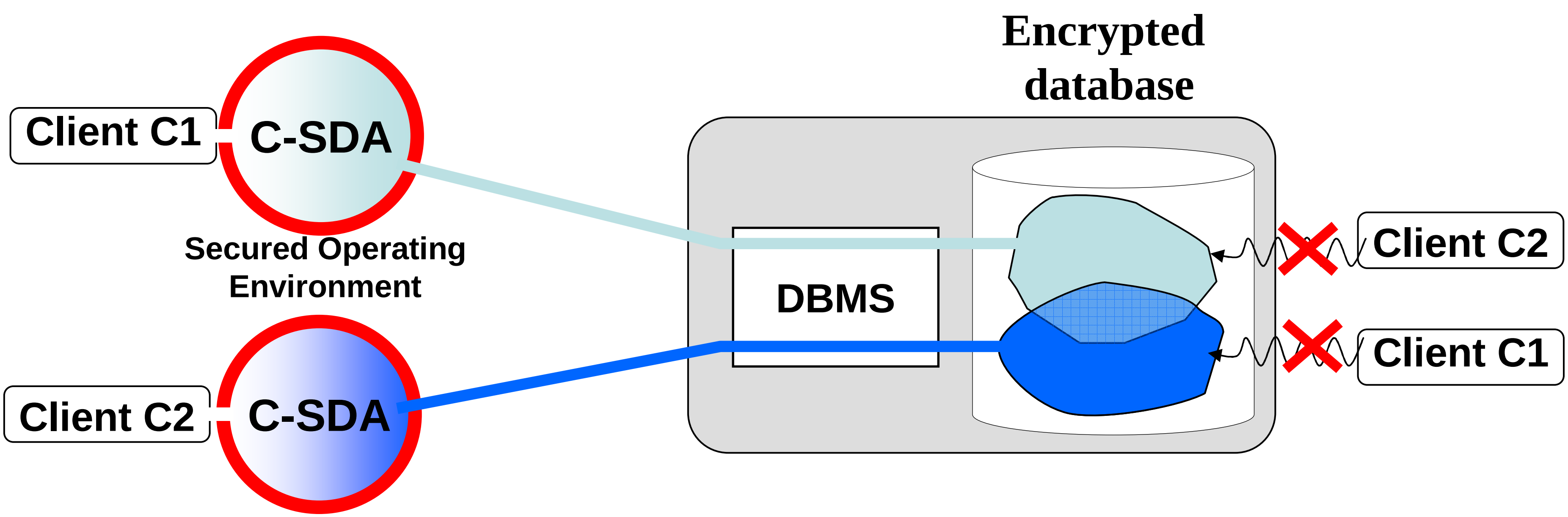
- Process entire queries on SCPU (!)
- Dedicate (one) SCPU per query or equivalent
  - e.g., limit TPS by SCPU TPS
- Synchronize CPU with SCPU
  - e.g., block main CPU until SCPU completes
- Transfer >= O(n) on SCPU-CPU bus (!)
- Anything else un-smart ☺

Bouganim (VLDB 2002)



