Public-Key Encryption Indistinguishable Under Plaintext-Checkable Attacks

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Motivation: Encryption Schemes under Plain DDH

Cyclic group $\mathbb{G}$ order p. Message $M \in \mathbb{G}$

	ElGamal
public key pk	$g,\ h$ $\in \mathbb{G}^2$
ciphertext c	$g^r,\ h^r \cdot M$ $\in \mathbb{G}^2$
security	IND-CPA ind. under chosen-plaintext attacks

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	ElGamal	**Cramer-Shoup**
public key pk	$g,\ h$ $\in \mathbb{G}^2$	$g_1,\ g_2,\ h,\ c,\ d$ $\in \mathbb{G}^5$
ciphertext c	$g^r,\ h^r \cdot M$ $\in \mathbb{G}^2$	${g_1}^r,\ {g_2}^r,\ h^r \cdot M,\ (cd^{\xi})^r$ $\in \mathbb{G}^4$ $(\xi = H({g_1}^r, {g_2}^r, h^r \cdot M))$
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	ElGamal	**Short Cramer-Shoup**	**Cramer-Shoup**
public key pk	$g,\ h$ $\in \mathbb{G}^2$	$g,\ h,\ c,\ d$ $\in \mathbb{G}^4$	$g_1,\ g_2,\ h,\ c,\ d$ $\in \mathbb{G}^5$
ciphertext c	$g^r,\ h^r \cdot M$ $\in \mathbb{G}^2$	$g^r,\ h^r \cdot M,\ (cd^\xi)^r$ $\in \mathbb{G}^3$ $(\xi = H(g^r, h^r \cdot M))$	${g_1}^r,\ {g_2}^r,\ h^r \cdot M,\ (cd^\xi)^r$ $\in \mathbb{G}^4$ $(\xi = H({g_1}^r, {g_2}^r, h^r \cdot M))$
security	IND-CPA	IND-PCA	IND-CCA
	ind. under chosen-plaintext attacks	ind. under plaintext-checkable [OP01] attacks	ind. under chosen-ciphertext attacks

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Encryption Scheme

$(pk, sk) \xleftarrow{\$} \mathsf{KG}(1^{\mathfrak{K}})$ generates a key pair (pk, sk)

$c \xleftarrow{\$} \mathsf{Enc}(pk, M)$ encrypts the plaintext M

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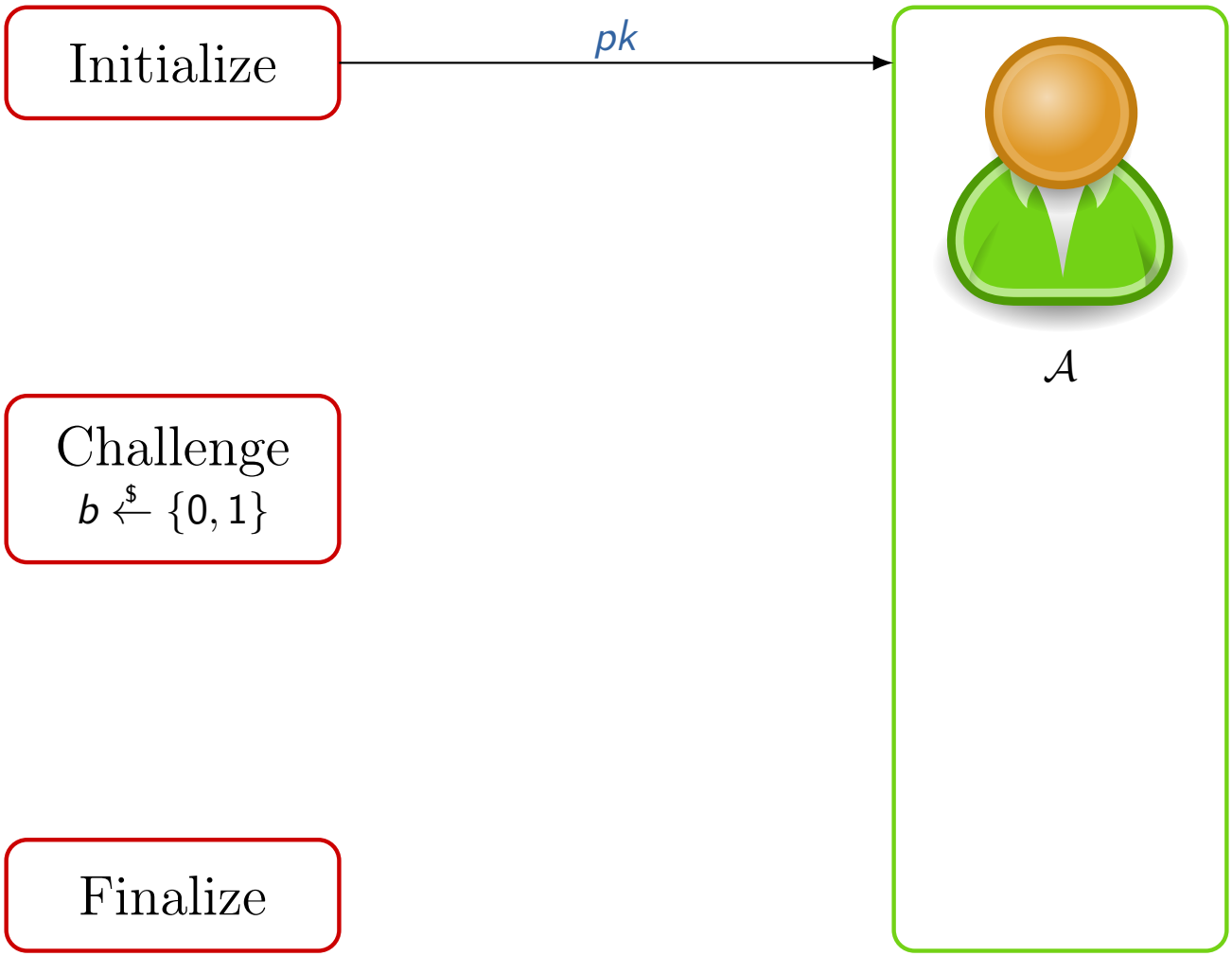
Correctness: if $(pk, sk) \xleftarrow{\$} \mathsf{KG}(1^{\mathfrak{K}})$,

$$\mathsf{Dec}(sk, \mathsf{Enc}(pk, M)) = M.$$

IND-**CPA** Security Notion



Advantage: $2\Pr[b = b'] - 1$.

