Towards Fine-Grained Secure Communications

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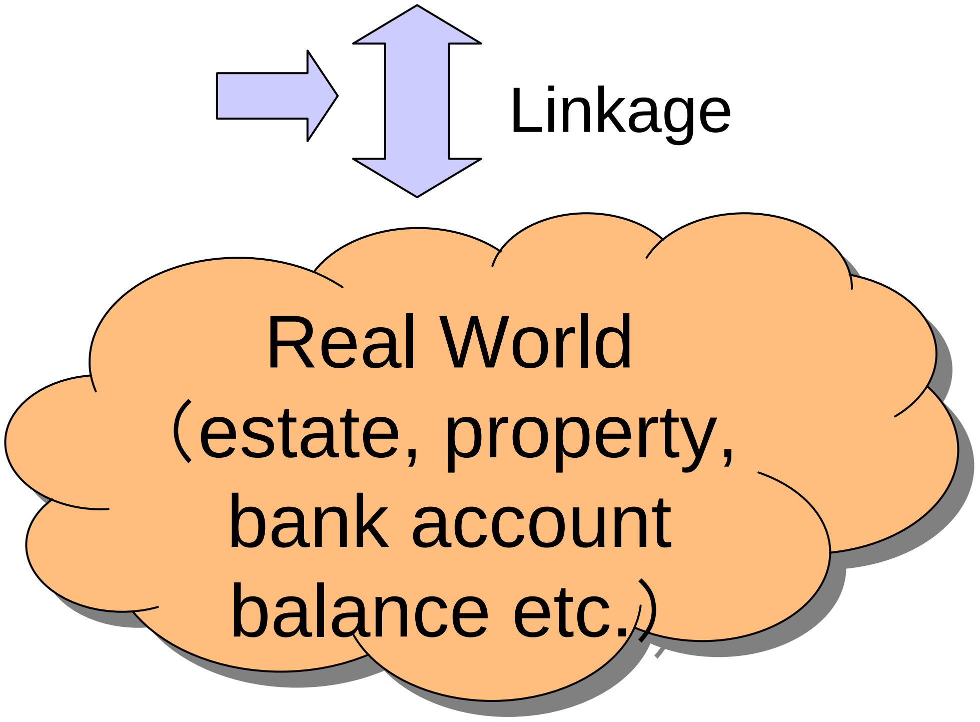
The Role of Cryptography and Information Security

ICT systems ・・・ Virtual World

（Every information is communicated and recorded by digital data）

Cryptography and

Information Security



Basic Properties of Cryptography

- Confidentiality: Data flow control

  (a data item is only accessed by qualified persons) … encryption
- Authentication: Correctness of data and users/parties … signatures, identification
- Privacy: Anonymity of users/parties

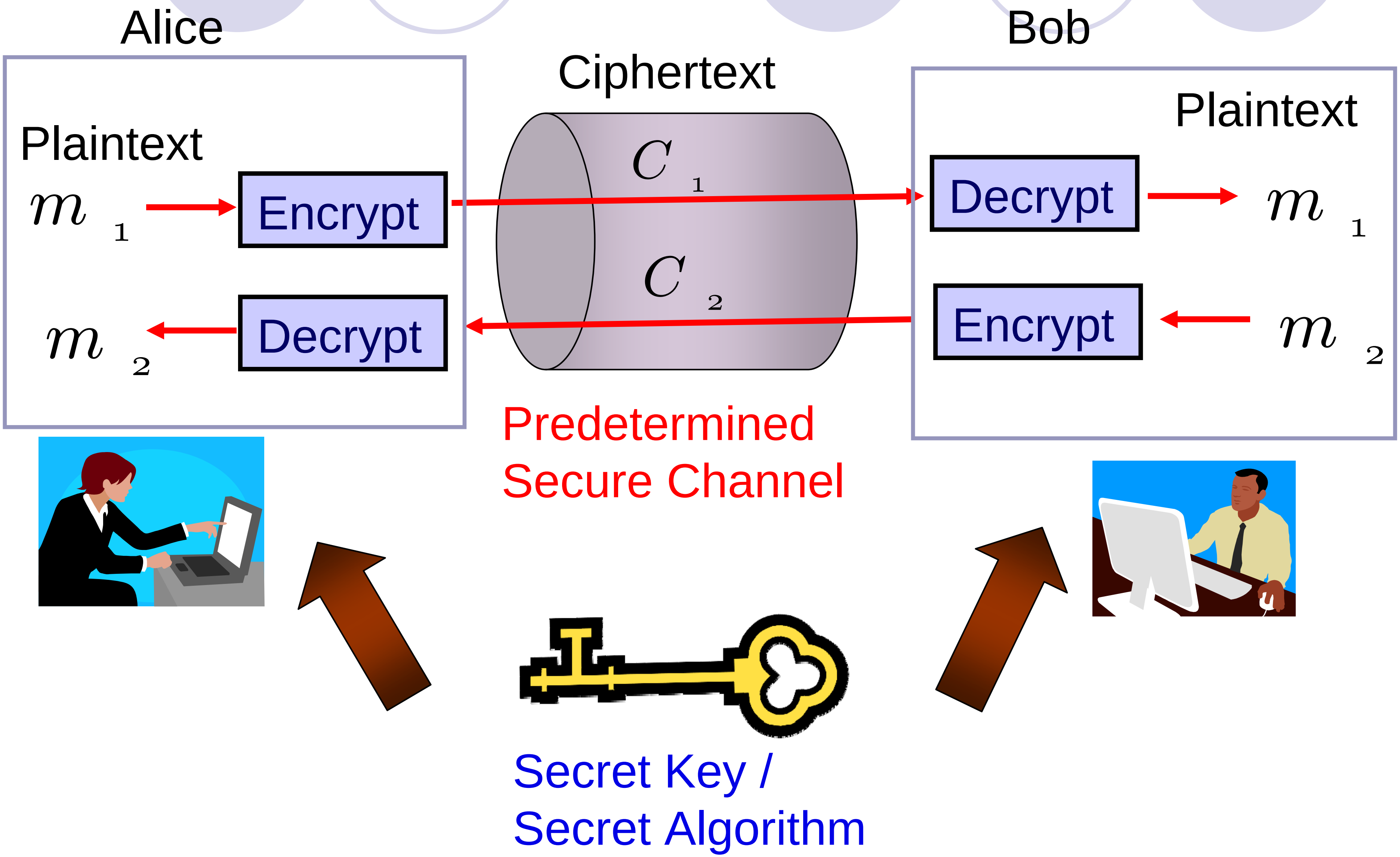
  … privacy-enhanced primitives

Confidentiality

The Most Traditional Way to Realize Confidentiality

- Symmetric Encryption: realized by sharing a secret algorithm or a secret key between a pair of sender and receiver.
- Long history for several thousand years (similar to that of civilizations of human beings).