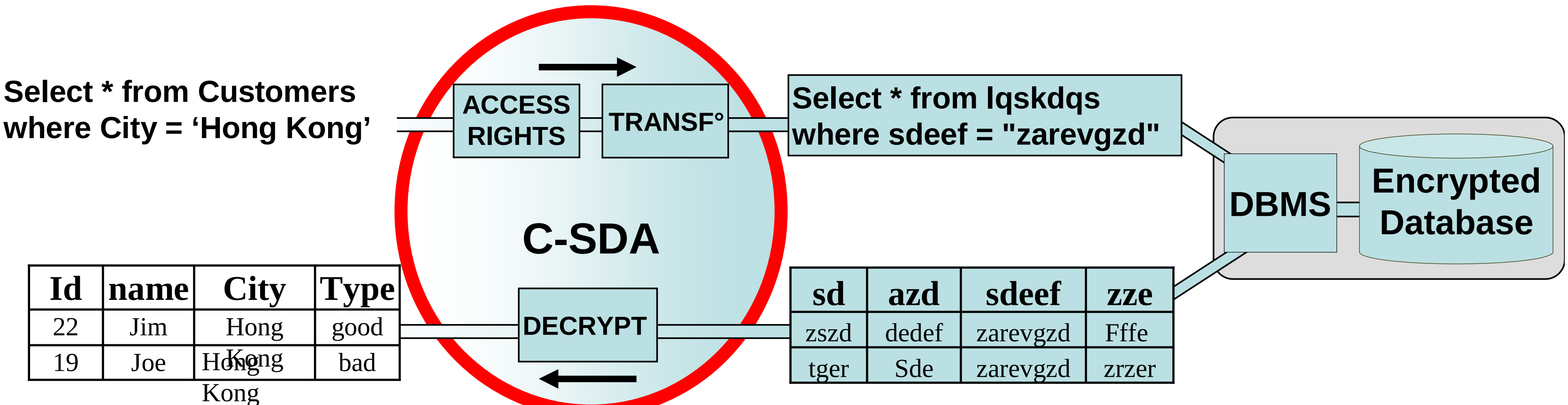


Chip-Secured Data Access:

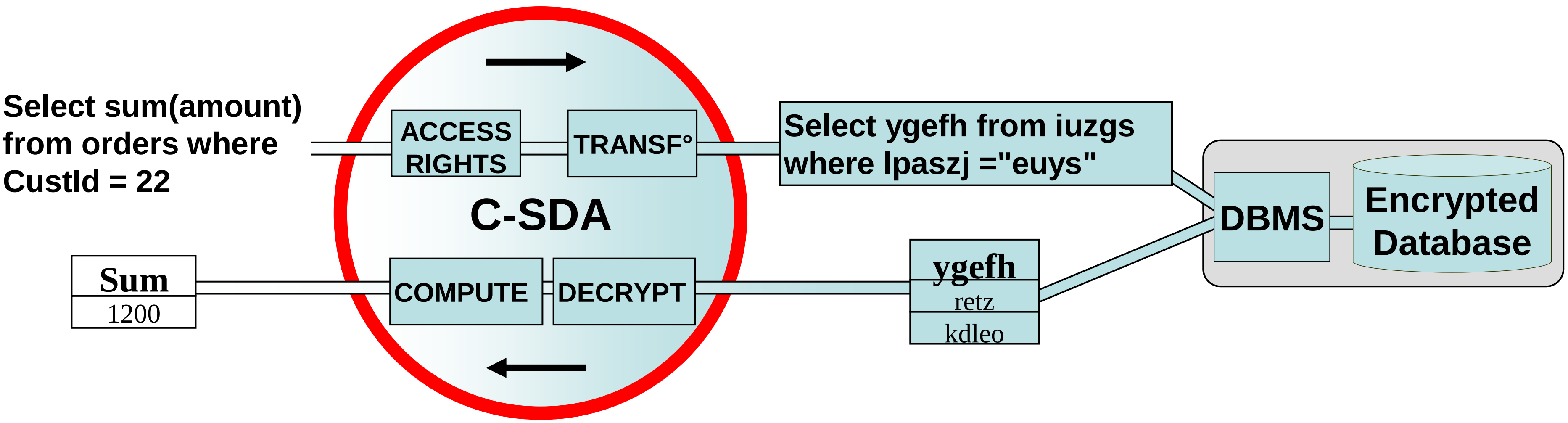


Smartcard: 32 bit RISC processor (≈ 40Mips), limited communication bandwidth (10 to100 Kbps), tiny RAM, writes in EEPROM very costly.

