Data Security and Privacy in the Cloud

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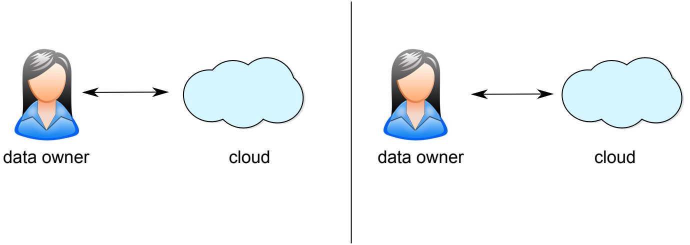
Cloud computing

- The Cloud allows users and organizations to rely on external providers for storing, processing, and accessing their data
  - \+ high configurability and economy of scale
  - \+ data and services are always available
  - \+ scalable infrastructure for applications
- Users lose control over their own data
  - – new security and privacy problems
- Need solutions to protect data and to securely process them in the cloud

Cloud computing: Today

Cloud Service Providers (CSPs) apply security measures in the services they offer but these measures protect only the perimeter and storage against outsiders



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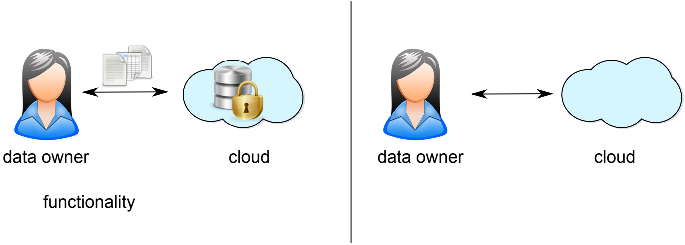

- functionality

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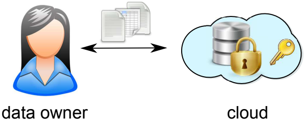
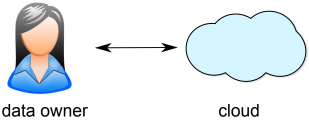


functionality but no protection
(key is with the CSP)



- functionality implies full trust in the CSP that has full access to the data (e.g., Google Cloud Storage, iCloud)

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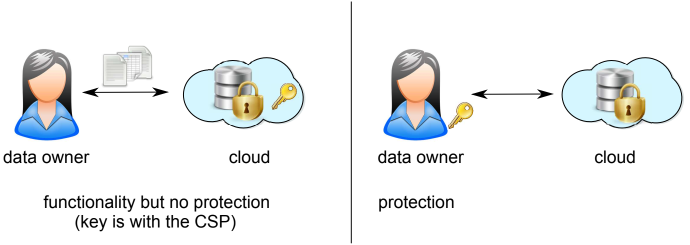

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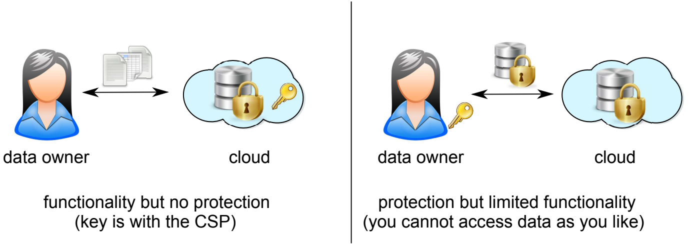
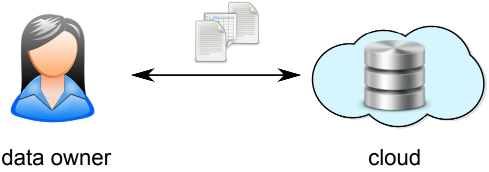


- functionality implies full trust in the CSP that has full access to the data (e.g., Google Cloud Storage, iCloud)
- protection but limited functionality since the CSP cannot access data (e.g., Boxcryptor, SpiderOak)

Cloud computing: ESCUDO-CLOUD's vision

Solutions that provide protection guarantees giving the data owners both: full control over their data and cloud functionality over them



H2020 project "Enforceable Security in the Cloud to Uphold Data Ownership" (ESCUDO-CLOUD).