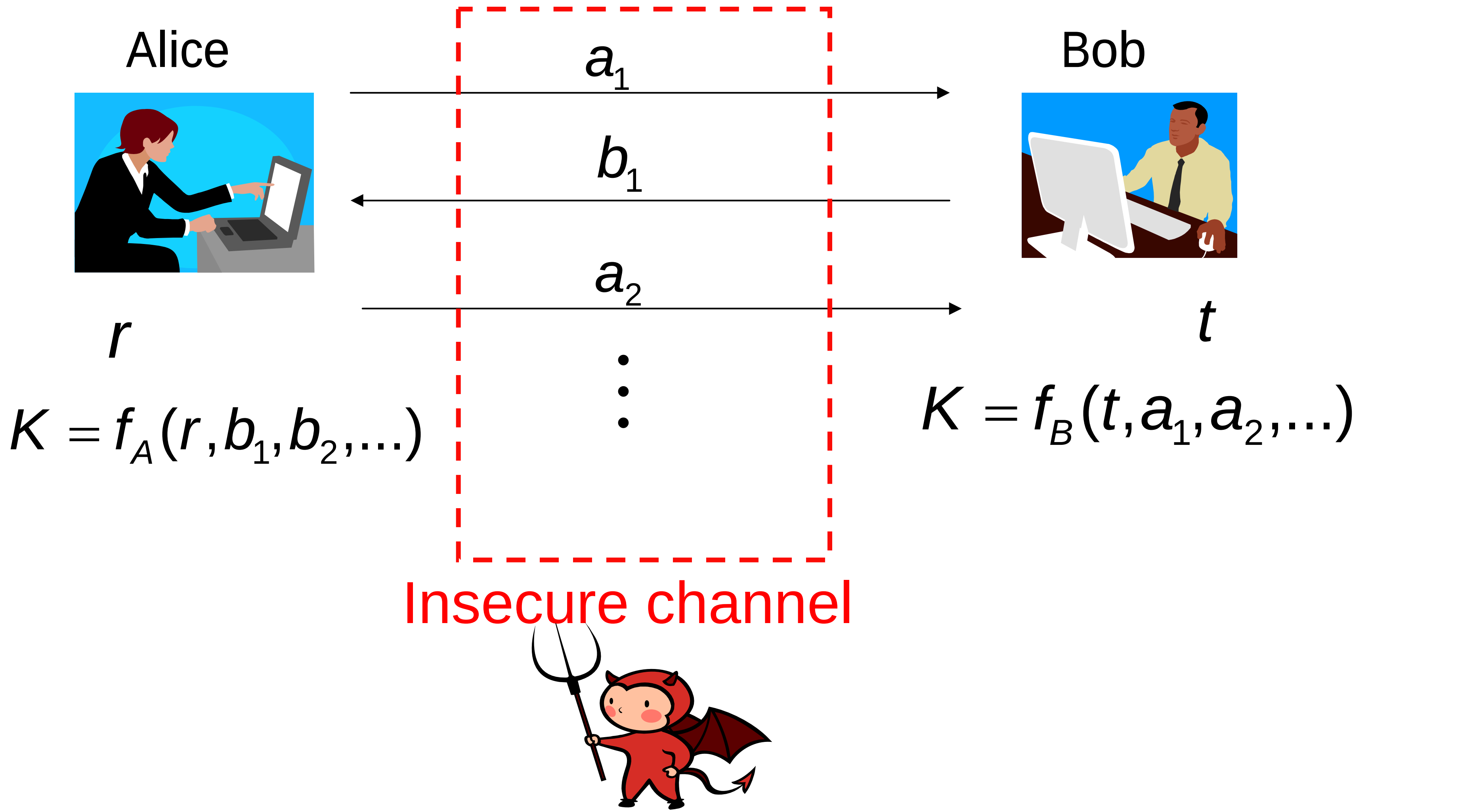
Symmetric Encryption



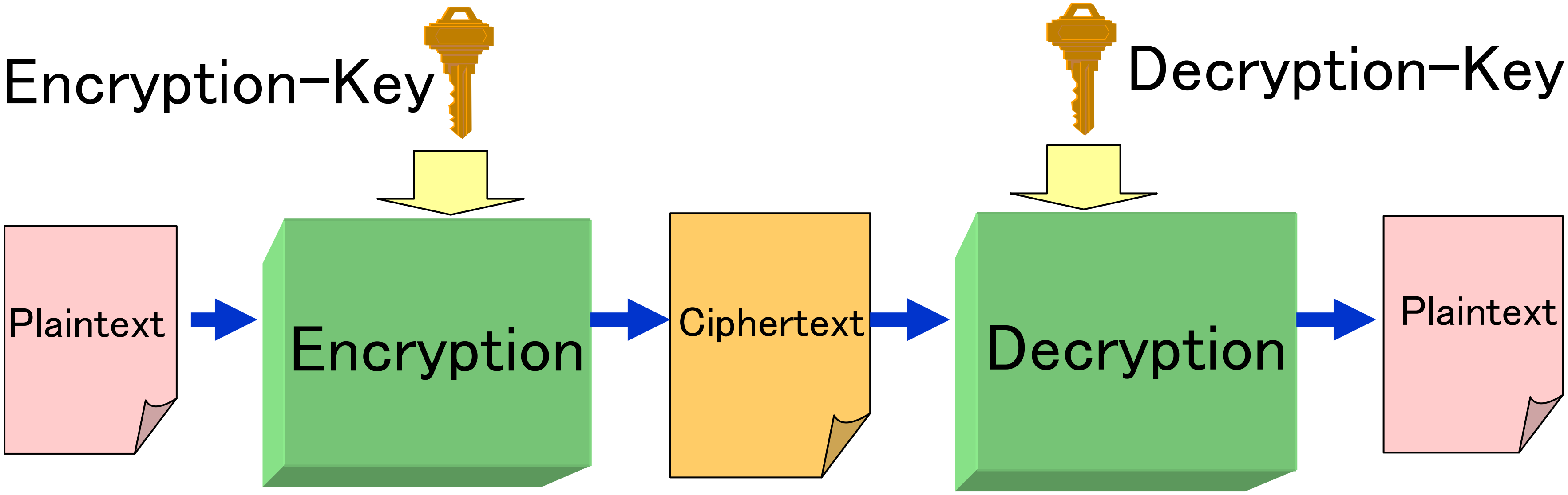
A problem raised in the early 1970's

- The early 1970's： ARPANET (the origin of the Internet）started growing.
- Problem: Is it possible for two parties to share a secret key securely through an insecure channel, where all messages exchanged by the two parties are wiretapped by the adversary?

Secret Key Sharing over Insecure Channels

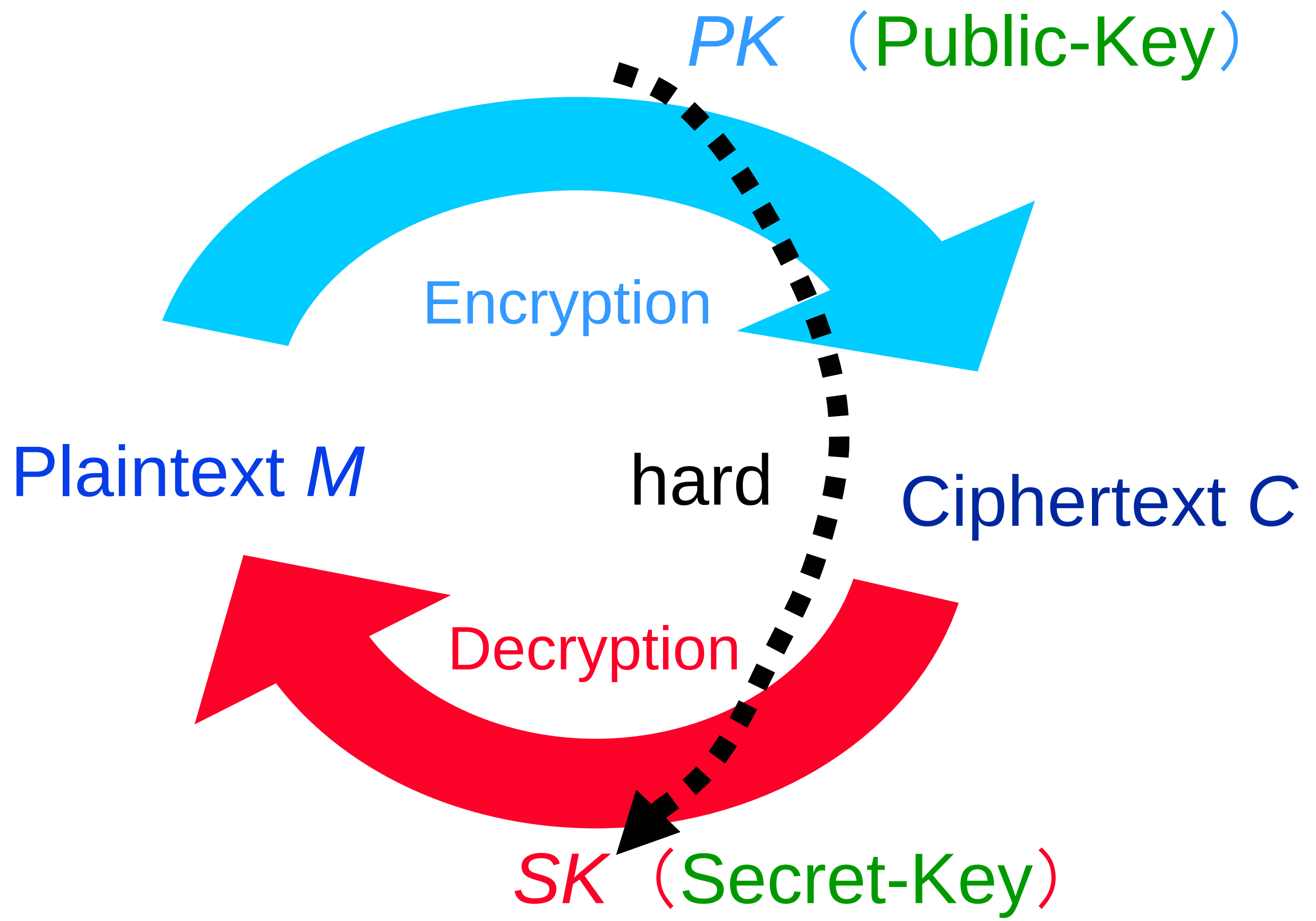


Public-key Encryption（1976 ）

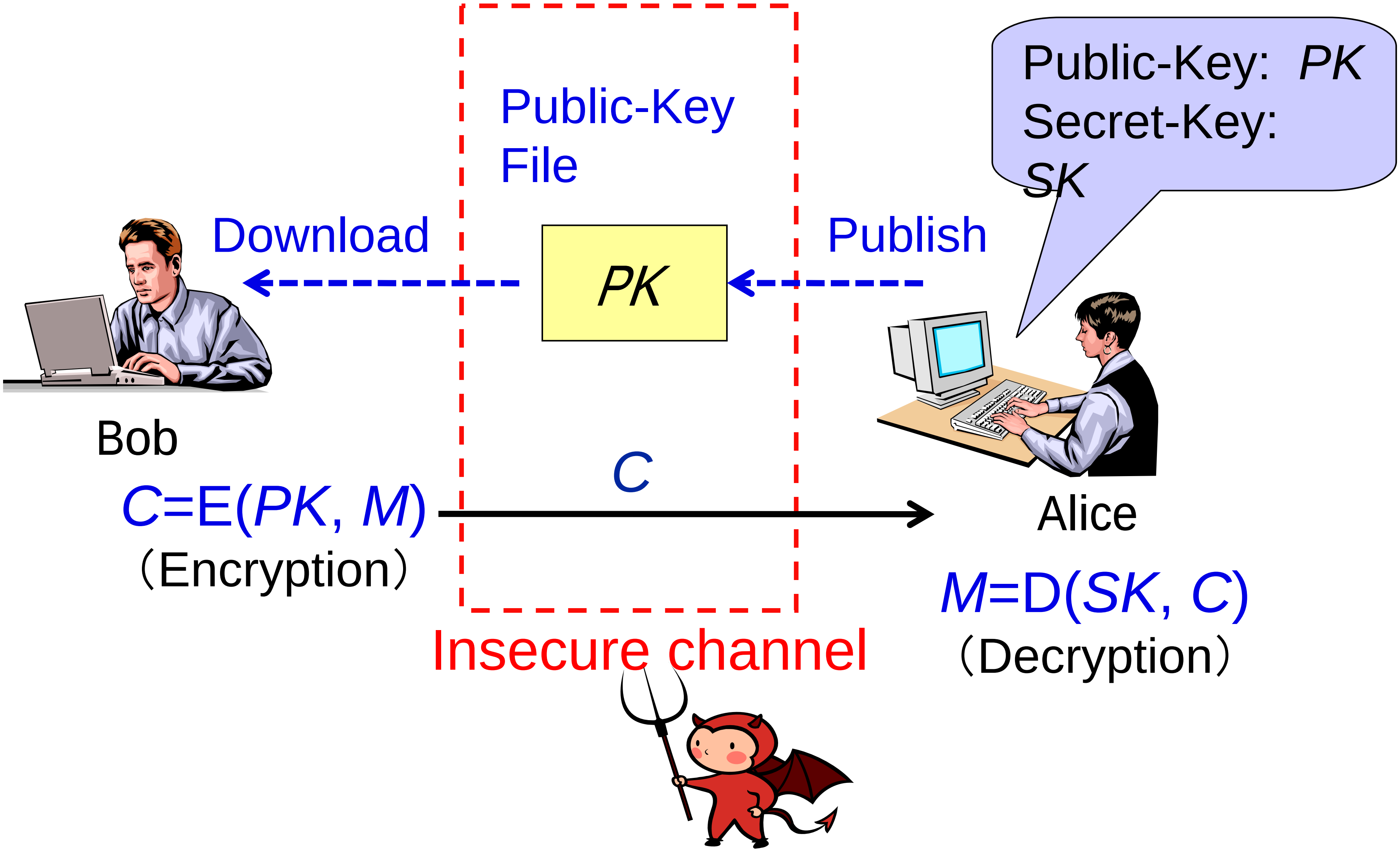


Symmetric Encryption	Encryption−Key ＝ Decryption−Key
Public−key Encryption	Encryption−Key ≠ Decryption−Key