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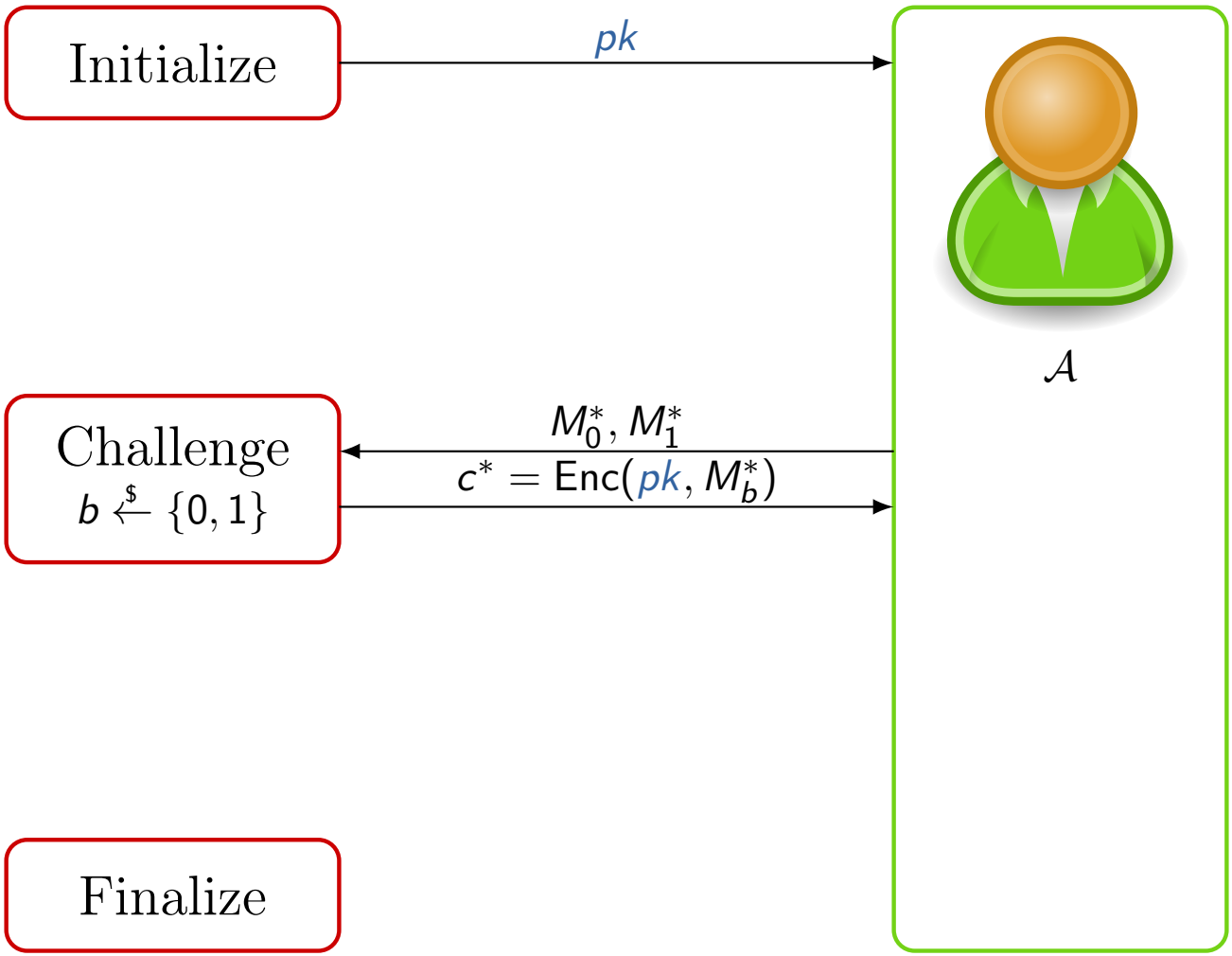

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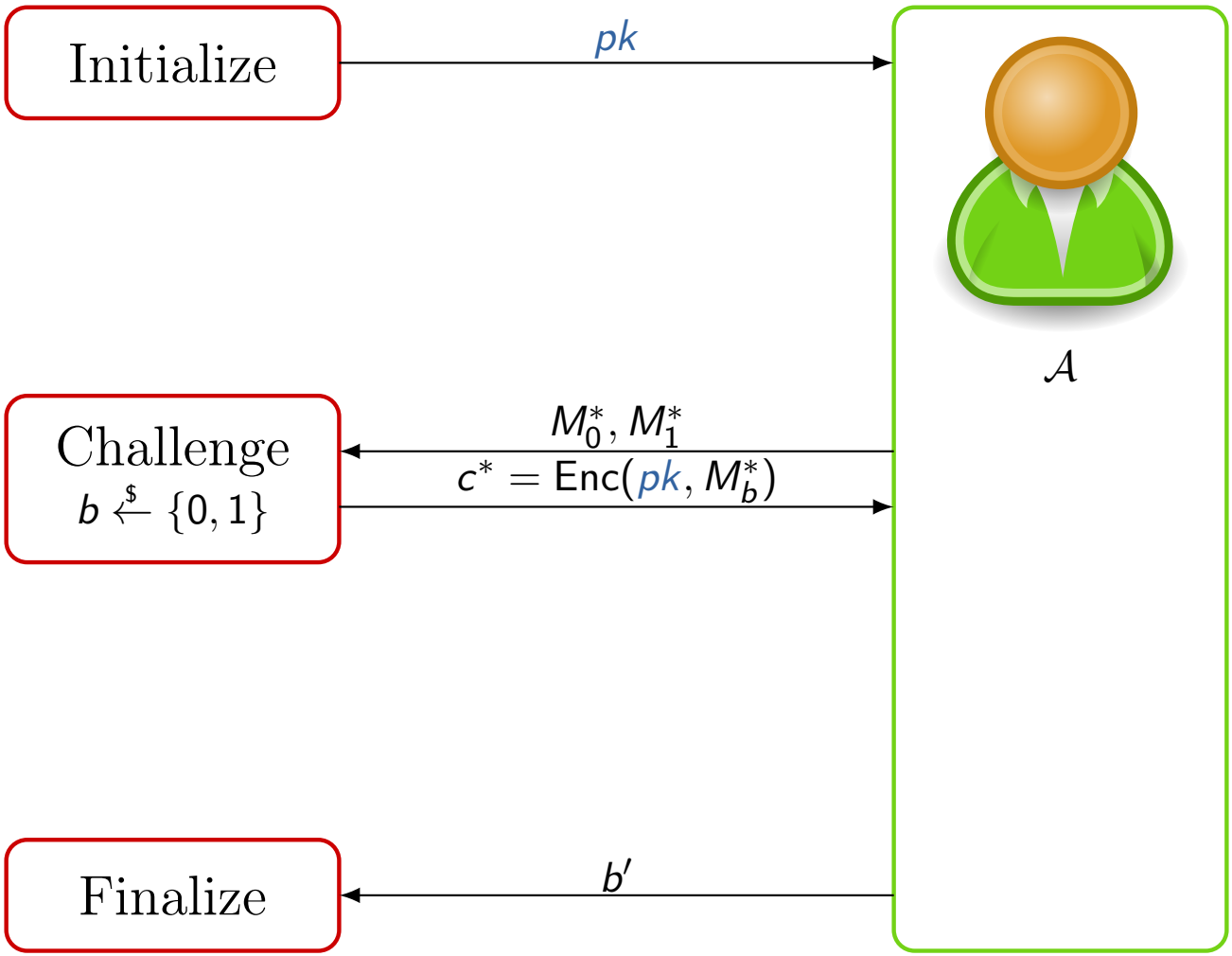

