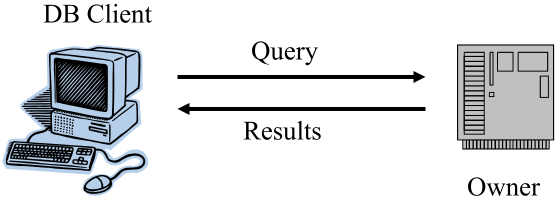
Security in Outsourced Databases (Query Answer Assurance)

Traditional Client-Server Arch.



DB Client

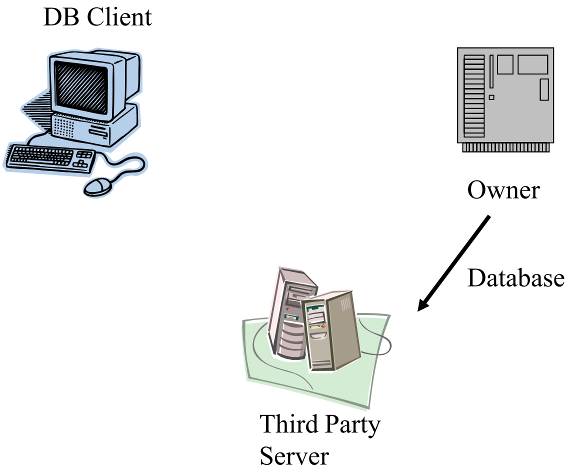
Query

Results

Owner

- Client queries are satisfied by a trusted server
- Secure the server
- Secure the communication channel, e.g. use SSL

Data Publishing (Database-as-a-Service)



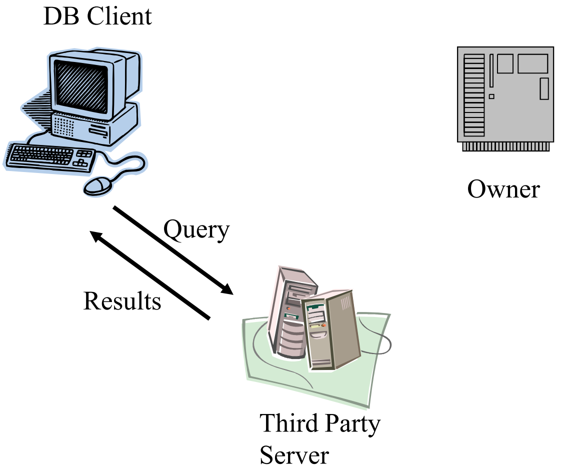
DB Client

Owner

Database

Third Party Server

Data Publishing



DB Client

Owner

Query

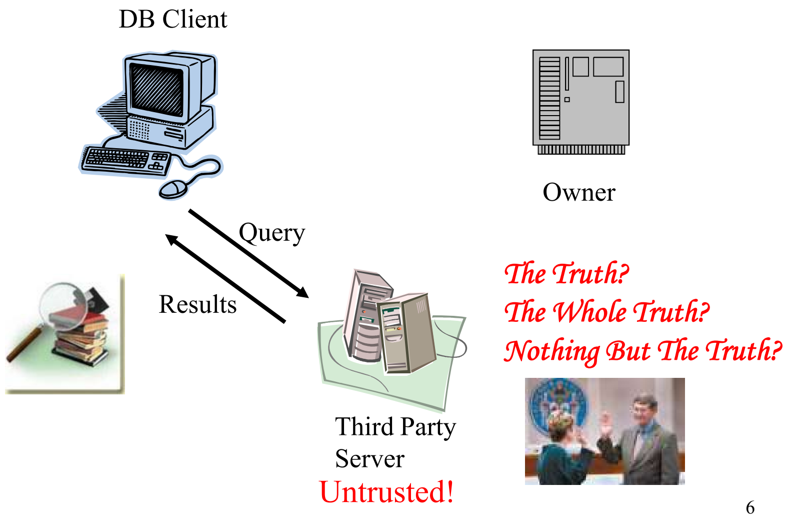
Results

Third Party Server

Data Publishing

- Pushes business logic and data processing from corporate data centers to third party servers at the “edge” of the network
  - Distribution of (part of) the database to edge servers
  - Edge servers perform query processing
- **Why?**
  - Most organizations need DBMSs
  - DBMSs extremely complex to deploy, setup, maintain
  - Require skilled DBAs (at very high cost!)
- Advantages
  - Cuts down network latency and produces faster responses
  - Cheaper way to achieve scalability
  - Lowers dependency on corporate data center (removes single point of failure)
  - Reduced cost to client
    - Get what you need, pay for what you use and not for: hardware, software infrastructure or personnel to deploy, maintain, upgrade…
  - Reduced overall cost
    - cost amortization across users
  - Better service
    - leveraging experts

The Challenge

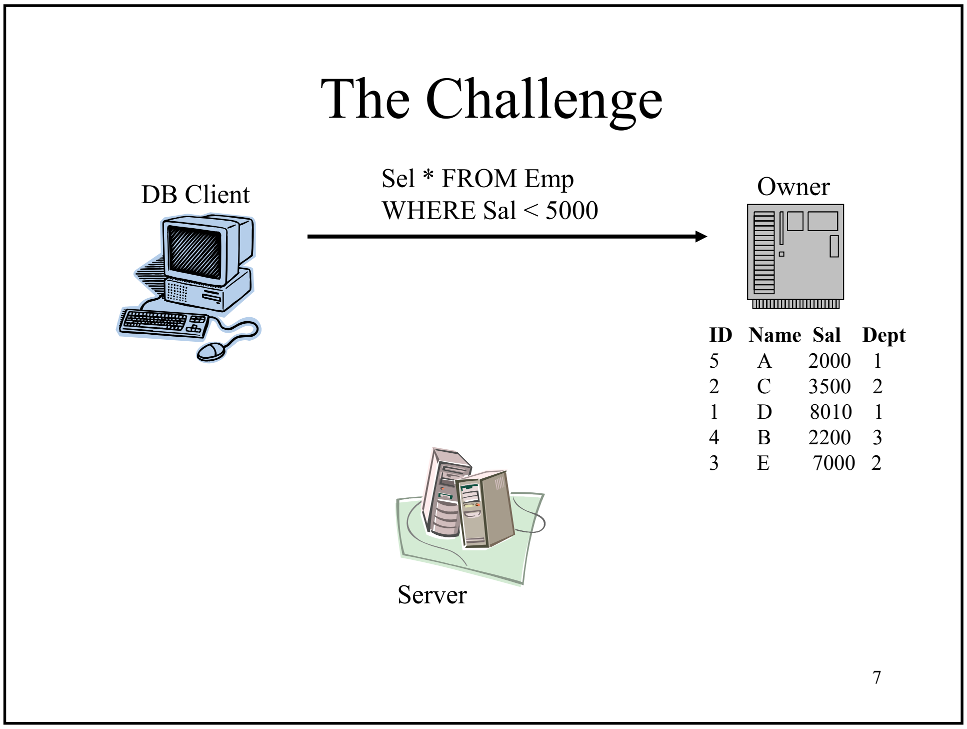


Untrusted!

The Truth?

The Whole Truth?

Nothing But The Truth?