Principle of Public-key Encryption



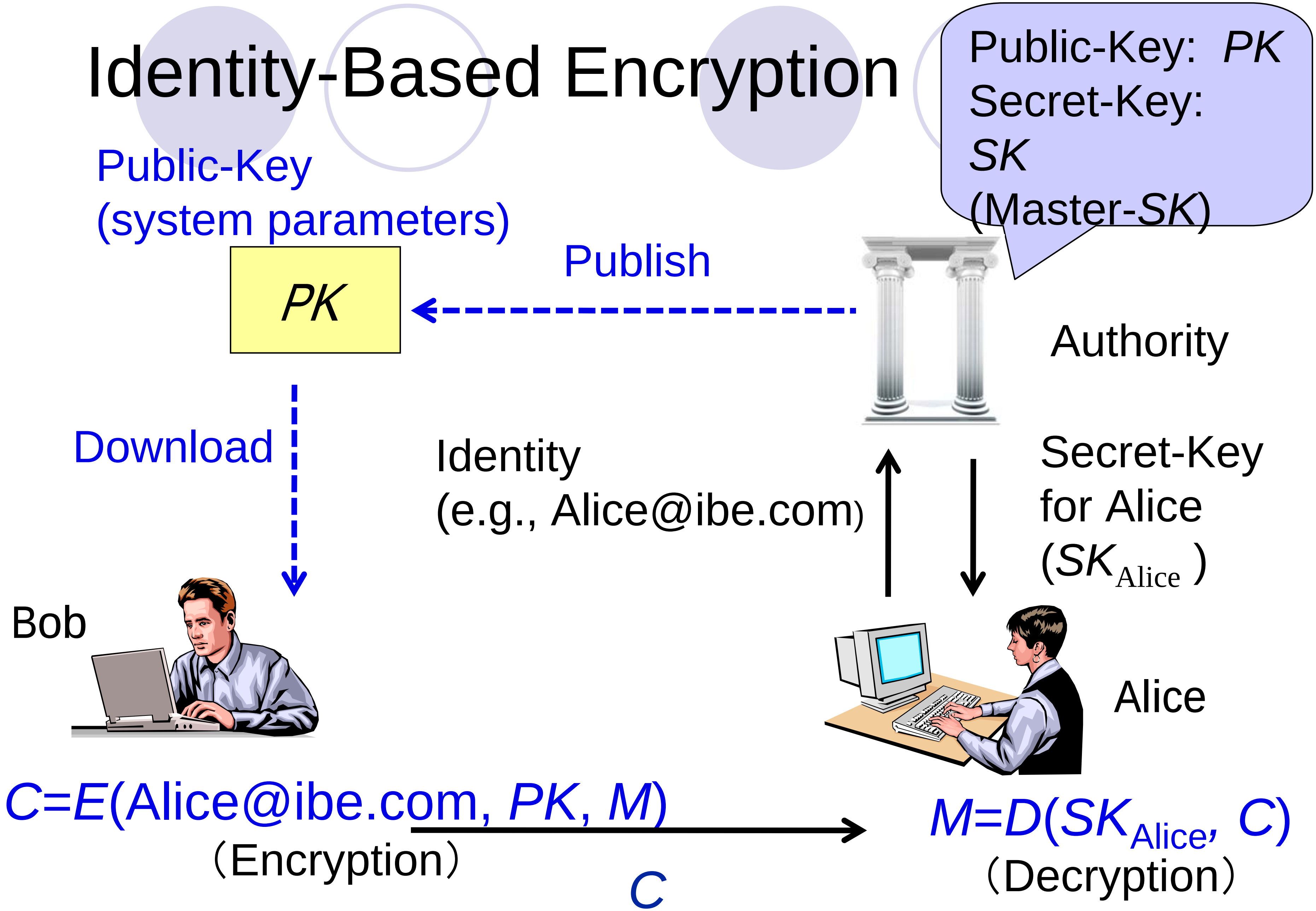
Public-key Encryption



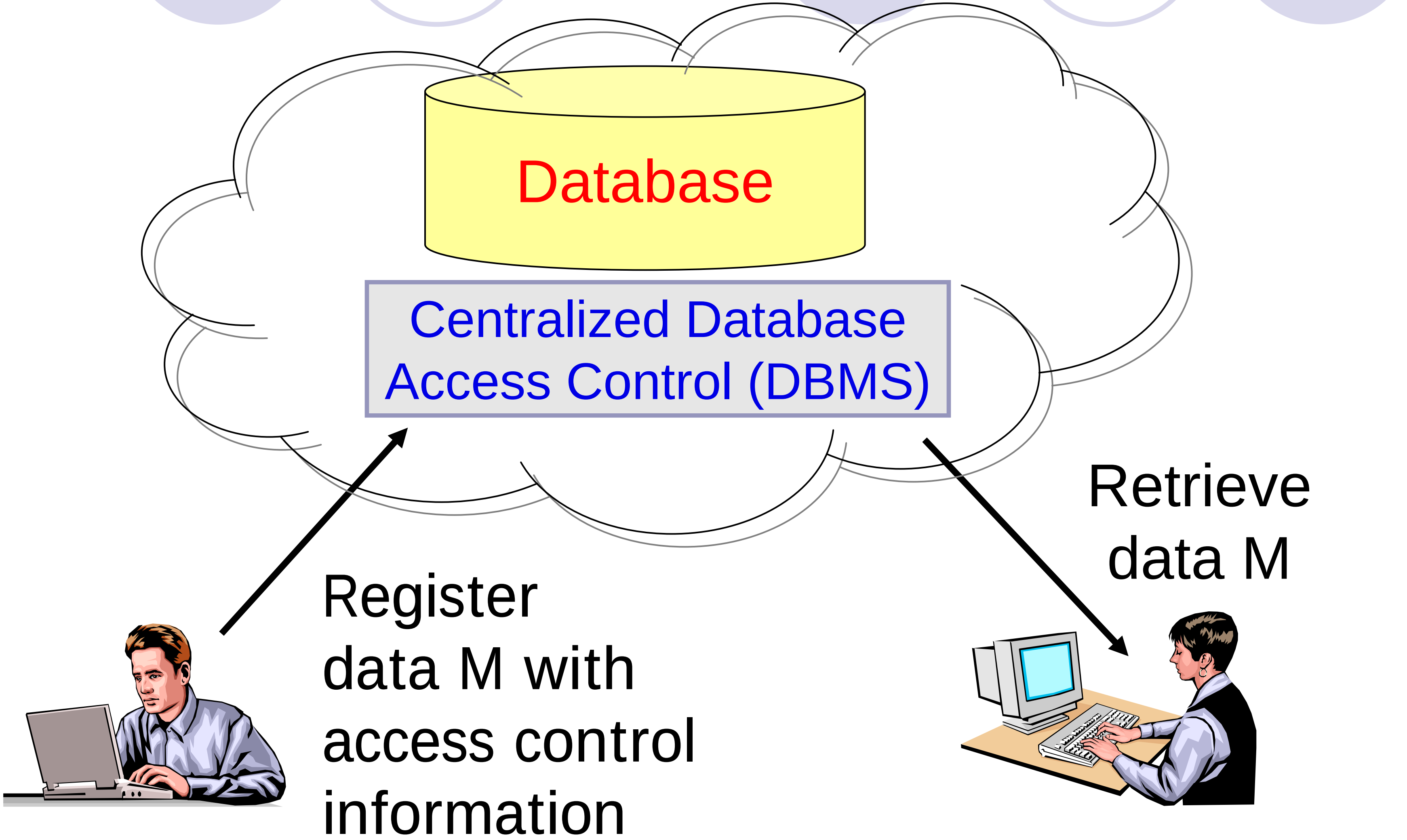
A New Concept of Encryption

- Public-key encryption as well as symmetric encryption are now widely used in many applications, especially in the internet.
- To get a public-key of each receiver may be a problem in some applications.
- Can we use an identity (e.g., email address) of a receiver in place of the public-key?
- No, it is impossible, in the concept of public-key encryption.
- It may be possible in a new concept of encryption.

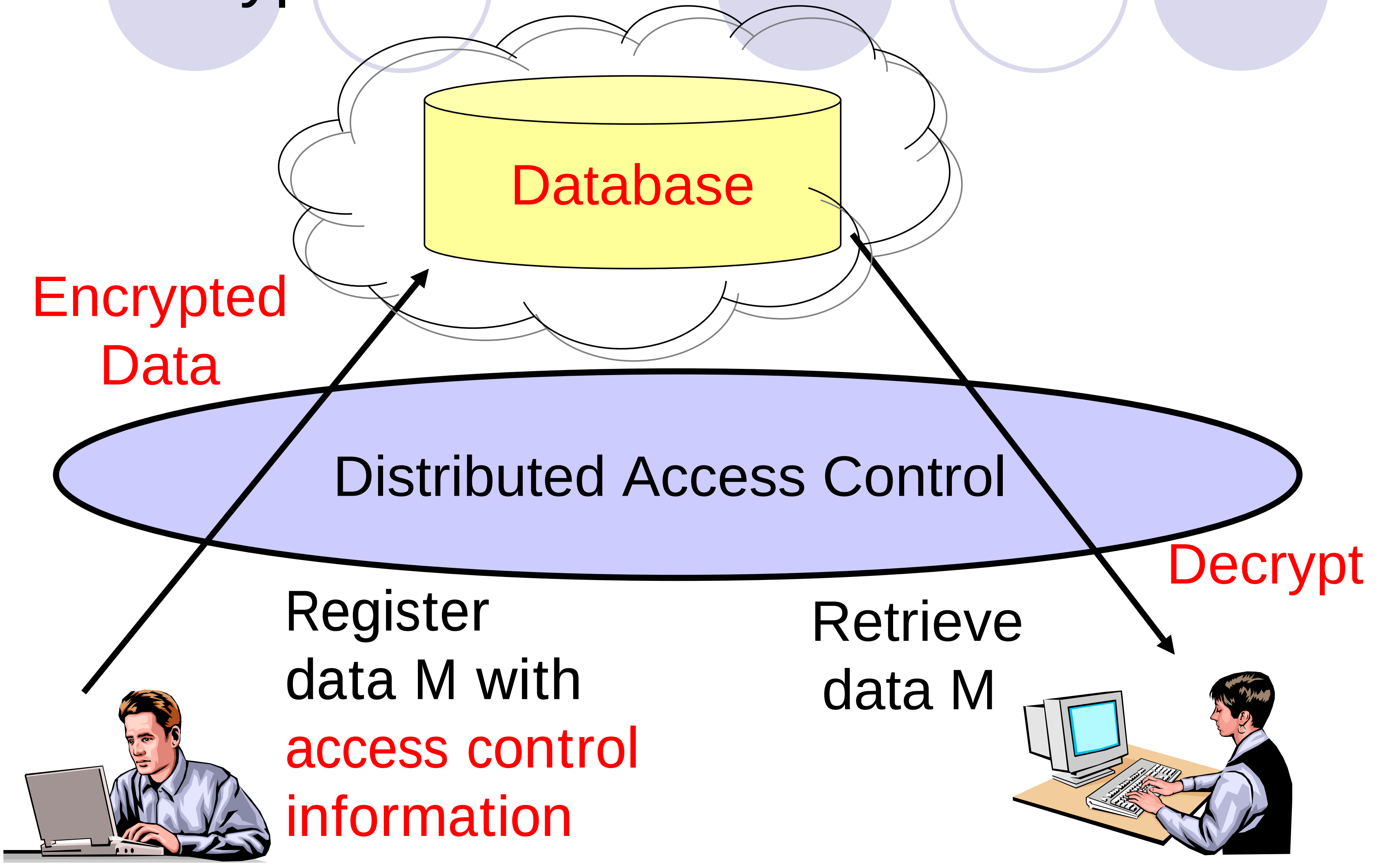
Identity-Based Encryption



Centralized Access Control of Database Services



Distributed Access Control with Encryption for Database Services



Fine-Grained Encryption (Predicate Encryption)