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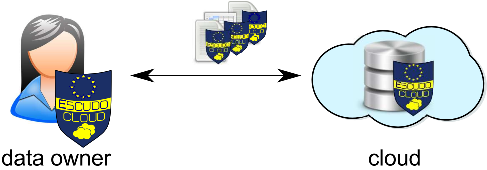

- client-side trust boundary: only the behavior of the client should be considered trusted

  $\Longrightarrow$ techniques and implementations supporting direct processing of encrypted data in the cloud

H2020 project "Enforceable Security in the Cloud to Uphold Data Ownership" (ESCUDO-CLOUD).

Some challenges in data protection

- Protection of and fine-grained access to outsourced data
  - confidentiality (and integrity) of data at rest
  - fine-grained retrieval and query execution
- Selective information sharing
  - access control on resources in the cloud
- Confidentiality of data access
  - privacy of users' actions (access and pattern confidentiality)
- Integrity
  - integrity of stored data and query results

P. Samarati, S. De Capitani di Vimercati, "Cloud Security: Issues and Concerns," in *Encyclopedia on Cloud Computing,* S. Murugesan, I. Bojanova (eds.), Wiley, 2016.

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Selective Information Sharing

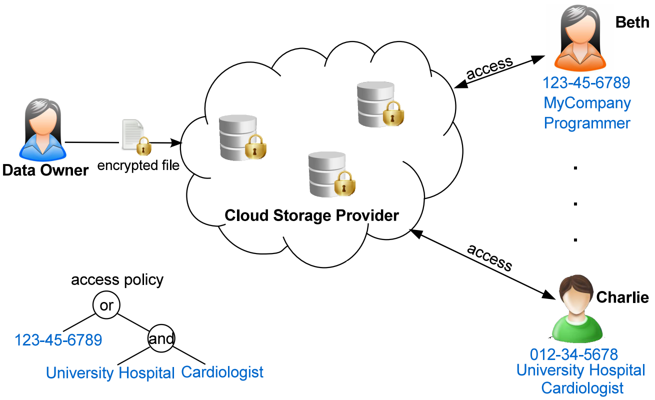
S. De Capitani di Vimercati, S. Foresti, S. Jajodia, S. Paraboschi, P. Samarati, "Encryption Policies for Regulating Access to Outsourced Data," in *ACM Transactions on Database Systems (TODS)*, vol. 35, n. 2, April 2010, pp. 12:1-12:46.

Selective information sharing

- Different users might need to enjoy different views on the outsourced data
- Enforcement of the access control policy requires the data owner to mediate access requests
  $\Longrightarrow$ impractical (if not inapplicable)
- Authorization enforcement may not be delegated to the provider
  $\Longrightarrow$ data owner should remain in control

Selective information sharing: Approaches – 1

- Attribute-based encryption (ABE): allow derivation of a key only by users who hold certain attributes (based on asymmetric cryptography)



Selective information sharing: Approaches – 2

- Selective (policy-based) encryption: the authorization policy defined by the data owner is translated into an equivalent encryption policy
  - users will be able to access only the resources for which they have the key

Selective encryption – 1

- Selective encryption: different keys are used to encrypt different data and users can know (or can derive) the keys of the data they can access
  - data themselves need to directly enforce access control
  - authorization to access a resource translated into knowledge of the key with which the resource is encrypted

	r_1	r_2	r_3	r_4	r_5
A	1	1	0	0	0
B	1	1	1	0	0
C	1	1	1	0	0
D	0	1	1	1	1
E	0	0	0	1	1

A knows the keys of r_1, r_2
B knows the keys of r_1, r_2, r_3
C knows the keys of r_1, r_2, r_3
D knows the keys of r_2, r_3, r_4, r_5
E knows the keys of r_3, r_5

Selective encryption – 2

Requirements:

- one version of data (no replication)
- one key per user

Basic idea:

- key derivation method: via public tokens a user can derive all keys of the resources she is allowed to access

	r_1	r_2	r_3	r_4	r_5
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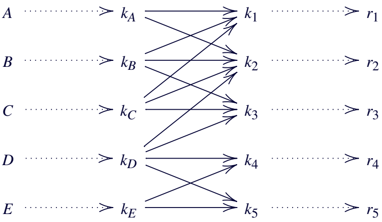
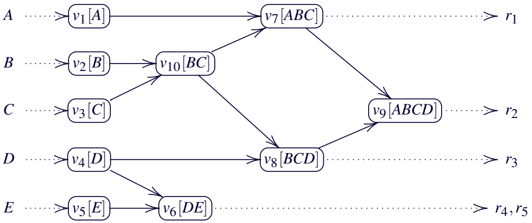


Selective encryption – 3

Exploit ACLs to minimize number of keys and tokens

- Keys:
  - one key per user
  - an additional key for each non-singleton ACL
- Resources are encrypted with the key of their ACLs
- Tokens allow users to derive the keys of the ACLs to which they belong



Policy updates

- When authorizations dynamically change, the data owner needs to:
  - download the resource from the provider
  - create a new key for the resource
  - decrypt the resource with the old key
  - re-encrypt the resource with the new key
  - upload the resource to the provider and communicate the public catalog updates

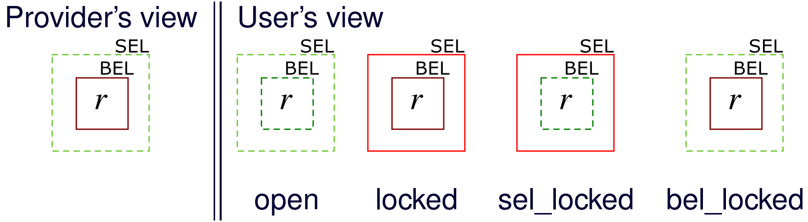
  $\Longrightarrow$ inefficient

- Possible solution: over-encryption

Over-encryption – 1

- Resources are encrypted twice
  - by the owner, with a key shared with the users and unknown to the provider (Base Encryption Layer - BEL level)
  - by the provider, with a key shared with authorized users (Surface Encryption Layer - SEL level)
- To access a resource a user must know both the corresponding BEL and SEL keys
- Grant and revoke operations may require
  - the addition of new tokens at the BEL level
  - the re-encryption of resources at the SEL level to guarantee the enforcement of policy updates

Over-encryption – 2

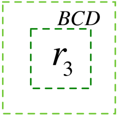


- Each layer is depicted as a fence
  - discontinuous, if the key is known
  - continuous, if the key is not known (protection cannot be passed)

Over-encryption – 3

- Revoke
  to protect resources for which the revokee has the BEL key

  EXAMPLE
  r_3 is encrypted with a key known to B, C, D at BEL
  r_3 is not encrypted at SEL



user B view

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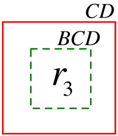
  revoke B access to r_3:
  - over-encrypt r_3, using a key at SEL known to C, D only



user B view

Over-encryption – 4

- Grant
  if a BEL key protects multiple resources and access is to be granted only to a subset of them, there is the need to protect at SEL level the resources on which access is not being granted

  EXAMPLE
  r_4, r_5 are encrypted with the same key known to D, E at BEL
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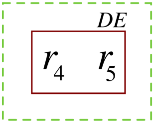

user C view

Over-encryption – 4

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  EXAMPLE

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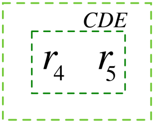
  grant C access to r_4
  - add a token at BEL enabling C to derive the key of r_4



user C view

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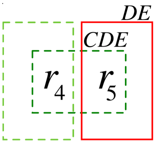
  - add a token at BEL enabling C to derive the key of r_4
  - over-encrypt r_5, using a key at SEL known to D, E only



user C view

Mix&Slice for Policy Revocation

E. Bacis, S. De Capitani di Vimercati, S. Foresti, S. Paraboschi, M. Rosa, P. Samarati, “Mix&Slice: Efficient Access Revocation in the Cloud,” in *Proc. of the 23rd ACM Conference on Computer and Communications Security (CCS 2016)*, Vienna, Austria, October 2016.