The Challenge

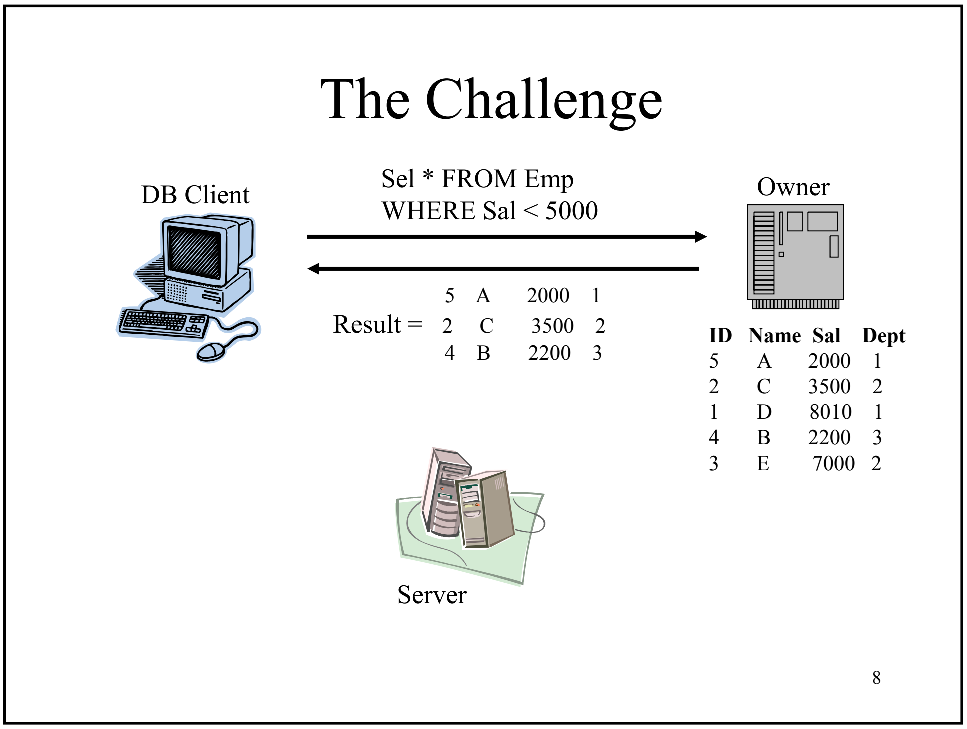
DB Client

Sel * FROM Emp
WHERE Sal < 5000

Owner

ID	Name	Sal	Dept
5	A	2000	1
2	C	3500	2
1	D	8010	1
4	B	2200	3
3	E	7000	2

Server



The Challenge

DB Client

Sel * FROM Emp
WHERE Sal < 5000

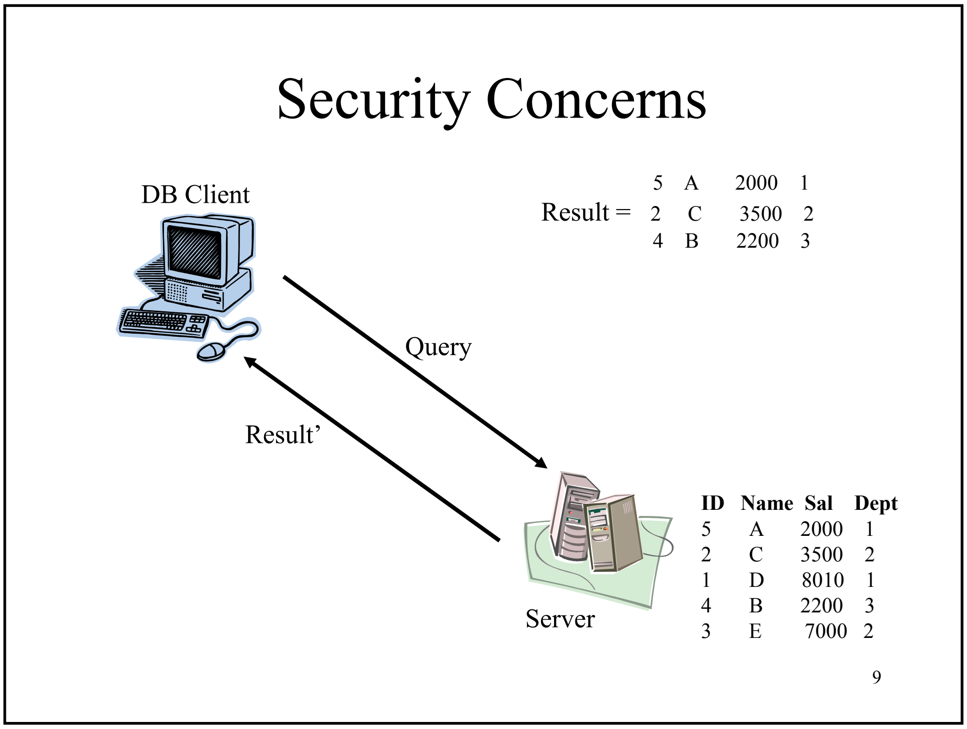
Owner

Result =

5	A	2000	1
2	C	3500	2
4	B	2200	3

ID	Name	Sal	Dept
5	A	2000	1
2	C	3500	2
1	D	8010	1
4	B	2200	3
3	E	7000	2

Server



Security Concerns

DB Client

Result =

5	A	2000	1
2	C	3500	2
4	B	2200	3

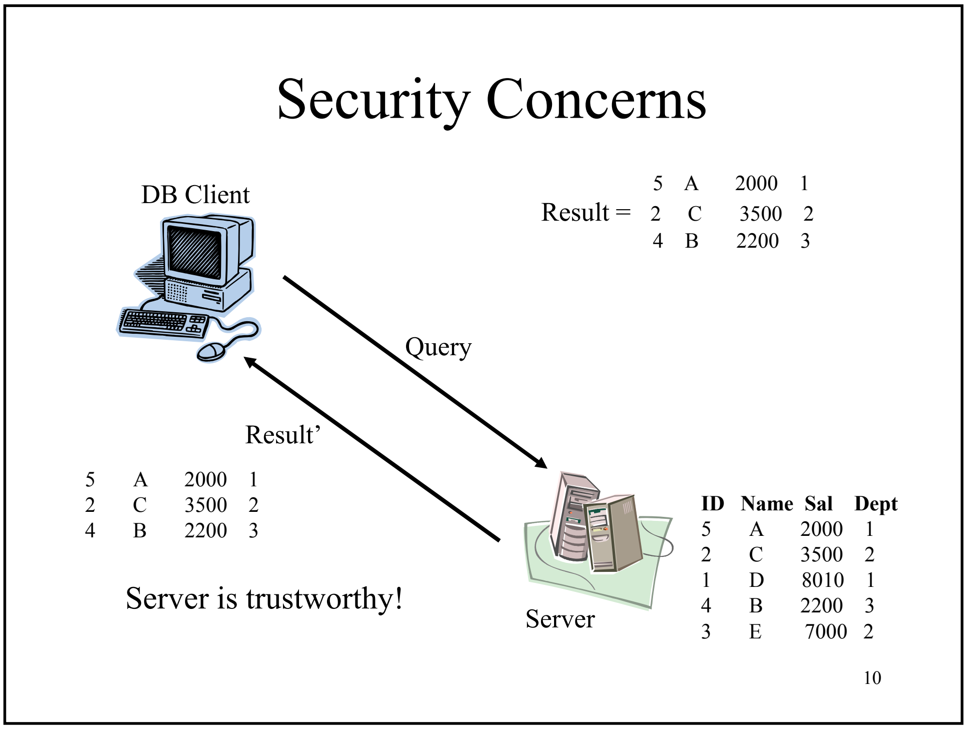
Query

Result’

Server

ID	Name	Sal	Dept
5	A	2000	1
2	C	3500	2
1	D	8010	1
4	B	2200	3
3	E	7000	2

9



Security Concerns

DB Client

Result =

5	A	2000	1
2	C	3500	2
4	B	2200	3

Query

Result’

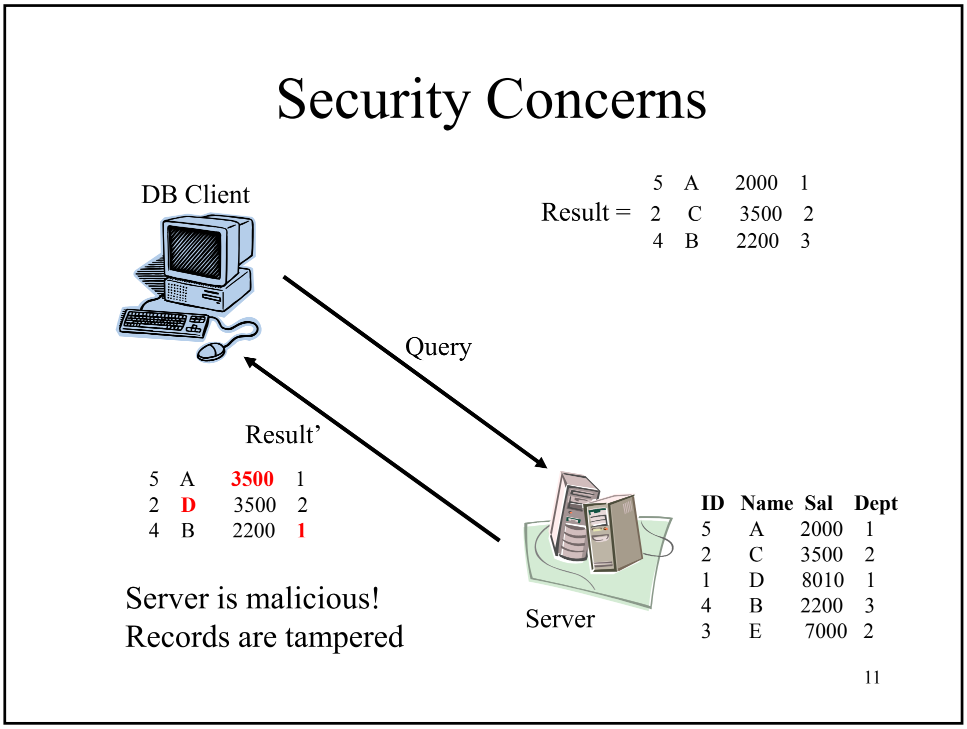
5	A	2000	1
2	C	3500	2
4	B	2200	3

Server is trustworthy!

Server

ID	Name	Sal	Dept
5	A	2000	1
2	C	3500	2
1	D	8010	1
4	B	2200	3
3	E	7000	2

10



Security Concerns

DB Client

Result =

5	A	2000	1
2	C	3500	2
4	B	2200	3

Query

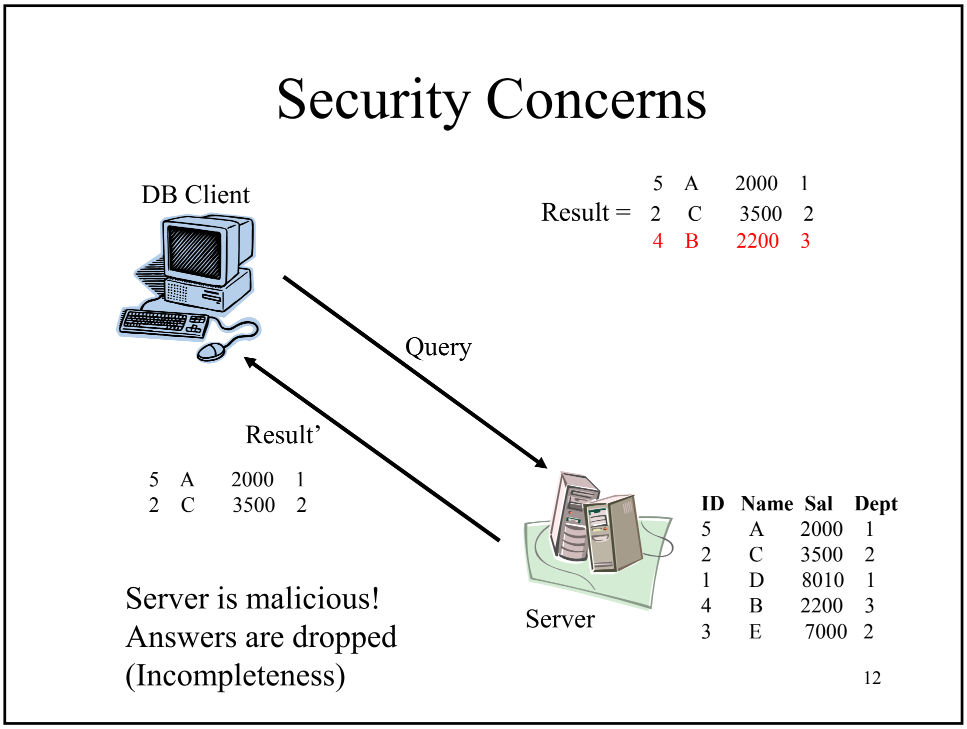
Result'

5	A	**3500**	1
2	**D**	3500	2
4	B	2200	**1**

Server is malicious!
Records are tampered

Server

ID	Name	Sal	Dept
5	A	2000	1
2	C	3500	2
1	D	8010	1
4	B	2200	3
3	E	7000	2



Security Concerns

DB Client

Result =

5	A	2000	1
2	C	3500	2
4	B	2200	3

Query

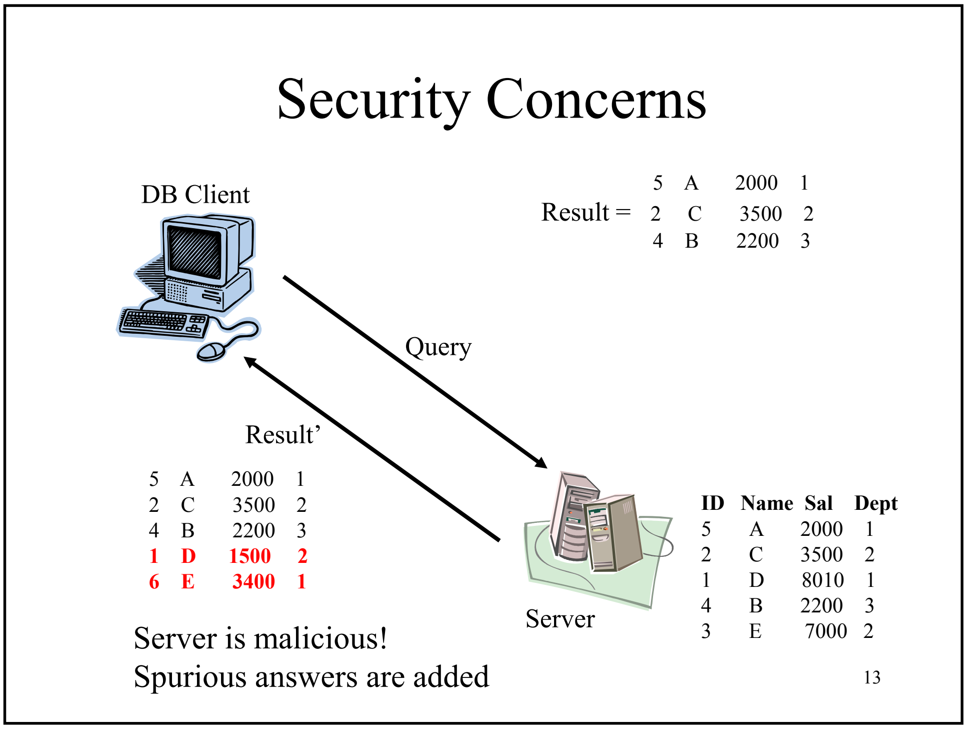
Result'