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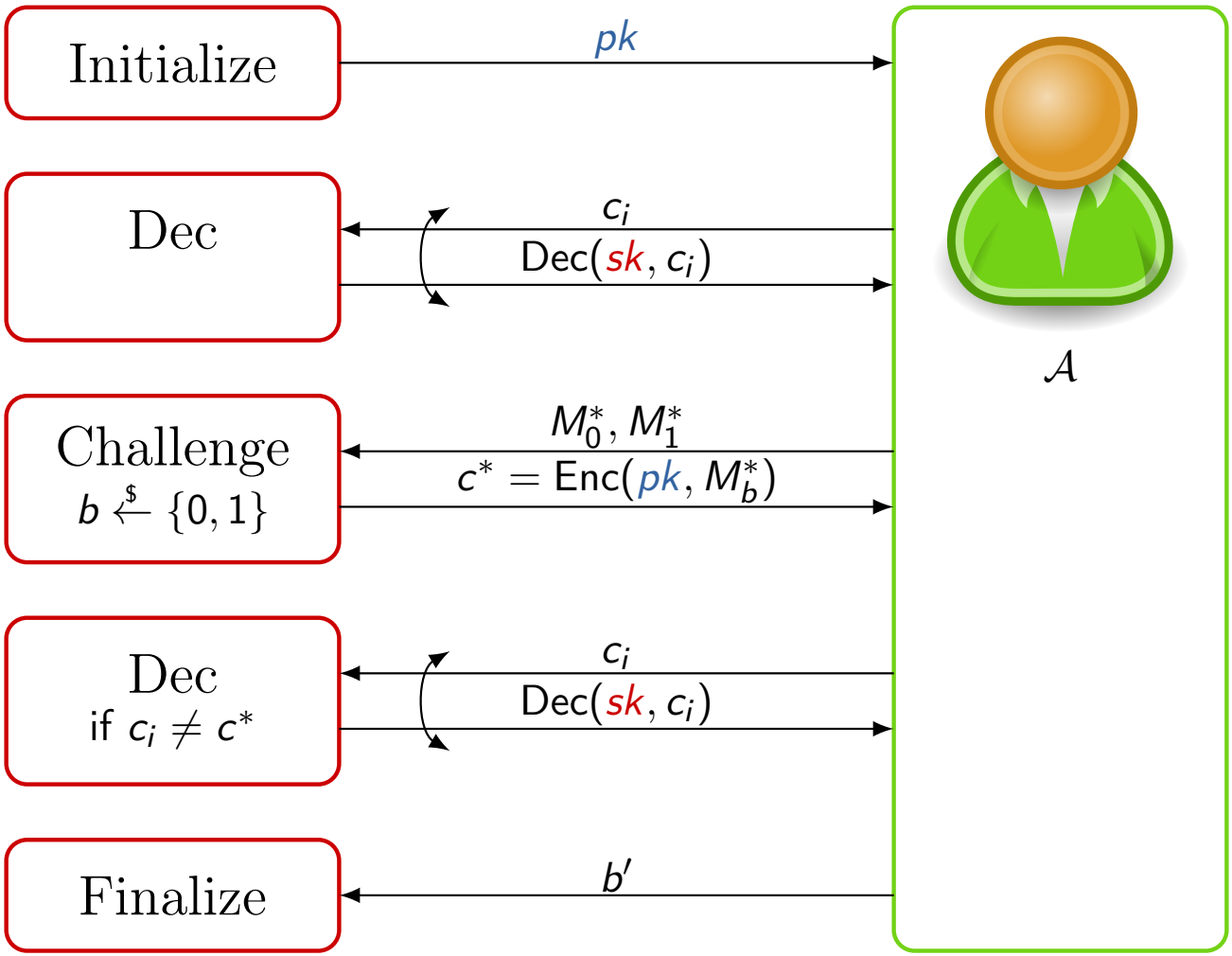
IND-**CCA** Security Notion



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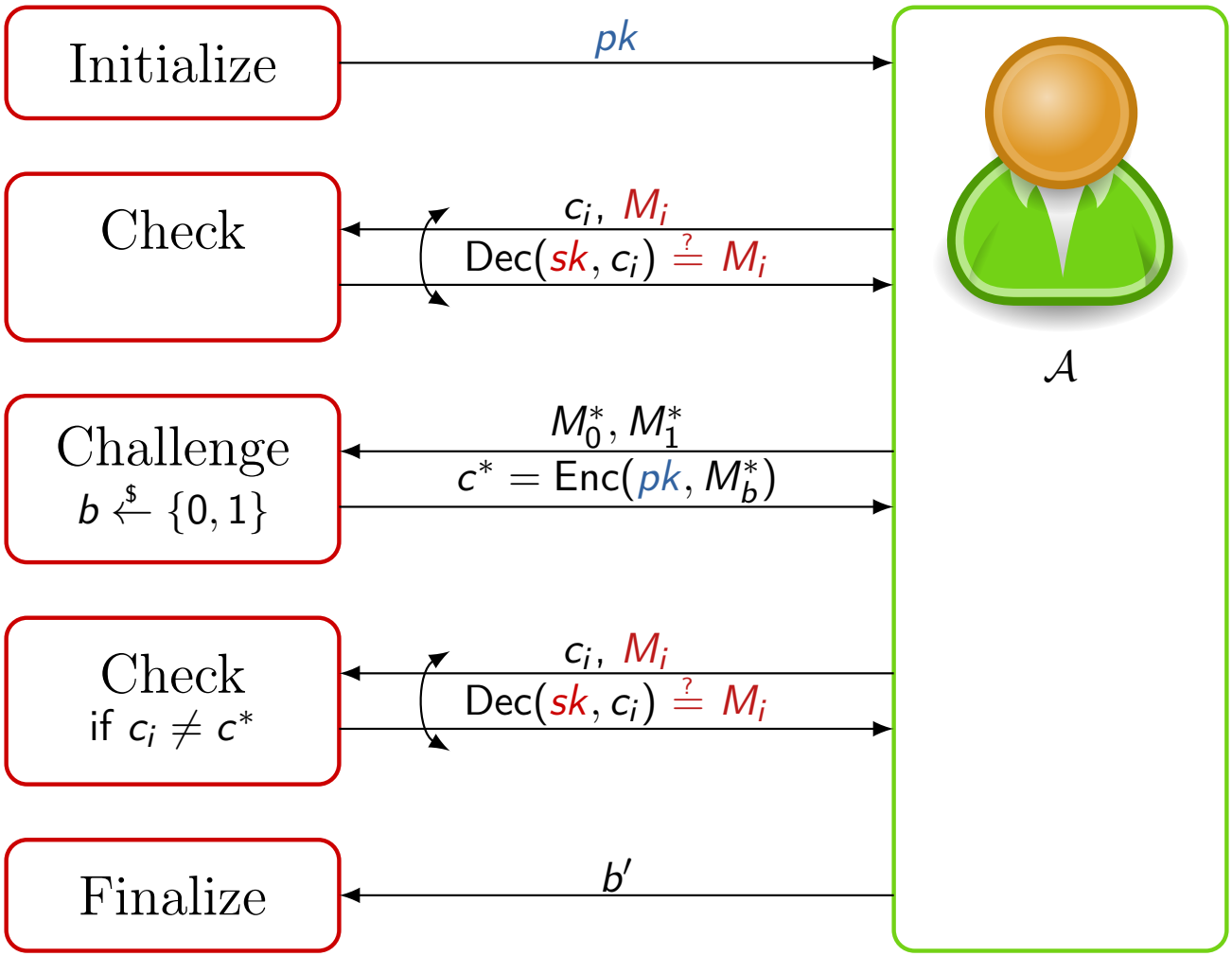
IND-**PCA** Security Notion