Public-Key: *PK*
Secret-Key: *SK*
(Master-*SK*)

Public-Key
(system parameters)

PK

Publish

Authority

Download

Predicate *f*

Secret-Key for *f*
(SK_f)

Bob

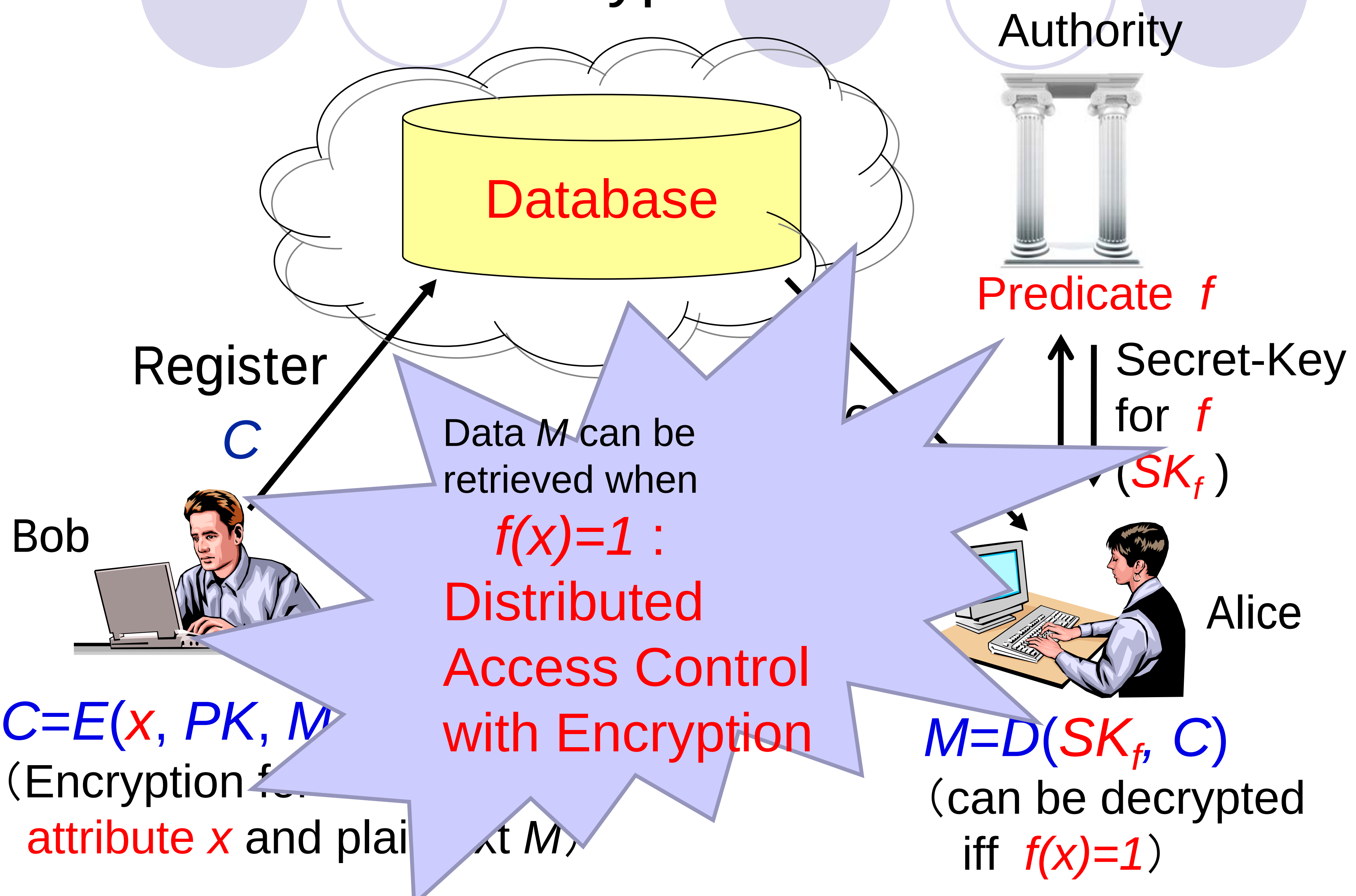
Alice

$C=E(x, PK, M)$
（Encryption for attribute *x* and plaintext *M*）

C

$M=D(SK_f, C)$
（can be decrypted iff $f(x)=1$）

Distributed Access Control by Fine-Grained Encryption



Example 1 of Predicates and Attributes

- Predicate f with parameters a :

  $$f(X) \equiv (X=a)$$

- Acceptable attribute x is a,
- Application: Identity-based encryption

a = Alice@ibe.com

$SK_{Alice} = SK_{a}$

Alice

$C=E(a, PK, M)$
(Encryption)

C

$M=D(SK_{a}, C)$
(Decryption)

Example 2 of Predicates and Attributes

- Predicate *f* with parameters *a, b* and *c* :

  $f(X,Y,Z) \equiv (X=a) \wedge ((Y=b) \vee (Z=c))$

- Acceptable attributes: *x = (a,b,d), (a,e,c)*
- Application Example:

  a $\equiv$ [Type: Animation],

  b $\equiv$ [Price: Zone 2],

  c $\equiv$ [Restriction: Class 1],

- Secret-key SK_f is given to a person (receiver) who purchases the secret key.
- A ciphertext of a content with attribute (Animation, Price Zone 2, Class 2) or (Animation, Price Zone 1, Class 1) can be decrypted by SK_f .

Fine-Grained Encryption (Predicate Encryption)

Public-Key: *PK*
Secret-Key: *SK*
(Master-*SK*)

Public-Key
(system parameters)

PK

Publish

Authority

Download

Predicate *f* =
(X=Animation) ∧
(Y=Price Zone 2 ∨ Z=Class 1)

Secret-Key
for *f*
(SK_f)

Bob

Alice

$C=E(x, PK, M)$
(Encryption for
attribute $x = (X,Y,Z)$ =
(Animation, Price Zone 2, Class 2))

C

$M=D(SK_f, C)$
(can be decrypted
iff $f(x)=1$)

Example 3 of Predicates and Attributes

- Predicate f with parameters a, b and c :

  $f(X,Y,Z) \equiv (X \neq a) \wedge ((Y < b) \vee (Z = c))$
- Acceptable attributes: $x = (c,d,e)$ (s.t. $c \neq a$ and $d < b$), (c,e,c) (s.t. $c \neq a$ and $e > b$), …
- Application Example:

  a $\equiv$ [Type: Animation],

  b $\equiv$ [Price: $100],

  c $\equiv$ [Restriction: Class 1],
- Secret-key SK_f is given to a person (receiver) who purchases the secret key.
- A ciphertext of a content with attribute (Drama, $70, Class 2) or (News, $200, Class 1) can be decrypted by SK_f .

Fine-Grained Encryption (Predicate Encryption)

Public-Key: *PK*
Secret-Key: *SK*
(Master-*SK*)

Public-Key
(system parameters)

PK

Publish

Authority

Download

Predicate f =
($X \neq Animation$) ∧
(Y< \$100 ∨ Z=Class 1)

Secret-Key for f (SK_f)

Bob

Alice

$C=E(x, PK, M)$
(Encryption for attribute $x = (X,Y,Z)$ =
(Drama, \$70 , Class 2))

C

$M=D(SK_f, C)$
(can be decrypted iff $f(x)=1$)

Example 4 of Predicates and Attributes

- Predicate f with parameters a, b, c and d :

  $f(X,Y,Z,W) \equiv$ TH2 [$(X = a)$, $((Y < b) \vee (Z = c))$, $(W \neq d)$]

  (TH2: threshold function that accepts if at least 2 terms are true.)

- Acceptable attributes: $x = (a,e,g,d)$ (s.t. $e < b$), (d,e,c,g) (s.t. $d \neq a$, $e > b$, $g \neq d$), …

- Application Example:

  a $\equiv$ [Type: Animation], b $\equiv$ [Price: $100],

  c $\equiv$ [Membership: Gold], d $\equiv$ [Restriction: Class 1]

- Secret-key SK_f is given to a person (receiver) who purchases the secret key.

- A ciphertext of a content with attribute (Animation, $70, Silver, Class 1) or (News, $200, Gold, Class 2) can be decrypted by SK_f .

Fine-Grained Encryption (Predicate Encryption 2)

Public-Key: *PK*
Secret-Key: *SK*
(Master-*SK*)

Public-Key
(system parameters)

PK

Publish

Authority

Download

attribute *x*

Secret-Key for *x*
(SK_x)

Bob

Alice

$C=E(f, PK, M)$
（Encryption for predicate *f* and plaintext *M*）

C

$M=D(SK_x, C)$
（can be decrypted iff $f(x)=1$）

Fine-Grained Encryption (Predicate Encryption 2)

Public-Key: *PK*
Secret-Key: *SK*
(Master-*SK*)

Public-Key
(system parameters)

PK

Publish

Authority

Download

Attribute x = (*X*,*Y*,*Z*) =
(NTT, Age:30, Female)

Secret-Key
for *x*
(SK_x)

Bob

Alice

$C=E(f, PK, M)$
（Encryption for
predicate *f* =
X=NTT ∧ (*Y*< 35 ∨ *Z*=Male) ）

C

$M=D(SK_x, C)$
（can be decrypted
iff $f(x)=1$）

From Coarse-Grained to Fine-Grained Encryption

- Symmetric Encryption (ancient ～)

  - sender and receiver should be fixed/restricted.

- Public-Key Encryption (1976 ～) DH

  - receiver should be restricted by the public-key (registered string), but sender is not restricted.