5	A	2000	1
2	C	3500	2

Server is malicious!
Answers are dropped
(Incompleteness)

Server

ID	Name	Sal	Dept
5	A	2000	1
2	C	3500	2
1	D	8010	1
4	B	2200	3
3	E	7000	2



Security Concerns

Result =

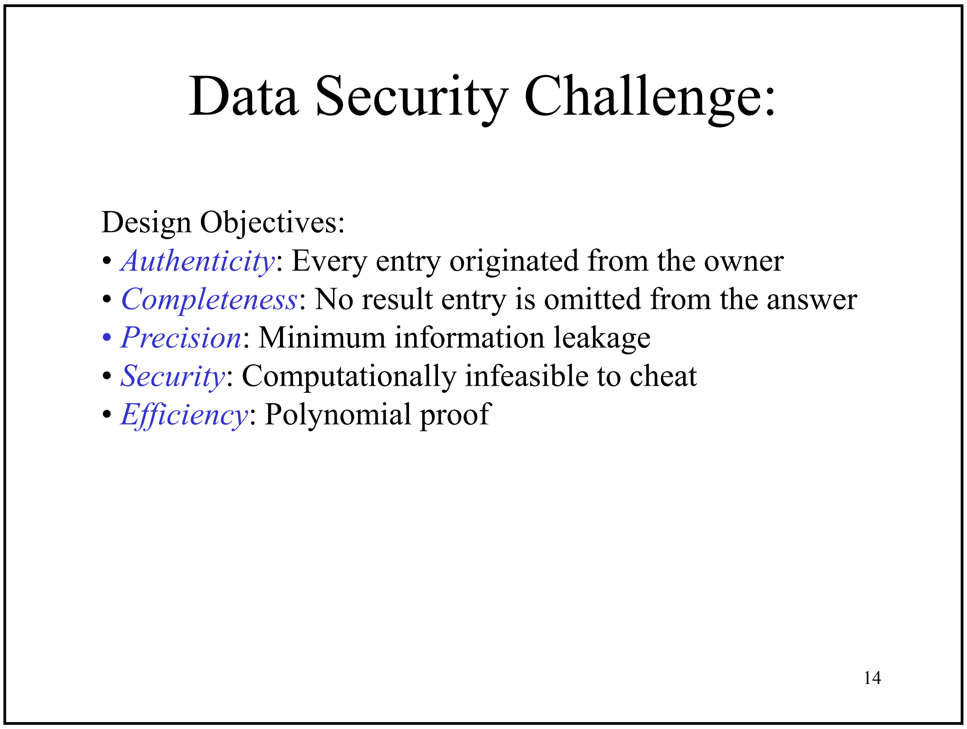
5	A	2000	1
2	C	3500	2
4	B	2200	3

Result'

5	A	2000	1
2	C	3500	2
4	B	2200	3
1	**D**	**1500**	**2**
6	**E**	**3400**	**1**

ID	**Name**	**Sal**	**Dept**
5	A	2000	1
2	C	3500	2
1	D	8010	1
4	B	2200	3
3	E	7000	2

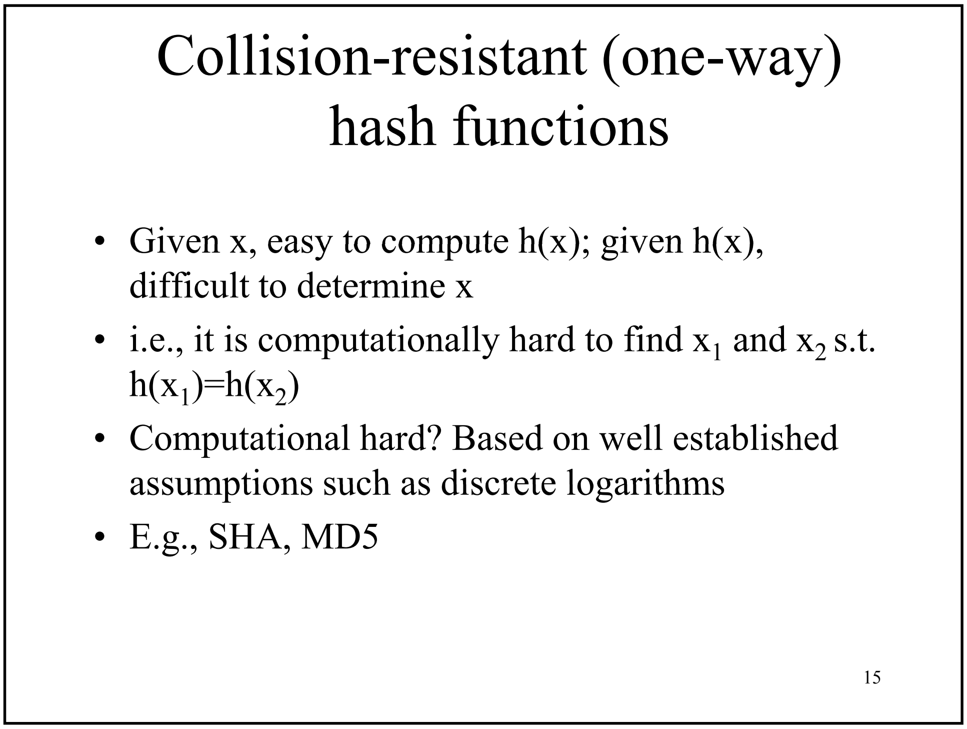
Server is malicious!
Spurious answers are added



Data Security Challenge:

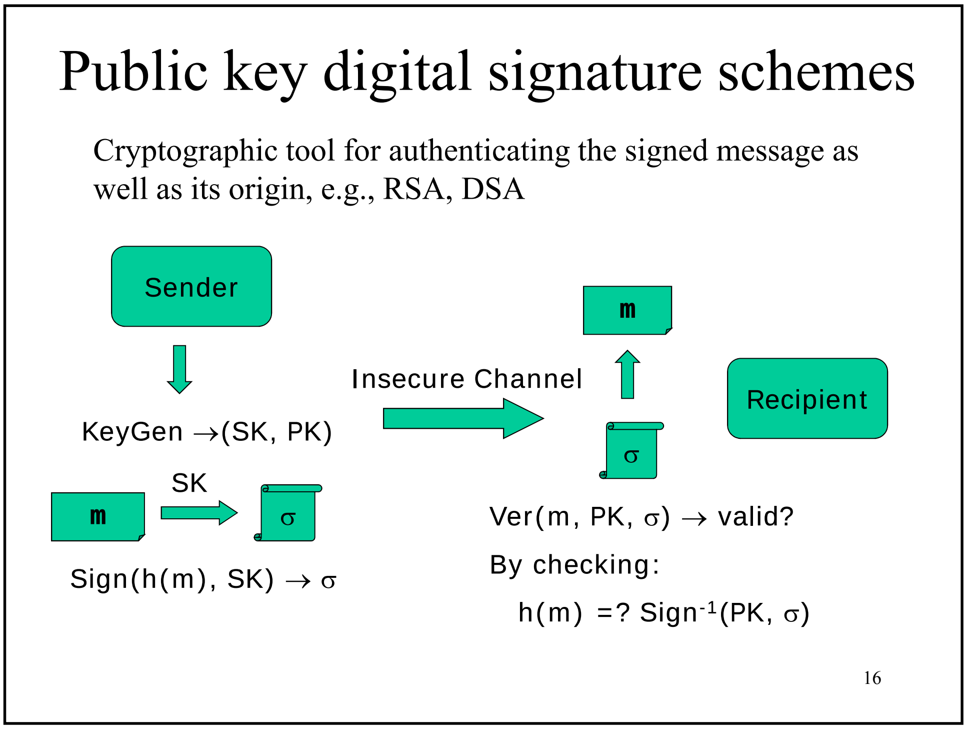
Design Objectives:

- *Authenticity*: Every entry originated from the owner
- *Completeness*: No result entry is omitted from the answer
- *Precision*: Minimum information leakage
- *Security*: Computationally infeasible to cheat
- *Efficiency*: Polynomial proof



Collision-resistant (one-way) hash functions

- Given x, easy to compute h(x); given h(x), difficult to determine x
- i.e., it is computationally hard to find x_1 and x_2 s.t. $h(x_1)=h(x_2)$
- Computational hard? Based on well established assumptions such as discrete logarithms
- E.g., SHA, MD5



Public key digital signature schemes

Cryptographic tool for authenticating the signed message as well as its origin, e.g., RSA, DSA

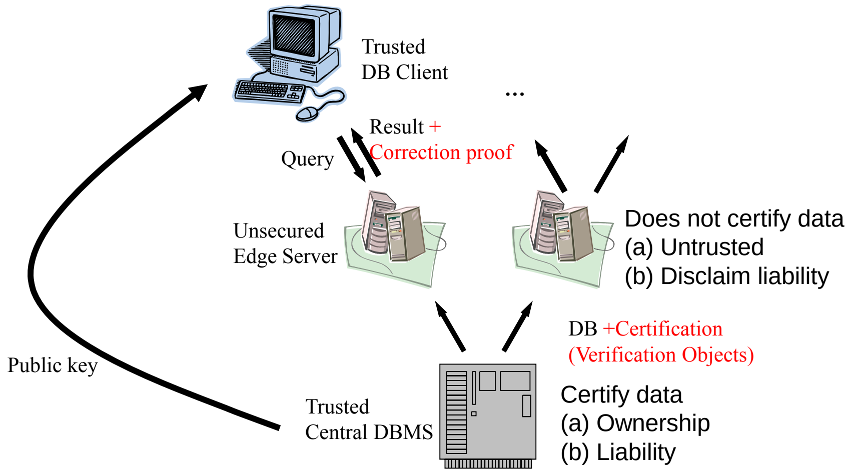
Sign(h(m), SK) → σ

Ver(m, PK, σ) → valid?