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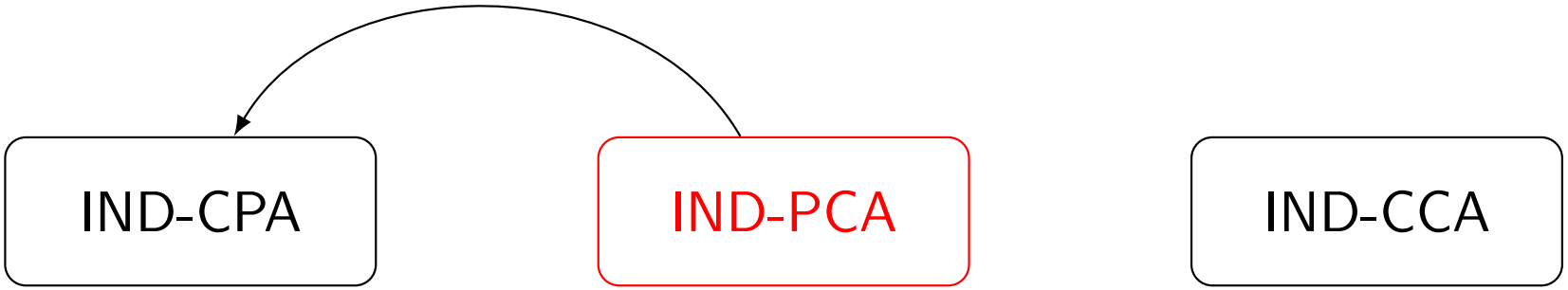

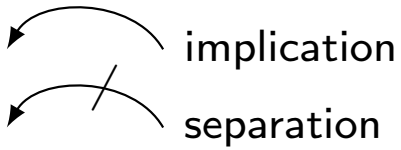

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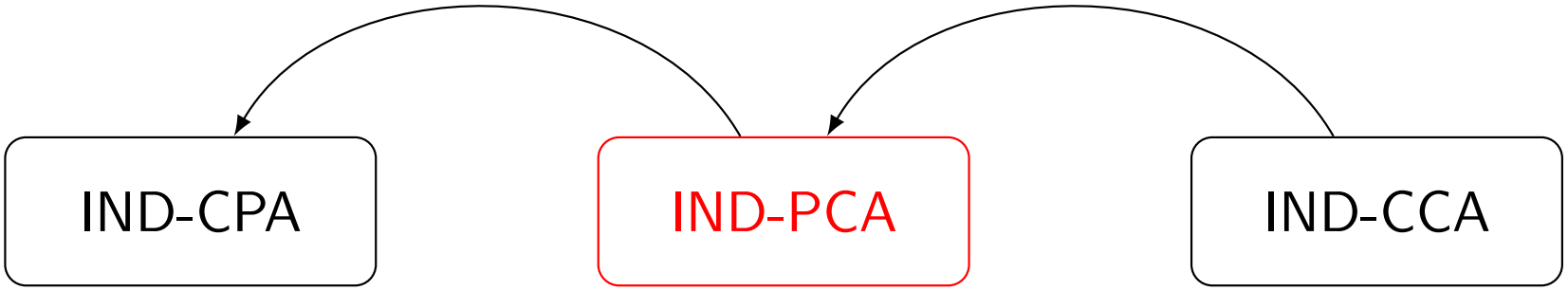

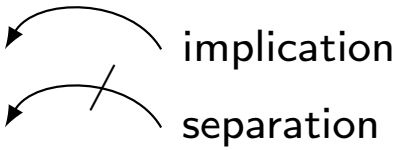

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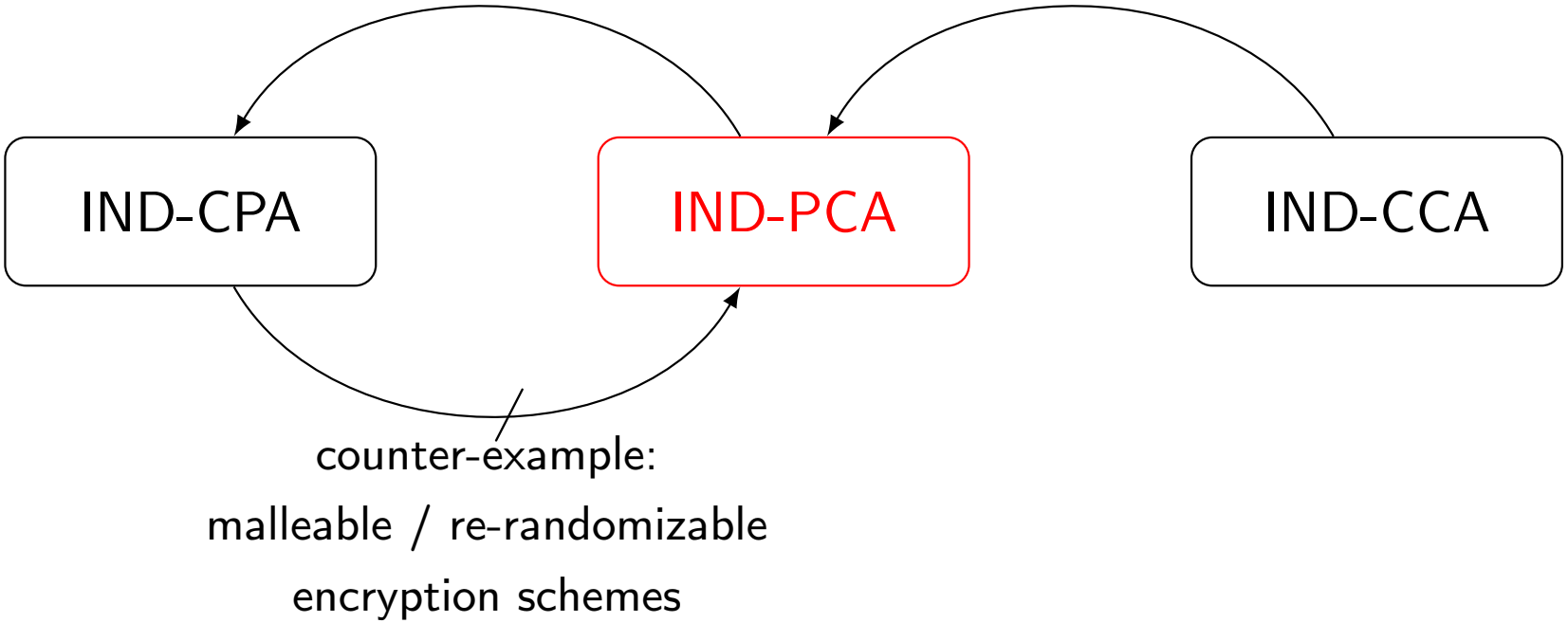