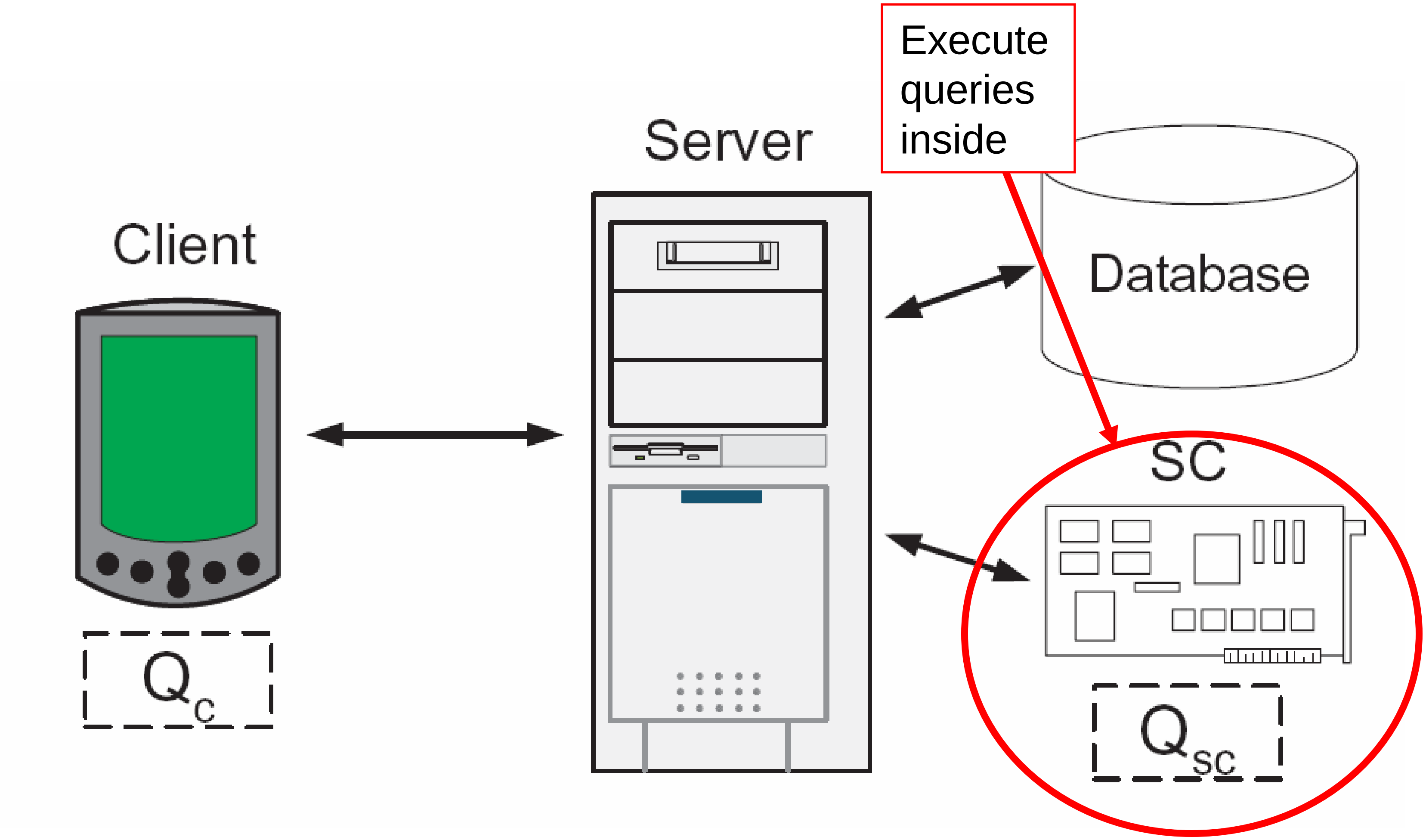
Equi-predicate-only Queries:



General queries:



Tsudik (2005)



Conclusions

Practical maturity: in infancy, barely crawling.

Very hard problems remain to be tackled:

- operators with integrated assurances
  - confidentiality
  - privacy of access
  - correctness
- scalable protocols for secure hardware
  - massive data
  - good utilization of host CPUs
- areas
  - relational data
  - file systems
  - streaming data

/bin/yes > /dev/lunchtime

THANK YOU !

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