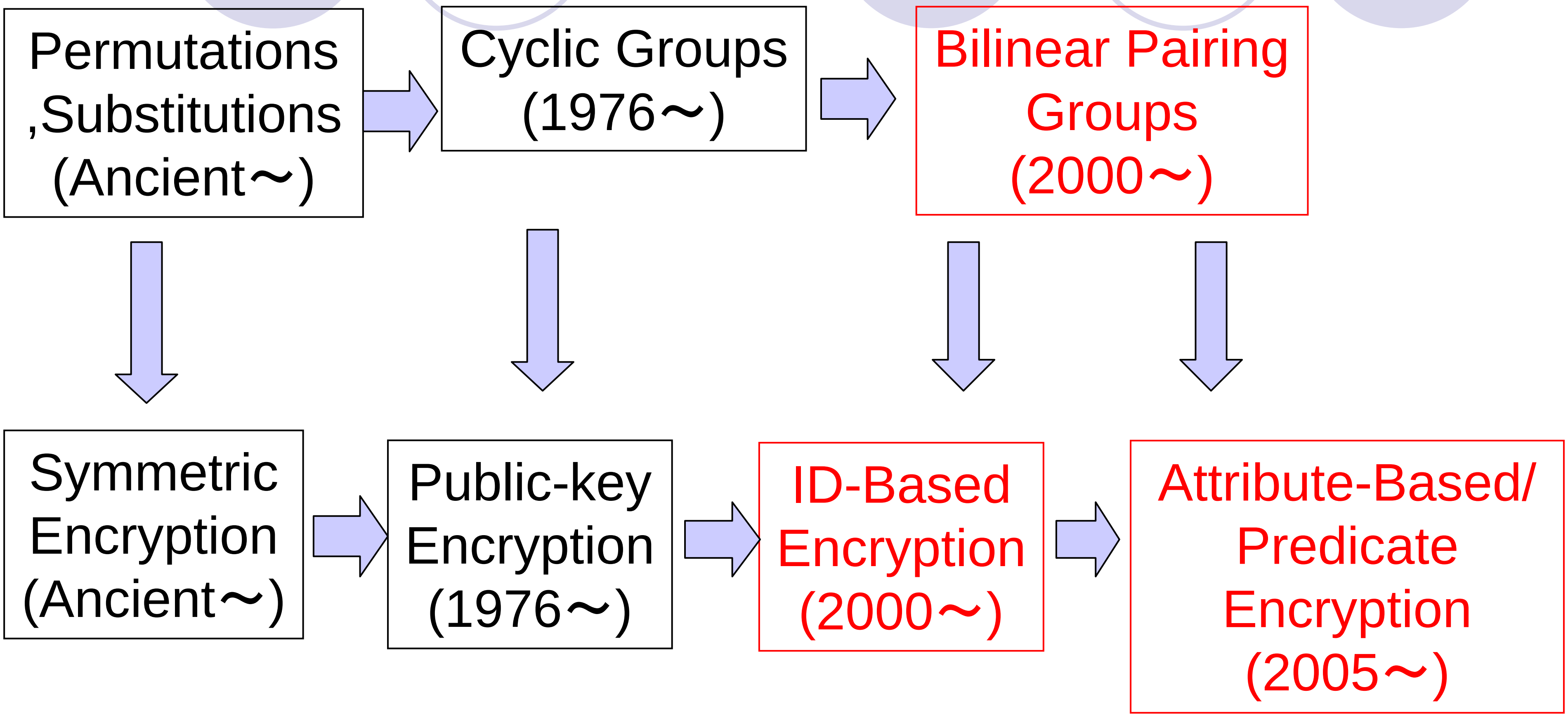
- Identity-Based Encryption (1984/2000～) S,SK/BF,..

  - senders and receivers are related by an arbitrary string (e.g., identity), and sender is not restricted.

- Predicate/Attribute-Based Encryption (2005～) SW,..

  - senders and receivers are only related by logical conditions (predicate-attribute relations）, and sender is not restricted.

Mathematics to Realize Cryptosystems



Cryptography and the Internet

Public-key cryptosystem

RSA scheme

IPSEC, SSL
PKI

Identity-Based Encryption

Attribute-Based / Predicate Encryption

1969 1976 1983 1988 1991 1993 2000 Present

Arpanet (the origin of the Internet) started

TCP/IP protocol (changed from original NCP)

Commercial usage started

World Wide Web by CERN

Browser (Mosaic)

Web 2.0

Cloud computing

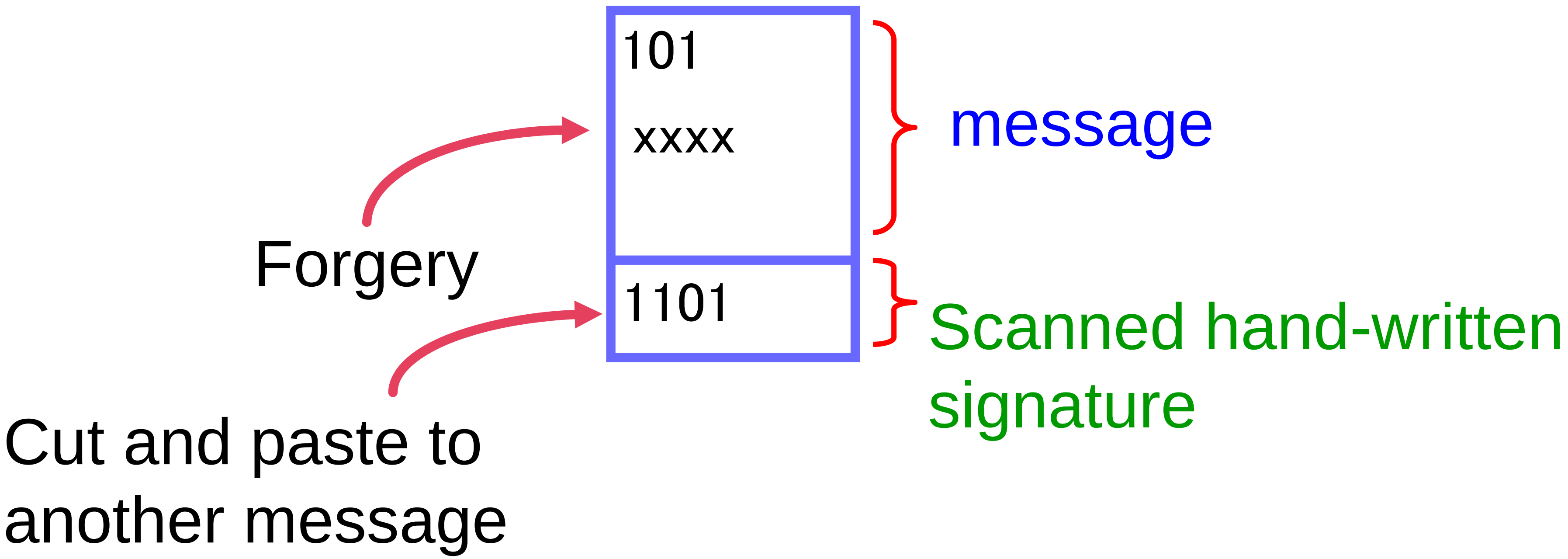
Authentication

Another problem raised in the early 1970's

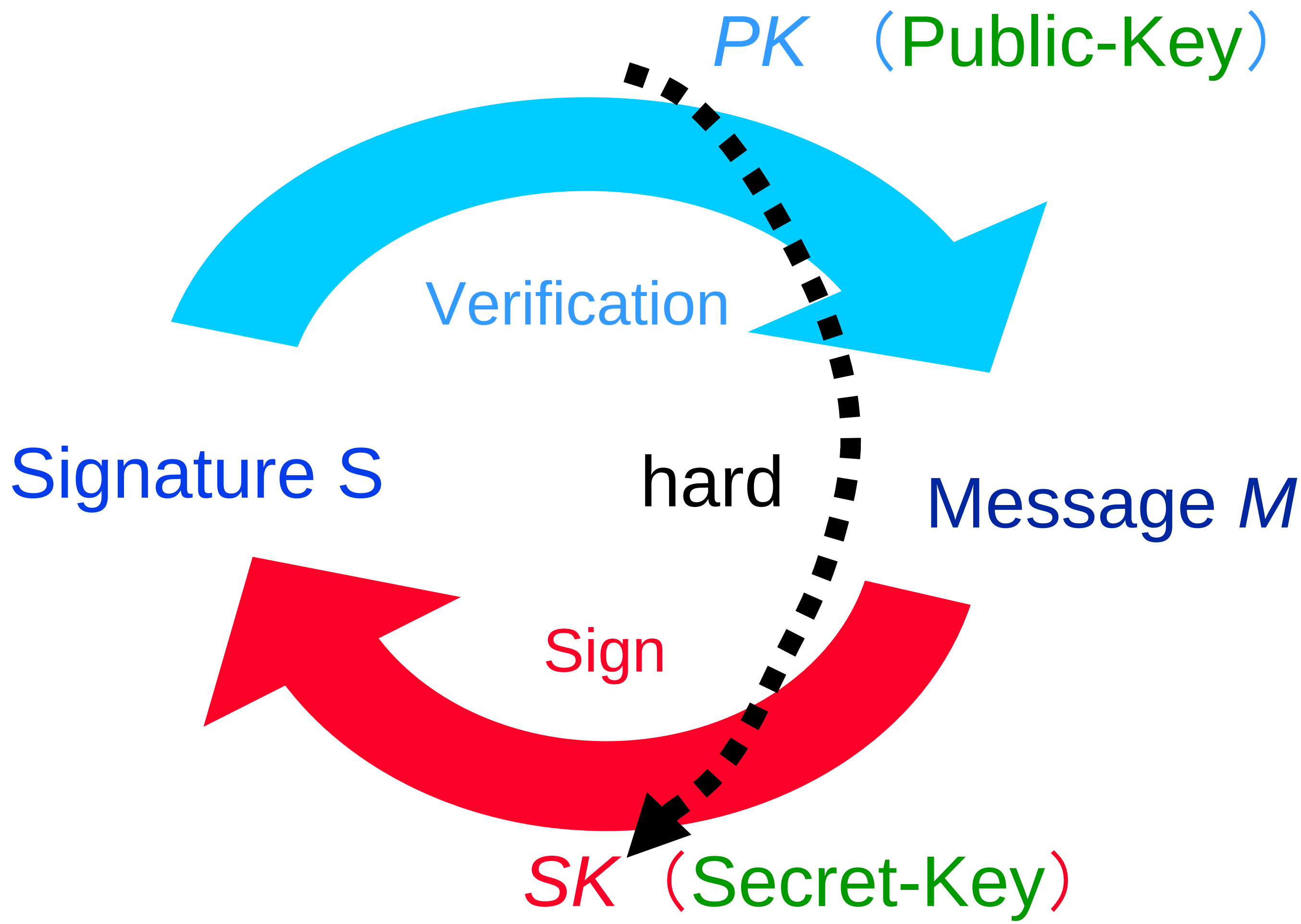
- Problem: Is it possible to sign on an electronic (digital) message?