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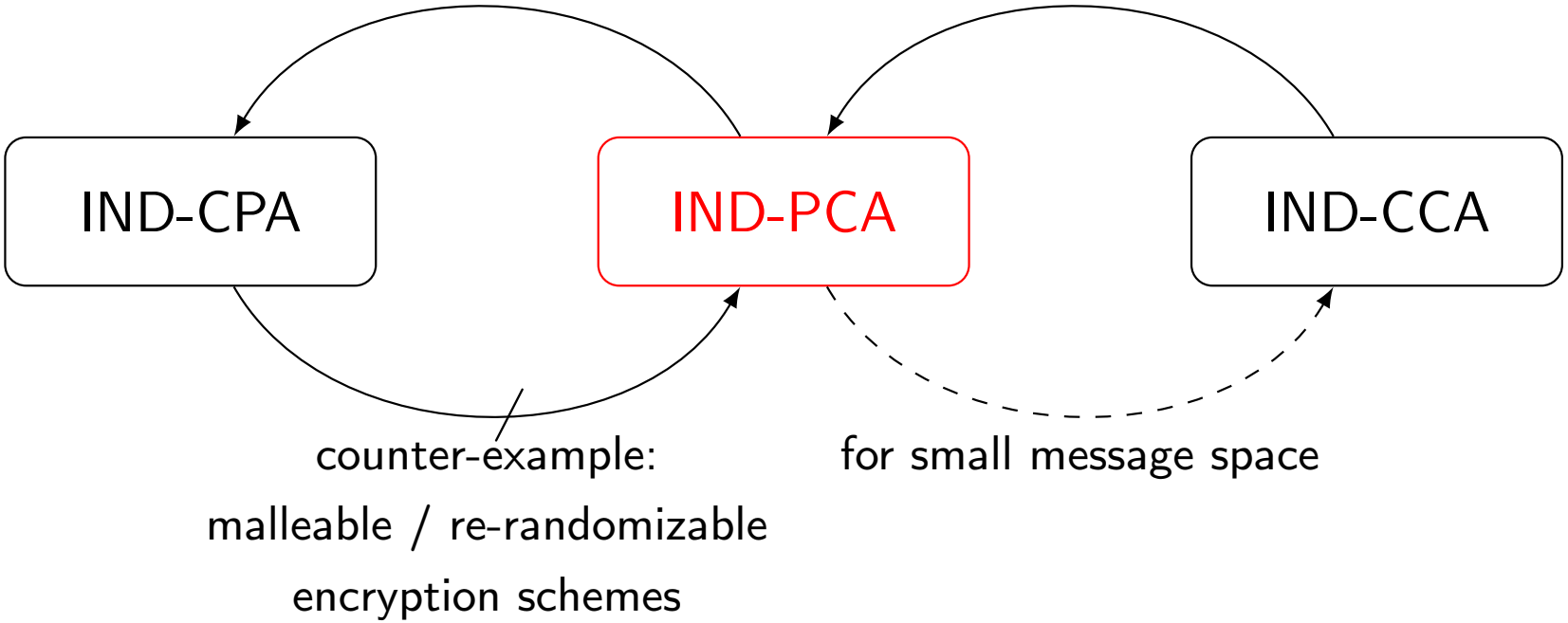

Applications of IND-PCA Schemes

- IND-CCA encryption with small message space
  - encryption of small passwords (e.g., PIN)
- IND-CCA encryption of bits
  - OT protocols based on hash proof systems [BBC+13]
  - bit-by-bit encryption of scalars
    e.g., Groth-Sahai proofs [GS08], blind signatures [BPV12], ...
- Direct use in PAKE schemes

Short Cramer-Shoup Encryption Scheme

- $\mathbb{G}$ cyclic group of order p, generator g;
- H: collision-resistant hash function;
- Key generation:

$$sk = (s,\ a,\ b,\ a',\ b') \xleftarrow{\$} \mathbb{Z}_p^5$$

$$pk = \left(g,\ h = g^s,\ c = g^a h^b,\ d = g^{a'} h^{b'}\right) \in \mathbb{G}^4$$

- Encryption of M: $r \xleftarrow{\$} \mathbb{Z}_p$

$$c \leftarrow \left(u = g^r,\ e = h^r \cdot M,\ v = \left(cd^{\xi}\right)^r\right) \in \mathbb{G}^3$$

with $\xi = H(u, e)$.

- Decryption of $c = (u, e, v)$:

$$M \leftarrow e/u^s \quad \text{and abort if } v \neq u^{a+\xi a'} \cdot (e/M)^{b+\xi b'}$$

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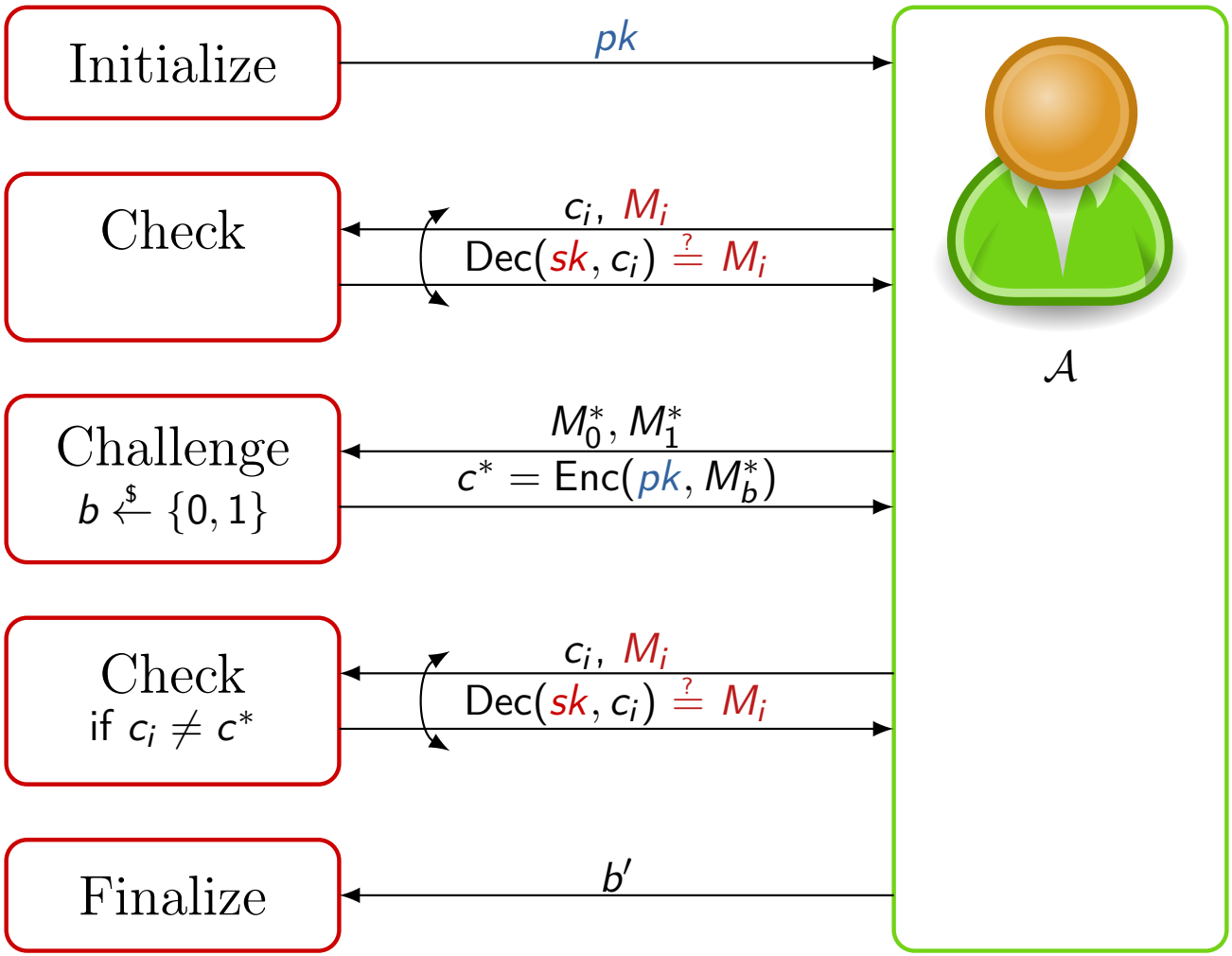