Mix&Slice

- Over-encryption requires support by the server (i.e., the server implements more than simple get/put methods)

- Alternative solution to enforce revoke operations: Mix&Slice

- Use different rounds of encryption to provide complete mixing of the resource

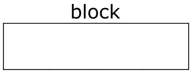
  $\Longrightarrow$ unavailability of a small portion of the encrypted resource prevents its (even partial) reconstruction

- Slice the resource into fragments and, every time a user is revoked access to the resource, re-encrypt a randomly chosen fragment

  $\Longrightarrow$ lack of a fragment prevents resource decryption

Resource organization

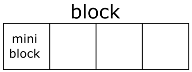
- Block: sequence of bits input to a block cipher
  AES uses block of 128 bits



Resource organization

- Block: sequence of bits input to a block cipher
  AES uses block of 128 bits

- Mini-block: sequence of bits in a block
  it is our atomic unit of protection
  mini-blocks of 32 bits imply a cost of
  2^{32} for brute-force attacks



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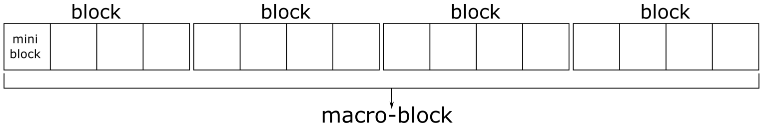
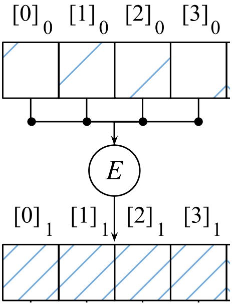
- Macro-block: sequence of blocks
  mixing operates at the level of macro-block
  a macro-block of 1KB includes 8 blocks



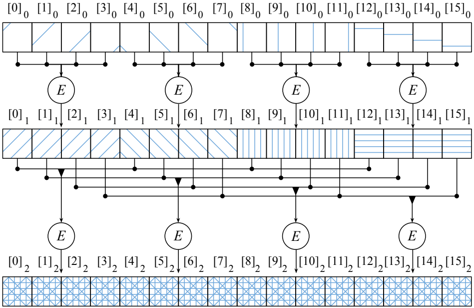
Mixing – 1

- When encryption is applied to a block, all the mini-blocks are mixed
  + absence of a mini-block in a block from the result prevents reconstruction of the block
  – does not prevent the reconstruction of other blocks in the resource



Mixing – 2

- Extend mixing to a macro-block
  - iteratively apply block encryption
  - at iteration i, each block has a mini-block for each encrypted block obtained at iteration $i-1$ (at distance 2^i)
  - x rounds mix 4^x mini-blocks