Difficulty of Realizing Electronic Sigantures

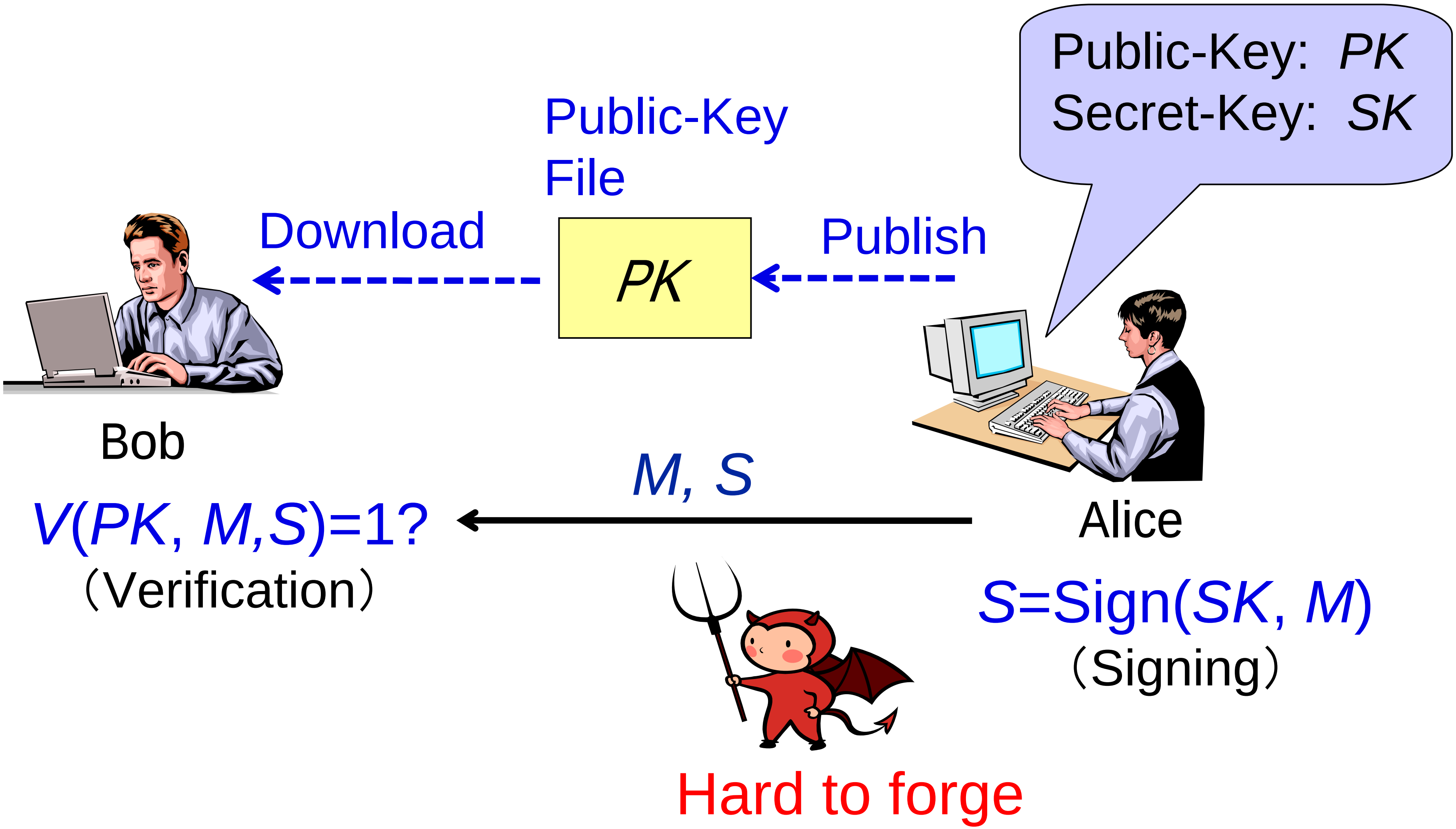
Easy to forge a digital message with no mark