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Security Proof

Check $c_i = (u_i, e_i, v_i)$ is an encryption of M_i:

$$M_i \stackrel{?}{=} e_i / u_i^s \quad (1) \qquad v_i \stackrel{?}{=} u_i^{a+\xi_i a'} \cdot (e_i / M_i)^{b+\xi_i b'} \quad (2)$$

Challenge:

$$c^* = (u^*, e^*, v^*) = \left(g^{r^*},\ h^{r^*} \cdot M_b^*,\ (cd^{\xi^*})^{r^*} \right) \quad \text{with } \xi^* = H(u^*, e^*).$$

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v: 2-universal hash proof [CS02]:

correctness if $u = g^r$ and $e = h^r \cdot M$:

$$(v =)\ \left(cd^{\xi}\right)^r = u^{a+\xi_i a'} \cdot (e/M)^{b+\xi b'}$$

2-universality for any u_i, e_i, if $M_i \neq e_i/u_i^s$:

$$u_i^{a+\xi_i a'} \cdot (e_i/M_i)^{b+\xi_i b'} \quad \approx \quad \$$$

even seeing $u^{*a+\xi^* a'} \cdot (e^*/M_b^*)^{b+\xi^* b'}$, for one (u^*, e^*).

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correctness of v

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g^{r^*}	$h^{r^*} \cdot M_b^*$	$u^{*a+\xi^* a'} \cdot (e^*/M_b^*)^{b+\xi^* b'}$		✓	2-universality of v

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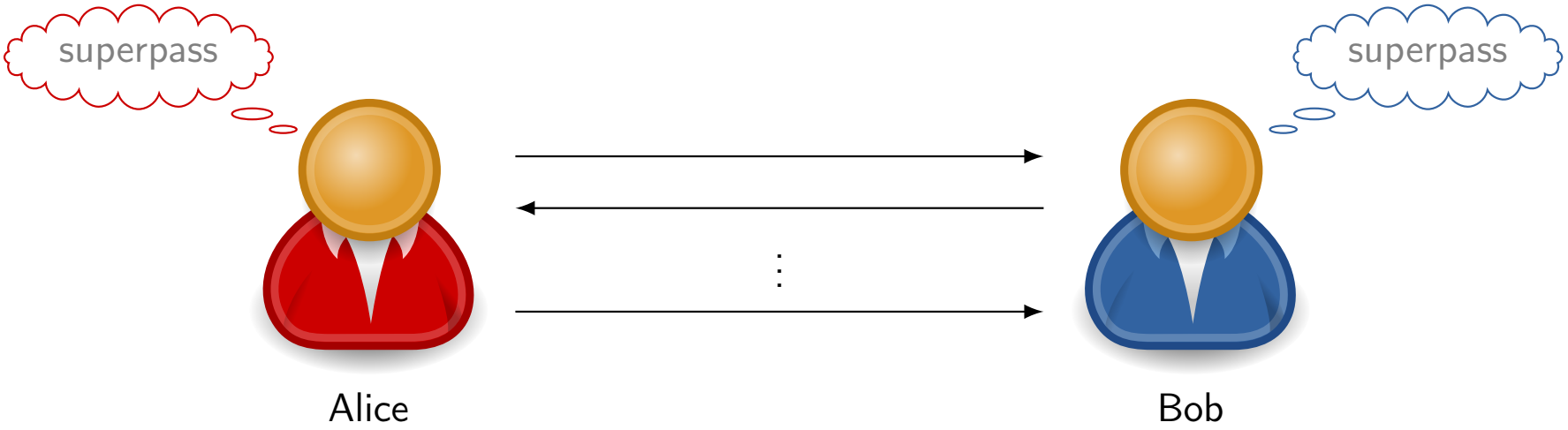
PAKE: Password-Authenticated Key Exchange

Goal: establishing a common secret key
from only a common low-entropy password



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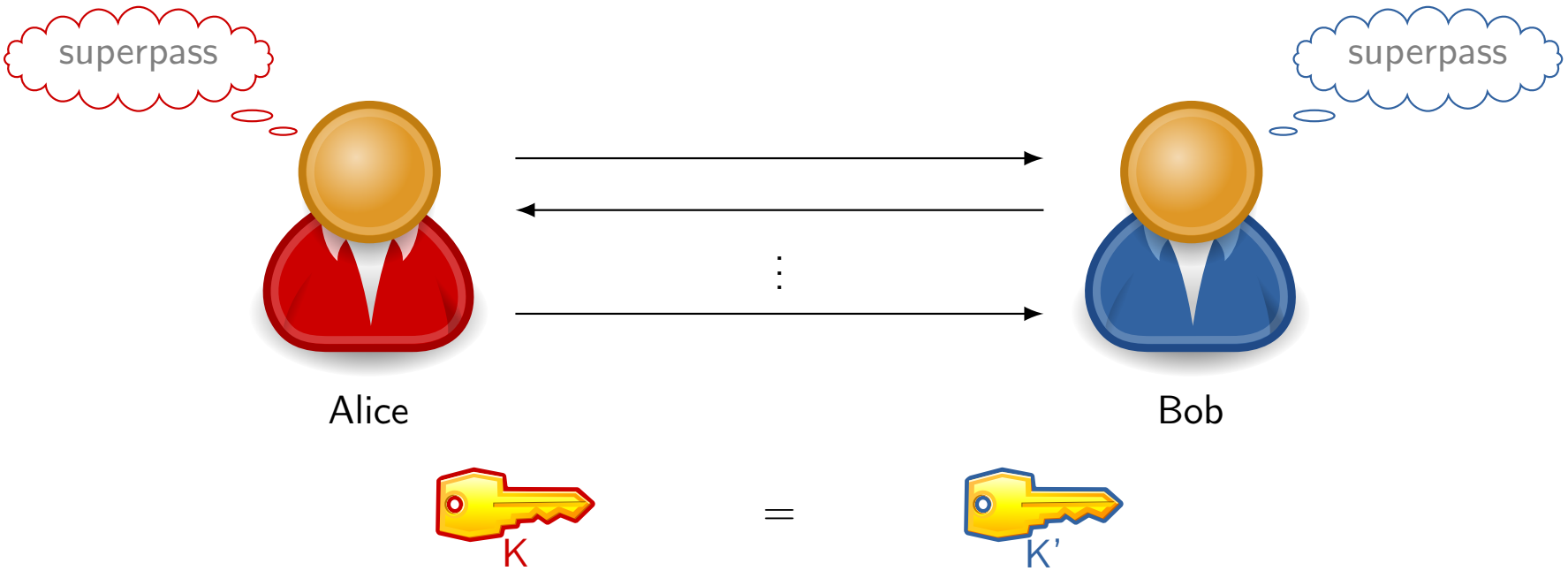