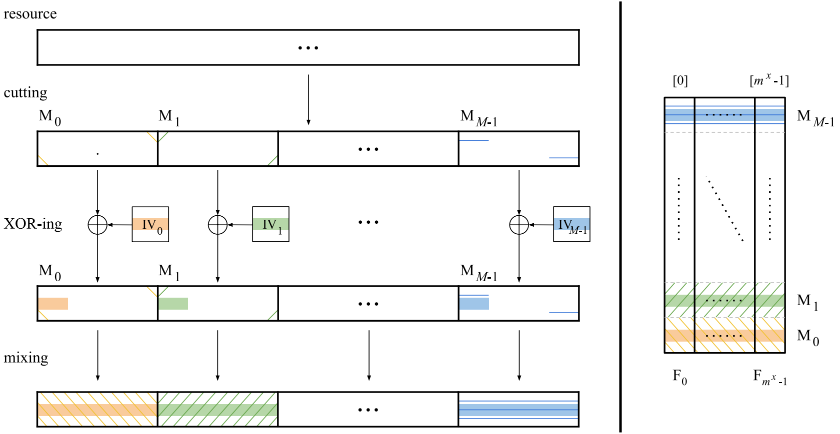


Slicing – 1

- To be mixed, large resources require large macro-blocks
  - many rounds of encryption
  - considerable computation and data transfer overhead
- Large resources are split in different macro-blocks for encryption
- Absence of a mini-block for each macro-block prevents the (even partial) reconstruction of the resource

Slicing – 2

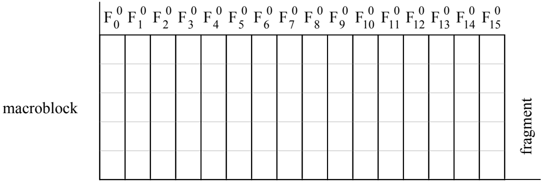
- Slice resources in fragments having a mini-block for each macro-block (the ones in the same position)
  - absence of a fragment prevents reconstruction of the resource



Revoke

To revoke user u access to a resource r

1. randomly select a fragment F_i of r and download it
2. decrypt F_i
3. generate a new key k_l that u does not know and cannot derive
4. re-encrypt F_i with the new key k_l
5. upload the encrypted fragment



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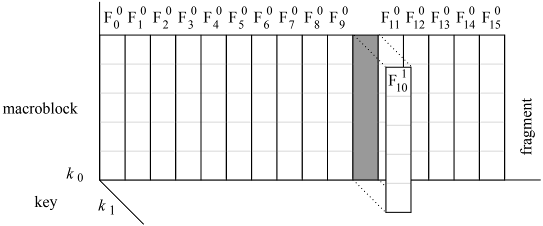

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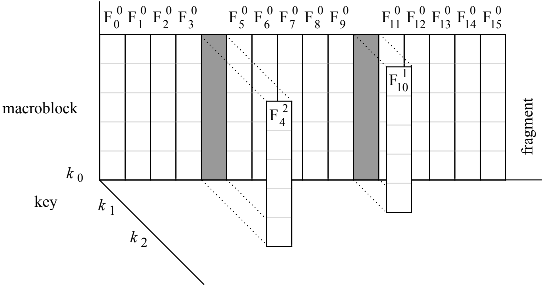

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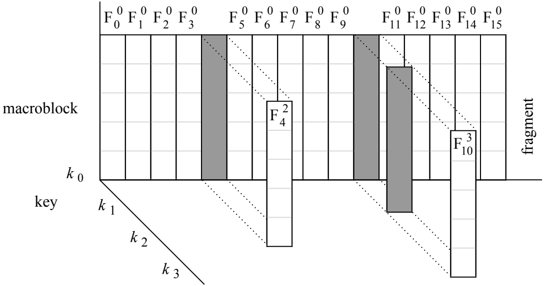


Effectiveness of the approach

- A revoked user does not know the encryption key of at least one fragment
  - necessary a brute force attack to reconstruct the fragment (and the resource)
  - 2^{msize} attempts, with msize the number of bits in a mini-block
- A user can locally store f_{loc} of the f fragments of a resource
- Probability to be able to reconstruct the resource after f_{miss} fragments have been re-encrypted: $P = (f_{\text{loc}}/f)^{f_{\text{miss}}}$
  - proportional to the number of locally stored fragments
  - decreases exponentially with the number of policy updates

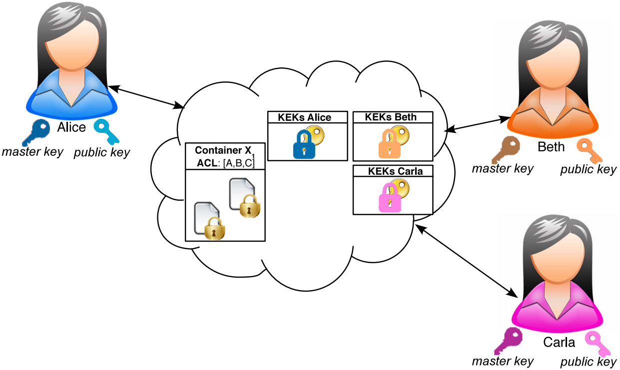
Applying Selective Encryption and Over-encryption in OpenStack Swift