By checking:

$h(m) =? \text{Sign}^{-1}(PK, \sigma)$

Authentic Publication Scheme



Trusted
DB Client

...

Query

Result +
Correction proof

Unsecured
Edge Server

Does not certify data
(a) Untrusted
(b) Disclaim liability

DB +Certification
(Verification Objects)

Public key

Trusted
Central DBMS

Certify data
(a) Ownership
(b) Liability

Naïve Scheme

Each attribute has a signed digest
Each tuple has a signed digest

Relation R

D_T	(A_1, D_1)	...	(A_i, D_i)		...

D_T – Signed tuple digest
D_{Ai} – attribute digest

Naïve Scheme

Query: SELECT A_3, A_4, … FROM R

Filtered attributes

Result tuples

D_T	A_3	A_4	…	D_1	D_2	D_5	…

D_T – Signed tuple digest
D_i – attribute digest of A_i

Naïve Scheme (Example)

A1	B1	C1	a1	b1	c1	T1
A2	B2	C2	a2	b2	c2	T2
A3	B3	C3	a3	b3	c3	T3

T = sign(g(h(A)|h(B)|h(C))

g and h are collision-resistant hash functions

ai = h(Ai)

Retrieve whole of first tuple:

Server returns A1, B1, C1, T1; Client can compute h(A1), h(B1) and h(C1), and verify T1 from A1, B1 and C1

Retrieve only attributes A1 and B1 of first tuple:

Server returns A1, B1, c1 and T1; Client has no access to C1, so c1 has to be provided

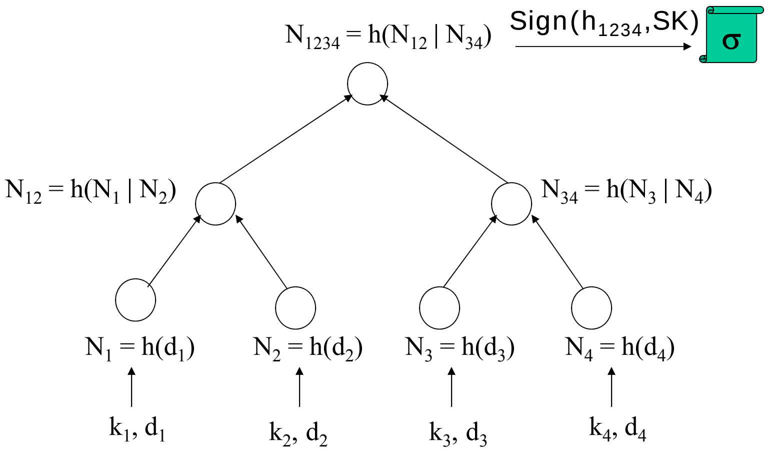
Issues??

Using Merke Hash Tree (MHT)

- For each tuple t, a tuple hash h(t) is computed

  h(t) = h(h(t.A1) | h(t.A2) | … | h(t.An))
- Assume a total order on attribute A of a relation R with |R| tuples (e.g., based on the primary key)
  - MHT(R,A) is a binary tree with |R| leaf nodes and hash values h(i) associated with node i
  - If i is a leaf node, then h(i) = h(ti), ti is the ith tuple in the order
  - If i is an internal node, then h(i) = h(h(l), h(r)) where l and r are the left and right children of node i.
  - The root hash is the digest of all values in the Merkle-hash tree MHT(R,A).

Merkle Hash Tree



$N_{1234} = h(N_{12} \mid N_{34})$

$\text{Sign}(h_{1234}, SK)$

σ

$N_{12} = h(N_1 \mid N_2)$

$N_{34} = h(N_3 \mid N_4)$

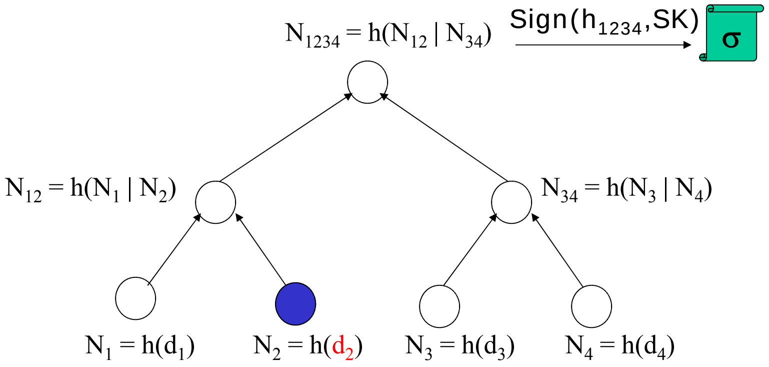
$N_1 = h(d_1)$ $N_2 = h(d_2)$ $N_3 = h(d_3)$ $N_4 = h(d_4)$

k_1, d_1 k_2, d_2 k_3, d_3 k_4, d_4

Ordering attribute: $k_1 < k_2 < k_3 < k_4$; d_i are tuples

Owner needs to sign root node (N_{1234})

MHT: Point Search



$N_{1234} = h(N_{12} \mid N_{34})$

$\text{Sign}(h_{1234}, SK) \longrightarrow \sigma$

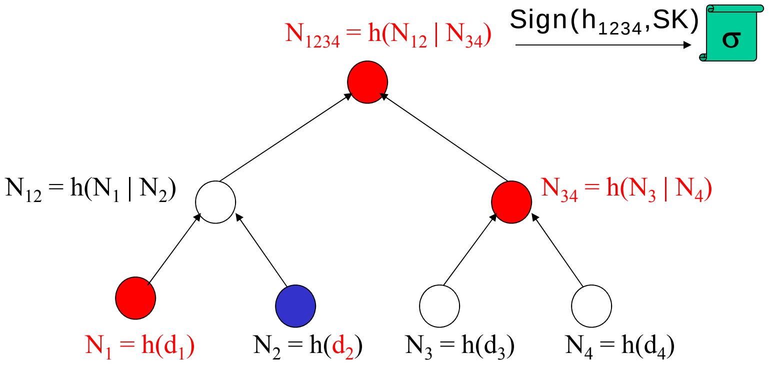
$N_{12} = h(N_1 \mid N_2)$

$N_{34} = h(N_3 \mid N_4)$

$N_1 = h(d_1)$ $N_2 = h(d_2)$ $N_3 = h(d_3)$ $N_4 = h(d_4)$

Query: Retrieve tuple d_2

MHT: Point Search



$N_{1234} = h(N_{12} \mid N_{34})$

$\text{Sign}(h_{1234}, SK) \longrightarrow \sigma$

$N_{12} = h(N_1 \mid N_2)$

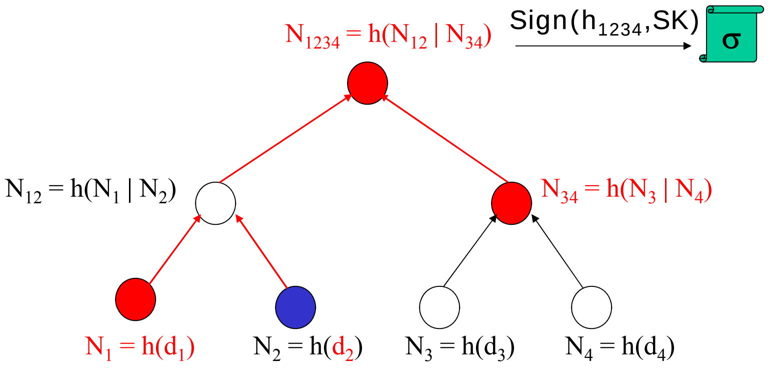
$N_{34} = h(N_3 \mid N_4)$

$N_1 = h(d_1)$ $N_2 = h(d_2)$ $N_3 = h(d_3)$ $N_4 = h(d_4)$

Edge server returns d_2, N_1, N_{34} and signed N_{1234}

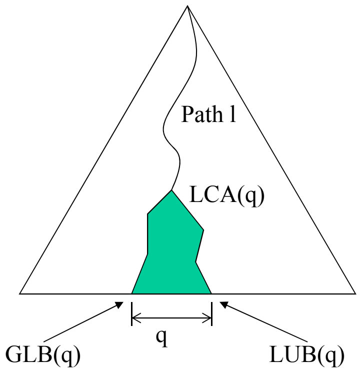
Client computes $N_{1234} = h(h(h(d_2)|N_1), N_{34})$ and verify that the signed value is correct

MHT: Point Search

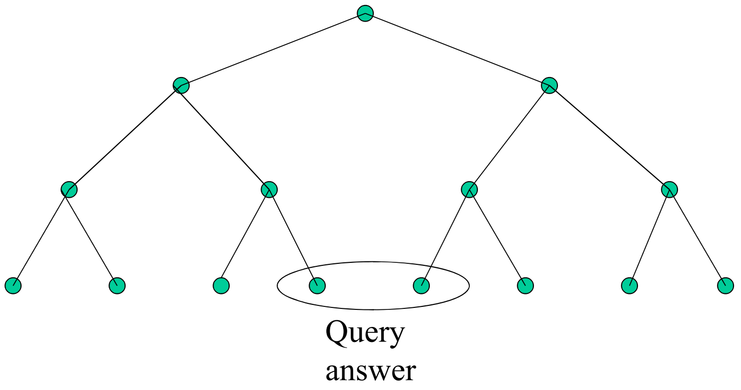


Edge server returns d_2, N_1, N_{34} and signed N_{1234} (and the structure)
Client computes $N_{1234} = h(h(h(d_2)|N_1), N_{34})$ and verify that the signed value is correct

Range Queries

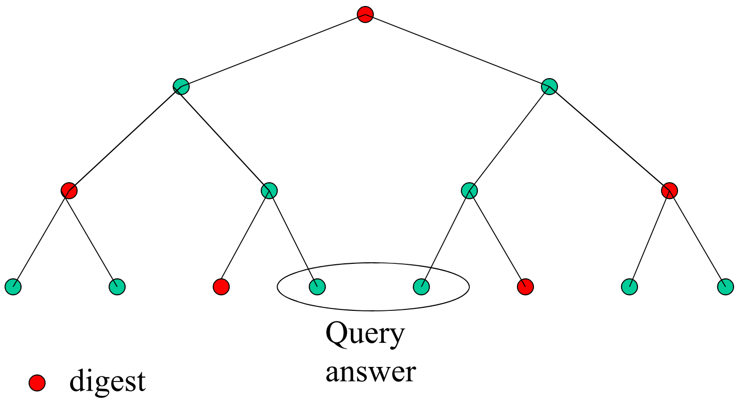


Example: Range queries



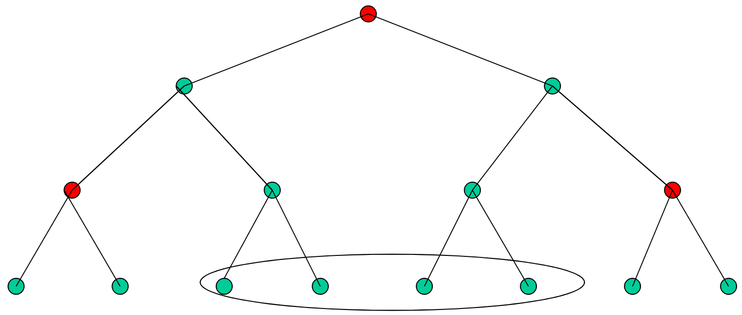
What are returned?