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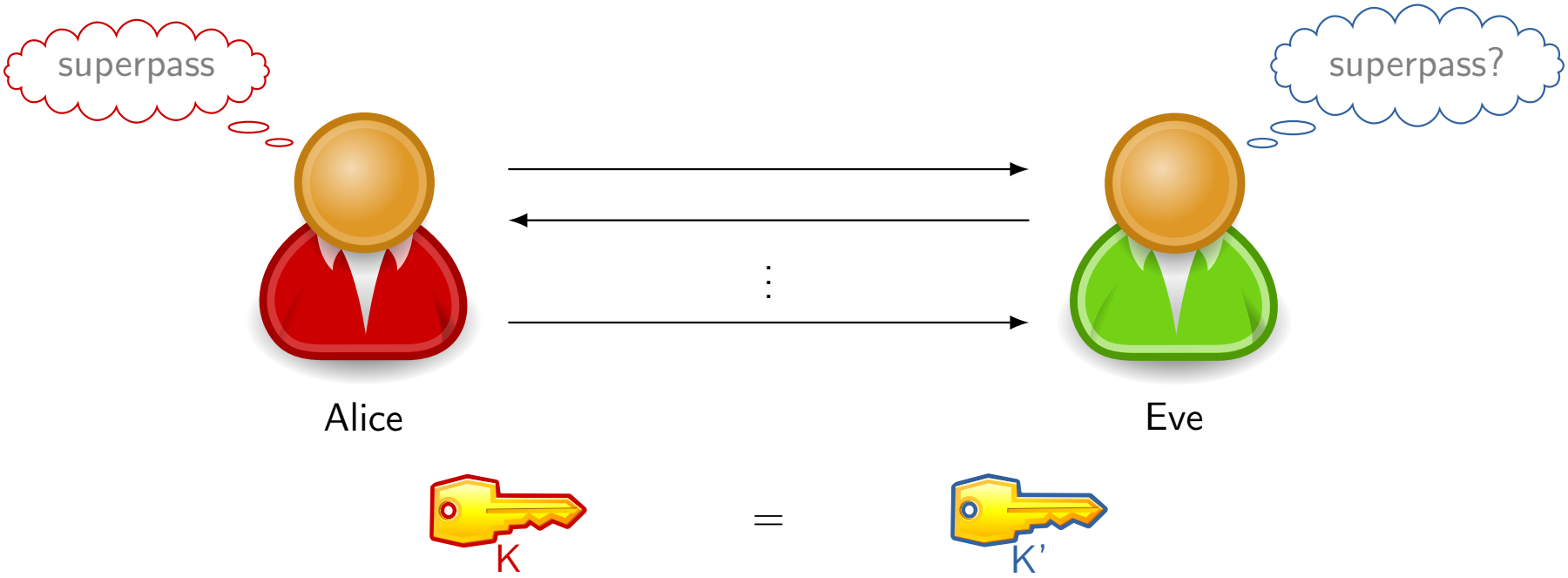

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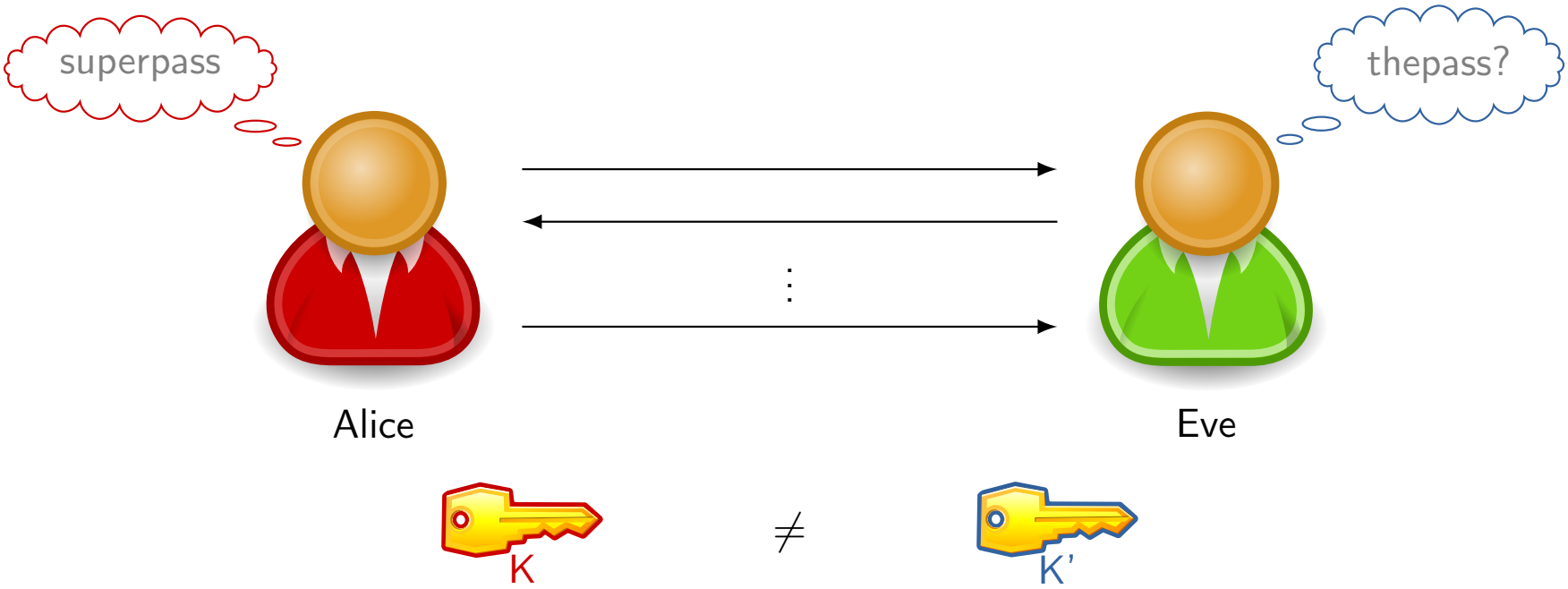
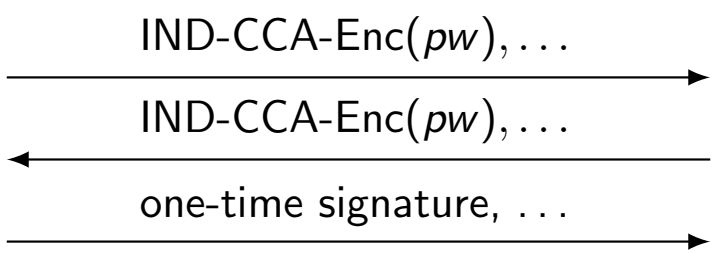