E. Bacis, S. De Capitani di Vimercati, S. Foresti, S. Paraboschi, M. Rosa, P. Samarati, “Access Control Management for Secure Cloud Storage,” in *Proc. of SecureComm 2016*, Guangzhou, China, October 10-12, 2016.

Policy-based encryption in OpenStack Swift – 1

- Swift module: an object storage service allowing users to store and access data in the form of objects
- Swift enforces access control associating an Access Control List (ACL) with each container
- Policy-based encryption:
  - associates a DEK (Data Encryption Key) with each container, used to encrypt objects in the container
  - associates a MEK (Master Encryption Key) and an asymmetric encryption key pair with each user
  - stores a KEK (Key Encryption Key) for each user authorized for a container, enabling her to derive the container DEK from her private or master key

Policy-based encryption in OpenStack Swift – 2

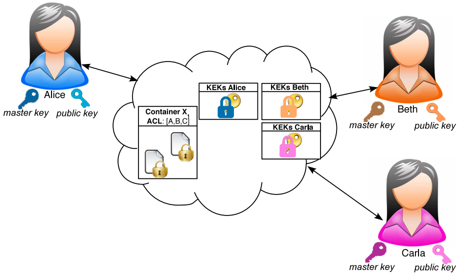


Alice generates a container X_1 and grants Beth and Carla access to it

Policy changes: Grant

User u grants to user u_j access to a container C

- User u_j is added to the ACL of container C
- User u computes a new KEK for u_j, which allows u_j to derive the DEK of container C



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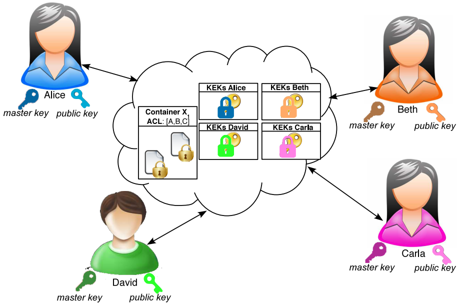
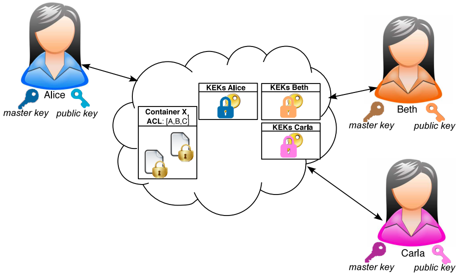


Alice grants to David access to container X_1

Policy changes: Revoke with Over-encryption

User u revokes access to container C from user u_j

- User u removes u_j from the ACL of container C
- User u asks the storing server to over-encrypt the objects in container C with a SEL key that only non-revoked users can derive



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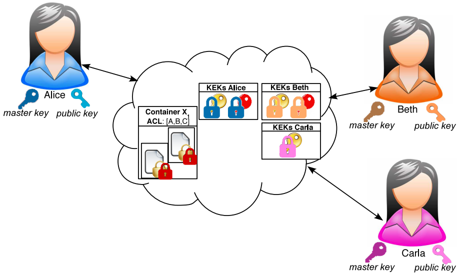

Alice revokes from Carla access to container X_1

Conclusions and future directions

Solutions based on policy-based encryption

- enable users to regulate access to their resources
- guarantee that resources self-enforce access restrictions
- support efficient policy updates through over-encryption and mix&slice approaches
- can be integrated with current cloud technology

Open issues include:

- support for write authorizations
- combine with techniques for efficient query evaluation
- address collusion
- ...