Example: Range queries



What are returned?

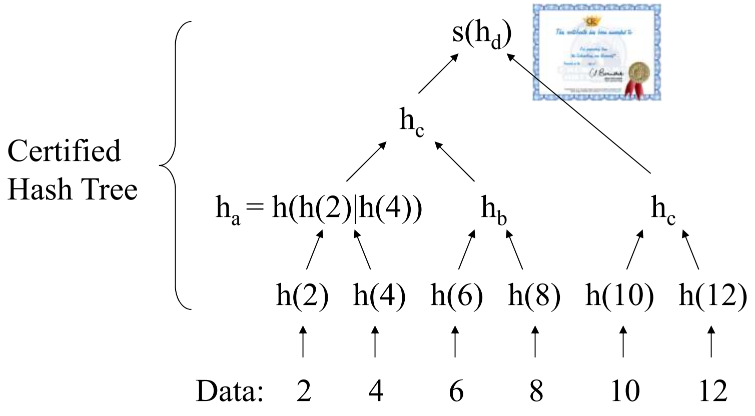
Example: Range queries



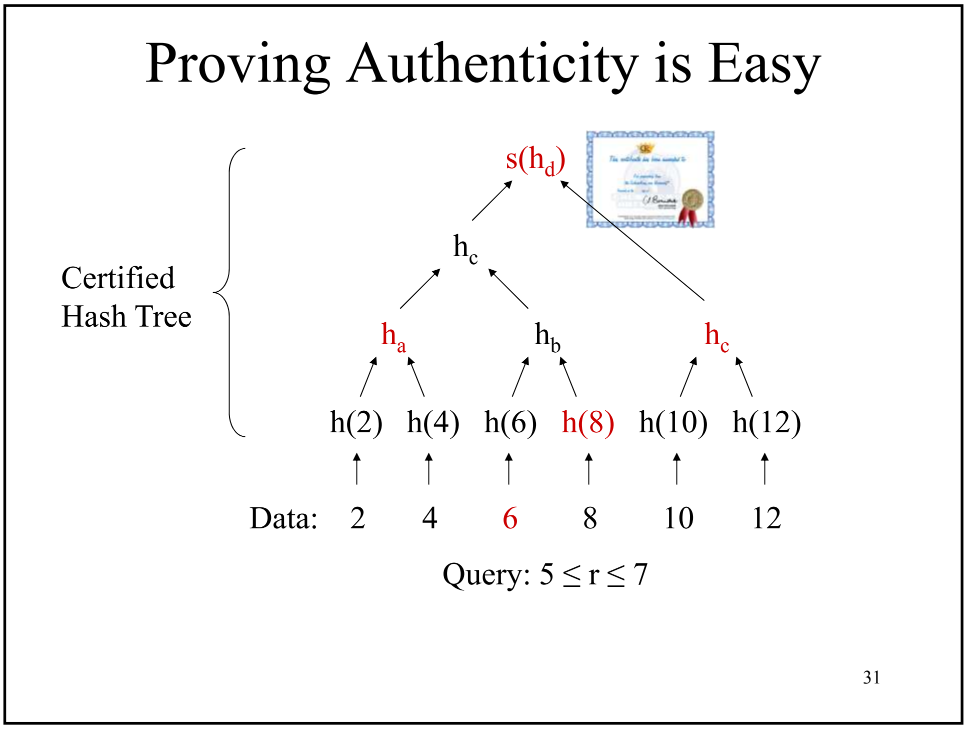
● digest

What are returned?

Proving Authenticity is Easy



Query: $5 \leq r \leq 7$



Proving Authenticity is Easy

$s(h_d)$

h_c

h_a h_b h_c

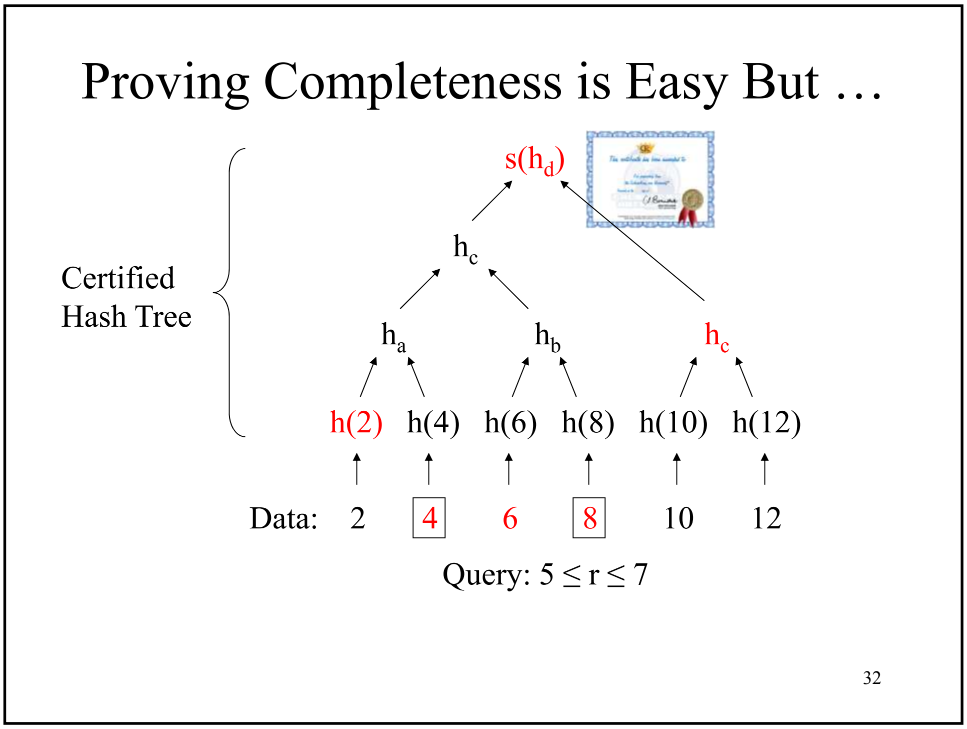
Certified
Hash Tree

h(2) h(4) h(6) h(8) h(10) h(12)

Data: 2 4 6 8 10 12

Query: $5 \le r \le 7$

31



Proving Completeness is Easy But …

$s(h_d)$

h_c

h_a h_b h_c

Certified
Hash Tree

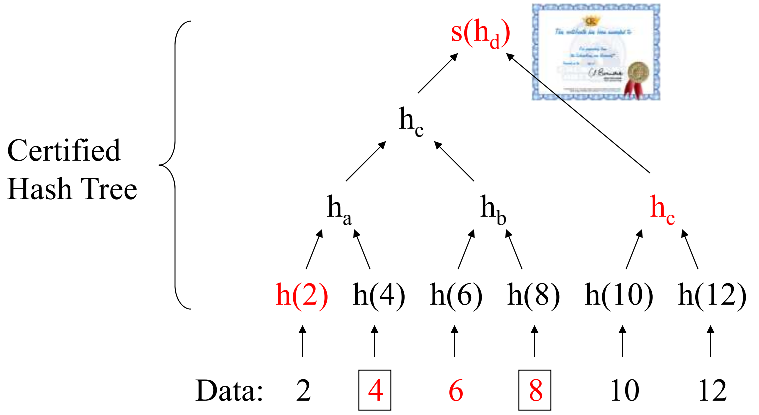
h(2) h(4) h(6) h(8) h(10) h(12)

Data: 2 $\boxed{4}$ 6 $\boxed{8}$ 10 12

Query: $5 \le r \le 7$

32

Precision may be compromised!



Query: $5 \leq r \leq 7$

- Compromise precision: Disclose left and right neighbors
- May violate access control policy

Example

- Access control: U can only see records with salary < 8000
- Results are records 2, 3, and 5.
- If system does not return record 1, U will not know that the answer is complete since it is possible that there is a record with Sal > 7000 but < 8000 that is not returned.
- If system returns record 1, then it violates the access control policy!
- Need an authentication mechanism that verifies completeness without compromising access control rules

ID	Name	Sal	Dept
5	**A**	**2000**	**1**
2	**C**	**3500**	**2**
1	D	8010	1
4	B	2200	3
3	**E**	**7000**	**2**

What's the problem?

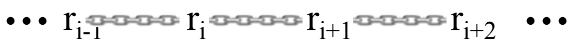
- A Merkle hash tree is needed for every sort-order on a table
- VO (Verification Object – the data used for verification) needs to contain links all the way to the root,
  - VO grows linearly to query result and logarithmic to base table size
- Projections may have to be performed by clients
- No provision for dynamic updates on the database
- Weak in terms of access control
  - Attributes that are supposed to be filtered out must also be returned for verification

A signature-chain-based scheme: Let's start simple …

- Consider a sorted list of distinct integers, $R = \{r_1 \ldots, r_{i-1}, r_i, r_{i+1}, \ldots r_n\}$
- Retrieve record whose value is greater than or equal to α
  - $\alpha \leq r$ (i.e., $\sigma_{\alpha \leq r}$ (R))
- Result $Q = \{r_a, r_{a+1}, \ldots r_b \}$, i.e., $r_{a-1} < \alpha \leq r_a < r_{a+1} < \ldots r_{b\,=}\, r_n$
- Result is complete iff:
  - Contiguity: Each pair of successive entries r_i, r_{i+1} in Q also appears in R (based on Signature Chain)
  - Terminal: Last element of Q is also last element of R, i.e., $r_b = r_n$ (based on Signature Chain)
  - Origin: r_a is the first element in R that satisfies the query condition, i.e.,$r_{a-1} < \alpha \leq r_a$ (based on Private Boundary Proof)

Signature Chain

- For each data value, there is an associated signature
  - Computed from its own value, and that of its left and right neighbors
  - $sig(r_i) = s(h(g(r_{i-1}) \mid g(r_i) \mid g(r_{i+1})))$