Principle of Digital Signatures

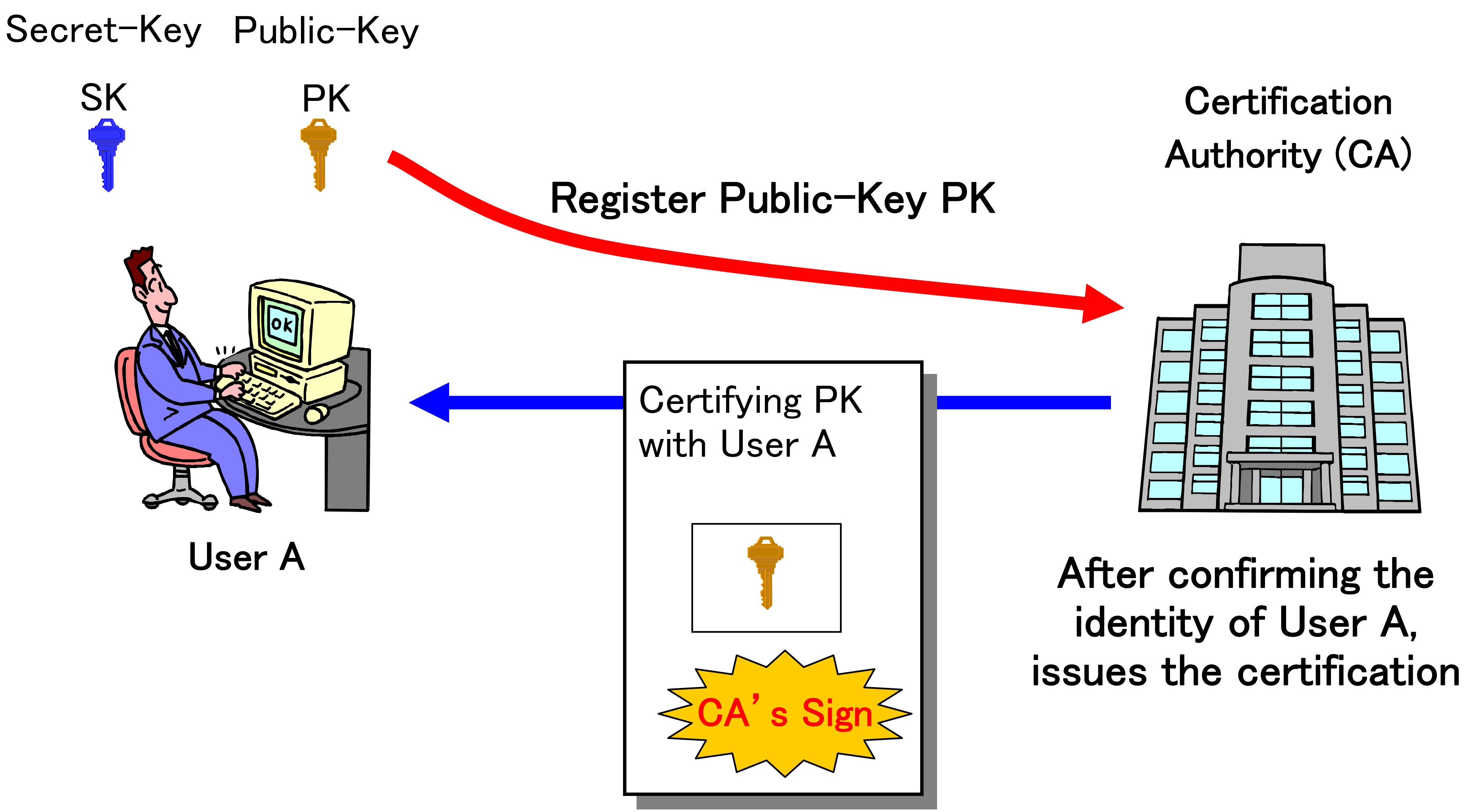


Digital Signatures



Public-Key Infrastructures (PKI) Certification Authority（CA）

Organization to certify a public-key

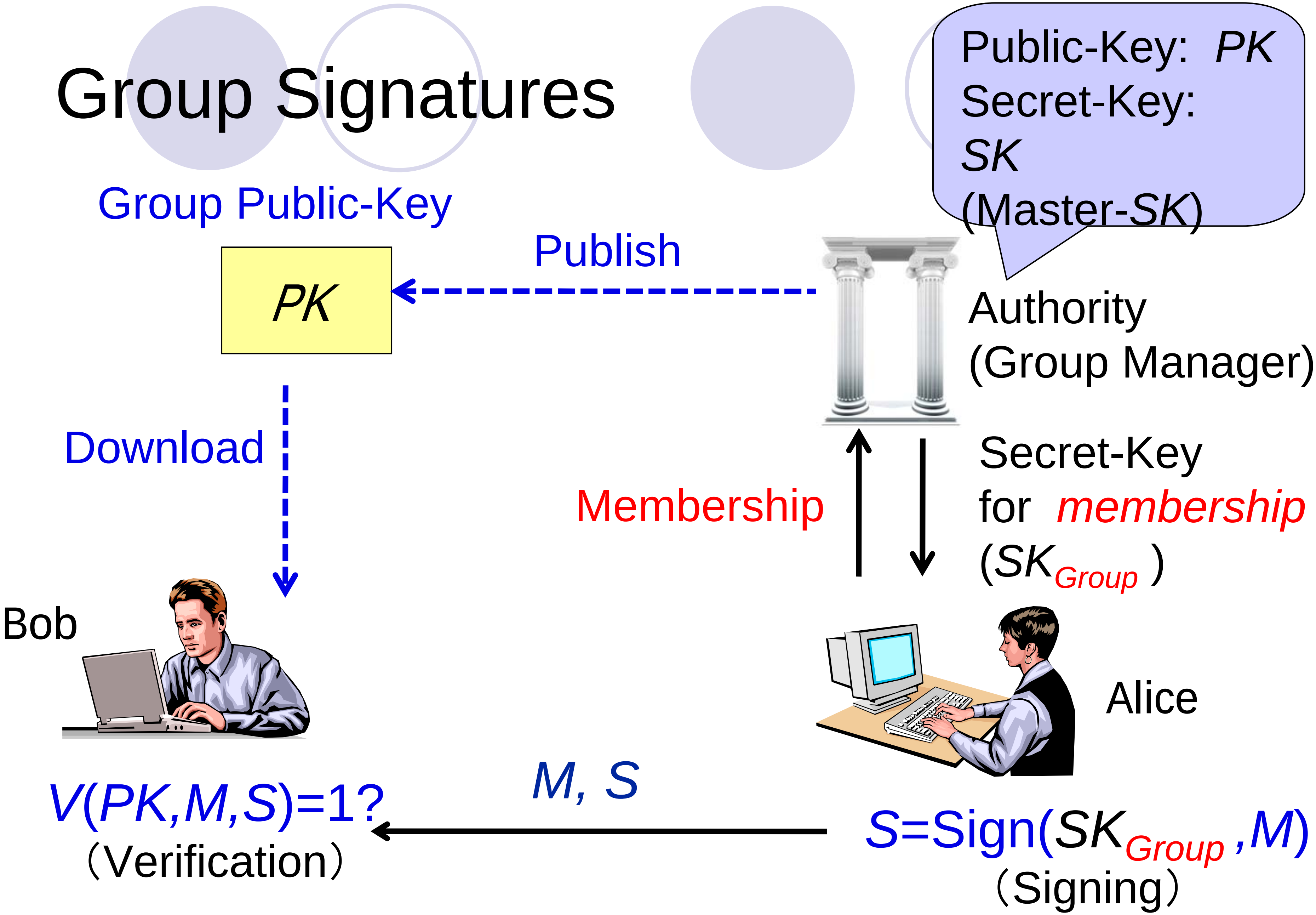


Privacy-Enhanced Authetication

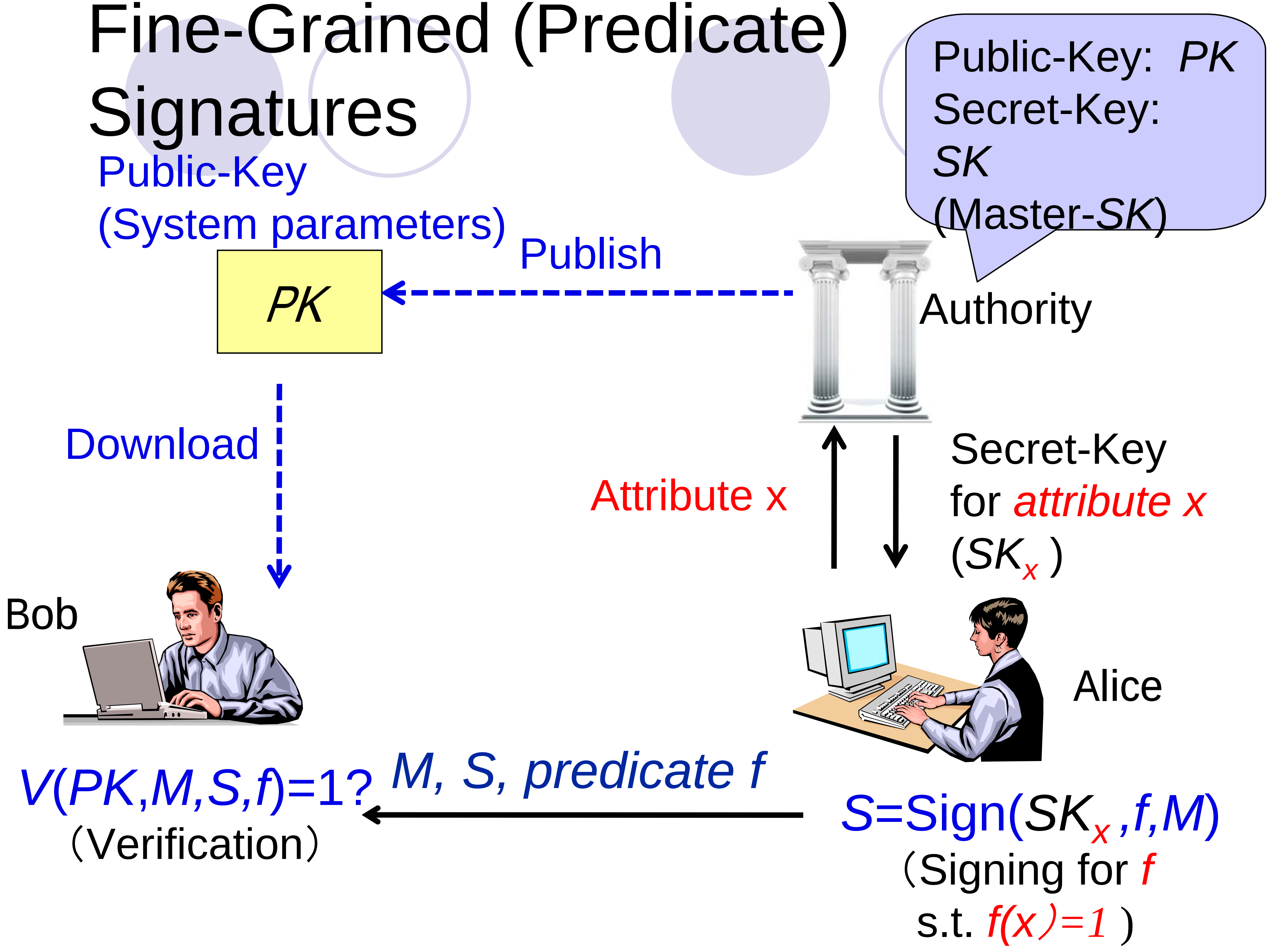
Privacy-Enhanced Signatures

- PKI-based digital signatures:

  The signer's identity of signatures is rigorously confirmed. It is good for the standard usage of applications of signatures.
- In some applications, it is not good, where the signer should be anonymous, and some qualification (e.g., a member of a group) of the signer should be authenticated.


Group Signatures
Public-Key: PK
Secret-Key: SK (Master-SK)
Group Public-Key
PK
Publish
Authority (Group Manager)
Download
Membership
Secret-Key for membership (SK_{Group})
Bob
Alice
M, S
V(PK,M,S)=1?
(Verification)
S=Sign(SK_{Group}, M)
(Signing)

Fine-Grained (Predicate) Signatures



Example of Predicates and Attributes

- Attribute x = (X,Y,Z)
  = ([Group: Group 2], [Age: 30], [Gender: Female])
- Secret-key SK_x is given to a person who has the attributes.
- Predicate *f* with parameters *a, b* and *c*:

  $f(X,Y,Z) \equiv (X = a) \wedge ((Y < b) \vee (Z = c))$, where

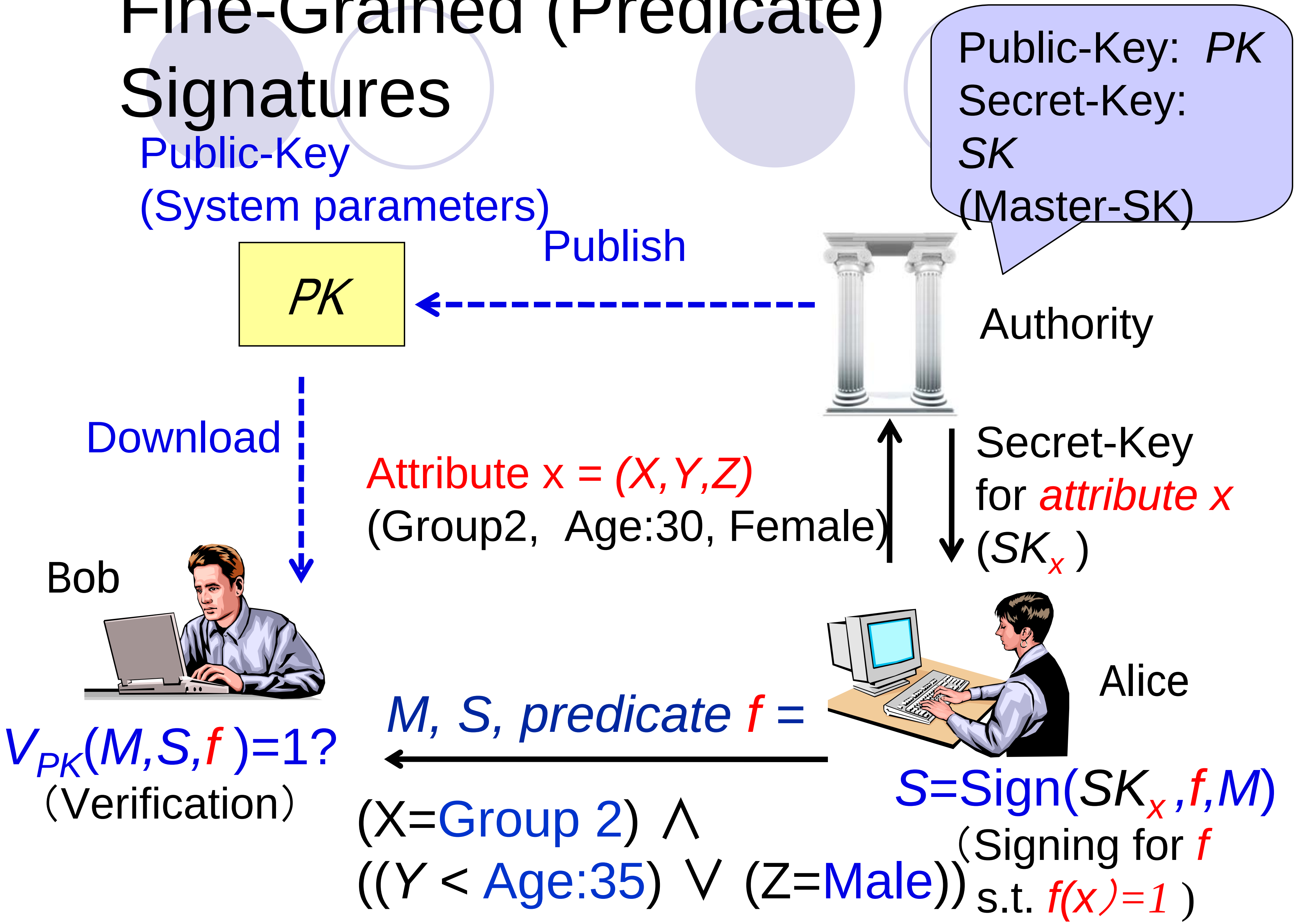
  a $\equiv$ [Group: Group 2],

  b $\equiv$ [Age: 35],

  c $\equiv$ [Gender: Male]
- A signature with predicate *f* implies that the attributes of the signer satisfies the predicate *f*,

  i.e., $(X=\mathit{Group\ 2}) \wedge ((Y < 35) \vee (Z=\mathit{Male})) = 1$ (True)

Fine-Grained (Predicate) Signatures



Example of Predicates and Attributes

- Attribute x = (X,Y,Z,W) = ([Group:Group 1], [Age: 20], [Gender:Male], [Member:Silver])
- Secret-key SK_x is given to a person who has the attributes.
- Predicate *f* with parameters *a, b, c* and *d*:

  $f(X,Y,Z,W) \equiv$ TH2 [(X = a), ((Y < b) $\vee$ (Z = c)), (W $\neq$ d)]