Intuitive security notion: only online dictionary attack works:

- at most one password can be tested per interaction;
- impossible to test password from an honest transcript.

PAKE Constructions from KOY/GL [KOY01, GL03] and JG/GK [JG04, GK10] Frameworks

- Each user sends a ciphertext of his password pw;



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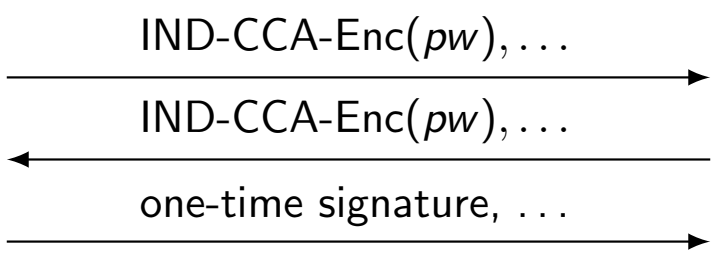

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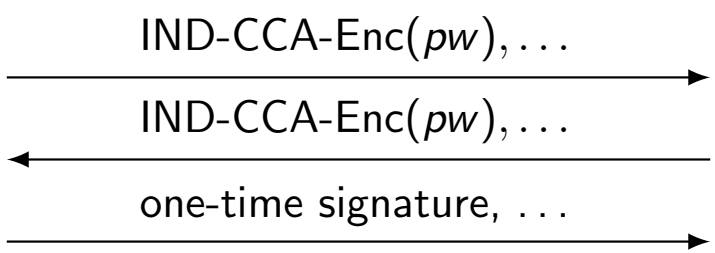

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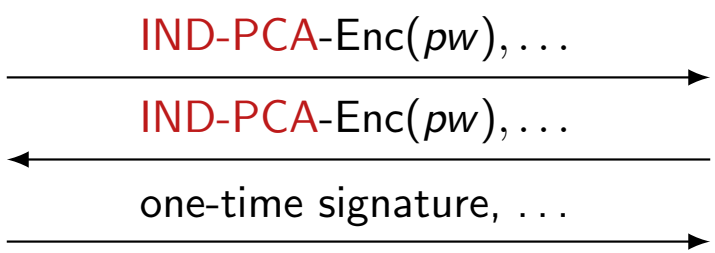
- Here: direct proof with IND-PCA (in the model in [BPR00]);



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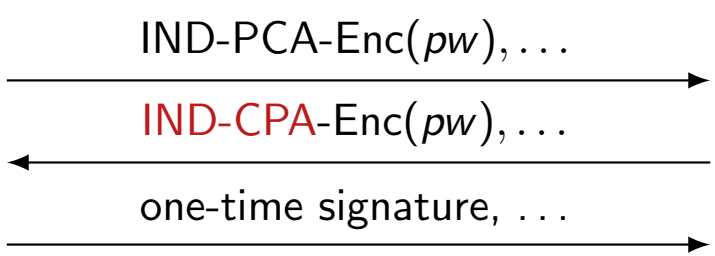
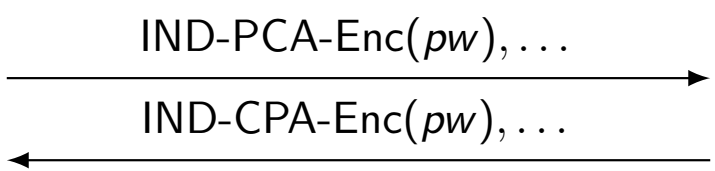
- Each user sends a ciphertext of his password pw;
- Small number of passwords $\longrightarrow$ IND-PCA sufficient;
  - ⚠ reduction loss = number of passwords;
- Here: direct proof with IND-PCA (in the model in [BPR00]);
  - \+ for KOY/GL, bonus can be applied:
    1 IND-CCA/PCA $\rightarrow$ 1 IND-CPA,



KOY/GL

PAKE Constructions from KOY/GL [KOY01, GL03] and JG/GK [JG04, GK10] Frameworks

- Each user sends a ciphertext of his password pw;
- Small number of passwords $\longrightarrow$ IND-PCA sufficient;
  - ⚠ reduction loss = number of passwords;
- Here: direct proof with IND-PCA (in the model in [BPR00]);
  - \+ for KOY/GL, bonus can be applied:
    1 IND-CCA/PCA $\rightarrow$ 1 IND-CPA, $\Rightarrow$ remove 1 round + 1 sig.



KOY/GL

Diffie-Hellman Based PAKE Constructions (BPR model)

	R / F	Assumptions		Complexity: Com.	Complexity: Time
EKE [BM92, BPR00]	1 / 2	ICM	CDH	$2 \times G$	4 exp
SPAKE2 [AP05]	1 / 2	ROM	CDH	$2 \times G$	4 exp
GK [JG04, GK10]	3 / 3	CRS	$\text{DDH}_{+\text{PRG}}$	$7 \times G$	18 exp
GL [KOY01, GL03]	3 / 3	CRS	DDH	$\approx 10 \times G$	27 exp
KV [KV11, BBC+13]	1 / 2	CRS	DDH	$12 \times G$	34 exp
GK-SPOKE	2 / 2	CRS	$\text{DDH}_{+\text{PRG}}$	$6 \times G$	17 exp
GL-SPOKE	2 / 2	CRS	DDH	$7 \times G$	21 exp
KV-SPOKE	1 / 2	CRS	DDH	$10 \times G$	30 exp

R: rounds, F: flows;
ICM: ideal-cipher model, ROM: random-oracle model
CRS: common reference string;
Variant of GK with Kurosawa-Desmedt [KD04, GS04] possible.

Thank you for your attention!

- New security notion: IND-PCA inspired from [OP01];
- New (algebraic) encryption scheme: Short Cramer-Shoup:

$$c = \left(u = g^r,\ e = h^r \cdot M,\ v = \left(cd^{\xi}\right)^r\right) \quad \text{with } \xi = H(u, e);$$

- Applications:
  - small messages/scalar/bit IND-CCA encryption;
  - PAKE from KOY / GL and GK frameworks;

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