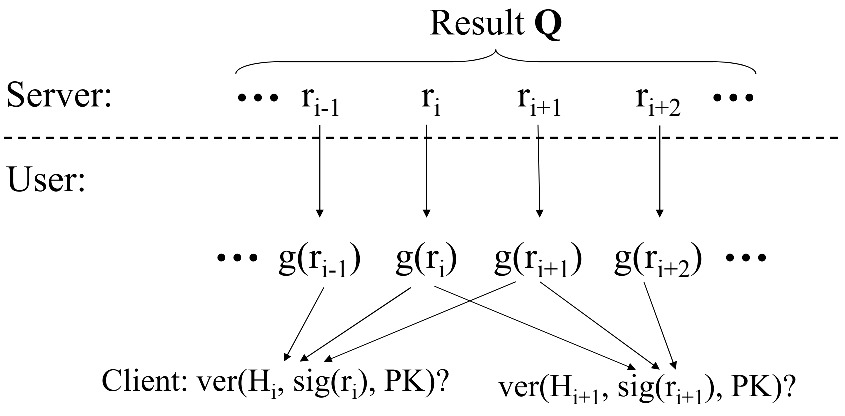


- Owner stores the $(r_i, sig(r_i))$ pair in the server
- During querying, server returns (answer, signature) pairs and more …(verification objects) …

$h^i(r) = h^{i-1}(h(r))$ $h^0(r) = h(r)$ $g(r) = h^{U-r-1}(r)$
U = max value outside of domain (known to all users)
s is a signature function using owner's private key

Signature Chain Ensures Contiguity

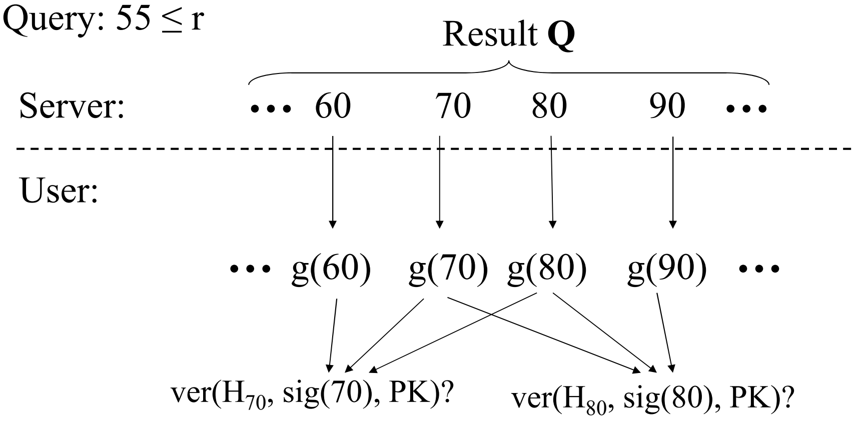
Server returns $(r_i, sig(r_i))$-pairs


Result **Q**
Server:
••• r_{i-1} r_i r_{i+1} r_{i+2} •••
User:
••• $g(r_{i-1})$ $g(r_i)$ $g(r_{i+1})$ $g(r_{i+2})$ •••
Client: ver(H_i, sig(r_i), PK)?
ver(H_{i+1}, sig(r_{i+1}), PK)?

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

Signature Chain Ensures Contiguity

Query: $55 \leq r$



Result **Q**

Server: ••• 60 70 80 90 •••

User:

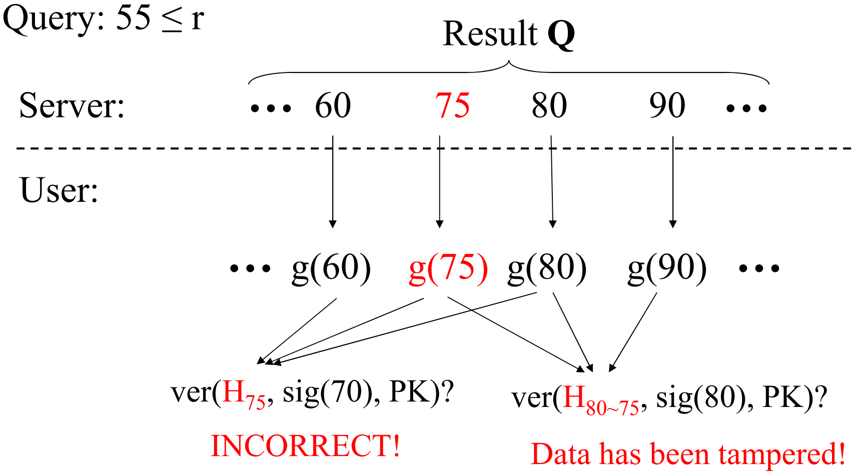
••• g(60) g(70) g(80) g(90) •••

ver(H_{70}, sig(70), PK)?

ver(H_{80}, sig(80), PK)?

Signature Chain Ensures Contiguity

Query: $55 \leq r$



Result **Q**

Server: ••• 60 75 80 90 •••

User:

••• g(60) g(75) g(80) g(90) •••

ver(H_{75}, sig(70), PK)?

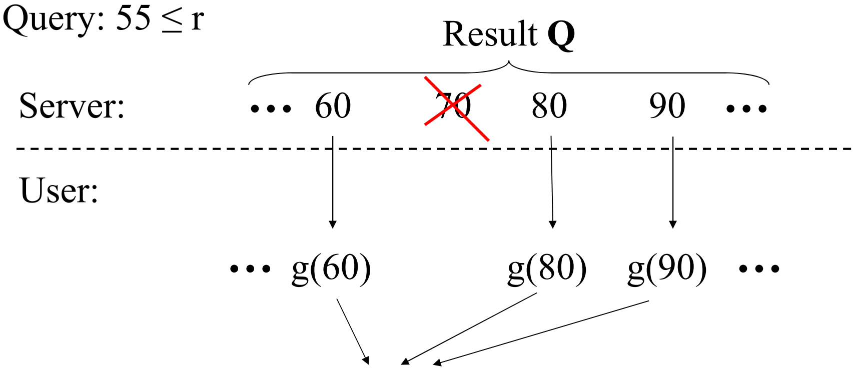
INCORRECT!

ver($H_{80\sim75}$, sig(80), PK)?

Data has been tampered!

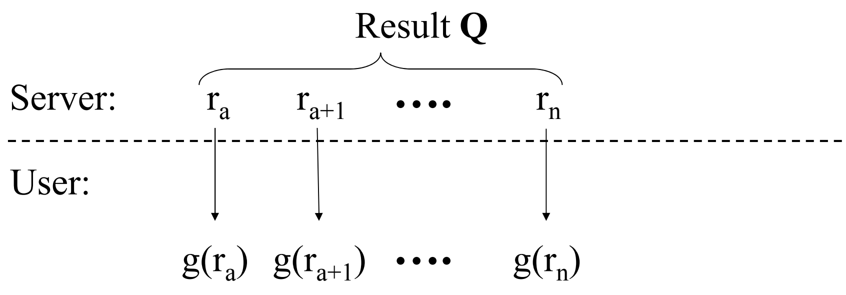
Signature Chain Ensures Contiguity

Query: 55 ≤ r



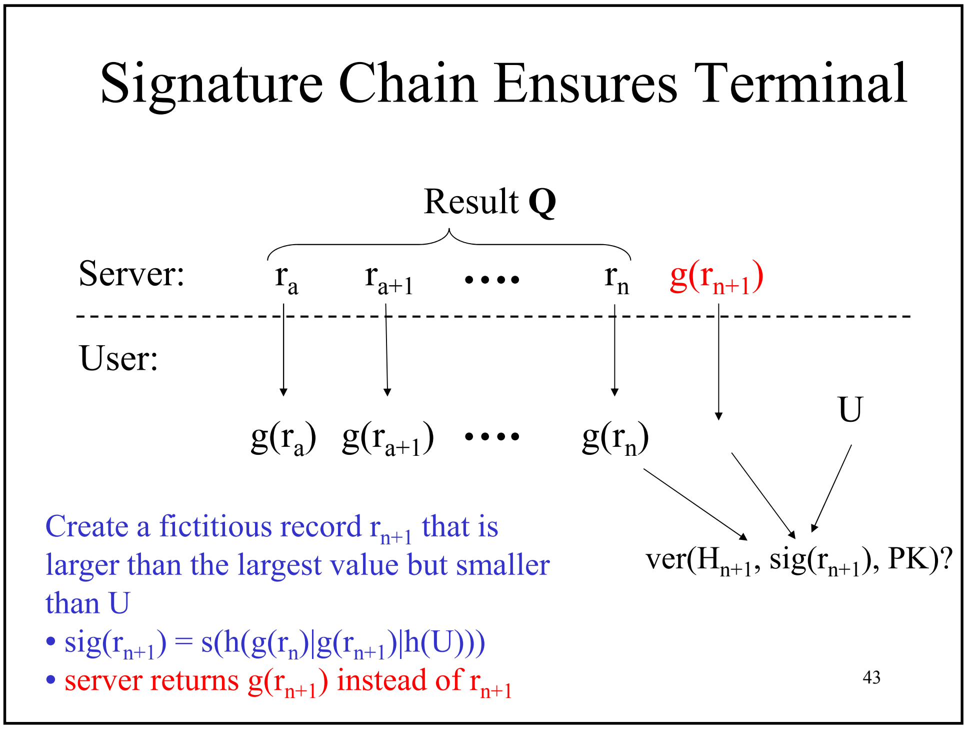
ver(H_{80}, sig(80), PK)?
$H_{60\sim80}$ will be computed (without 70) -
will not match sig(80). INCORRECT!!!!

How To Ensure r_n Is The Last Record?