  (TH2: threshold function that accepts if at least 2 terms are true.)
- Application Example:

  a $\equiv$ [Group: Group 2], b $\equiv$ [Age: 30],

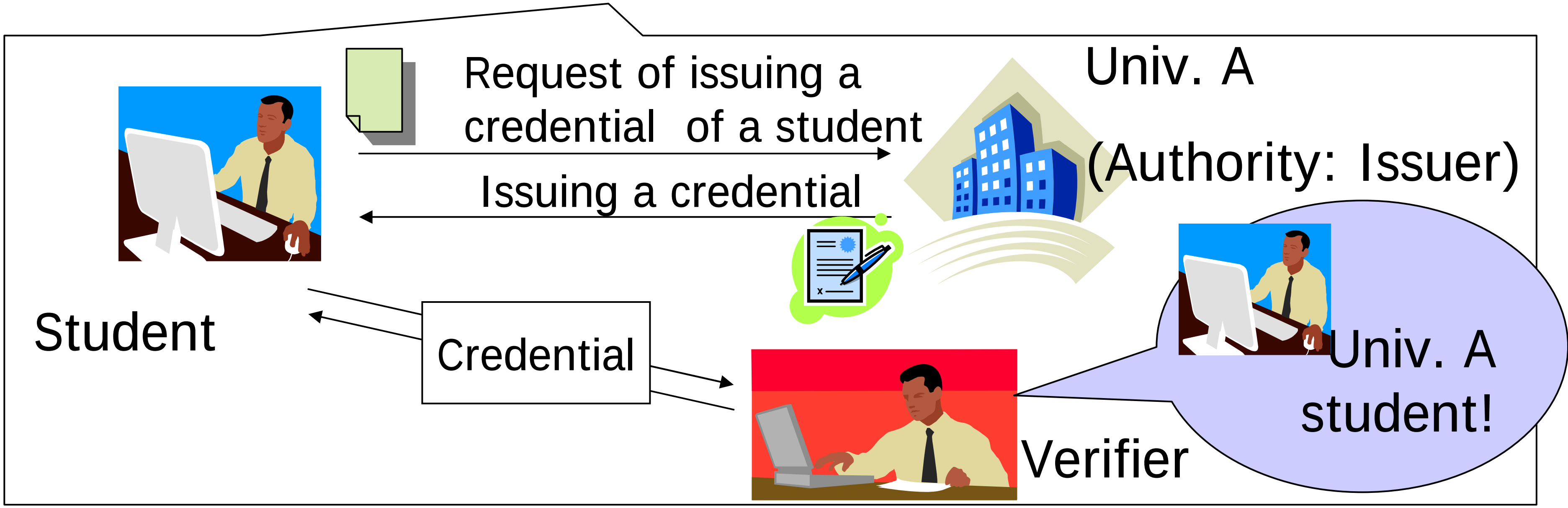
  c $\equiv$ [Gender: Female], d $\equiv$ [Member: Gold],
- A signature with predicate *f* implies that the attributes of the signer satisfies the predicate *f*, i.e.,

  TH2 [(X=*Group 2*), ((*Y* < *30*) $\vee$ (Z=Female)), (W $\neq$ Gold)] =1.

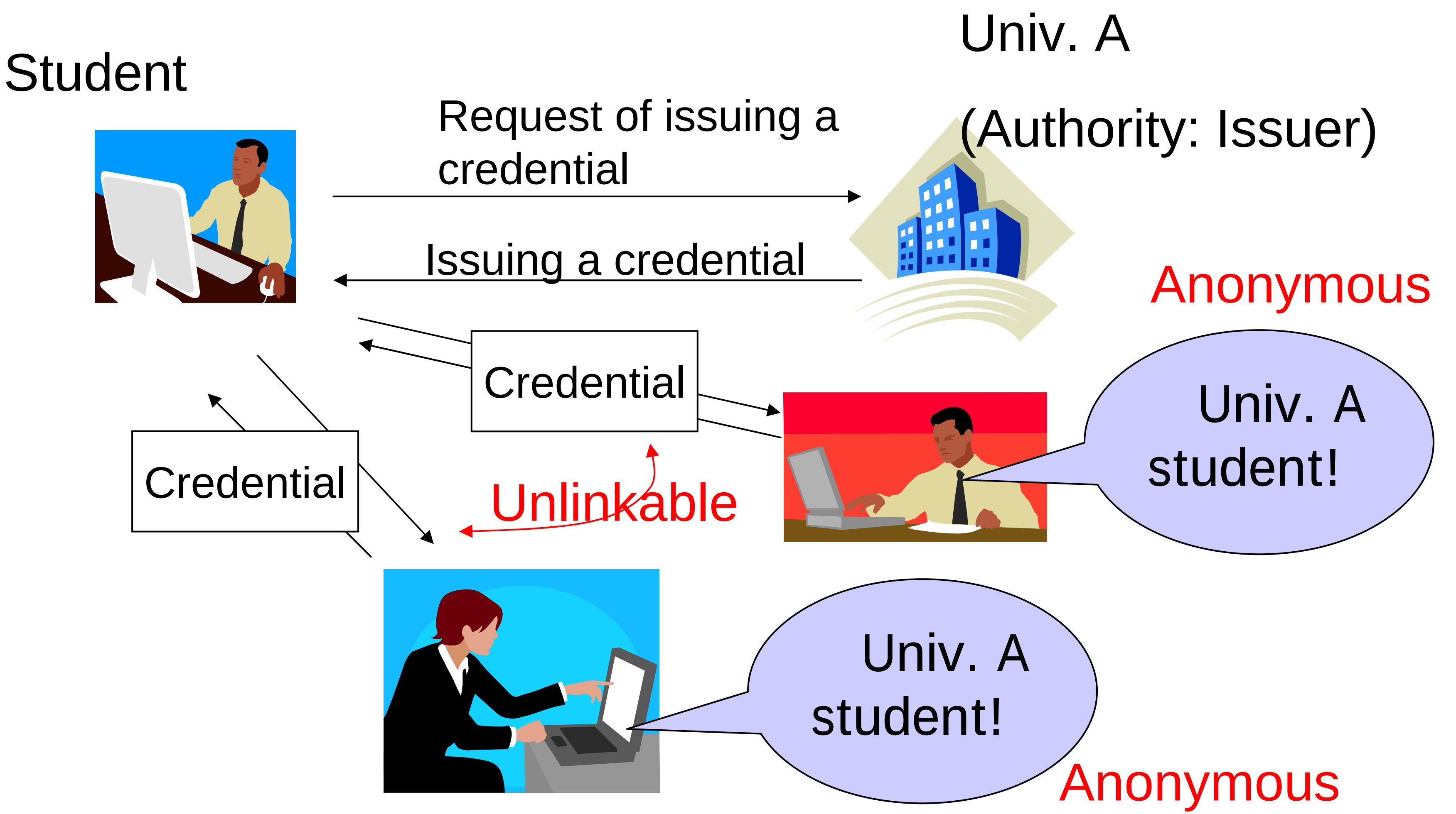
Credential

Certificate for person's qualification/attribut

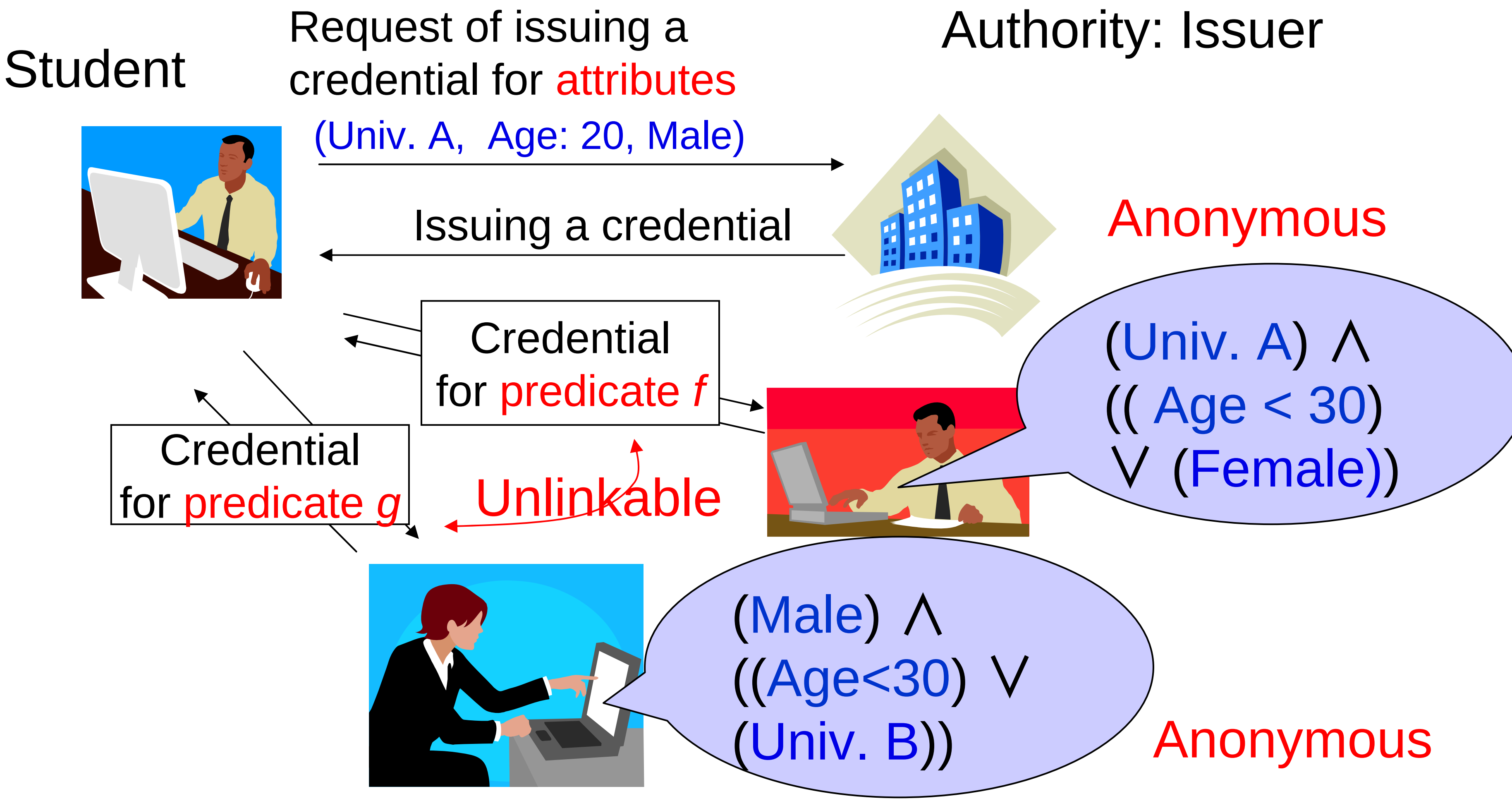
Eg.) "Student of University A", "Right to enter a room"



Anonymous Credential



Fine-Grained Anonymous Credential



For Applications of Fine-Grained Crypto to Practice

- Some standard frameworks (classifications and formats) defining attributes and predicates
- Management and usage rules and tools: New infrastructures (like PKI)
- It took around 20 years to establish PKI after the concept of public-key cryptosystem was proposed. It will take a certain period for the fine-grained cryptosystems to be widely used in practice.

For Your Further Study

- IACR (International Association for Cryptologic Research) ePrint Archive

  http://www.iacr.org/

- Key Words:

  - Predicate Encryption

  - Attribute-Based Encryption (ABE)

  - Attribute-Based Signatures (ABS)

Thank you !!