Create a fictitious record r_{n+1} that is larger than the largest value but smaller than U

- $sig(r_{n+1}) = s(h(g(r_n)|g(r_{n+1})|h(U)))$



Signature Chain Ensures Terminal

Result **Q**

Server: r_a r_{a+1} •••• r_n $g(r_{n+1})$

User:

$g(r_a)$ $g(r_{a+1})$ •••• $g(r_n)$

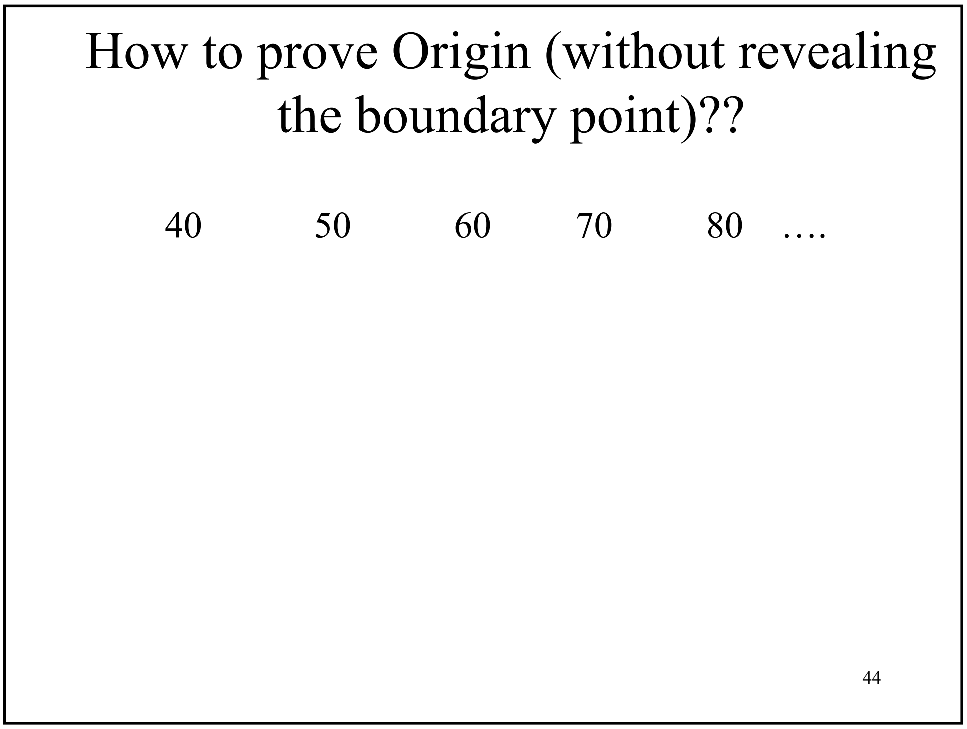
U

ver(H_{n+1}, sig(r_{n+1}), PK)?

Create a fictitious record r_{n+1} that is larger than the largest value but smaller than U

- $sig(r_{n+1}) = s(h(g(r_n)|g(r_{n+1})|h(U)))$
- server returns $g(r_{n+1})$ instead of r_{n+1}

43

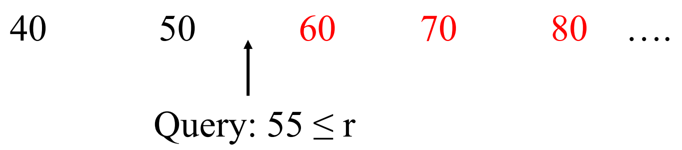


How to prove Origin (without revealing the boundary point)??

40 50 60 70 80 ….

44

How to prove Origin??

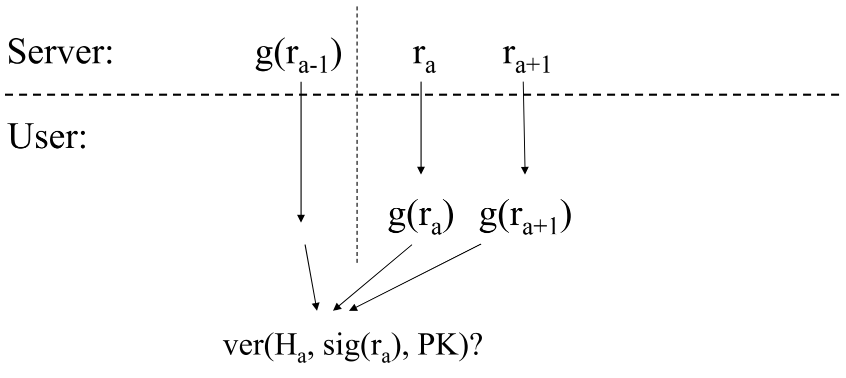


40 50 60 70 80 ….

Query: $55 \leq r$

A naïve solution is to return 50. By proving that 50 is chained to 60, we know that no answer has been dropped. But, this reveals the value of 50.

How about this …



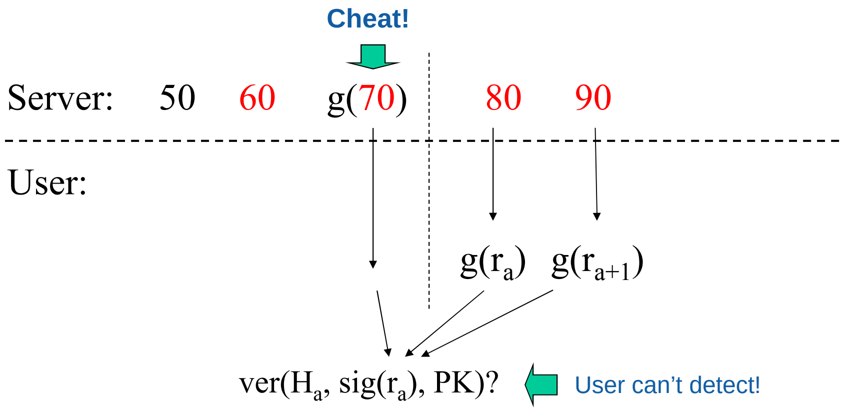
Server: $g(r_{a-1})$ r_a r_{a+1}

User: $g(r_a)$ $g(r_{a+1})$

$ver(H_a, sig(r_a), PK)$?

Query: $\alpha \leq r$

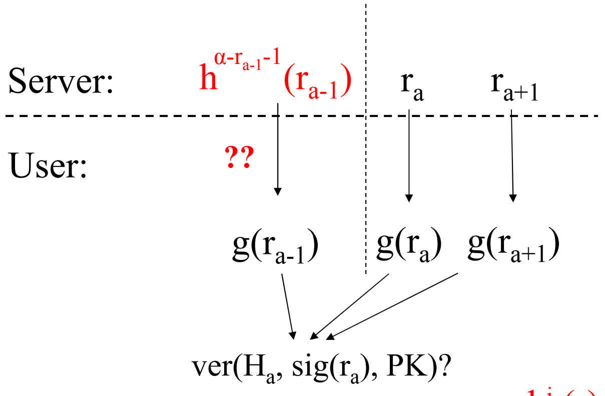
The basic idea fails …



Query: $55 \le r$

47

Private Boundary Proof Ensures Origin

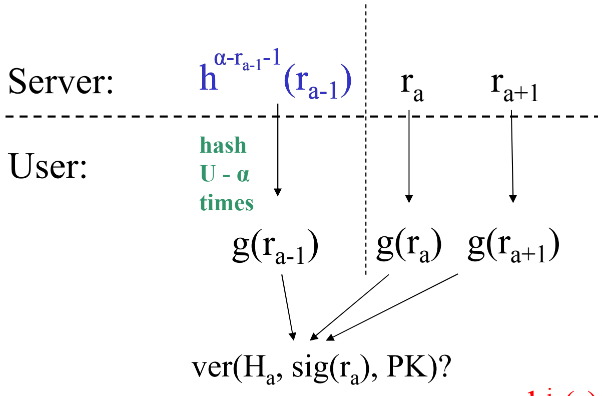

Server:
$h^{\alpha - r_{a-1} - 1}(r_{a-1})$
r_a
r_{a+1}
User:
??
$g(r_{a-1})$
$g(r_a)$
$g(r_{a+1})$
ver(H_a, sig(r_a), PK)?

$$h^i(r) = h^{i-1}(h(r))$$
$$g(r) = h^{U-r-1}(r)$$

Query: $\alpha \le r$

48

Private Boundary Proof Ensures Origin



A **collaborative scheme** to compute the hash value

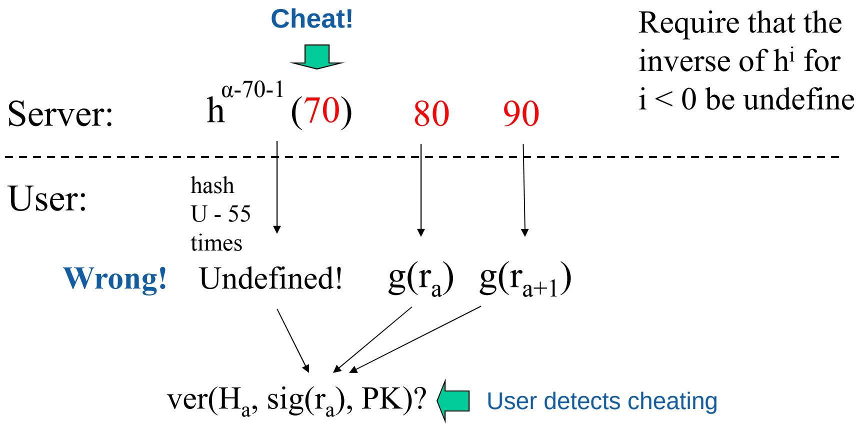
$h^i(r) = h^{i-1}(h(r))$

$g(r) = h^{U-r-1}(r)$

$= \mathbf{h}^{\mathbf{U-\alpha}}(\mathbf{h}^{\alpha\text{-}r\text{-}1}(\mathbf{r}))$

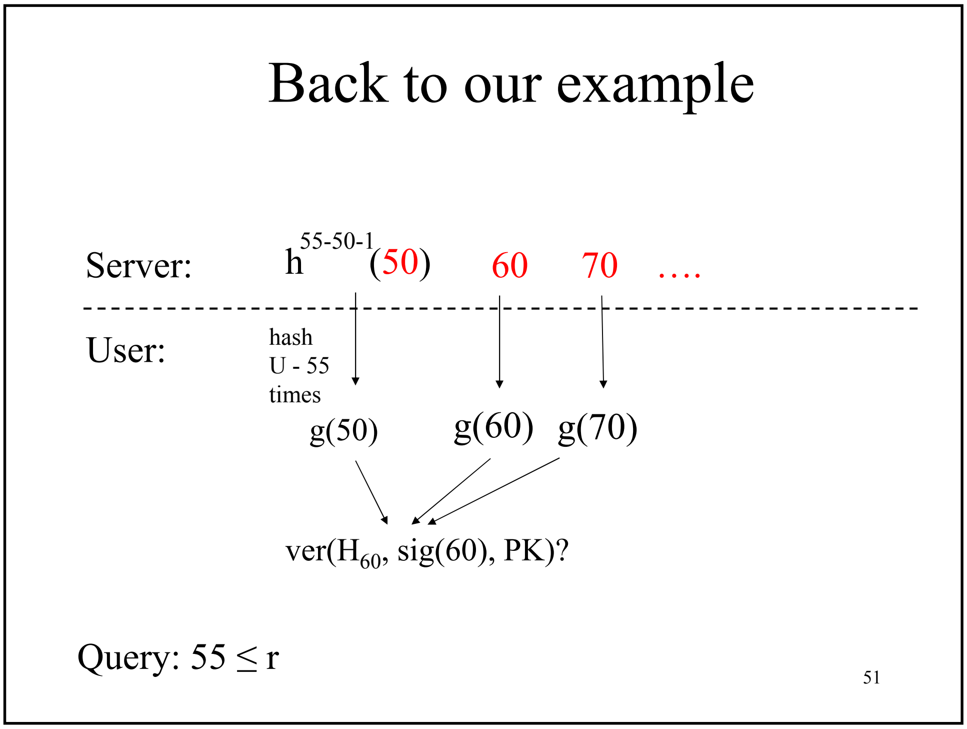
Query: $\alpha \leq r$

Back to our example



Require that the inverse of h^i for $i < 0$ be undefined

Query: $55 \leq r$



Back to our example

Server: $h^{55-50-1}(50)$ 60 70 ….

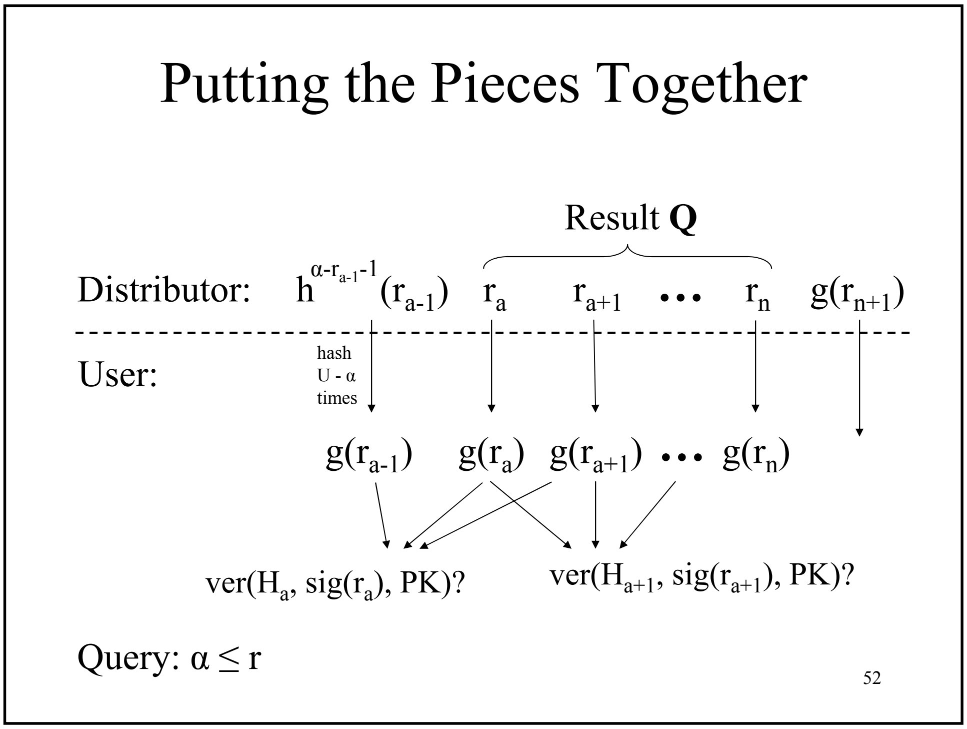
User: hash U - 55 times

$g(50)$ $g(60)$ $g(70)$

$ver(H_{60}, sig(60), PK)$?

Query: $55 \leq r$

51



Putting the Pieces Together

Result **Q**

Distributor: $h^{\alpha - r_{a-1} - 1}(r_{a-1})$ r_a r_{a+1} ••• r_n $g(r_{n+1})$

User: hash U - α times

$g(r_{a-1})$ $g(r_a)$ $g(r_{a+1})$ ••• $g(r_n)$

$ver(H_a, sig(r_a), PK)$? $ver(H_{a+1}, sig(r_{a+1}), PK)$?

Query: $\alpha \leq r$

52

Other cases

- $\alpha \leq r$
- $\beta \geq r$ (Result = $\{r_a, r_{a+1}, \ldots r_b\}$, i.e., $r_a, \ldots r_b \leq \beta < r_{b+1}$
  - Need to verify that $r_{b+1} > \beta$
  - Define $g(r) = \mathbf{h}^{\mathbf{r-L-1}}\mathbf{(r)} = \mathbf{h}^{\mathbf{\beta - L}}(\mathbf{h}^{\mathbf{r-\beta-1}}\mathbf{(r)})$ where L is a value outside of the minimum value of the domain
- So, we have $\alpha \leq r \leq \beta$
- $r = \alpha \equiv \alpha \leq r \leq \alpha$
- $\alpha < r < \beta \equiv \alpha+1 \leq r \leq \beta-1$
- $\alpha \neq r \equiv (L < r < \alpha) \cup (\alpha < r < R)$

NULL Answers??

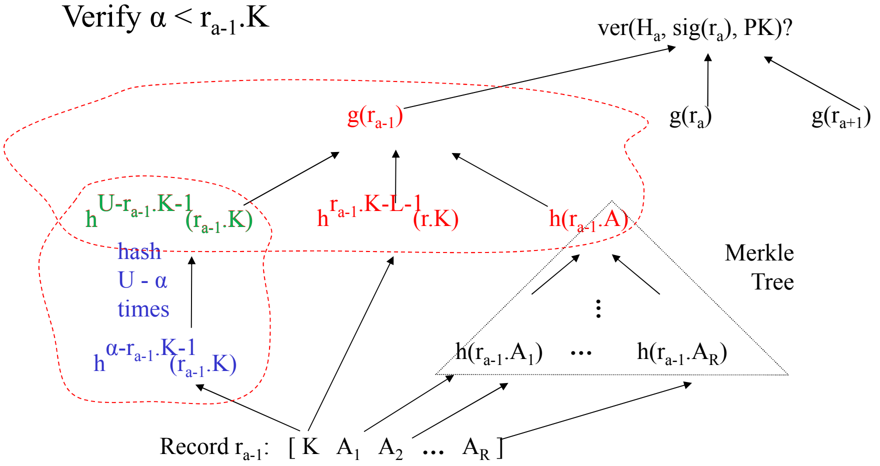
- Consider Q: $\alpha \leq r$.
- $Q = \emptyset$ because $r_n < \alpha$.
  - Server returns $\mathbf{h}^{\alpha\mathbf{-r_n-1}}\mathbf{(r), g(r_{n+1}), sig(r_{n+1})}$
  - User computes $\mathbf{h}^{\mathbf{U} - \alpha}(\mathbf{h}^{\alpha\mathbf{-r_n-1}}\mathbf{(r)})$ and verifies $ver(H_{n+1}, sig(r_{n+1}), PK)$?
- How about $r_i < \alpha \leq \beta < r_{i+1}$?

One More Vulnerability

- User can discover r_{a-1} through brute force enumeration of numbers below r_a
- Solution:
  - Record $[K, A_1, .., A_m]$, K = ordering attribute
  - $g(r_i.K \mid r_i.A_1 \mid \dots \mid r_i.A_m)$
  - Brute-force attack is no longer feasible

Completeness Verification for Range Queries

Verify $\alpha < r_{a-1}.K$



$ver(H_a, sig(r_a), PK)$?

$g(r_{a-1})$

$g(r_a)$

$g(r_{a+1})$

$h^{U-r_{a-1}.K-1}(r_{a-1}.K)$

$h^{r_{a-1}.K-L-1}(r.K)$

$h(r_{a-1}.A)$

hash U - α times

$h^{\alpha-r_{a-1}.K-1}(r_{a-1}.K)$

Merkle Tree

$h(r_{a-1}.A_1)$ … $h(r_{a-1}.A_R)$

Record r_{a-1}: $[K \;\; A_1 \;\; A_2 \;\; \dots \;\; A_R]$

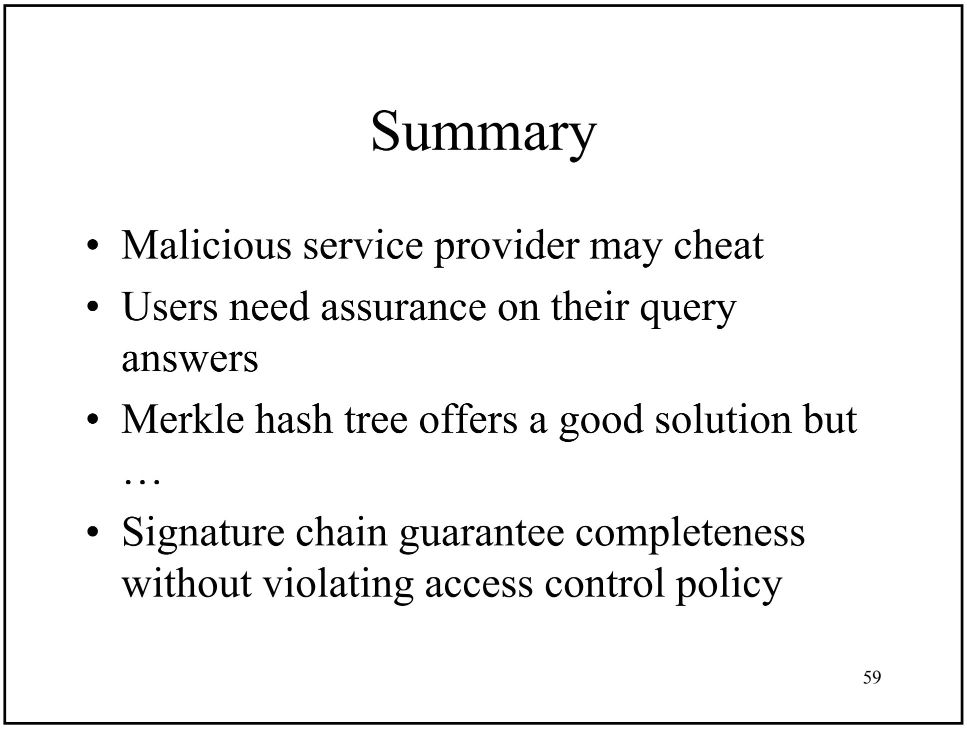
Query: $\alpha \le K \le \beta$. Result: $\{ r_a, r_{a+1}, \dots, r_b \}$

Other queries

- SP Query
  - Based on MHT(r.A)
  - Ordering attribute has to be returned (even if it is not part of the target attributes). Why?
  - For attributes that are filtered out, digests may need to be returned
- SPJ Query
  - R.Ai = S.Aj (Ai is foreign-key in R, Aj is primary key in S)
    - Referential integrity constraint mandates that every instance of R.Ai must have a matching entry in S.Aj
    - So, only need to deal with selection conditions on R.Ai or S.Aj
    - Create a signature chain for R.Ai

What else?

- What about data freshness?
- More efficient scheme
- Ad-hoc joins
- Aggregates
- Multi-dimensional data
- Computation
- Complete (complex) queries



Summary

- Malicious service provider may cheat
- Users need assurance on their query answers
- Merkle hash tree offers a good solution but …
- Signature chain guarantee completeness without violating access control policy